TOMSK POLYTECHNIC UNIVERSITY
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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

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

MASTER'S GRADUATION THESIS

Topic of research work
Design and production of an individual collimator for electron radiation therapy using rapid prototyping technologies

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Nuclear medicine	Cherepennikov Yu.M	Ph.D		

Tomsk – 2020

EXPECTED LEARNING OUTCOMES

Learning outcome (LO) code	Learning outcome (a graduate should be ready)	Requirements of the FSES HE, criteria and / or interested parties
Professional competencies		
LO1	To apply deep mathematical, scientific, socio-economic and professional knowledge for conducting theoretical and experimental research in the field of the use of nuclear science and technology.	FSES HE Requirements (BPC-1,2, PC-3, UC-1,3), Criterion 5 RAEE (p 1.1) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of “medical physicist”
LO2	To demonstrate ability to define, formulate, and solve interdisciplinary engineering tasks in the nuclear field using professional knowledge and modern research methods.	FSES HE Requirements (PC-9,10,13,14,15, BPC-1,3), Criterion 5 RAEE (p 1.2) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of “medical physicist”
LO3	To plan and conduct analytical, simulation and experimental studies in complex and uncertain conditions using modern technologies, and to evaluate critically research results.	FSES HE Requirements (PC-1,13,22, UC-2, BPC-1), Criterion 5 RAEE (p 1.3) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of “medical physicist”
LO4	To use basic and special approaches, skills and methods for identification, analysis, and solution of technical problems in the field of nuclear science and technology.	FSES HE Requirements (PC-2,4,6,8, UC-2, BPC-1), Criterion 5 RAEE (p 1.4) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of “medical physicist”
LO5	To operate modern physical equipment and instruments, to master technological processes in the course of preparation for the production of new materials, instruments, installations, and systems.	FSES HE Requirements (PC-5,7,11,12, UC-2, BPC-1), Criterion 5 RAEE (p 1.4) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of “medical physicist”
LO6	To demonstrate ability to develop multioption schemes for achieving production goals with the effective use of available technical means and resources.	FSES HE Requirements (PC-16-21,23), Criterion 5 RAEE (p 1.5) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of “medical physicist”

Learning outcome (LO) code	**Learning outcome (a graduate should be ready)**	**Requirements of the FSES HE, criteria and / or interested parties**
Cultural competencies		
LO7	To demonstrate ability to use a creative approach to develop new ideas and methods for designing nuclear facilities, as well as to modernize and improve the applied technologies of nuclear production.	FSES HE Requirements (BPC-1,3, UC-3), Criterion 5 RAEE (p 2.4,2.5)
Basic professional competencies		
LO8	To demonstrate skills of independent learning and readiness for continuous self-development within the whole period of professional activity.	FSES HE Requirements (UC-3, PC-1, BPC-1), Criterion 5 RAEE (p 2.6) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of "medical physicist"
LO9	To use a foreign language at a level that enables a graduate to function successfully in the international environment, to develop documentation, and to introduce the results of their professional activity.	FSES HE Requirements (PC-11,16,17, BPC-3), Criterion 5 RAEE (p 2.2) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of "medical physicist"
LO10	To demonstrate independent thinking, to function efficiently in command-oriented tasks and to have a high level of productivity in the professional (sectoral), ethical and social environments, to lead professional teams, to set tasks, to assign responsibilities and bear liability for the results of work.	FSES HE Requirements (PC-18,23, UC-2), Criterion 5 RAEE (p 1.6,2.3) requirements of the Ministry of Health and Social Development of the Russian Federation under the unified skills guide for positions of managers, specialists and non-manual workers for the position of "medical physicist"

TOMSK POLYTECHNIC UNIVERSITY
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School School of Nuclear Science & Engineering
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Level of education Master Degree Program
Division Division for Nuclear-Fuel Cycle
Period of completion 2018/2019 and 2019/2020 academic years

Form of presenting the work:

Master's Thesis

SCHEDULED ASSESSMENT CALENDAR
for the Master's Graduation Thesis completion

Deadline for completion of Master's Graduation Thesis:	

Assessment date	Title of section (module) / type of work (research)	Maximum score for the section (module)
10.01.2020	1. Preparation of technical specifications and selection of research areas	10
12.02.2020	2. Development of a common research methodology	5
20.02.2020	3. Selection and study of materials on the topic	10
16.03.2020	4. Manufacturing collimation devices	15
23.03.2020	5. Experimental research	20
31.03.2020	6. Processing received data	15
15.04.2020	7. Registration of the work performed	15
29.05.2020	8. Preparation for defending a dissertation	10

COMPILED BY:
Scientific supervisor

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Cherepennikov Yu.M.	Ph.D		

Adviser

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Stuchebrov S.G.	Ph.D		

AGREED BY:
Director of the programme

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Cherepennikov Yu.M.	Ph.D		

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

For a student:

Group	Full name
0AM8M	Grigorieva Anna Anatolievna

School	School of Nuclear Science & Engineering	**Division**	Division for Nuclear-Fuel Cycle
Degree	Master Degree Program	**Field of training/programme**	14.04.02 Nuclear physics and technology / Nuclear medicine

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*	*Costs of special equipment 39 790 rub.* *Basic salary 146 642 rub.* *Additional salary 14 655 rub.* *Labor tax 47 965 rub.* *Overhead 47 965 rub.* *Material costs 25 046 rub.*
2. *Expenditure rates and expenditure standards for resources*	*Industrial Electricity Tariff 5.8 rubles per 1 kWh* *The regional coefficient of the city of Tomsk – 1.3*
3. *Current tax system, tax rates, charges rates, discounting rates and interest rates*	*Amount of insurance contributions – 30%* *Institutions conducting educational and scientific activities have rate - 27.1%*
The list of subjects to study, design and develop:	
1. *Assessment of commercial and innovative potential of STR*	*Evaluation of the competitiveness of technical solutions*
2. *Scheduling of STR management process: structure and timeline, budget, risk management*	*The organizational structure of the project* *Project limitations* *Project Schedule* *The budget of the scientific and technical research (STR)*
3. *Determination of resource, financial, economic efficiency*	*Evaluation of the competitiveness of technical solutions* *SWOT Matrix* *Budget of scientific research* *Gantt Chart*

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

The task was issued by adviser:

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Menshikova E.V.	Ph.D		

The task was accepted by the student:

Group	Full name	Signature	Date
0AM8M	Grigorieva Anna Anatolievna		

TASK FOR SECTION «SOCIAL RESPONSIBILITY»

For a student:

Group	Full name
0AM8M	Grigorieva Anna Anatolievna

School	School of Nuclear Science & Engineering	**Division**	Division for Nuclear-Fuel Cycle
Degree	Master Degree Program	**Field of training/programme**	14.04.02 Nuclear Physics and Technology/ Nuclear Medicine

Topic of research work:

Design and production of an individual collimator for electron radiation therapy using rapid prototyping technologies	
Initial data for section «Social Responsibility»:	
1. Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application	Individual plastic collimators. Application area: Oncology Dispensaries, Cancer Research Institutes
List of items to be investigated and to be developed:	
1. Legal and organizational issues to provide safety: – Special (specific for operation of objects of investigation, designed workplace) legal rules of labor legislation; – Organizational activities for layout of workplace.	– Labour code of Russian Federation #197 from 30/12/2001 GOST 12.2.032-78 SSBT – Sanitary Rules 2.2.2/2.4.1340-03. Hygienic requirements for PC and work with it
2. Work Safety: 2.1. Analysis of identified harmful and dangerous factors 2.2. Justification of measures to reduce probability of harmful and dangerous factors	– Enhanced electromagnetic radiation level – Insufficient illumination of workplace – Excessive noise – Deviation of microclimate indicators – Electric shock – Ionizing radiation
3. Ecological safety:	– Indicate impact of plastics production on hydrosphere, atmosphere and lithosphere
4. Safety in emergency situations:	– Fire safety;

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

The task was issued by adviser:

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Verigin D.A.	Ph.D		

The task was accepted by the student:

Group	Full name	Signature	Date
0AM8M	Grigorieva Anna Anatolievna		

Definitions, designations, abbreviations, normative references

References to the following standards are used in this work:

1. GOST 12.1.038-82 OSS. Electrical safety. Maximum permissible levels of touch voltages and currents;
2. GOST R12.1.004-85 Occupational safety standards system. Fire safety
3. Sanitary Rules 2.2.2/2.4.1340–03. Sanitary and epidemiological rules and regulations "Hygienic requirements for personal electronic computers and the organization of work.";
4. Sanitary Rules 2.2.1/2.1.1.1278–03. Hygienic requirements for natural, artificial and combined lighting of residential and public buildings.
5. Sanitary rules 2.2.4/2.1.8.562–96. Noise at workplaces, in premises of residential, public buildings and in the construction area.
6. Sanitary rules 2.2.4.548–96. Hygienic requirements for the microclimate of industrial premises.
7. Sanitary Rules 2.6.1.2523 -09. Radiation Safety Standards (NRB-99/2009).

The following abbreviations are used in this thesis:

RT – radiation therapy;

TPS – treatment planning system;

MLC – multileaf collimator;

FMD – fused deposition modeling;

3D – three dimensional;

AM – additive technologies;

CAD – computer-aided design

STL – stereolithography

PLA – polylactide acid.

Table of contents

1. Literature review

This chapter discusses the theoretical and methodological foundations of this work.

Within the framework of this chapter, the features of the interaction of electrons with matter and biological objects, the basics of electron beam radiotherapy, methods for the collimation of an electron beam, and devices for conducting electron beam radiotherapy were examined.

Additionally, an analysis of existing additive technologies was carried out, modern methods and materials for 3D printing were described.

1.1 Electron radiation therapy

Today, irradiation with high-energy electron beams is a popular method of RT. Active introduction of electron beam treatment in the field of RT and medical physics appeared with the first medical electron accelerators. The proliferation of medical linear particle accelerators is primarily due to the improvement of the design of medical linear accelerators. Auxiliary factors contributing to the proliferation of medical devices were the emergence and development of computed tomography methods, the development of accurate algorithms for dosimetric planning systems. The development of a system of double scattering foils and applicators for electron beams has become an important design feature of modern accelerators.

Electron beam RT is the process of irradiating a pathological focus with an electron beam. Irradiation can be carried out remotely on linear accelerators, betatrons and microtrons, which generate electrons with energies in the range from 1 to 45 MeV [1]. The advantages of electronic radiotherapy over other methods are greater dose uniformity of the irradiated focus, a high gradient of the spatial distribution of doses, and a lower dose for healthy underlying tissues [8]. These advantages increase the effectiveness of the treatment of malignant neoplasms, reducing the dose burden on healthy tissues and organs.

Electron beam RT is used to treat superficially located neoplasms, for example, skin and lip cancer, breast and neck cancer, upper respiratory tract and gastrointestinal tract lesions from 1 to 5 cm deep, oral mucosa, relapses of the mammary glands, skin lymphomas, metastases in superficial lymphatic nodes, residual tumors and scars [9, 10].

1.1.1 The interaction of electrons with matter and biological objects

In the interaction of electrons, whose energy is in the range from several keV to tens of MeV with biological organs and tissues, electron energy is lost on various kinds of interactions with the electrons of the atomic shells of matter. The peculiarities of the interaction of electrons with matter compared to heavy charged particles are the small rest mass of electrons, which leads to a large change in momentum at each collision of electrons with atoms of the medium, causing a noticeable change in the direction of motion of the electron and, as a result, electromagnetic radiation of electrons [11, 12].

There are several types of energy loss of an electron in a substance: elastic and inelastic interaction. The elastic scattering of electrons is due to the action of the Coulomb field of the atom. In this case, the total kinetic energy of the recoil atom remains unchanged, changing only the direction of motion of the electron. Inelastic interaction is divided into the following types:

– ionization energy loss (knocking out an orbital electron from an atom);

– radiation energy losses (radiation losses include: bremsstrahlung, synchrotron, Cherenkov and transition radiation of photons;).

The total loss of electron energy when passing through a substance is equal to the sum of ionization and radiation losses:

$$\left(-\frac{dE}{dx}\right)^{e}_{total} = \left(-\frac{dE}{dx}\right)^{e}_{ion} + \left(-\frac{dE}{dx}\right)^{e}_{rad} \qquad (1.1)$$

Ionization losses of electron energy are the main mechanism of energy transfer to matter by an electron beam. The ionization loss of an electron per unit path length depends on the initial electron energy and atomic number of the medium. In the region of low electron energies (E <1 MeV), the main contribution to energy loss is made by inelastic collisions with atomic electrons, including ionization of atoms.

Specific ionization losses can be calculated using the Bethe-Bloch formula:

$$\left(\frac{dE}{dx}\right)_{ion} = -\frac{2\pi}{\beta^2} n_e r_0^2 m_e c^2 \left[ln\left(\frac{m_e c^2 T_e}{\bar{I}^2} \frac{\beta^2}{2(1-\beta^2)}\right) - \left(2\sqrt{1-\beta^2} - 1 + \beta^2\right) ln2 + 1 - \beta^2 \right], \qquad (1.2)$$

where m_e – electron mass,

T_e – kinetic energy of an electron;

c – speed of light;

$\beta = \vartheta/c$; ϑ – particle speed;

$n_e = N_A(Z/A)\rho$ – electron density of matter, where N_A – Avogadro constant, Z – nuclear charge, A – atomic weight of the medium, ρ – medium density;

$\bar{I}$ – average ionization potential of atoms of the substance of the medium through which the particle passes;

r_0 – electron radius.

Radiation energy losses of charged particles occur when particles move in a medium with acceleration. In this case, the radiation loss values are inversely proportional to the square of the particle mass. Accordingly, for electrons, which are light particles, the contribution of radiation losses can reach 100% in the total energy loss. The energy loss of electrons moving with acceleration occurs due to the emission of radiation by particles.

The reasons for the accelerated motion of electrons are:

- electron deceleration caused by rectilinear motion;
- electron motion along a curved path;
- the movement of electrons at a higher speed than the speed of light in an optically dense medium;
- the motion of electrons in an inhomogeneous medium that changes density over time.

The above reasons lead to the appearance of bremsstrahlung, Cherenkov, synchrotron and transition radiation.

With increasing electron energy, energy losses increase due to the emission of bremsstrahlung. Bremsstrahlung is electromagnetic radiation emitted by a charged particle when it is scattered in the field of a nucleus and atomic electrons [11]. Bremsstrahlung is generated by electron accelerators: betatrons, microtrons, linear accelerators, synchrotrons and cascade generators. The values of the bremsstrahlung intensity depend on the electron beam energy, current, material, and target thickness. The intensity is directly proportional to the beam current and increases sharply with increasing beam energy. The following elements act as targets of electron accelerators: tungsten, gold, iron, etc.

The radiation loss of electrons to bremsstrahlung is described by the following formulas:

$$\left(-\frac{dE}{dx}\right)_{brem} = \frac{16}{3} n_e E \frac{Zr_0^2}{137} \; at\; E < m_e c^2 = 511\; keV, \tag{1.3}$$

$$\left(-\frac{dE}{dx}\right)_{brem} = n_e E \frac{Zr_0^2}{137}\left(4ln\frac{2E}{m_e c^2} - \frac{4}{3}\right) \; at\; 1 < \frac{E}{m_e c^2} < \frac{137}{Z^{1/3}}, \tag{1.4}$$

$$\left(-\frac{dE}{dx}\right)_{brem} = n_e E \frac{Zr_0^2}{137}\left(4ln\frac{183}{Z^{1/3}} - \frac{2}{9}\right) \; at\; \frac{E}{m_e c^2} > \frac{137}{Z^{1/3}}, \tag{1.5}$$

where m_e – electron mass;

c – speed of light;

Z – particle charge in positron charge units;

n_e – electron density of matter;

r_0 – electron radius.

Features of radiation energy loss to bremsstrahlung are presented below:

– losses due to bremsstrahlung are proportional to the electron energy, density of the medium and the squared charge of the atoms of the medium and inversely proportional to the square of the particle mass:

$$\left(-\frac{dE}{dx}\right)_{brem} \sim T_e, \left(-\frac{dE}{dx}\right)_{brem} \sim \frac{1}{m_{particle}^2}, \left(-\frac{dE}{dx}\right)_{brem} \sim nZ^2;$$

– with increasing electron energy, the angle of emission of gamma rays decreases;

– bremsstrahlung occurs in the field of an individual electron of the medium.

Synchrotron radiation - electromagnetic radiation that occurs when electrons move in a constant magnetic field of cyclic accelerators at a speed close to the speed of light. In a constant magnetic field of cyclic accelerators, a relativistic electron becomes a source of powerful electromagnetic radiation. Sources of synchrotron radiation are electronic synchrotrons and storage rings. The synchrotron radiation spectrum ranges from millimeter waves to x-rays.

The energy loss due to synchrotron radiation is described by the following relation:

$$\left(-\frac{dE}{dx}\right)_{synch} = -\frac{c}{v}\cdot\frac{2}{3}\frac{e^2\beta^4}{R^2}\left(\frac{E_e}{m_e c^2}\right)^4 = -\frac{2}{3}\frac{e^2\beta^3\gamma^4}{R^2}, \qquad (1.6)$$

where m_e – electron mass;

e – particle charge;

c – speed of light;

v – charged electron velocity;

E_e – electron energy in eV;

R– radius of rotation of an electron in a magnetic field;

$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \beta = \vartheta/\text{c}$.

Features of radiation energy losses due to synchrotron radiation are presented below.:

– synchrotron radiation occurs when electrons move in a constant magnetic field with centripetal acceleration;

– synchrotron radiation losses increase with increasing electron energy:

$$\left(-\frac{dE}{dx}\right)_{synch} \sim \gamma^4;$$

– losses due to synchrotron radiation in a magnetic field are inversely proportional to the square of the radius of rotation of the electron:

$$\left(-\frac{dE}{dx}\right)_{synch} \sim \frac{1}{R^2}.$$

The radiation that occurs when a charged particle moves in a medium at a speed exceeding the phase velocity of light in a given medium is called Vavilov-Cherenkov radiation [11].

A charged particle emitting Vavilov-Cherenkov radiation moves uniformly and rectilinearly at a speed exceeding the propagation velocity in a given substance $v = c/n$, where n – the refractive index.

The physical nature that describes the occurrence of Vavilov-Cherenkov radiation is the phenomenon of the polarization effect that occurs when a charged particle passes through a substance. Under the influence of an electric field, the electron shell of the atom is displaced relative to the nucleus by a short period of time, while the return of the atom from the state of polarization to its initial state is accompanied by the emission of photons [11].

Energy losses due to Cherenkov radiation are thousands of times less than ionization losses. However, despite the fact that bremsstrahlung is more intense than Cherenkov's radiation, in the visible part of the spectrum, the energy loss from Cherenkov radiation is five times higher than the loss from bremsstrahlung.

The features of Vavilov-Cherenkov radiation are presented below:

- the occurrence of Cherenkov radiation is due to the movement of charged particles at a constant speed in a medium with a refractive index greater than unity;
- the intensity of the Cherenkov radiation does not depend on the particle mass, charge and atomic weight of the atoms of the medium;
- the angle of emission of Cherenkov radiation increases with increasing energy of the charged particles;
- energy losses on Cherenkov radiation:

$$\left(-\frac{dE}{dx}\right)_{cher} \sim z^2.$$

Transition radiation is the emission of electromagnetic waves by a uniformly and rectilinearly moving charged particle when it crosses the interface of two media with different refractive indices [11].

When an electron moves in an inhomogeneous medium, with a varying density of the medium, photons are emitted along the flight path of the charged particle.

Features of transition radiation are presented below.:

- radiation intensity is directly proportional to the number of interfaces;
- for nonrelativistic electrons:

$$\left(-\frac{dE}{dx}\right)_{trans} \sim T^2.$$

- the spectrum region has a wide frequency range with the forward direction of the transition radiation of relativistic electrons;

1.1.2 Radiation therapy equipment

The use of electron beams in RT was made possible thanks to the development of the Van de Graaff generator in the late 1930s. The Van de Graaff generator was one of the first machines used for electron beam radiation therapy [13]. However, these accelerators were limited in energy, the values of which were only a few MeV, so the electron beam could only be used to treat surface diseases.

In parallel with the development of the Van de Graaff generator, a betatron (cyclic electron accelerator) was developed. However, a reliably functioning betatron was created only in 1940 - 1941 [13]. The principle of operation of the betatron is based on the phenomenon of generation of a vortex electric field by an alternating magnetic field [14]. Betatrons were able to generate electron beams in the energy range from 5 to 30 MeV.

In the same time period, linear electron accelerators with microwave sources used in the field of radar systems were developed. Linear electron accelerators are axially rectilinear structures that capture the beam from the electron injector and accelerate it to the required energy [15].

As accelerators developed, they gradually became the preferred equipment in RT. A number of studies have been conducted aimed at meeting the various requirements of electron beam therapy. Thanks to the improvement of the systems of scattering foils, which were developed for use with betatrons [16], complex double-foil scattering systems [17] are used today, which make it possible to create large fields with a plane electron beam. The device of a typical accelerator head used to generate electron beams is shown in Figure 1.1.

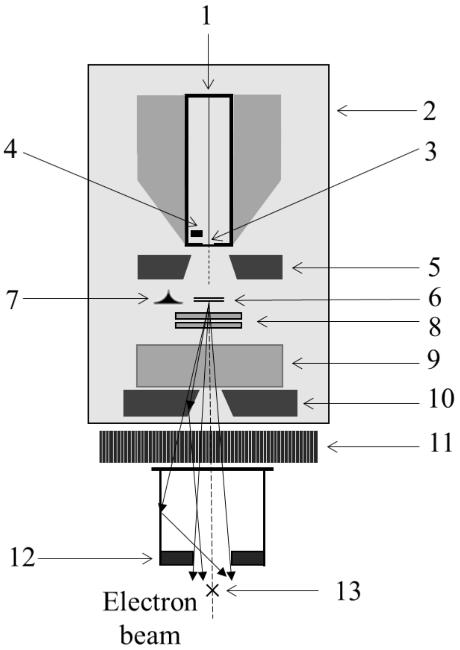

Figure 1.1 – Schematic representation of a typical medical linac head with depicting the important components briefly described in for production of clinical electron beams: 1 – electron pencil beam (from waveguide), 2 – linac head, 3 – beryllium window, 4 – bremsstrahlung target, 5 – primary collimator, 6 – scattering foils, 7 – flattering filter, 8 – ionization chambers, 9 – secondary collimator (upper jaws), 10 – secondary collimator (lower jaws), 11 – multileaf collimator, 12 – electron cone, 13 – isocenter

In addition to linear accelerators for RT purposes, a microtron was developed, which is a type of resonant cyclic accelerator [18]. The principle of operation of a microtron is based on the acceleration of an electron beam in a magnet by passing it repeatedly through a resonant microwave cavity to obtain the desired energy.

The currently used therapeutic machines in RT are linear accelerators, which are designed to generate both photon and electron beams in the energy range 4 – 20 MeV.

1.1.3 Methods of electron beam collimation

The outgoing electron beam from the acceleration system of a linear accelerator in the form of a thin beam passes through the system of formation of a wide diverging beam using a system of scattering foils of heavy elements [17] (Figure 1.1). In this system, the first foil, due to multiple electron scattering, turns a thin beam into a diverging beam, and the second one forms a uniform profile in the beam cross section [1].

Primary collimators provide collimation near the source, secondary collimators - near the patient. In order to form an individual beam field shape, it is necessary to change the secondary collimation characteristics. A linear accelerator configuration for standard collimation of an electron beam can include a set of replaceable alignment foils, applicators, edge frames, a set of tubes of various sizes, designed to form an electron beam of a given energy.

The standard treatment procedure with electron beams involves the use of standard applicators (Figure 1.2a) or individual collimators cast from metal alloys (for example, Cerrobend alloy) (Figure 1.2b).

The manufacturing technology for Cerrobend alloy metal blocks is described in detail in Section 3.2.

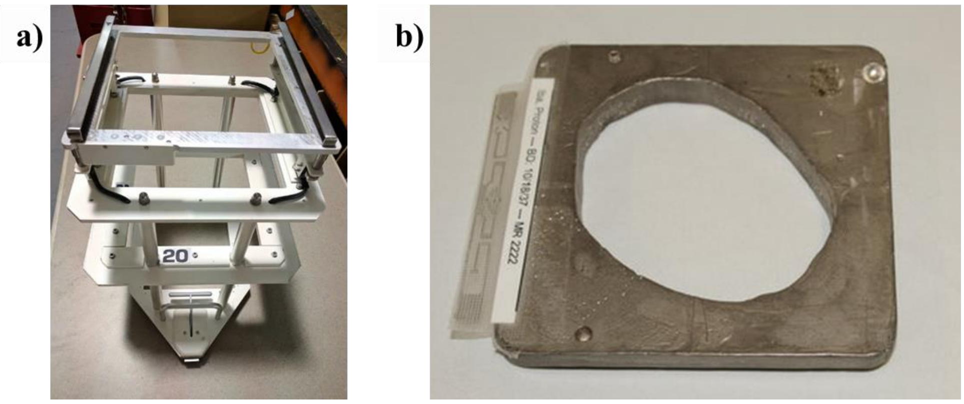

Figure 1.2 – Devices for forming an electron beam: a) a standard applicator for an ELEKTA linear accelerator [19] b) an example of an individual block smelted from an alloy [20]

The manufacture of metal individual blocks from alloys requires the cost of manual labor, qualified trained personnel for working with materials, the availability of equipped premises for the production of blocks. In addition, the production of metal blocks is accompanied by the release of toxic substances during the melting of materials.

Also, transferring the contour from the TPS to the cutting tool introduces uncertainty in the field shape and layout errors of several millimeters (since the polystyrene foam model is manually placed in the mold for pouring with alloy). Other disadvantages of Cerrobend alloy blocks are presented in [21–23].

The main direction of increasing the accuracy of electron beam RT is the development of electron multi-leaf collimators (MLC) [24, 25]. Although they can replace Cerrobend alloy blocks and provide modulation of intensity, they significantly increase the weight and complexity of a linear accelerator. Electron MLC also require additional quality assurance (QA), cost and service. One of the main disadvantages is the leakage between the collimator petals [26], in addition, the penumbra regions created using MLC are larger than the regions generated by alloy blocks [24].

Recently, given the wide availability of 3D printers, a bolus 3D-printing for radiation therapy is actively developing [27 - 29]. A bolus is a device for modifying a radiation beam placed on the surface of a patient's body (Figure 1.3). The material of the bolus consists of a substance of equivalent body tissue. The result of using boluses is to increase the dose in the skin and other surface structures directly below it, delivering the minimum dose to neighboring critical structures and normal tissues.

When using boluses in electron beam RT, the electron beam delivers a uniform dose of radiation to the planned volume of exposure and has a sharp distal drop, in addition, it reduces unnecessary irradiation of the main healthy normal tissue. However, inhomogeneous dose delivery in the target volume may occur due to irregularities in the skin surface and different target depths [31]. The solution to this problem can be the use of step boluses, in turn, the use of step boluses leads to the appearance of hot and cold spots in the dose distribution.

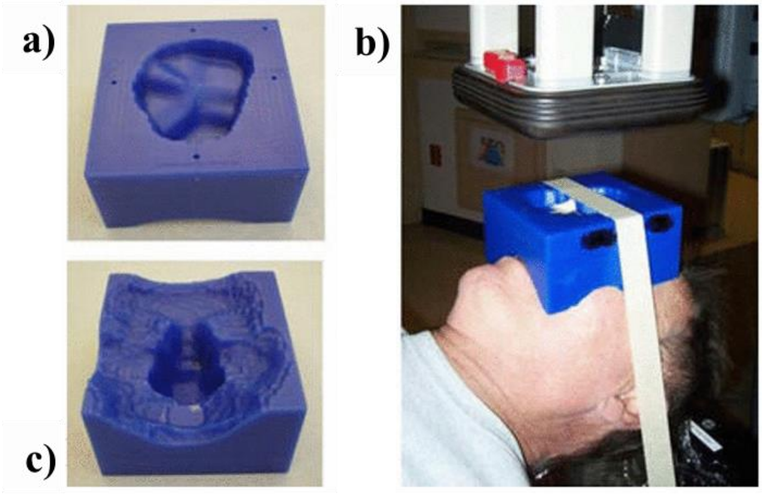

Figure 1.3 – An example of the use of a bolus in electron beam therapy [30]: a) the surface of the bolus facing the electron beam, b) the placement of the bolus on the patient, c) the image of the bolus

In the framework of this work, a plastic collimator was made using three-dimensional printing technologies to form an electron beam field. A dosimetric assessment of the formed field by a polymer collimator was carried out.

1.2 Additive Manufacturing

The term additive manufacturing refers to the process of layer-by-layer creation of three-dimensional objects of any geometric configuration based on their digital data. Additive manufacturing uses software based on computer-aided design (CAD) systems, which are necessary for directing hardware that applies material layer by layer in precise geometric shapes [32].

As the name implies, additive manufacturing adds material in layers to create an object. On the contrary, when creating objects using traditional methods, it is often necessary to remove material using milling, machining, and threading to give a concrete shape to the object.

Growing a 3D object one superthin layer at a time, each subsequent layer is bonded to the previous layer of molten or partially molten material. Various materials can be used as materials, including metal powders, various thermoplastics, glass, ceramics, and composite materials.

AM are widely used for prototyping and production in various fields of human activity from architecture, construction, industrial design to engineering and medical industries, bioengineering [33, 34].

1.2.1 General principles of 3D printing

Using CAD, a 3D scanner, or a conventional digital camera and photometry software, 3D objects can be created. 3D objects created using CAD software have relatively fewer errors when compared with other methods [35]. All possible errors in three-dimensional models can be identified and eliminated before printing. CAD models can be saved in a stereolithography (STL) file format, which stores data based on surface triangulation of CAD models.

The next step in preparing a 3D model for printing on a 3D printer is processing with software called a “slicer”. Slicers convert models into a series of thin transverse layers, creating a G-code containing instructions for moving 3D printers and their commands (feeding material, speed of movement, heating the nozzle, etc.). The 3D printer according to the G-code stacks successive layers of loaded raw materials, subsequently obtaining a model from a series of cross-sections. These layers, corresponding to the virtual sections of the CAD model, are automatically combined to create the final model [36].

The resolution in 3D printing is horizontal (XY), that is, the minimum movement of the printer extruder that it can perform along the X and Y axes and vertical (or layer height) is the minimum layer thickness produced by the printer in one pass. Standard parameters, for example, FDM-printers is a layer thickness of 0.15 to 0.3 mm, depending on the diameter of the nozzle.

The time frame for building 3D models using modern printing methods can vary from several hours to several days, depending on the 3D printing method used, the size and geometric complexity of the model.

After the manufacture of the printed object, depending on the print resolution or the presence of auxiliary supporting structures and supports, further post-processing of the model (grinding, steam baths using various solvents) is necessary, improving the surface quality of the part.

1.2.2 Technologies and methods of 3D printing

The main differences between 3D printing processes are primarily in the method of applying layers of material on the printing surface. Also, printing processes differ in the type of materials used, as noted earlier, both metal powders and thermoplastic plastics and composite materials can be used as materials. Each method has its advantages and disadvantages. The technological features of the three-dimensional printing process mainly depend on the additive manufacturing technology underlying this process. Some methods are based on the melting of the material (metal, plastic, ceramics), these include the method of fused deposition modeling (FFF / FDM), selective laser sintering (SLS), selective laser melting (DMLS / SLM). Other methods are based on the hardening of the polymer material, for example, under the influence of a laser (stereo lithography (SLA), digital LED projection (DLP)). In addition to melting materials and solidification of liquid polymers, there are additive technologies based on lamination of materials (LOM) and inkjet deposition of materials (MJ, NPJ, BJ).

The classification of the main methods and technologies used in three-dimensional printing today is presented in Table A.1 (Appendix A).

Fused deposition modeling (FDM / FFF) is by far the most affordable and widespread 3D printing method [32].

This method involves the creation of a 3D model by extruding material flows in the form of microdrops or thin jets, which immediately solidifies, forming layers. The schematic diagram of the device FDM 3D-printer is shown in Figure 1.4.

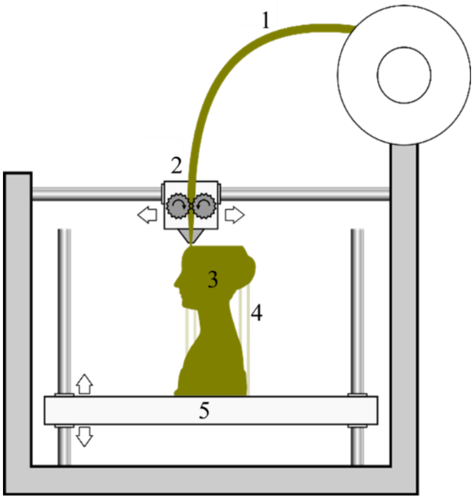

Figure1.4 – Schematic representation of extrusion deposition [37]:
1 – filament, 2 – heated moving head, 3 – printing object, 4 – vertical support structures, 5 – moving platform

A filament of thermoplastic material passes through a heated moving print head, which heats the material to the desired melting point and extrudes it, depositing layer by layer according to the transverse layer of the CAD model on the working surface of the table. A moving platform is lowered after applying each layer. Depending on the 3D printer device, instead of lowering the work platform, the print head may be lifted. For printing complex geometric models with overhanging elements, additional support structures can be used, which can be removed later mechanically or dissolved in water or solvent depending on the support material used.

1.2.3 Materials for Fused Deposition Modeling

This section describes the basic materials for 3D printing by the method of FDM, their main properties and characteristics.

To perform this work, the test sample was prepared by the method of FDM. As noted earlier, the FDM method is the most common and commercially available three-dimensional printing method, which has the widest range of filaments. Various types of polymers and composites are used as extrusion printing supplies, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polypropylene (PP), polylactide acid (PLA), polyethylene terephthalate (PET), polyvinyl alcohol (PVA), nylon (Nylon), high impact polystyrene (HIPS) and others [38, 39].

PLA plastic is one of the most widely used thermoplastics in 3D extrusion printing, made from renewable resources (sugar cane, corn). Low thermal conductivity, heat resistance and toughness, biodegradability and biocompatibility are key advantages of PLA. The disadvantages of PLA plastic are: the fragility of printed objects, due to the environmental friendliness of the material, and hygroscopicity (the ability of substances to absorb water vapor from air) [40]. The presence of hygroscopicity in plastics requires the use of special storage conditions and periodic drying of the plastic before printing. Some physical properties of PLA plastic are presented in Table 1.1.

Table 1.1 – Physical properties of PLA plastic [40]

Criteria	**Value**
Density, g/cm³	1,23 - 1,38
Melting temperature, °C	170 - 180
Glass transition temperature, °C	60 - 65
Bending strength, MPa	55.3
Tensile strength, MPa	57.8
Tensile modulus, GPa	3.3
Print accuracy, %	± 0.1
Shrinkage in the manufacture of products	–
Water absorption, %	0,5−50

The low melting point of PLA plastic (170-180°C) contributes to the relatively low power consumption of the 3D printer; You can also use inexpensive nozzles with low thermal conductivity (brass and aluminum) for printing. Another advantage of PLA plastic is its low cost, adding to the prevalence of the use of this material.

ABS plastic (acrylonitrile butadiene styrene) is a common thermoplastic polymer. ABS is a polymer obtained by the polymerization of styrene and acrylonitrile with butadiene. ABS has a high toughness, sufficient rigidity, good thermal stability and high resistance to chemical attack and cracking under the influence of environmental factors. Other important properties of ABS include low cost, durability, and low coefficient of thermal expansion [41]. The widespread use of ABS plastic is due to its mechanical, chemical properties (Table 1.2).

Table 1.2 – Physical properties of ABS plastic [41]

Criteria	**Value**
Density, g/cm^3	~1.05
Melting temperature, °C	~240-260
Glass transition temperature, °C	~105
Bending Strength, MPa	41
Tensile Strength, MPa	22
Tensile modulus, MPa	1627
Shrinkage during cooling, %	up to 0.8

The main disadvantage of ABS plastic can be considered a high degree of shrinkage during cooling - the material can lose up to 0.8% of the volume, which in turn can lead to significant deformations, violation of the integrity of the models, twisting of the first layers of the print.

PVA (polyvinyl alcohol) is an artificially created, water-soluble thermoplastic polymer obtained by the alkaline/acid hydrolysis of polyvinyl esters [42]. The main raw material for the production of polyvinyl alcohol is polyvinyl acetate.

The main feature of PVA plastic is its water-solubility. 3D printers equipped with double extruders can print models with PVA support structures. When printing is complete, the supports can be dissolved in water, leaving a finished model that does not require mechanical or chemical treatment [43].

The physical properties of PVA plastic are presented in Table 1.3. With increasing humidity, strength decreases, but elasticity increases. The extrusion temperature is 160-175°C, which allows the use of PVA in printers designed for printing with ABS and PLA plastics.

Table 1.3 - Physical properties of polyvinyl alcohol [42]

Criteria	**Value**
Density, g/cm^3	1.27 - 1.3
Melting temperature, °C	220 - 230
Glass transition temperature, °C	85 - 90
Degradation temperature, °C	230
Tensile strength, MPa	60 - 120
Elongation in tension, %	10 - 30

When heated, PVA plastic above 220°C can lead to plastic pyrolysis, which must be taken into account when printing.

HIPS (high impact polystyrene) is a thermoplastic polymer, a copolymer of styrene with butadiene and styrene butadiene rubber. As a result of mixing these polymers, a durable and flexible material is obtained. In three-dimensional printing, polystyrene demonstrates physical properties (Table 1.4), similar to ABS plastic, which makes this material more and more common among consumers.

Table 1.4 - Physical properties of HIPS [39]

Criteria	**Value**
Density, g/cm^3	1.069 - 1.125
Melting temperature, °C	240
Decomposition temperature, °C	290
Glass transition temperature, °C	90
Tensile strength, MPa	40 - 50
Flexural modulus, GPa	3.2
Cooling shrinkage, %	up to 0.8

HIPS is soluble in the organic solvent limonene. For example, ABS plastic is not soluble in limonene, so it is possible to use high-impact polystyrene as a material for building soluble supporting supports, which is extremely useful when building geometrically complex models with internal supports. This is one of the reasons why HIPS is best combined with ABS plastic. Another reason is that the temperature range of printing between these materials is very similar, which facilitates the complex task of 3D printing of two materials. The disadvantage of HIPS plastic is the emission of toxic fumes when it is heated to its melting point.

In this work, PLA plastic was chosen for 3D printing, since this material is affordable, durable and unpretentious in use, due to the low melting point it is possible to print small objects, and the presence of plastic with a low level of thermal expansion allows printing large models with virtually no mechanical defects [38].

4. Financial management, resource efficiency and resource saving

Today, the prospect of scientific research is determined not so much by the scale of the discovery, which can be difficult to assess at the first stages of the life cycle of a high-tech and resource-efficient product, but rather a commercial development value. Evaluation of the commercial value of the development is a prerequisite in the search for funding sources for scientific research and the commercialization of its results. This is important for developers who need to represent the state and prospects of ongoing research.

Achieving the goal is provided by solving the following problems:

- assessment of the commercial potential and prospects of conducting research;
- identification of possible alternatives for conducting scientific research that meet modern requirements in the field of resource efficiency and resource conservation;
- planning of research work;
- definition of resource (resource-saving), financial, budgetary, social and economic effectiveness of the study.

4.1 Competitiveness analysis of technical solutions

To analyze the competitiveness of a plastic collimator printed on a FDM 3D-printer, we will use the evaluation card shown in Table 4.1. As a competing development, we will consider a standard metal collimator for electron beam radiotherapy. The position of research and competitors is evaluated for each indicator by you on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators determined by you in the amount should be 1.

Analysis of competitive technical solutions is determined by the formula 4.1:

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

where C - the competitiveness of research or a competitor,

W_i– criterion weight,

P_i – point of i-th criteria.

From this analysis, we can conclude that there is a clear advantage of using plastic collimators in electron beam radiotherapy.

Table 4.1 − Evaluation card for comparison of competitive technical solutions

Evaluation criteria	**Criterion weight**	**Points**		**Competitiveness** *Taking into account weight coefficients*	
		P_f	P_{f1}	C_f	C_{f1}
Technical criteria for evaluating resource efficiency					
1. Field shaping of an electron beam of a given configuration	0.15	5	4	0.75	0.6
2. Normal tissue and organs protection	0.15	5	3	0.75	0.45
3. Efficacy and effectiveness of treatment	0.15	5	4	0.75	0.6
4. Collimating device manufacturing time	0.1	5	2	0.5	0.2
5. Precision manufacturing collimating device	0.1	5	2	0.5	0.2
6. Individual approach to treatment	0.1	5	4	0.5	0.4
7. Ease of use	0.05	5	5	0.25	0.25
Economic criteria for performance evaluation					
1. The cost of manufacturing a collimating device	0.1	5	2	0.5	0.2
2. Product competitiveness	0.1	4	3	0.4	0.3
3. Market penetration rate	0.1	5	4	0.5	0.4
Total:	**1**	-	-	**4.9**	**3.5**

As the analysis showed, the use of plastic collimators in radiation therapy is the most competitive, since this device promotes high accuracy of dose delivery, lower dose values to critical organs and tissues, and as a result, high treatment efficiency. In addition, this development has high manufacturing accuracy and low cost of production compared to the standard method of manufacturing.

4.2 SWOT analysis

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

The final matrix of the SWOT analysis presented in Table 4.2.

Table 4.2 − SWOT matrix

	Strengths: − S1. Increasing the effectiveness of the treatment of malignant neoplasms; − S2. The relevance of the idea of scientific research; − S3. Simplicity and ease of use; − S4. Relatively low cost.	**Weaknesses:** − W1. The complexity of introducing a new method of treating malignant neoplasms and obtaining a license to carry out this medical activity; − W2. Duration and difficulty of a number of studies.
Opportunities: − O1. Increased interest in the development due to the possibility of increasing the effectiveness of the treatment of malignant neoplasms; − O2. The development of medical physics will lead to the expansion of this market, which will increase interest in this technique. − O3. Experiment Cost Reduction. − O4 An increase in the number of jobs in the field of research data, the emergence of new specialists in this industry.	1. Due to the ease of use and the creation of plastic filters, the opportunity to enter new markets. 2. Creation of similar techniques for further use in medical and scientific research	1. Lack of a large number of research orders. 2. The priority of competitive organizations due to the long term of research.
Threats: − T1. Lack of commercial interest in the project; − T2. Not demand on the market, due to excessive conservative potential customers; −T3. High market competition.	1. Improving competitiveness due to the low cost of materials in the market; 2. Using a combination of ease of use and low prices will lead to increased competitiveness in the market for these products. 3. Reducing the cost of experimental materials by expanding the boundaries of applicability.	1. Attraction of capital from private medical institutions; 2. Writing articles and speaking at conferences to attract stakeholders and increase awareness of this method.

Based on the results of the analysis, it can be concluded that the most optimal strategy for developing a product on the market is a joint business strategy.

4.3 Project Initiation

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

4.3.1 Purpose and results of the project

This section provides information on project stakeholders, the hierarchy of project purposes, and criteria for achieving goals.

Stakeholders of a project are individuals or organizations that actively participate in the project, whose interests can be affected both positively and negatively during the execution or as a result of the completion of the project. Information on project stakeholders is presented in Table 4.3.

Table 4.3 − Stakeholders of the project

Project stakeholders	**Stakeholder expectations**
Russian oncology clinics and dispensaries	An innovative technique for the formation of an electron beam during radiation treatment.
Russian Cancer Research Institutes	Expanding the possibilities of electron therapy, conducting new research in this area.
Oncologists	Conformal irradiation. Improving the effectiveness of the treatment of malignant neoplasms. Implementation of radiation treatment with a reduced dose load on critical organs and structures. Low probability of relapse.
Oncology patients	Improving the effectiveness of treatment. Reducing the risks of late radiation reactions of the body. Reduced recovery time after radiation treatment due to reduced radiation exposure.

Table 4.4 provides information on the project purpose and criteria for achieving the purpose.

Table 4.4 − Purpose and results of the project

Purpose of project:	Production of a device for forming a transverse profile of dose fields of therapeutic electron beams using rapid prototyping technology for radiation therapy procedures with a configuration calculated individually for each patient.
Expected results of the project:	1. Application of the research results will create a personalized method for the formation of dose fields of electron beams that increase the effectiveness of radiation therapy procedures. 2. Reducing the production time of an individual collimator compared to the standard method. 3. The use of 3D printed polymer devices will increase the accuracy of delivering the required dose to a given area and improve the quality of radiation therapy procedures. 4. The demand for polymer devices in medical institutions conducting radiation therapy procedures.
Criteria for acceptance of the project result:	1. The accuracy of manufacturing a polymer device is not less than 2%. 2. Reduced manufacturing time of the device by 30% compared with the standard method. 3. Reduced cost of the polymer collimator by 50% in contrast to the metal collimator.
Requirements for the project result:	**Requirement:**
	1. The project should be completed by June 1, 2020.
	2. The results obtained must satisfy the acceptance criteria of the project result.
	3. Test the polymer collimator in a real clinical case.
	4. The results of scientific research should be presented at one of the all-Russian/international/regional conferences and have a publication in one of the scientific journals.

4.3.2 The organizational structure of the project

At this stage of the work, the composition of the working group of this project and the definition of the roles of each project participant were determined. Functions were determined, the functions performed by each of the participants and their labor costs in the project. This information is presented in Table 4.5.

Table 4.5 − Project working group

№	Participant	Role in the project	Functions	Labor time, hours.
1.	Cherepennikov Yury Mikhailovich. Associate Professor, School of Nuclear Science & Engineering, TPU	Project Manager	Coordination of activities of project participants; Conducting experimental research at Dmitry Rogachev National Research Center of Pediatric Hematology, Oncology and Immunology;	243
2.	Miloichikova Irina Alekseevna, Medical physicist of the Radiotherapy Department of the Cancer Research Institute of the Tomsk National Research Medical Center of the Russian Academy of Science	Project Executor, project consultant	Calculation of a dosimetric plan for a clinical case; Purchase of a metal collimator; purchase of consumables (PLA plastic) for a 3D printer; Conducting experimental research at Dmitry Rogachev National Research Center of Pediatric Hematology, Oncology and Immunology; Help in processing the results of experimental studies;	171
3	Grigorieva Anna Anatolievna, Undergraduate, School of Nuclear Science & Engineering, TPU	Project Executor	Creation of a 3D model of a collimator for a clinical case and the production of a plastic collimator on a 3D printer; Writing a review of literary sources and technical literature; Processing the results of experimental studies; Presentation of project results at conferences; Drawing up a report on research work (writing a master's thesis).	621
Total:				1035

4.3.3 Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members. The limitations and assumptions of this project are presented in Table 4.6.

Table 4.6 - Project limitations and assumptions

Factors	**Limitations/Assumptions**
1. Project's budget	322 063 rub.
1.1. Source of financing	Russian Science Foundation (project No. 18-79-10052)
2. Project timeline:	01/02/2020 – 01/06/2020
2.1. Date of approval of plan of project	10/02/2020
2.2. Completion date	01/06/2020

4.3.4 Project Schedule

At this stage, as part of the planning of a scientific project, it is necessary to build a project timeline and a Gantt Chart of the project. A project timeline is presented in Table 4.7.

Table 4.7 – Project timeline

Job title	Duration, working days	Start date	Date of completion	Participants
Development of technical specification	1	10/02/2020	11/02/2020	Supervisor
Drawing up technical specifications	3	12/02/2020	14/02/2020	Supervisor
Determining the direction of research	3	17/02/2020	19/02/2020	Supervisor Student
Review and analysis of literary sources	17	20/02/2020	13/03/2020	Student
Calculation of the field shape for the clinical case in the dosimetric planning system	5	02/03/2020	06/03/2020	Consultant
Purchase of consumables for experimental research	5	26/02/2020	03/03/2020	Consultant
Creating a 3D model of the forming device	3	10/03/2020	12/03/2020	Student
Plastic collimator manufacturing	2	16/03/2020	17/03/2020	Student
Experimental research	5	23/03/2020	27/03/2020	Supervisor Consultant
Processing experiment data	4	31/03/2020	04/04/2020	Student Consultant
Analysis of the results	7	06/04/2020	14/04/2020	Student
Compilation of an explanatory note	16	15/04/2020	07/05/2020	Student
Preparing to defend graduation skilled work	15	11/05/2020	29/05/2020	Student Supervisor

Based on the data from Table 4.7, a Gantt chart was built (Appendix B, Figure B.1). A Gantt chart, or harmonogram, is a type of histogram that illustrates a project schedule. This table lists the tasks that you must complete on the vertical axis and the time intervals on the horizontal axis. The width of the horizontal bars on the graph shows the duration of each action. At the same time, the work on the chart is highlighted in different colors, depending on the performers responsible for a particular work.

4.4 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.

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

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

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

The budget for scientific and technical research is shown in Table 4.8:

Table 4.8 – The budget for scientific and technical research

Name	Material costs	Costs of special equipment	Basic salary	Additional salary	Labor tax	Overhead	Total cost
Cost, rubles	25 046	39 790	146 642	14 655	47 965	47 965	**322 063**

4.4.1. Calculation of material costs

The calculation of material costs is carried out according to the formula 4.2:

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

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

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

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

In this project, the main contribution is made by GafChromic EBT3 dosimetry films, because their cost is the highest. The calculation of the material cost is presented in Table 4.9.

Table 4.9 – Material costs

Name	**Unit**	**Amount**	**Price per unit, rub.**	**Material costs, rub.**
1. Metal collimator	-	1	10 000	10 000
2. PLA plastic (bobbin)	kg	0.6	1 590	954
3. Dosimetric films GafChromic EBT3	sheet	2	6 244	12 488
The total cost of materials				23 442
Transportation costs (5%)				1 172
Total:				**24 614**

Energy costs are calculated by the formula 4.3:

$$C = P_{el} \cdot P \cdot F_{eq}, \tag{4.3}$$

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

P – power of equipment, kW;

F_{eq} – equipment usage time, hours.

The calculated energy costs are shown in Table 4.10.

Table 4.10 – Energy costs

Name	**Work time, h**	**Electric energy consumption, kW**	**Price per unit, rub.**	**Material costs, rub.**
1. 3D printer Original Prusa i3 Mk2	16	0.1	5.8	9.28
2. Linear accelerator Elekta Synergy	4	3.5		81.2
3. Computer	345	0.17		340.17
4. 2D ionization chamber array MatriXX Evolution	2	0.07		0.81
Total:				**432**

Calculation of costs for special equipment for scientific (experimental): This article includes all the costs associated with the acquisition of special equipment necessary to carry out work on a particular topic. The cost of depreciation of equipment is calculated by the formula 4.4:

$$C_{amount} = \frac{C_r}{T}, \tag{4.4}$$

where, C_r – cost of equipment (rubles);

T – service life (days).

In order to calculate the amount of depreciation of equipment during use during scientific work, it is necessary to multiply by the number of days of use.

Depreciation deductions of equipment are presented in the Table 4.11.

Table 4.11 – Deprecation deductions

Name of equipment	**Cost, rub.**	**Service life, years**	**Days of operation**	**Depreciation deductions, rub.**
1. 3D printer Original Prusa i3 Mk2	85 000	3	2	155
2. Linear accelerator Elekta Synergy	125 000 000	20	2	32 247
3. 2D ionization chamber array MatriXX Evolution	1 040 000	6	2	950
4. Solid phantom miniPhantom	800 000	10	2	438
5. EpsonPerfection V750 Pro	6 000	3	1	6 000
Total:	126 931 000	42	9	39 790

4.4.2 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 following formula 4.5:

$$S_b = S_a \cdot T_w, \tag{4.5}$$

where S_b – basic salary per participant;

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

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

The average daily salary is calculated by the formula 4.6:

$$S_d = \frac{S_m \cdot M}{F_v}, \quad (4.6)$$

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

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

at holiday in 24 days, M = 11.2 months, 5 day per week;

at holiday in 48 days, M = 10.4 months, 6 day per week;

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

The current annual working time fund is shown in the Table 4.12.

Table 4.12 – The valid annual fund of working time

Working time indicators	
Calendar number of days	365
The number of non-working days - weekend - holidays	 104 14
Loss of working time - vacation - sick absence	 24
The valid annual fund of working time	251

Monthly salary is calculated by formula (4.7):

$$S_{month} = S_{base} \cdot (k_{premium} + k_{bonus}) \cdot k_{reg}, \quad (4.8)$$

where S_{base} – base salary, rubles;

$k_{premium}$ – premium rate;

k_{bonus} – bonus rate;

k_{reg} – regional rate.

The calculation of the base salary is presented in the Table 4.13.

Table 4.13 – Calculation of the base salaries

Performers	**S_{base}, rubles**	**$k_{premium}$**	**k_{bonus}**	**k_{reg}**	**S_{month}, rub.**	**W_d, rub.**	**T_p, work days**	**W_{base}, rub.**
Supervisor Cherepennikov Yu. M., Associate Professor	35120			1.3	45 773	2 043	26	53 118
Consultant Miloichikova I. A., Medical physicist	21 760				28 288	1 262	19	23 978
Student Grigorieva A.A.,	17890				23 257	1 038	67	69 546
Total:								**146 642**

4.4.3Additional 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 (formula 4.9):

$$W_{add} = k_{extra} \cdot W_{base}, \tag{4.9}$$

where W_{add} – additional salary, rubles;

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

W_{base} – base salary, rubles.

Additional salaries of employees are presented in the Table 4.14.

Table 4.14 – Additional salaries

	Supervisor	**Consultant**	**Student**
Additional salary coefficient	0.1		
Salary, rub.	53 118	23 978	69 546
Additional salary, rub.	5 312	2 397	6 946
Total, rub.	**14 655**		

4.4.4. 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 4.10:

$$P_{social} = k_b \cdot (W_{base} + W_{add}), \tag{4.10}$$

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%.

Taxes to extrabudgetary funds are presented in the Table 4.15.

Table 4.15 – Labor tax

	Supervisor	**Consultant**	**Student**
Overhead rate	0.3		
Salary, rubles	53 118	23 978	69 546
Labor tax, rubles	19 935	7 193	20 834
Total:	**47 965**		

4.4.5 Overhead costs

Overhead costs include other management and maintenance costs that can be allocated directly to the project. In addition, this includes expenses for the maintenance, operation and repair of equipment, production tools and equipment, buildings, structures, etc. Overhead costs account from 30% to 90% of the amount of base and additional salary of employees.

Overhead is calculated according to the formula 4.11:

$$C_{ov} = k_{ov} \cdot (W_{base} + W_{add}), \tag{4.11}$$

where k_{ov} – overhead rate.

Overhead costs are presented in the Table 4.16.

Table 4.16 – Overhead

	Supervisor	**Consultant**	**Student**
Coefficient of deductions	0.3		
Salary, rubles	53 118	23 978	69 546
Labor tax, rubles	19 935	7 193	20 834
Total:	**47 965**		

4.4.6 Formation of budget costs

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

Determining the budget for the scientific research is given in the Table 4.17.

Table 4.17 – Items expenses grouping

Name	Cost, rubles
1. Material costs	25 046
2. Costs of special equipment	39 790
3. Basic salary	146 642
4. Additional salary	14 655
5. Labor tax	47 965
6. Overhead	47 965
Total planned cost:	**322 063**

4.5 Evaluation of the comparative effectiveness of the project

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

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

The integral financial measure of development is defined as (formula 4.12):

$$I_f^d = \frac{C_i}{C_{max}}, \tag{4.12}$$

where I_f^d – integral financial measure of development;

C_i – the cost i-th version;

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

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

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows (formula 4.13):

$$I_m^a = \sum_{i=11}^{n} a_i b_i^a \,, I_m^p = \sum_{i=11}^{n} a_i b_i^p \tag{4.13}$$

where I_m – integral indicator of recourse 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 integral indicator of resource efficiency is presented in the form of Table 4.18.

Table 4.18 – Evaluation of the performance of the project

Criteria / **Object of study**	**Weight criterion**	**Points**
1. Time spent on manufacturing plastic collimators	0,2	4
2. The complexity of manufacturing	0,3	5
3. Ease of use	0,15	5
4. Energy costs for the implementation of processes with this technology	0,15	5
5. The amount of consumed capital goods	0,2	5
Total:	**1**	

Integral indicator of resource efficiency:

$$I_m = 4 \cdot 0.2 + 5 \cdot 0.3 + 5 \cdot 0.15 + 5 \cdot 0.15 + 5 \cdot 0.2 = 4.05;$$

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 4.14:

$$I_e^p = \frac{I_m^p}{I_f^d}, I_e^a = \frac{I_m^a}{I_f^a} \ and \ etc. \quad (4.14)$$

Since the development has one performance: $I_e^p = \frac{4.05}{1} = 4.05$;

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

$$E_c = \frac{I_e^p}{I_e^e}. \quad (4.15)$$

Thus, the effectiveness of the development is presented in Table 4.19.

Table 4.19 – Comparative development efficiency

№	**Indicators**	**Points**
1	Integral financial measure of development	1
2	Integral indicator of resource efficiency of development	4.05
3	Integral indicator of the development efficiency	4.05

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

Conclusion

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 include:

- 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.

5. Social responsibility

5.1 Introduction

Radiation therapy using electron beams is used to treat tumors located on or near the surface of the skin. The advantage of using electron beam therapy is a predetermined value of the penetration depth of the radiation beam depending on its energy. This allows you to achieve a uniform dose distribution in the planned volume of exposure with a significant reduction in the dose on healthy organs and tissues.

Increasing requirements for the accuracy of dose delivery in radiation therapy makes the issue of manufacturing individual forming devices, collimators relevant. Individual collimators allow you to create irradiation fields of complex shape, repeating the contour of the tumor, in accordance with the tomographic data of the patient. In clinical practice, the spread of this approach is hampered by the fact that the use of equipment designed for smelting metal medical collimators is limited by high requirements for the working room and the working conditions and staff qualifications.

In the framework of this work, modern three-dimensional printing technologies were used to create an individual plastic collimator.

As a result, a complex shape of the electron beam field of the accelerator was obtained, which was formed by a plastic collimator in a solid-state tissue-equivalent phantom.

5.2 Legal and organizational items in providing safety

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

Occupational safety is a system of legislative, socio-economic, organizational, technological, hygienic and therapeutic and prophylactic measures and tools that ensure the safety, preservation of health and human performance in the work process [70].

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

- to have a workplace that meets Occupational safety requirements;
- to have a compulsory social insurance against accidents at manufacturing and occupational diseases;
- to receive reliable information from the employer, relevant government bodies and public organizations on conditions and Occupational safety at the workplace, about the existing risk of damage to health, as well as measures to protect against harmful and (or) hazardous factors;
- to refuse carrying out work in case of danger to his life and health due to violation of Occupational safety requirements;
- be provided with personal and collective protective equipment in compliance with Occupational safety requirements at the expense of the employer;
- for training in safe work methods and techniques at the expense of the employer;
- for personal participation or participation through their representatives in consideration of issues related to ensuring safe working conditions in his workplace, and in the investigation of the accident with him at work or occupational disease;
- for extraordinary medical examination in accordance with medical recommendations with preservation of his place of work (position) and secondary earnings during the passage of the specified medical examination;
- for warranties and compensation established in accordance with this Code, collective agreement, agreement, local regulatory an act, an employment contract, if he is engaged in work with harmful and (or) hazardous working conditions.

The labor code of the Russian Federation states that normal working hours may not exceed 40 hours per week. The employer must keep track of the time worked by each employee.

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

5.3 Basic ergonomic requirements for the correct location and arrangement of researcher’s workplace

The workplace when working with a PC should be at least 6 square meters. The legroom should correspond to the following parameters: the legroom height is at least 600 mm, the seat distance to the lower edge of the working surface is at least 150 mm, and the seat height is 420 mm. It is worth noting that the height of the table should depend on the growth of the operator.

The following requirements are also provided for the organization of the workplace of the PC user: The design of the working chair should ensure the maintenance of a rational working posture while working on the PC and allow the posture to be changed in order to reduce the static tension of the neck and shoulder muscles and back to prevent the development of fatigue.

The type of working chair should be selected taking into account the growth of the user, the nature and duration of work with the PC. The working chair should be lifting and swivel, adjustable in height and angle of inclination of the seat and back, as well as the distance of the back from the front edge of the seat, while the adjustment of each parameter should be independent, easy to carry out and have a secure fit.

5.4 Occupational safety

A dangerous factor or industrial hazard is a factor whose impact under certain conditions leads to trauma or other sudden, severe deterioration of health of the worker [70]. A harmful factor or industrial health hazard is a factor, the effect of which on a worker under certain conditions leads to a disease or a decrease in working capacity.

5.4.1 Analysis of harmful and dangerous factors that can create object of investigation

The object of investigation is “Design and production of an individual collimator for electron radiation therapy using rapid prototyping technologies”. Therefore, object of investigation itself cannot cause harmful and dangerous factors.

5.4.2 Analysis of harmful and dangerous factors that can arise at workplace during investigation

The working conditions in the workplace are characterized by the presence of hazardous and harmful factors, which are classified by groups of elements: physical, chemical, biological, psychophysiological. The main elements of the production process that form dangerous and harmful factors are presented in Table 5.1.

Table 5.1 - Possible hazardous and harmful factors

Factors (GOST 12.0.003-2015)	Work stages			Legal documents
	Development	Manufacture	Exploitation	
1. Deviation of microclimate indicators	+	+	+	Sanitary rules 2.2.2 / 2.4.1340–03. Sanitary and epidemiological rules and regulations "Hygienic requirements for personal electronic computers and work organization." Sanitary rules 2.2.1 / 2.1.1.1278–03. Hygienic requirements for natural, artificial and combined lighting of residential and public buildings. Sanitary rules 2.2.4 / 2.1.8.562–96. Noise at workplaces, in premises of residential, public buildings and in the construction area. Sanitary rules 2.2.4.548–96. Hygienic requirements for the microclimate of industrial premises.
2. Excessive noise		+		
3.Increased level of electromagnetic radiation	+	+	+	
4.Insufficient illumination of the working area		+	+	
5. Abnormally high voltage value in the circuit, the closure which may occur through the human body	+	+	+	Sanitary rules GOST 12.1.038-82 SSBT. Electrical safety. Maximum permissible levels of touch voltages and currents.
6. Increased levels of ionizing radiation	+	+	+	Sanitary Rules 2.6.1. 2523 -0 9. Radiation Safety Standards (NRB-99/2009).

The following factors effect on person working on a computer:

- physical:
  - temperature and humidity;
  - noise;
  - static electricity;
  - electromagnetic field of low purity;
  - illumination;
  - presence of radiation;
- psychophysiological:
  - psychophysiological dangerous and harmful factors are divided into:
    - physical overload (static, dynamic)
    - mental stress (mental overstrain, monotony of work, emotional overload).

5.4.2.1 Deviation of microclimate indicators

The air of the working area (microclimate) is determined by the following parameters: temperature, relative humidity, air speed. The optimum and permissible values of the microclimate characteristics are established in accordance with [71] and are given in Table 5.2.

Table 5.2 - Optimal and permissible parameters of the microclimate

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

5.4.2.2 Excessive noise

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

5.4.2.3 Increased level of electromagnetic radiation

The screen and system blocks produce electromagnetic radiation. Its main part comes from the system unit and the video cable. According to [71], the intensity of the electromagnetic field at a distance of 50 cm around the screen along the electrical component should be no more than:

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

The magnetic flux density should be no more than:

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

5.4.2.4 Abnormally high voltage value in the circuit

Depending on the conditions in the room, the risk of electric shock to a person increases or decreases. Do not operate the electronic device in conditions of high humidity (relative air humidity exceeds 75% for a long time), high temperature (more than 35 ° C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with metal components connected to the ground and the metal casing of electrical equipment. The operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

- with direct contact with current-carrying parts during computer repair;
- when touched by non-live parts that are under voltage (in case of violation of insulation of current-carrying parts of the computer);
- when touched with the floor, walls that are under voltage;
- short-circuited in high-voltage units: power supply and display unit.

The upper limits of the contact current and voltage are shown in Table 5.3.

Table 5.3 – Upper limits for values of contact current and voltage

	Voltage, V	**Current, mA**
Alternate, 50 Hz	2	0.3
Alternate, 400 Hz	3	0.4
Direct	8	1.0

5.4.2.6 Increased levels of ionizing radiation

Ionizing radiation is radiation that could ionize molecules and atoms. This effect is widely used in energetics and industry. However, there is health hazard. In living tissue, this radiation could damage cells that result in two types of effects. Deterministic effects (harmful tissue reactions) due to exposure with high doses and stochastic effects due to DNA destruction and mutations (for example, induction of cancer).

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

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

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

c) keep individual radiation doses from all radiation sources as low as possible.

There are two groups of people related to work with radiation: personnel, who works with ionizing radiation, and population. The main dose limits are given in Table 5.4.

Table 5.4 – Dose limits

Quantity	**Dose limits**	
	Personnel	**Population**
Effective dose	20 mSv per year in average during 5 years, but not higher than 50 mSv per year	1 mSv per year in average during 5 years, but not higher than 5 mSv per year
Equivalent dose per year in eye’s lens	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	50 mSv

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

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

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

5.4.3 Justification of measures to reduce the levels of exposure to hazardous and harmful factors on the researcher

5.4.3.1 Deviation of microclimate indicators

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

– at least 30 m^3 per hour per person for the volume of the room up to 20 m^3 per person;

– natural ventilation is allowed for the volume of the room more than 40 m^3 per person and if there is no emission of harmful substances.

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

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

5.4.3.2 Excessive noise

In research audiences, there are various kinds of noises that are generated by both internal and external noise sources. The internal sources of noise are working equipment, personal computer, printer, ventilation system, as well as computer equipment of other engineers in the audience. If the maximum permissible conditions are exceeded, it is sufficient to use sound-absorbing materials in the room (sound-absorbing wall and ceiling cladding, window curtains). To reduce the noise penetrating outside the premises, install seals around the perimeter of the doors and windows.

5.4.3.3 Increased level of electromagnetic radiation

There are the following ways to protect against EMF:

– increase the distance from the source (the screen should be at least 50 cm from the user);

– the use of pre-screen filters, special screens and other personal protective equipment.

When working with a computer, the ionizing radiation source is a display. Under the influence of ionizing radiation in the body, there may be a violation of normal blood coagulability, an increase in the fragility of blood vessels, a decrease in immunity, etc. The dose of irradiation at a distance of 20 cm to the display is

50 µrem/hr. According to the norms [71], the design of the computer should provide the power of the exposure dose of x-rays at any point at a distance of 0.05 m from the screen no more than 100 µR/h.

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

5.4.3.4 Increased levels of ionizing radiation

In case of radiation accident, responsible personnel must take all measures to restore control of radiation sources and reduce to minimum radiation doses, number of irradiated persons, radioactive pollution of the environment, economic and social losses caused with radioactive pollution.

Radiation control is a main part of radiation safety and radiation protection. It is aimed at not exceeding the established basic dose limits and permissible levels of radiation, obtaining the necessary information to optimize protection and making decisions about interference in the case of radiation accidents, contamination of the environment and buildings with radionuclides.

The radiation control is control of:

- Radiation characteristics of radiation sources, pollution in air, liquid and solid wastes.
- Radiation factors developed with technological processes in working places and environment.
- Radiation factors of contaminated environment.
- Irradiation dose levels of personnel and population.

The main controlled parameters are:

- Annual effective and equivalent doses
- intake and body content of radionuclides
- volume or specific activity of radionuclides in air, water, food products, building materials and etc.
- radioactive contamination of skin, clothes, footwear, working places and etc.

– dose and power of external irradiation.

– particles and photons flux density.

Radiation protection office establish control levels of all controlled parameters in according to not exceed dose limits and keep dose levels as low as possible. In case of exceeding control levels radiation protection officers start investigation of exceed causes and take actions to eliminate this exceeding.

During planning and implementation of radiation safety precautions, taking any actions about radiation safety and analysis of effectiveness of mentioned action and precautions one must value radiation safety with next factors:

– characteristics of radioactive contamination of the environment;

– probability of radiation accidents and scale of accidents;

– degree of readiness to effective elimination of radiation accidents and its aftermath;

– number of persons irradiated with doses higher than controlled limits of doses;

– analysis of actions for providing radiation safety, meeting requirements, rules, standards of radiation safety;

– analysis of irradiation doses obtained by groups of population from all ionizing radiation sources.

5.4.3.5 Abnormally high voltage value in the circuit

Measures to ensure the electrical safety of electrical installations:

- disconnection of voltage from live parts, on which or near to which work will be carried out, and taking measures to ensure the impossibility of applying voltage to the workplace;
- posting of posters indicating the place of work;
- electrical grounding of the housings of all installations through a neutral wire;
- coating of metal surfaces of tools with reliable insulation;

- inaccessibility of current-carrying parts of equipment (the conclusion in the case of electroporating elements, the conclusion in the body of current-carrying parts) [72].

5.4.3.6 Insufficient illumination of the working area

Desktops should be placed in such a way that the monitors are oriented sideways to the light openings, so that natural light falls mainly on the left.

Also, as a means of protection to minimize the impact of the factor, local lighting should be installed due to insufficient lighting, window openings should be equipped with adjustable devices such as blinds, curtains, external visors, etc.

5.5. Ecological safety

5.5.1 Analysis of the impact of the research object on the environment

Sources of ionizing radiation used in medicine could be divided into two groups: radioactive substances and radiation generators. The difference is that radiation generators like accelerators and x-ray tubes emit ionizing radiation only when they are turned on.

In ordinary work with necessary safety precautions, there are insignificant impact of using sources of ionizing radiation on environment. The immediate effect of ionizing radiation is ionization of air in room, but after a specified time the ionization disappears.

The danger of using radioactive materials could occur only in accidents with stealing and loosing these materials due to high toxicity.

Mass production of plastic began only 60 years ago. During this time, its output increased 180 times. Recycling takes only 9% of the plastic. Another 12% is burned, and 79% goes to landfills and the environment.

As a result, there is pollution by debris of the lithosphere and hydrosphere. Due to the circulation of currents in the oceans, “garbage islands” are formed. At the same time, plastic not only drifts on the surface, but sinks to the bottom.

In addition to large plastic wastes, there are also wastes due to microplastics. According to international classification, any plastic particle less than 5 mm in length falls into this category. Microplastic is divided into primary and secondary. Primary is most often fibers added to synthetic clothing. When rubbing on a surface or washing, thousands of fibers are separated from it, “hanging” in the air or washed off into the sewer. The second most important source is particles of artificial rubber from tires, which each car leaves 20 grams per 100 km of track. In addition, cars erase markings from roads, which also contain plastic. Secondary microplastic is added to this - “large” debris, broken up into small pieces. As you know, plastic has decomposed for centuries. But it can quickly degrade to tiny parts, while maintaining its molecular structure.

The solutions to the plastic problem today are legislative restrictions on the use of plastic and disposable products, sorting and processing of waste. But they are still not effective solutions to the problem.

In the framework of this work, PLA plastic was used as a consumable for 3D printing. Polylactide - biodegradable, biocompatible, thermoplastic, plastic. The raw materials for the production of PLA plastic are annually renewable resources (corn and sugarcane).

5.5.2 Analysis of the environmental impact of the research process

Process of investigation itself in the thesis do not have essential effect on environment. One of hazardous waste is fluorescent lamps. Mercury in fluorescent lamps is a hazardous substance and its improper disposal greatly poisons the environment.

Outdated devices goes to an enterprise that has the right to process wastes. It is possible to isolate precious metals with a purity in the range of 99.95–99.99% from computer components. A closed production cycle consists of the following stages: primary sorting of equipment; the allocation of precious, ferrous and non-ferrous metals and other materials; melting; refining and processing of metals. Thus, there is an effective disposal of computer devices.

5.5.3 Justification of environmental protection measures

Pollution reduction is possible due to the improvement of devices that produces electricity, the use of more economical and efficient technologies, the use of new methods for generating electricity and the introduction of modern methods and methods for cleaning and neutralizing industrial waste. In addition, this problem should be solved by efficient and economical use of electricity by consumers themselves. This is the use of more economical devices, as well as efficient regimes of these devices. This also includes compliance with production discipline in the framework of the proper use of electricity.

Simple conclusion is that it is necessary to strive to reduce energy consumption, to develop and implement systems with low energy consumption. In modern computers, modes with reduced power consumption during long-term idle are widely used.

5.6 Safety in emergency

5.6.1 Analysis of probable emergencies that may occur at the workplace during research

The fire is the most probable emergency in our life. Possible causes of fire:

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

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

5.6.2 Substantiation of measures for the prevention of emergencies and the development of procedures in case of emergencies

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

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

The regime measures include the establishment of rules for the organization of work, and compliance with fire-fighting measures. To prevent fire from short circuits, overloads, etc., the following fire safety rules must be observed [73]:

- elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);
- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials;
- the correct operation of the equipment (proper inclusion of equipment in the electrical supply network, monitoring of heating equipment);
- correct maintenance of buildings and territories (exclusion of the source of ignition - prevention of spontaneous combustion of substances, restriction of fire works);
- training of production personnel in fire safety rules;
- the publication of instructions, posters, the existence of an evacuation plan;
- compliance with fire regulations, norms in the design of buildings, in the organization of electrical wires and equipment, heating, ventilation, lighting;
- the correct placement of equipment;
- well-time preventive inspection, repair and testing of equipment.

In the case of an emergency, it is necessary to:

- inform the management (duty officer);
- call the Emergency Service or the Ministry of Emergency Situations - tel. 112;
- take measures to eliminate the accident in accordance with the instructions.

Conclusions

In this section about social responsibility the hazardous and harmful factors were revealed. All necessary safety measures and precaution to minimize probability of accidents and traumas during investigation are given.

Possible negative effect on environment were given in compact form describing main ecological problem of using nuclear energy.

It could be stated that with respect to all regulations and standards, investigation itself and object of investigation do not pose special risks to personnel, other equipment and environment.

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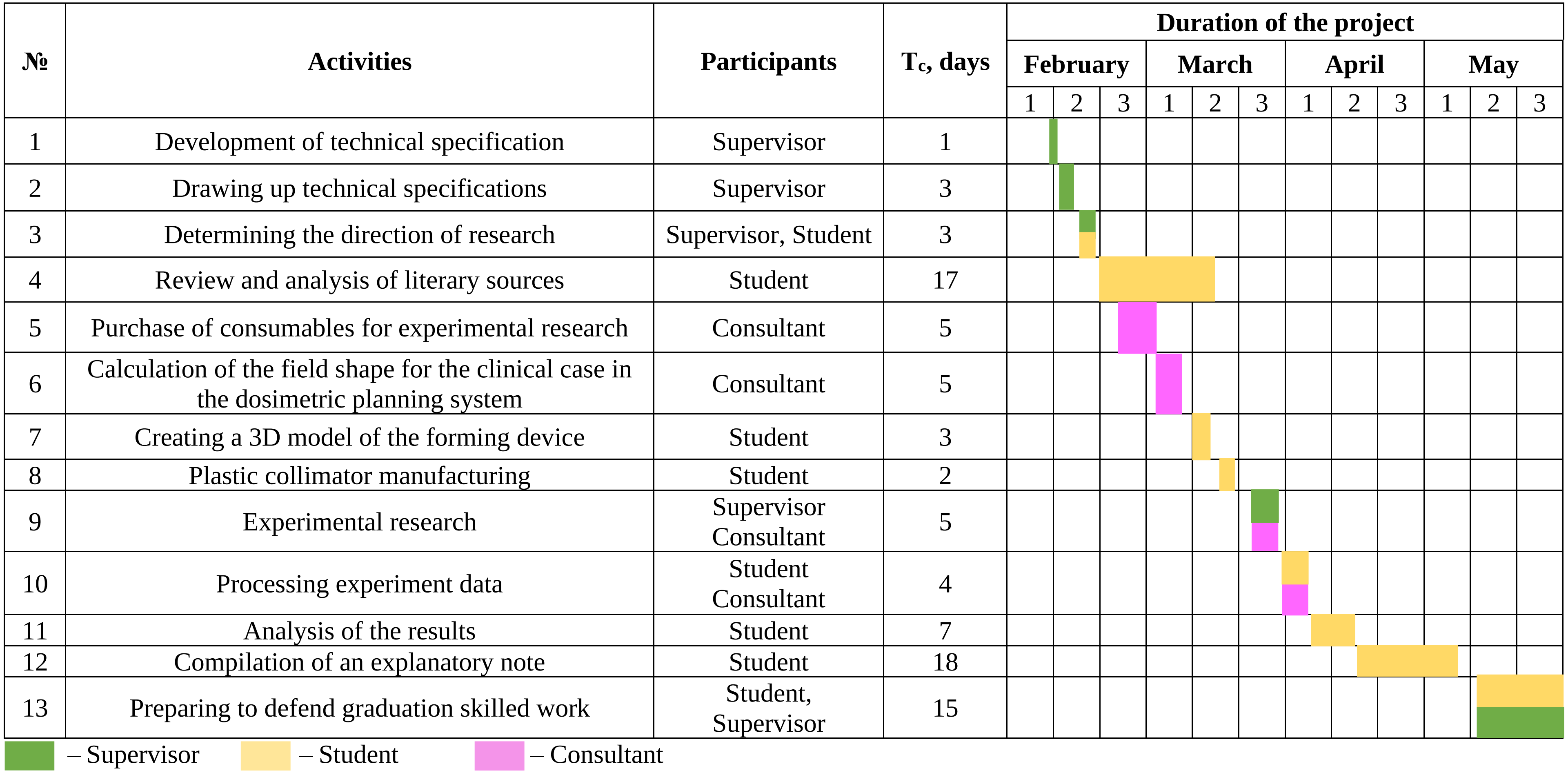
Appendix A

Table A.1 – Additive manufacturing technologies

Method	**Technology**	**Feature of the working principle**	**Materials**
VAT photopolymerization	Stereolithography (SLA)	Curved with laser	Standard, tough, flexible, transparent and castable resins
	Digital Light Processing (DLP)	Cured with projector	Standard and castable resins
	Continuous Digital Light Processing (cDLP)	Cured with LED and oxygen	Standard, tough, flexible, transparent and castable resins
Material Extrusion	Fused Deposition Modeling (FDM)		ABS, PLA, Nylon, PC, fiber-reinforced Nylon, ULTEM, exotic filaments (wood-filled, metal-filled etc)
Material Jetting	Material Jetting (MJ)	Cured with UV light	Rigid, transparent, multi-color, rubber-like, ABS-like
	NanoParticle Jetting (NPJ)	Cured with heat	Stainless steel, ceramics
	Drop On Demand (DOD)	Milled to form	Wax
Binder Jetting	Binder Jetting (BJ)	Joined with bonding agent	Silica sand, PMMA particle material, gypsum, stainless steel, ceramics, cobalt-chrome, tungsten-carbide
Powder Bed Fusion	Multi Jet Fusion (MJF)	Fused with agent and energy	Nylon
	Selective Laser Sintering (SLS)	Fused with laser	Nylon, alumide, carbon-fiber filled nylon, PEEK, TPU
	Direct Metal Laser Sintering/Selective Laser Melting (DMLS/SLM)		Aluminum, titanium, stainless steel, nickel alloys, cobalt-chrome
	Electron Beam Melting (EBM)	Fused with electron beam	Titanium, cobalt-chrome
Direct energy deposition	Laser Engineering Net Shape (LENS)	Fused with laser	Titanium, stainless steel, aluminum, copper, tool steel
	Electron Beam Additive Manufacturing (EBAM)	Fused with electron beam	Titanium, stainless steel, aluminum, copper nickel, 4340 steel
Sheet lamination	Laminated Object Manufacturing (LOM)		Composite, paper

Appendix B



№	Activities	Participants	T_c, days	Duration of the project											
				February			**March**			**April**			**May**		
				1	2	3	1	2	3	1	2	3	1	2	3
1	Development of technical specification	Supervisor	1	🟩											
2	Drawing up technical specifications	Supervisor	3		🟩										
3	Determining the direction of research	Supervisor, Student	3		🟩 🟨										
4	Review and analysis of literary sources	Student	17			🟨	🟨	🟨							
5	Purchase of consumables for experimental research	Consultant	5			🟪	🟪								
6	Calculation of the field shape for the clinical case in the dosimetric planning system	Consultant	5				🟪								
7	Creating a 3D model of the forming device	Student	3					🟨							
8	Plastic collimator manufacturing	Student	2					🟨							
9	Experimental research	Supervisor Consultant	5						🟩 🟪						
10	Processing experiment data	Student Consultant	4							🟨 🟪					
11	Analysis of the results	Student	7							🟨	🟨				
12	Compilation of an explanatory note	Student	18								🟨	🟨	🟨		
13	Preparing to defend graduation skilled work	Student, Supervisor	15											🟨 🟩	🟨 🟩

🟩 – Supervisor 🟨 – Student 🟪 – Consultant

Figure B.1 – A Gantt chart