TOMSK POLYTECHNIC UNIVERSITY

Томский политехнический университет

Школа Инженерная школа ядерных технологий
Направление подготовки 14.03.02 Ядерные физика и технологии
Отделение школы (НОЦ) Отделение ядерно-топливного цикла

БАКАЛАВРСКАЯ РАБОТА

Тема работы
Моделирование поля излучения гамма установки РОКУС-АМТ с использованием программного комплекса GEANT4

УДК 539.166.2-047.58:004.41

Студент

Группа	ФИО	Подпись	Дата
0А8Д	Кузьменко Анна Сергеевна		

Руководитель ВКР

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОЯТЦ ИЯТШ	Тимченко Сергей Николаевич	к.т.н.		

Консультант

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Старший преподаватель ОЯТЦ ИЯТШ	Побережников Андрей Дмитриевич			

КОНСУЛЬТАНТЫ ПО РАЗДЕЛАМ:

По разделу «Финансовый менеджмент, ресурсоэффективность и ресурсосбережение»

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОСГН ШБИП	Якимова Т.Б.	к.э.н.		

По разделу «Социальная ответственность»

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОЯТЦ ИЯТШ	Передерин Ю.В.	к.т.н.		

ДОПУСТИТЬ К ЗАЩИТЕ:

Руководитель ООП	ФИО	Ученая степень, звание	Подпись	Дата
Ядерные физика и технологии	Бычков П.Н.	к.т.н.		

Томск – 2022 г.

School of Nuclear Science & Engineering
Field of training (speciality): 14.03.02 Nuclear Science and Technology
Nuclear Fuel Cycle Division

BACHELOR THESIS

Тема работы
Modeling the Radiation Field of the ROKUS-AMT Gamma Unit Using the GEANT4 Software Package

UDC 539.166.2-047.58:004.41

Student

Group	Full name	Signature	Date
0A8D	Kuzmenko A.S.		

Scientific supervisor

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor of NFCD	Timchenko S.N.	PhD		

Consultunt

Position	Full name	Academic degree, academic rank	Signature	Date
Senior lecturer of NFCD	Poberezhnikov A.D.			

ADVISERS:

Section «Financial Management, Resource Efficiency and Resource Saving»

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor	Yakimova T.B.	PhD		

Section «Social Responsibility»

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor	Perederin Y.V.	PhD		

ADMITTED TO DEFENCE:

Programme Director	Full nmae	Academic degree, academic rank	Signature	Date
Nuclear Science and Technology	Bychkov P.N.	PhD		

Tomsk – 2022 y.

ПЛАНИРУЕМЫЕ РЕЗУЛЬТАТЫ ОБУЧЕНИЯ

Код компетенции	Результаты освоения ООП (компетенции)
Универсальные	
УК(У)-1	Способен осуществлять поиск, критический анализ и синтез информации, применять системный подход для решения поставленных задач
УК(У)-2	Способен определять круг задач в рамках поставленной цели и выбирать оптимальные способы их решения, исходя из действующих правовых норм, имеющихся ресурсов и ограничений
УК(У)-3	Способен осуществлять социальное взаимодействие и реализовывать свою роль в команде
УК(У)-4	Способен осуществлять деловую коммуникацию в устной и письменной формах на государственном языке Российской Федерации и иностранном(-ых) языке(-ах)
УК(У)-5	Способен воспринимать межкультурное разнообразие общества в социально-историческом, этическом и философском контекстах
УК(У)-6	Способен управлять своим временем, выстраивать и реализовывать траекторию саморазвития на основе принципов образования в течение всей жизни
УК(У)-7	Способен поддерживать должный уровень физической подготовленности для обеспечения полноценной социальной и профессиональной деятельности
УК(У)-8	Способен создавать и поддерживать безопасные условия жизнедеятельности, в том числе при возникновении чрезвычайных ситуаций
УК(У)-9	Способен проявлять предприимчивость в профессиональной деятельности, в т.ч. в рамках разработки коммерчески перспективного продукта на основе научно-технической идеи
Общепрофессиональные	
ОПК(У)-1	Способен использовать базовые знания естественнонаучных дисциплин в профессиональной деятельности, применять методы математического анализа и моделирования, теоретического и экспериментального исследования
ОПК(У)-2	Способен осуществлять поиск, хранение, обработку и анализ информации из различных источников и баз данных, предоставлять ее в требуемом формате с использованием информационных, компьютерных и сетевых технологий
ОПК(У)-3	Способен использовать в профессиональной деятельности современные информационные системы, анализировать возникающие при этом опасности и угрозы, соблюдать основные требования информационной безопасности, в том числе защиты государственной тайны
Профессиональные компетенции	
ПК(У)-1	Способен использовать научно-техническую информацию, отечественный и зарубежный опыт по тематике исследования, современные компьютерные технологии и информационные ресурсы в своей предметной области
ПК(У)-2	Способен проводить математическое моделирование процессов и объектов атомной отрасли с использованием стандартных методов и компьютерных кодов для проектирования и анализа
ПК(У)-3	Готов к проведению физических экспериментов по заданной методике, составлению описания проводимых исследований и анализу полученных экспериментальных данных
ПК(У)-4	Способен использовать технические средства для измерения основных параметров объектов исследования
ПК(У)-5	Готов к составлению отчета по выполненному заданию, к участию во внедрении результатов исследований и разработок
ПК(У)-6	Способен использовать информационные технологии при разработке новых установок, материалов и приборов, к сбору и анализу исходных данных для проектирования объектов атомной отрасли
ПК(У)-7	Способен к расчету и проектированию деталей и узлов приборов и установок в соответствии с техническим заданием
ПК(У)-8	Готов к разработке проектной и рабочей технической документации, оформлению законченных проектно-конструкторских работ
ПК(У)-9	Способен к контролю соответствия разрабатываемых проектов и технической документации стандартам, техническим условиям, требованиям безопасности и другим нормативным документам
ПК(У)-10	Готов к проведению предварительного технико-экономического обоснования проектных решений при разработке установок и приборов
ПК(У)-11	Способен к контролю за соблюдением технологической дисциплины и обслуживанию технологического оборудования
ПК(У)-12	Готов к эксплуатации современного физического оборудования, приборов и технологий
ПК(У)-13	Способен к оценке ядерной и радиационной безопасности, к оценке воздействия на окружающую среду, к контролю за соблюдением экологической безопасности, техники безопасности, норм и правил производственной санитарии, пожарной, радиационной и ядерной безопасности, норм охраны труда

ПК(У)-14	Готов разрабатывать способы применения ядерно-энергетических, плазменных, лазерных, сверхвысокочастотных и мощных импульсных установок, электронных, нейтронных и протонных пучков, методов экспериментальной физики в решении технических, технологических и медицинских проблем
ПК(У)-15	Способен к составлению технической документации (графиков работ, инструкций, планов, смет, заявок на материалы, оборудование), а также установленной отчетности по утвержденным формам

LEARNING OUTCOMES

Competencies code	Competence name
Universal competences	
UC(U)-1	Ability to make critical analysis of problem-based situations using the systems analysis approach, and generate decisions and action plans.
UC(U)-2	Ability to determine the range of tasks within the framework of the goal and choose the best ways to solve them, based on current legal regulations, available resources and restrictions
UC(U)-3	Ability to carry out social interaction and realize their role in the team
UC(U)-4	Ability to carry out business communication in oral and written forms in the state language of the Russian Federation and foreign language(s)
UC(U)-5	Ability to perceive the intercultural diversity of society in the socio-historical, ethical and philosophical contexts
UC(U)-6	Ability to manage his time, build and implement a trajectory of self-development based on the principles of education throughout life
UC(U)-7	Ability to maintain the proper level of physical fitness to ensure full-fledged social and professional activities
UC(U)-8	Ability to create and maintain safe living conditions, including in case of emergencies
UC(U)-9	Ability to show entrepreneurship in professional activities, incl. as part of the development of a commercially promising product based on a scientific and technical idea
General professional competences	
GPC(U)-1	Ability to use basic knowledge of natural sciences in professional activities, apply methods of mathematical analysis and modeling, theoretical and experimental research
GPC(U)-2	Ability to search, store, process and analyze information from various sources and databases, provide it in the required format using information, computer and network technologies
GPC(U)-3	Ability to use modern information systems in professional activities, analyze the dangers and threats arising from this, comply with the basic requirements of information security, including the protection of state secrets
Professional competences	
PC(U)-1	Ability to use scientific and technical information, domestic and foreign experience on research topics, modern computer technologies and information resources in their subject area
PC(U)-2	Ability to carry out mathematical modeling of processes and objects of the nuclear industry using standard methods and computer codes for design and analysis
PC(U)-3	Ready for conducting physical experiments according to a given methodology, compiling a description of ongoing research and analyzing the experimental data obtained
PC(U)-4	Ability to use technical means to measure the main parameters of research objects
PC(U)-5	Ready to draw up a report on the completed task, to participate in the implementation of research and development results
PC(U)-6	Ability to use information technologies in the development of new installations, materials and devices, to the collection and analysis of initial data for the design of nuclear industry facilities
PC(U)-7	Ability to calculate and design parts and assemblies of devices and installations in accordance with the terms of reference
PC(U)-8	Ready for the development of design and working technical documentation, registration of completed design work
PC(U)-9	Capable of monitoring the compliance of developed projects and technical documentation with standards, specifications, safety requirements and other regulatory documents
PC(U)-10	Ready to conduct a preliminary feasibility study of design solutions in the development of installations and devices
PC(U)-11	Capable of monitoring the observance of technological discipline and maintenance of technological equipment
PC(U)-12	Ready for operation of modern physical equipment, instruments and technologies
PC(U)-13	Ability to assess nuclear and radiation safety, to assess the impact on the environment, to monitor compliance with environmental safety, safety regulations, norms and rules of industrial sanitation, fire, radiation and nuclear safety, labor protection standards
PC(U)-14	Ready to develop ways to use nuclear power, plasma, laser, microwave and high-power pulse installations, electron, neutron and proton beams, methods of experimental physics in solving technical, technological and medical problems
PC(U)-15	Ability to draw up technical documentation (work schedules, instructions, plans, estimates, applications for materials, equipment), as well as established reporting in approved forms

TOMSK
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Томский
политехнический
УНИВЕРСИТЕТ

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

Школа Инженерная школа ядерных технологий
Направление подготовки 14.03.02 Ядерные физика и технологии
Отделение школы (НОЦ) Отделение ядерно-топливного цикла

УТВЕРЖДАЮ:
Руководитель ООП

_____ _____ Бычков П.Н.
(Подпись)   (Дата)   (Ф.И.О.)

ЗАДАНИЕ
на выполнение выпускной квалификационной работы

В форме:

Бакалаврской работы

(бакалаврской работы, дипломного проекта/работы, магистерской диссертации)

Студенту:

Группа	ФИО
0А8Д	Кузьменко Анне Сергеевне

Тема работы:

Моделирование поля излучения гамма установки РОКУС-АМТ с использованием программного комплекса GEANT4	
Утверждена приказом директора (дата, номер)	01.02.2022 г., № 32-52/с

Срок сдачи студентом выполненной работы:	31.05.2022

ТЕХНИЧЕСКОЕ ЗАДАНИЕ:

Исходные данные к работе	Экспериментальные данные измерения мощности поглощенной дозы. Размеры помещения с гамма установкой РОКУС-АМТ.

Перечень подлежащих исследованию, проектированию и разработке вопросов	Разработка программы в программном комплексе для моделирования поля излучения гамма установки РОКУС-АМТ. Результаты моделирования мощности поглощенной дозы от расстояния, распределение в плоскости и панели.
Перечень графического материала	– Презентация – Геометрия моделируемого мира – Результаты моделирования

Консультанты по разделам выпускной квалификационной работы
(с указанием разделов)

Раздел	Консультант
Литературный обзор; Статистическое моделирование в GEANT4; Результаты моделирования поля излучения гамма установки РОКУС-АМТ	Побережников А.Д.
Финансовый менеджмент, ресурсоэффективность и энергосбережение	Якимова Т.Б.
Социальная ответственность	Передерин Ю.В.

Дата выдачи задания на выполнение выпускной квалификационной работы по линейному графику	01.02.2022

Задание выдал руководитель / консультант:

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОЯТЦ ИЯТШ	Тимченко С.Н.	к.т.н.		
Старший преподаватель ОЯТЦ ИЯТШ	Побережников А.Д.			

Задание принял к исполнению студент:

Группа	ФИО	Подпись	Дата
0А8Д	Кузьменко Анна Сергеевна		

TOMSK POLYTECHNIC UNIVERSITY
Томский политехнический университет

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

School of Nuclear Science & Engineering
Field of training (speciality): 14.03.02 Nuclear Science and Technology
Nuclear Fuel Cycle Division

APPROVED BY:
Program Director

_____ _____ Bychkov P.N.
  (Signature)   (Date)   (Full name)

ASSIGNMENT
for the Graduation Thesis completion

In the form:

Bachelor Thesis

Student:

Group	Full name
0A8D	Kuzmenko Ann Sergeevna

Topic of the research work:

Modeling the Radiation Field of the ROKUS-AMT Gamma Unit Using the GEANT4 Software Package	
Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	01.02.2022 y., № 32-52/с

Deadline for completion of Bachelor Thesis:	31.05.2022

TERMS OF REFERENCE:

Initial date for research work:	Experimental data of measurement of the absorbed dose rate. Dimensions of the room with the ROKUS-AMT gamma unit.

List of the issues to be investigated, designed and developed	Development of a program in the software package for modeling the radiation field of the gamma radiation facility ROKUS-AMT. Results of simulation of absorbed dose rate versus distance, in-plane and panel distribution.
List of graphic material	– Presentation – Geometry of modeling area – Results of modeling

Advisors to the sections of the Bachelor Thesis

(with indications of sections)

Section	Advisor
Literature Review; Statistical Simulation of the Radiation Field in GEANT4; Results of Simulation of the Radiation Field of the Gamma Facility of the ROCUS-AMT Unit	Poberezhnikov A.D.
Financial Management, Resource Efficiency and Resource Saving	Yakimova T.B.
Social Responsibility	Perederin Y.V.

Date of issuance of the assignment for Bachelor Thesis completion according to the schedule	01.02.2022

Assignment issued by a scientific supervisor / advisor:

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor of NFCD	Timchenko S.N.	PhD		
Senior lecturer of NFCD	Poberezhnikov A.D.			

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0A8D	Kuzmenko Ann Sergeevna		

ЗАДАНИЕ ДЛЯ РАЗДЕЛА
«ФИНАНСОВЫЙ МЕНЕДЖМЕНТ, РЕСУРСОЭФФЕКТИВНОСТЬ И РЕСУРСОСБЕРЕЖЕНИЕ»

Студенту:

Группа	ФИО
0А8Д	Кузьменко Анне Сергеевне

Школа	ИЯТШ	Отделение школы (НОЦ)	ОЯТЦ
Уровень образования	Бакалавриат	Направление/специальность	Ядерные физика и технологии

Исходные данные к разделу «Финансовый менеджмент, ресурсоэффективность и ресурсосбережение»:	
1. Стоимость ресурсов научного исследования (НИ): материально-технических, энергетических, финансовых, информационных и человеческих	*Стоимость материальных ресурсов в соответствии с рыночными ценами г. Томска. Тарифные ставки исполнителей в соответствии со штатным расписанием НИ ТПУ.*
2. Нормы и нормативы расходования ресурсов	*Коэффициенты для расчета заработной платы.*
3. Используемая система налогообложения, ставки налогов, отчислений, дисконтирования и кредитования	*Коэффициент отчислений во внебюджетные фонды – 30,2 %.*
Перечень вопросов, подлежащих исследованию, проектированию и разработке:	
1. Оценка коммерческого потенциала, перспективности и альтернатив проведения НИ с позиции ресурсоэффективности и ресурсосбережения	*Анализ потенциальных потребителей результатов исследования. Исследование конкурентных технических решений. Проведение SWOT-анализа*
2. Планирование и формирование бюджета научных исследований	*Определение трудоемкости работ. Разработка графика проведения научного исследования. Формирование бюджета затрат научно-исследовательского проекта*
3. Определение ресурсной (ресурсосберегающей), финансовой, бюджетной, социальной и экономической эффективности исследования	*Проведение оценки сравнительной эффективности проекта.*
Перечень графического материала *(с точным указанием обязательных чертежей)***:**	
1. Оценка конкурентоспособности технических решений *2. Матрица SWOT* *3. График проведения и бюджет НИ* *4. Оценка ресурсной, финансовой и экономической эффективности НИ*	

Дата выдачи задания для раздела по линейному графику	15.03.2022

Задание выдал консультант:

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОСГН	Якимова Т.Б.	канд. экон. наук		15.03.2022

Задание принял к исполнению студент:

Группа	ФИО	Подпись	Дата
0А8Д	Кузьменко А.С.		15.03.2022

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

Student:

Group	Full name
0A8D	Kuzmenko Ann Sergeevna

School	Nuclear Science and Engineering	Division	Nuclear Fuel Cycle
Degree	Bachelor	Field of training	Nuclear physics and technologies

Initial data to the section «Financial management, resource efficiency and resource saving»:

1.	*The cost of scientific research resources (SR): logistical, energy, financial, informational and human*	*The cost of material resources in accordance with the market prices of the city of Tomsk. Tariff rates of performers in accordance with the staffing table of NR TPU.*
2.	*Norms and standards of resource spending*	*Coefficients for payroll calculation.*
3.	*Taxation system used, tax rates, deductions, discounting and lending*	*The coefficient of deductions to off-budget funds is 30.2 %.*

The list of subjects to study, design and develop:

1.	*Evaluation of the commercial potential, prospects and alternatives for conducting scientific research from the standpoint of resource efficiency and resource saving*	*Analysis of potential consumers of the research results. Research of competitive technical solutions. Conducting a SWOT analysis*
2.	*Planning and budgeting for scientific research*	*Determination of labor intensity of work. Development of a schedule for conducting a scientific study. Formation of the budget for the costs of a research project*
3.	*Determination of resource (resource-saving), financial, budgetary, social and economic efficiency of the study*	*Conducting an assessment of the comparative effectiveness of the project.*

A list of a graphic material:

1. *Assessment of the competitiveness of technical solutions*
2. *SWOT matrix*
3. *Schedule and budget for NI*
4. *Assessment of resource, financial and economic efficiency of research*

Date of issue of the task for the section according to the schedule	15.03.2022

Assignment issued by an advisor:

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor	Yakimova T.B.	PhD		15.03.2022

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0A8D	Kuzmenko A.S.		15.03.2022

ЗАДАНИЕ ДЛЯ РАЗДЕЛА
«СОЦИАЛЬНАЯ ОТВЕТСТВЕННОСТЬ»

Студенту:

Группа	ФИО
0А8Д	Кузьменко Анне Сергеевне

Школа	ИЯТШ	Отделение (НОЦ)	ОЯТЦ
Уровень образования	Бакалавр	Направление/специальность	Ядерные физика и технологии

Тема ВКР:

Моделирование поля излучения гамма установки РОКУС-АМТ с использованием программного комплекса GEANT4

Исходные данные к разделу «Социальная ответственность»:	
1. Характеристика объекта исследования (вещество, материал, прибор, алгоритм, методика, рабочая зона) и области его применения	Объект исследования: гамма-установка РОКУС-АМТ Область применения: атомная промышленность.

Перечень вопросов, подлежащих исследованию, проектированию и разработке:	
1. Правовые и организационные вопросы обеспечения безопасности: – специальные (характерные при эксплуатации объекта исследования, проектируемой рабочей зоны) правовые нормы трудового законодательства; – организационные мероприятия при компоновке рабочей зоны.	– Правовые нормы трудового законодательства; – Требования к организации и оборудованию рабочих мест с ПЭВМ: – ГОСТ 22269-76. Система «человек-машина». Рабочее место оператора. Взаимное расположение элементов рабочего места. Общие эргономические требования.
2. Производственная безопасность: 2.1. Анализ выявленных вредных и опасных факторов 2.2. Обоснование мероприятий по снижению воздействия	Вредные и опасные факторы: – отклонение показателей микроклимата; – повышенный уровень электромагнитных излучений; – недостаточная освещенность рабочей зоны; – повышенный уровень шума; – психофизиологические факторы; – опасность поражения электрическим током.
3. Экологическая безопасность:	– анализ влияния объекта и процесса исследования на окружающую среду; – разработка организационных и технических мероприятий по защите окружающей среды.
4. Безопасность в чрезвычайных ситуациях:	– выбор и описание типичной ЧС: пожар; – обоснование мероприятий по предотвращению ЧС; – порядок действий при возникновении ЧС.

Дата выдачи задания для раздела по линейному графику	15.03.2022

Задание выдал консультант:

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОЯТЦ ИЯТШ	Передерин Ю. В.	к.т.н.		15.03.2022 г.

Задание принял к исполнению студент:

Группа	ФИО	Подпись	Дата
0А8Д	Кузьменко А.С.		15.03.2022 г.

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ASSIGNMENT FOR SECTION
«SOCIAL RESPONSIBILITY»

Student:

Group	Full name
0A8D	Kuzmenko Ann Sergeevna

School	Nuclear Science and Engineering	Division		Nuclear Fuel Cycle
Degree	Bachelor	Field of training		Nuclear physics and technologies

Topic of the research work:

Modeling the Radiation Field of the ROKUS-AMT Gamma Unit Using the GEANT4 Software Package

Initial data to the section «Social responsibility»:	
1. Characteristics of the object of study (substance, material, device, algorithm, technique, working area) and areas of its application	Object of study: gamma-ray unit ROKUS-AMT Scope: nuclear industry.

List of issues to be researched, designed and developed:	
1. Legal and organizational issues of security: − special (characteristic for the operation of the object of study, the designed working area) legal norms of labor legislation; − organizational measures in the layout of the working area.	− Legal norms of labor legislation; − Requirements for the organization and equipment of workplaces with a PC: − GOST 22269-76. The «man-machine» system. Operator's workplace. Mutual arrangement of elements of the workplace. General ergonomic requirements.
2. Industrial safety: 2.1. Analysis of identified harmful and dangerous factors 2.2. Rationale for mitigation measures	Harmful and dangerous factors: − deviation of microclimate indicators; − increased level of electromagnetic radiation; − insufficient illumination of the working area; − increased noise level; − psychophysiological factors; − risk of electric shock.
3. Environmental safety:	− analysis of the impact of the object and the research process on the environment; − development of organizational and technical measures to protect the environment.
4. Safety in emergency situations:	− selection and description of a typical emergency situation: fire; − substantiation of measures to prevent emergencies; − procedure for action in the event of an emergency.

Date of issue of the task for the section according to the schedule	15.03.2022

Assignment issued by an advisor:

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor	Perederin Y.V	PhD		15.03.2022 y.

Assignment accepted for execution by a student:

Group	Full name	Signature	Date
0A8D	Kuzmenko A.S.		15.03.2022 y.

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

Школа Инженерная школа ядерных технологий
Направление подготовки (специальность) 14.03.02. Ядерные физика и технологии
Уровень образования высшее
Отделение школы (НОЦ) Отделение ядерно-топливного цикла
Период выполнения _____ (весенний семестр 2021 /2022 учебного года)

Форма представления работы:

Бакалаврская работа

(бакалаврская работа, дипломный проект/работа, магистерская диссертация)

КАЛЕНДАРНЫЙ РЕЙТИНГ-ПЛАН
выполнения выпускной квалификационной работы

Срок сдачи студентом выполненной работы:	31.05.2022

Дата контроля	Название раздела (модуля) / вид работы (исследования)	Максимальный балл раздела (модуля)
05.02.2022	Постановка цели и задач	5
07.02.2022	Составление и утверждение ТЗ	5
30.02.2022	Подбор и изучение материалов по тематике	10
01.03.2022	Разработка календарного плана	5
06.03.2022	Обсуждение литературы	10
12.04.2022	Разработка программы	15
17.04.2022	Исследование спектров	10
24.05.2022	Верификация программы	20
31.05.2022	Оформление расчетно-пояснительной записки	20

СОСТАВИЛ:
Руководитель ВКР

Должность	ФИО	Ученая степень, звание	Подпись	Дата
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Руководитель ООП

Должность	ФИО	Ученая степень, звание	Подпись	Дата
Доцент ОЯТЦ	Бычков П.Н.	к.т.н.		

TOMSK
POLYTECHNIC
UNIVERSITY

Томский
политехнический
УНИВЕРСИТЕТ

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

School of Nuclear Science & Engineering
Field of training (speciality): 14.03.02 Nuclear Science and Technology
Nuclear Fuel Cycle Division
Period of completion_____(spring semester 2021/2022 academic year)_____

Form of presenting the work:

Bachelor Thesis

SCHEDULED ASSESSMENT CALENDAR
for the Bachelor Thesis completion

Deadline for completion of Bachelor Thesis:	31.05.2022

Assessment date	Title of section (module) / type of work (research)	Maximum score for the section (module)
05.02.2022	*Setting goals and objectives*	*5*
07.02.2022	*Drafting and approval of TT*	*5*
30.02.2022	*Selection and study of materials on the subject*	*10*
01.03.2022	*Development of the calendar plan*	*5*
06.03.2022	*Literature discussion*	*10*
12.04.2022	*Program development*	*15*
17.04.2022	*Spectra study*	*10*
24.05.2022	*Program verification*	*20*
31.05.2022	*Registration of a settlement and explanatory note*	*20*

COMPILED BY:
Scientific supervisor:

Должность	Full name	Academic degree, academic rank	Signature	Date
Associate professor of NFCD	Timchenko S.N.	PhD		

APPROVED BY:
Program Director

Position	Full name	Academic degree, academic rank	Signature	Date
Associate professor	Bychkov P.N.	PhD		

ABSTRACT

Bachelor thesis: 92 pages, 33 figures, 32 tables, 33 references, 1 appendix.

Keywords: GEANT4, gamma unit, ROKUS-AMT, radiation source, absorbed dose rate, cobalt-60.

The object of the study is the ROKUS-AMT gamma unit.

The subject of the study is the radiation field of the ROKUS-AMT gamma installation.

The purpose of the work is to develop a program for modeling the radiation field of the ROKUS-AMT gamma-ray unit with a GIK-9-4 radiation source using the GEANT4 software package.

In the course of the study, a program was developed and verification was carried out according to known experimental data: the dependence of the absorbed dose rate on the distance from the gamma installation, distribution in the plane and panels with containers. The emission spectra were obtained in the source and phantom at a distance of 0 cm from the gamma-ray setup.

It is shown that the obtained spectra of gamma and electron radiation in the GIK-9-4 radiation source, obtained as a result of the decay of ^{60}Co, are in good agreement with the known experimental data. It has been determined that the largest contribution (97.2 %) to the absorbed dose rate is made by electrons produced as a result of Compton scattering.

It has been established that the program makes it possible to calculate the absorbed dose rate when simulating 10^7 decays of ^{60}Co with an accuracy of up to 10 %.

It is shown that the calculation of the absorbed dose rate in containers located on the panel at a distance of 760 cm is possible with an accuracy of up to 30 % when simulating 10^7 decays of ^{60}Co.

The developed program can be used to determine the absorbed dose rate in experiments on the effect of radiation on electronic components at the «Radian» test gamma complex.

TABLE OF CONTENTS

INTRODUCTION

A spacecraft in flight is exposed to a wide range of outer space factors: high-energy electron and ion flows, plasma, solar electromagnetic radiation, etc. As a result of such an impact, various physical and chemical processes occur in the materials and elements of spacecraft equipment, leading to a deterioration in their operational parameters. In this case, the occurrence of failures is associated mainly with certain radiation effects caused by the impact on spacecraft materials of electrons and ions, the energies of which lie in a very wide range.

In order to avoid failures in the operation of spacecraft equipment, studies are being carried out on the effects of radiation on materials, including on the electronic components of spacecraft, which must also withstand strong space radiation. When conducting research, it is necessary to accurately select the radiation dose, in connection with this, it is necessary to know the characteristics of the radiation field.

Engineering methods are used to calculate the radiation field and doses, however, in a complex system consisting of many elements of various materials, it is preferable to use simulation, and due to progress in the field of electronics, in particular processors, the calculation speed has increased significantly, which allows the use of Monte-Carlo methods for calculations. Therefore, it is important to develop a methodology for calculating the absorbed dose during research.

The purpose of the work is to develop a program for modeling the radiation field of the ROKUS-AMT gamma-ray unit with a GIK-9-4 radiation source using the GEANT4 software package.

To achieve this purpose, the following tasks are formulated:

1. Compose the geometry of the object being modeled.

2. Conduct a study of the spectra in the GIK-9-4 radiation source and silicon phantom.

3. Verify the developed program by comparing with experimental data: dependence of the absorbed dose rate on distance, distribution in the plane and containers located on the panel.

1. LITERATURE REVIEW

1.1. Interaction of Gamma Radiation with Matter

Gamma radiation (γ-radiation) is an electromagnetic radiation that belongs to the highest frequency part of the electromagnetic waves spectrum.

Atomic nuclei and particles, nuclear reactions and reactions between particles, in particular, the annihilation of particle-antiparticle pairs, can be sources of gamma radiation. Conversely, gamma radiation can be absorbed by atomic nuclei and can cause particle transformations. The study of spectrums of nuclear gamma-radiation and gamma-radiation, that appears in processes of particle interactions, gives important information of structure these micro-objects.
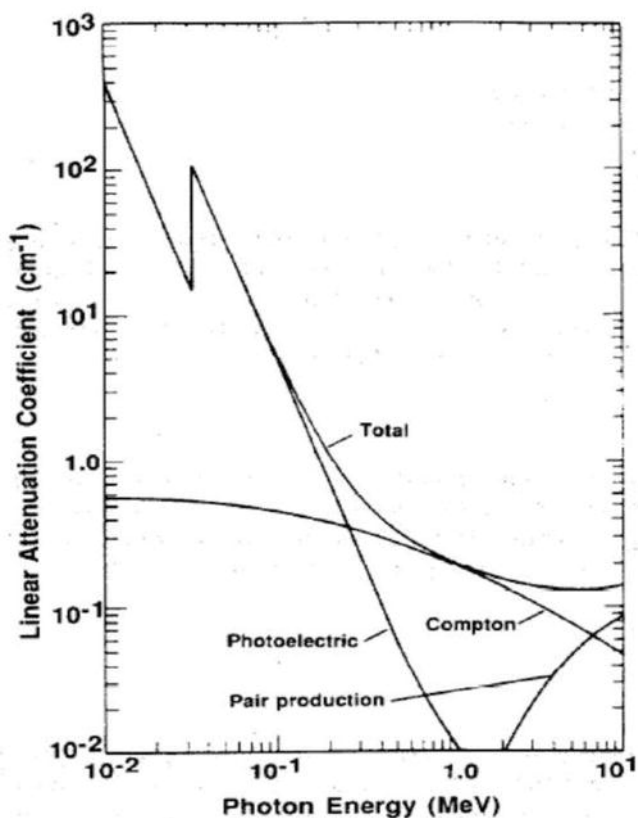

Figure 1 – Linear attenuation coefficient of NaI showing contributions from photoelectric absorption, Compton scattering, and pair production [1]

The photoelectric effect, the Compton effect and the formation of electron-positron pairs are the main types of interaction of gamma-radiation with matter [2]. All

three effects must be considered when interaction gamma-radiation with matter requires is studied. The total cross section is:

$$\sigma = \sigma_{ph} + \sigma_C + \sigma_{pair} \qquad (1)$$

where $\sigma_{ph} \sim Z^5 / E_\gamma^{7/2} \left(E_\gamma \right)$ – the photoelectric effect cross section;

$\sigma_C \sim Z / E_\gamma$ – the Compton effect cross section;

$\sigma_{pair} \sim Z^2 \ln 2E_\gamma$ – the gamma conversion cross section.

From the nature of the dependence of the cross sections on the energy of γ-radiation E_γ and the charge of the medium Z, shown in figure 1, it follows that in the region of low energies ($E_\gamma < E_1$) the main mechanism of interaction of γ-radiation with the medium is the photoelectric effect, in the intermediate region ($E_1 < E_\gamma < E_2$) is the Compton effect, and in the region of high energies ($E_\gamma > E_2$) is the process of formation of electron-positron pairs.

1.1.1. Photoelectric Effect

The photoelectric effect is a process of interaction γ-quantum with an electron associated with an atom, in which the entire energy of the γ-quantum is transferred to the electron. In this case, the electron is ejected outside the atom with kinetic energy:

$$T_e = E_\gamma - I_i \qquad (2)$$

where E_γ – energy of γ-quantum;

I_i – ionization potential of the i-th shell of atom.

The place vacated as a result of the photoelectric effect on the electron shell is filled with electrons from the higher shells. This process is accompanied by the emission of X-rays or the emission of Auger electrons.

The photoelectric effect is possible only on a bound electron. The smaller the bond between an electron and an atom compared to the energy of a photon, the less likely the photoelectric effect is.

1.1.2. Scattering γ-radiation

The interaction of γ-radiation with the medium can also lead to its scattering, i.e. deviation from the original direction of propagation by some angle θ.

Scattering can be of two types:

1. without changing the wavelength (coherent scattering, Thomson, classical);
2. with a change in wavelength (incoherent, Compton scattering).

1.1.2.1. Thomson Scattering

An electron under the influence of an electromagnetic wave incident $E = E_0 \exp(-ivt)$ comes into forced oscillations with the same frequency v, and, therefore, itself becomes an emitter of electromagnetic waves of the same frequency. This is the scattered wave.

In the simplest case, the scattering of an unpolarized primary wave by a free electron, the differential scattering cross section is

$$d\sigma = \left(r_e^2 / 2\right)\left(1 + \cos^2 \theta\right)d\Omega, \tag{3}$$

and the total scattering cross section

$$\sigma = \frac{8\pi}{3}r_e^2 = 0.66 \cdot 10^{-24} \text{ cm}^2 \tag{4}$$

1.1.2.2. Compton Scattering

The classical scattering theory is valid for $hv << m_e c^2$. If this condition is not met, then scattering with a change in wavelength is observed. In this process, electromagnetic radiation behaves like a stream of individual particles – corpuscles (which in this case are electromagnetic field quanta - photons), which proves the dual – corpuscular-wave – nature of electromagnetic radiation. From the point of view of classical electrodynamics, scattering of radiation with a change in frequency is impossible.

Compton scattering is the scattering by a free electron of an individual photon with energy $E = vh = hc / \lambda$ (h – Planck's constant, v – the frequency of an

electromagnetic wave, λ – its length, c – the speed of light) and momentum $p = E / c$. Scattering on an electron at rest, the photon transfers to it part of its energy and momentum and changes the direction of its movement. As a result of scattering, the electron begins to move. A photon after scattering will have an energy $E' = h\nu'$ (and frequency) less than its energy (and frequency) before scattering. Accordingly, after scattering, the photon wavelength λ' will increase. It follows from the laws of conservation of energy and momentum that the wavelength of a photon after scattering will increase by

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}\left(1 - \cos\theta\right),\tag{5}$$

where Θ – photon scattering angle;

m_e – electron mass;

$h / m_e c = 0,024\ \text{Å}$ – Compton wavelength of an electron.

1.1.3. Gamma Conversion into e⁺e⁻ Pair

At a sufficiently high photon energy ($h\nu > 2m_e c^2$), the process of pair formation becomes possible, in which a photon is absorbed in the field of the nucleus, and an electron and a positron are born. The process of pair formation cannot take place in a vacuum, but requires the obligatory neighborhood of a nucleus or an electron.

The process of formation of electron-positron pairs, along with radiative deceleration of electrons, is the cause of the appearance of electron-photon showers in cosmic rays. If the γ-quantum arising as a result of radiative deceleration of an electron has energy $E_\gamma > 2m_e c^2$, then it can form a pair, the electron and positron of which again create γ-quanta of radiative braking, and so on. The process grows like an avalanche until the critical energy is reached.

1.2. Gamma Unit ROKUS-AMT

The gamma unit is a stationary unit consisting of a radiation head from the Rokus-AM gamma therapeutic apparatus [3], fixed on a lifting device that allows you

to move the radiation head in height and rotate it in the semiaxes, a control panel, with which the shutter control process.

The manual head consists of a depleted uranium body and slide, sheathed in stainless steel. The shutter has a collimator hole, which in the «Open» position of the shutter is opposite the source, and in the «Closed» position it goes away from it by 180 degrees.

A diaphragm is attached to the body through the faceplate, which forms the radiation field. The position of the aperture shutters can be changed manually using the L-shaped knob. The scales on the diaphragm show the size of the field in centimeters at a distance of 75 cm from the source. The faceplate contains a depleted uranium plate for additional protection in the «Closed» position of the shutter. On the opposite side of the diaphragm is a lead cover weighing 180 kg, designed both for additional protection and for balancing the manual head relative to the axle shafts.

1.2.1. Source of Radiation

Compared with natural sources of gamma radiation (preparations of naturally radioactive elements), artificial sources, i.e., various radioactive isotopes, are currently much more powerful and more accessible. Among the latter, the cobalt isotope ^{60}Co, which is formed in a nuclear reactor from ordinary cobalt ^{59}Co due to the capture of slow neutrons by nuclei [4], is most widely used. ^{60}Co emits gamma rays at 1.1732 and 1.3325 MeV and has a half-life of 5.27 years. The decay scheme and spectrum of ^{60}Co are shown in figures 2 and 3, respectively.
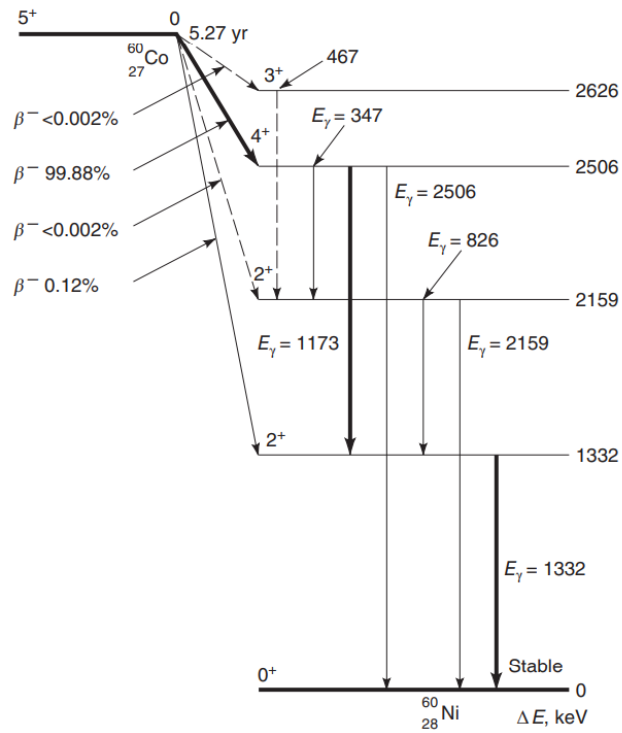
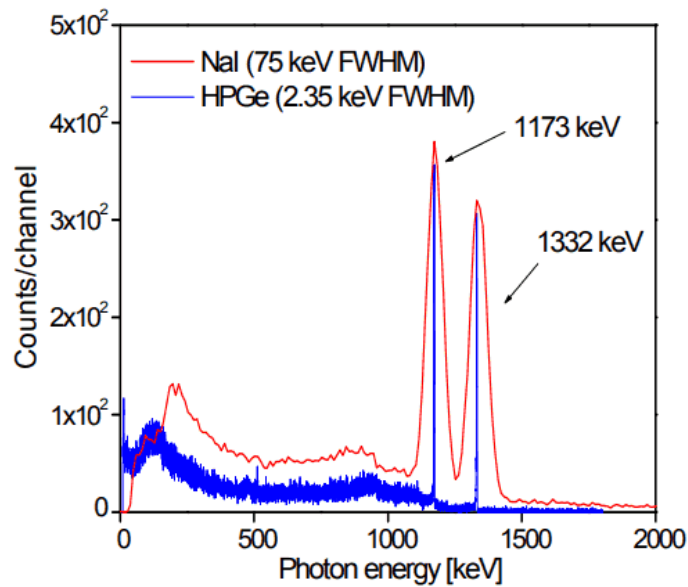Figure 2 – Decay scheme ^{60}Co [5]

Figure 3 – Radiation spectrum of ^{60}Co [5]

The ceramic matrix with ^{60}Co embedded in it is placed in a stainless steel case, which is hermetically sealed by laser welding. Source capsules can be made of titanium alloy. The design of the GIK type source used in the ROKUS-AMT gamma-ray facility is shown in the figure 4. The characteristics of such sources are given in the table 1.
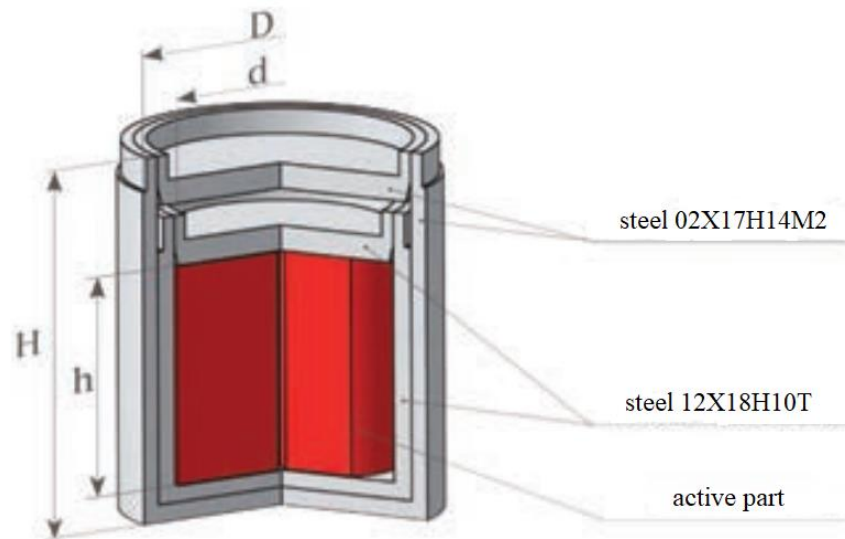
Figure 4 – Sources of radiation of types GIK-4-12, GIK-14, GIK-17M [6]

Table 1 – Characteristics of GIK-9 sources [6]

Source type	Source (active part) dimensions, mm		Rated DER at a distance of 1 m from the working surface of the source, A/kg	Maximum activity of ^{60}Co in the source	
ГИК-9-1			$2.50 \cdot 10^{14}$	$1.79 \cdot 10^{14}$	$4.85 \cdot 10^{3}$
ГИК-9-2	23(21)	33(24.5)	$3.20 \cdot 10^{14}$	$2.31 \cdot 10^{14}$	$6.25 \cdot 10^{3}$
ГИК-9-3			$4.00 \cdot 10^{14}$	$2.89 \cdot 10^{14}$	$7.80 \cdot 10^{3}$
ГИК-9-4			$5.00 \cdot 10^{14}$	$3.63 \cdot 10^{14}$	$9.80 \cdot 10^{3}$

The steel compositions are shown in table 2.

Table 2 – Steel composition, % [7, 8]

C	Si	Mn	Ni	S	P	Cr	Cu	Ti	Mo	Fe
12X18H10T										
0,12	0,8	2	9-11	0,02	0,035	17-19	0,3	0,4-1	-	67
02X17H14M2										
0,02	0,6	0,8	14-16	0,015	0,02	15-17	-	-	2-3	64

1.3. GEANT4

GEANT4 [9] is a software package for computer simulation of the processes of elementary particles passing through matter, based on a set of approaches, collectively called the «Monte Carlo method».

Working with GEANT4 comes down to writing C++ programs that connect its components to each other in a certain way, simulating some real system. At the same time, a three-dimensional model of the system is entered into GEANT4, the characteristics of the materials of which it consists, and electromagnetic fields are described. Various packages of physical processes are also involved, such as bremsstrahlung and ionization. During operation, GEANT4 calculates the trajectories of the passage of various elementary particles in a given system.

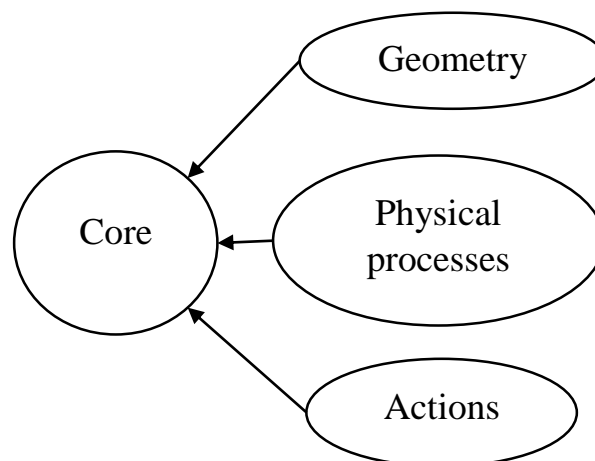The GEANT4 core and its interaction with the main classes can be represented as in figure 5.

Figure 5 – Sections of GEANT4

Through the implementation of each of the three sections, modeling is carried out in GEANT4. To work, it is necessary to describe at least the distribution of matter in the detector and fields, the generator of the primary vertex, and the list of physical processes taken into account in the simulation. In addition, it is also possible to describe: sensing elements and methods for modeling the response, visualization methods and a graphical interface.

2. STATISTICAL SIMULATION OF THE RADIATION FIELD IN GEANT4

2.1. Simulation Object

The work simulated the test gamma complex «Radian» located in bunker № 009 of building 18 of Tomsk Polytechnic University.

The composition of the test gamma-ray complex «Radian» includes:

1. Panoramic gamma unit «ROKUS-AMT» (figure 6) with a gamma radiation source of the type GIK-9-4 of a closed type based on the radionuclide cobalt-60 (source activity 8200 Ci as of February 17, 2011);

Figure 6 – Gamma unit ROKUS-AMT

2. Dosimetric control system for measuring the absorbed dose rate of gamma radiation in test objects based on the universal dosimeter «DKS-101» with an ionization chamber BMK-06.

3. The system for adjusting the absorbed dose rate of gamma radiation (figure 7), based on changing the distance along the geometric axis of the gamma radiation beam from the ROKUS-AMT gamma unit to the test objects placed with the ionization chamber of the dosimeter on a panel with (Pb- Al)-containers.

Figure 7 – Панель с облучаемыми контейнерами

4. (Pb-Al)-containers for placement of technological boards with irradiated electronic components.

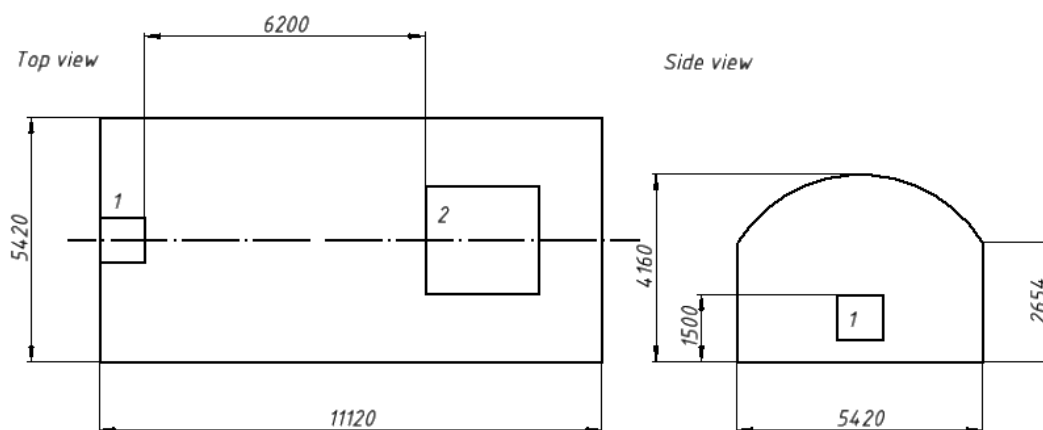The geometry of the room and the location of objects are shown in figure 8.

Figure 8 – Room layout

1 – gamma unit ROKUS-AMT; 2 – absorbed dose rate control system

2.2. Modeling in GEANT4

Figure 9 shows the room created in GEANT4 (bunker № 009 of TPU building 18). The dimensions of the room are made in accordance with figure 9. The

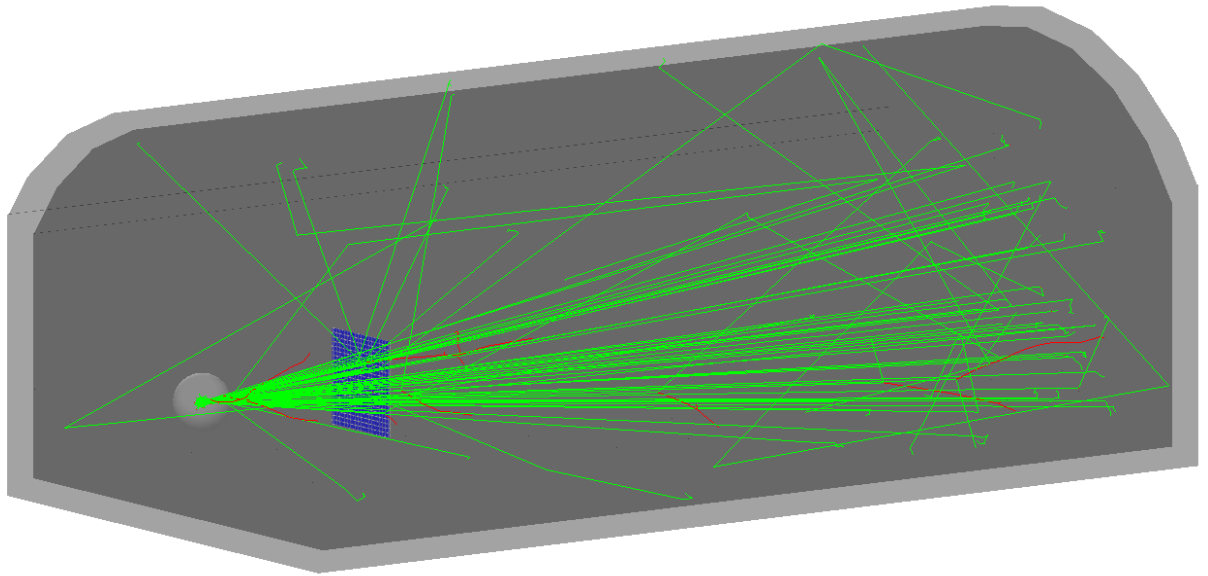material of the walls is heavy concrete from the NIST GEANT4 library, its density is 2.3 g/cm^3 [10].

Figure 9 – Modeled area

The model of the GIK-9-4 radiation source, the dimensions of the active part and steels are shown in figure 10. The dimensions are taken according to table 1.
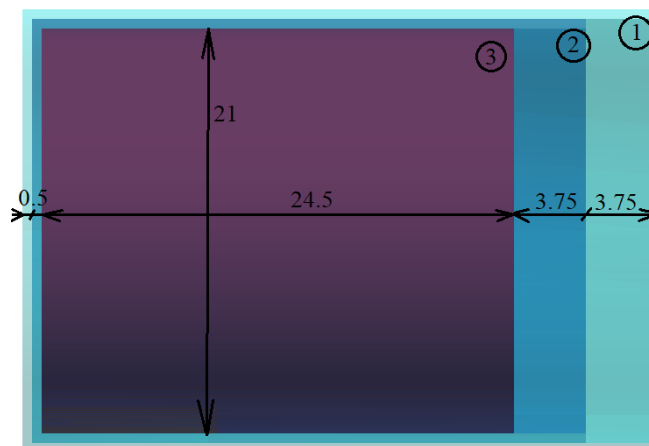

Figure 10 – Radiation source design
1 – stainless steel 02X17H14M2, 2 – stainless steel 12X18H10T, 3 – ^{60}Co

The material of the active part of the ^{60}Co source was specified from the NIST GEANT4 library [10]. The composition of stainless steels is set in accordance with table 2, the chemical elements are taken from the NIST GEANT4 library [10].

Figure 11 shows the geometry of the container. Inside is a silicon phantom, the container wall thickness is 1 mm for each layer. The first layer is aluminum, the second layer is lead. All materials are taken from the NIST GEANT4 library [10].
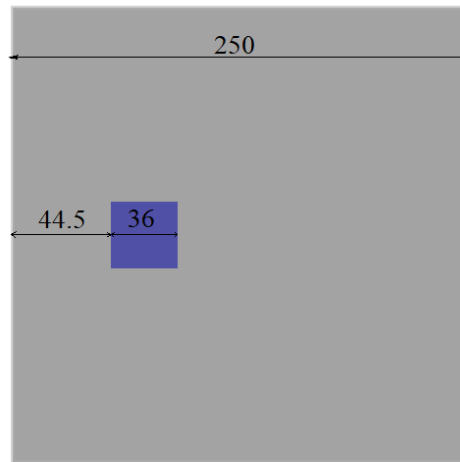
Figure 11 – Silicon phantom container design

During the development, a simplified model of the radiation head was used, the design of which is shown in figure 12. It is a sphere of depleted uranium with a trapezoid notch. Inside, at a distance of 337.5 mm, there is a GIK-9-4 radiation source.
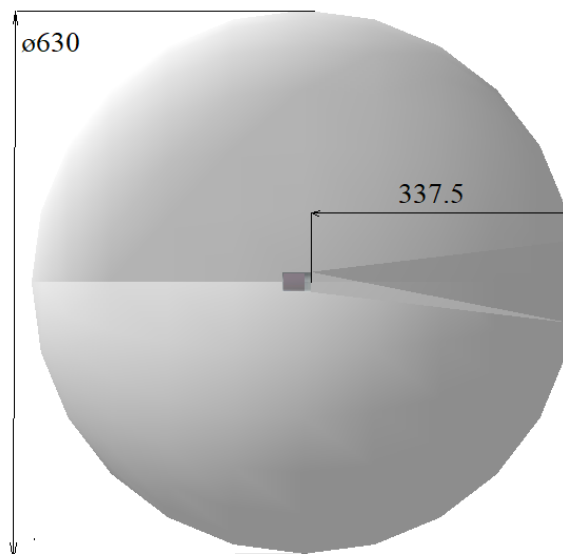
Figure 12 – The design of the radiation head

Figure 13 shows the geometry of the detectors when studying the distribution of the absorbed dose rate in the plane, and figure 14 shows the design of the containers.
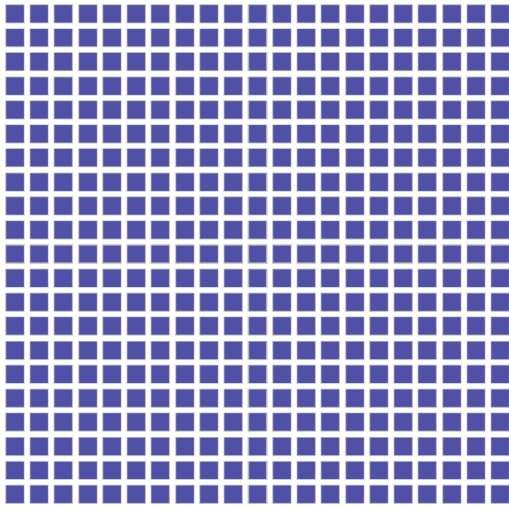
Figure 13 – Design of detectors in the study of dose rate distribution in the plane
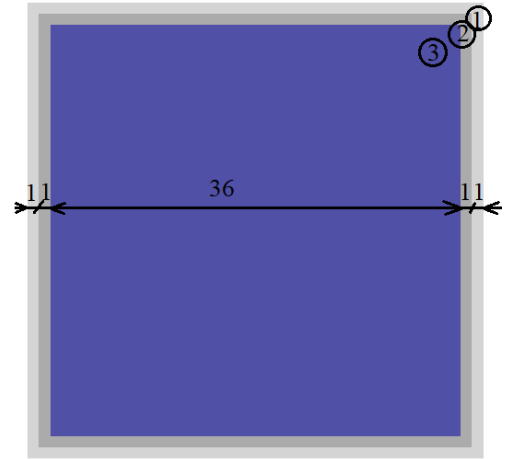
Figure 14 – Silicon phantom container design

1 – aluminum, 2 – lead, 3 – silicon

Figure 15 shows the geometry of the closet with containers. Containers are placed side by side in accordance with figure 7.
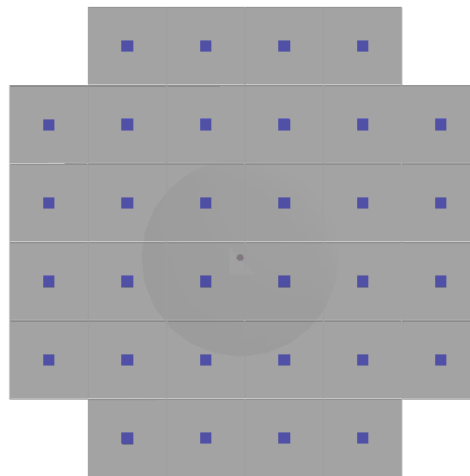
Figure 15 – Closet design with containers

The dimensions of the containers are given in accordance with figure 11.

2.3. Physics Model

The program models:

- pseudoparticle geantino;

- gamma quanta;

- leptons (electron, positron, neutrino and antineutrino);

- baryons (proton and neutron);

- ions.

For gamma quanta, processes are modeled: the photoelectric effect, the Compton effect, and the formation of electron-positron pairs. For electrons, the following are modeled: Coulomb scattering, ionization, bremsstrahlung radiation and conversion into $e^- e^+$ pair.

For processes: photoelectric effect, formation of electron-positron pairs and bremsstrahlung radiation, the interaction cross section is determined by interpolation according to formula (6) [11]:

$$\log\big(\sigma(E)\big) = \frac{\log(\sigma_1)\log(E_2/E) + \log(\sigma_2)\log(E/E_1)}{\log(E_2/E_1)}, \qquad (6)$$

where E – particle energy;

E_1, E_2 – the nearest lower and higher energy values for which the values are known σ_1 and σ_2.

For the Compton effect with a gamma-quantum energy less than 5 MeV, the analytical formula (7) [11] is used:

$$\sigma(E) = 2\pi \int_{-1}^{1} \frac{r_e^2}{2} \frac{E_C^2}{E^2} \left(\frac{E_C}{E} + \frac{E}{E_C} - \sin^2\theta \right) \cdot \sum_{shells} f_i \Theta(E - U_i) n_i \left(p_z^{\max} \right) d(\cos\theta), \quad (7)$$

where r_e – classical electron radius;

m_e – electron mass;

θ – scattering angle;

$$E_C = \frac{E}{1 + \dfrac{E}{m_e c^2}\ 1 - \cos\theta} \ – \text{Compton energy;}$$

f_i – the number of electrons in the i-th atomic shell;

U_i – ionization energy on the i-th atomic shell;

Θ – Heaviside step function;

p_z – projection of the initial electron momentum in the direction of the scattering angle;

$$p_z^{max} = \frac{E\,(E - U_i)\,(1 - \cos\theta) - m_e c^2 U_i}{c\sqrt{2E\,(E - U_i)\,(1 - \cos\theta) + U_i^2}} - \text{maximum possible value } p_z;$$

$$n_i(x) = \begin{cases} \left| \dfrac{1}{2} e^{\left[\frac{1}{2} - \left(\frac{1}{2} - \sqrt{2}J_{i0}x\right)^2\right]} \right| & \text{if } x<0 \\[20pt] \left| 1 - \dfrac{1}{2} e^{\left[\frac{1}{2} - \left(\frac{1}{2} - \sqrt{2}J_{i0}x\right)^2\right]} \right| & \text{if } x>0 \end{cases}, \text{ there } J_{i0} - \text{ the value of the } p_z\text{-distribution}$$

profile $J_i(p_z)$ for the i-th atomic shell calculated in $p_z = 0$. Values are taken from [12].

The total cross section $\sigma^-(E)$ for the inelastic collision of electrons of energy E is calculated analytically. It can be split into contributions from distant longitudinal, distant transverse and close interactions [11]:

$$\sigma^-(E) = \sigma_{dis,l} + \sigma_{dis,t} + \sigma_{clo}^-. \tag{8}$$

The contributions from distant longitudinal and transverse interactions are:

$$\sigma_{dis,l} = \frac{2\pi e^4}{m_e \upsilon^2} \sum_{shells} f_k \frac{1}{W_k} \ln\left(\frac{W_k}{Q_k^{min}} \frac{Q_k^{min} + 2m_e c^2}{W_k + 2m_e c^2} \right) \Theta(E - W_k) \tag{9}$$

and

$$\sigma_{dis,t} = \frac{2\pi e^4}{m_e \upsilon^2} \sum_{shells} f_k \frac{1}{W_k} \left[\ln\left(\frac{1}{1-\beta^2} \right) - \beta^2 - \delta_F \right] \Theta(E - W_k), \tag{10}$$

where m_e – mass of electron;

υ – velocity of the electron;

β – velocity of the electron units of c;

f_k – number of electrons in the k-th atomic shell;

Θ – Heaviside step function;

W_k – resonance energy of the k-th atomic shell oscillator;

$$Q_k^{min} = \sqrt{\left[\sqrt{E(E + 2m_e c^2)} - \sqrt{(E - W_k)(E - W_k + 2m_e c^2)} \right]^2 + 2m_e^2 c^4} - m_e c^2 \quad -$$

minimum kinematically allowed recoil energy for energy transfer W_k;

δ_F – Fermi density effect correction, calculated as [13].

The integrated cross section for close collisions is the Moller cross section [11]:

$$\sigma_{clo}^- = \frac{2\pi e^4}{m_e \upsilon^2} \int\limits_{W_k}^{E/2} \frac{1}{W^2} F^-(E,W)dW, \qquad (11)$$

where

$$F^-(E,W) = 1 + \left(\frac{W}{E-W}\right)^2 - \frac{W}{E-W} + \left(\frac{E}{E+m_e c^2}\right)^2 \left(\frac{W}{E-W} + \frac{W^2}{E^2}\right). \qquad (12)$$

Data [14] are used for the photoelectric effect, for the formation of electron-positron pairs [15] and bremsstrahlung radiation [16].

Beta decay is modeled by the emission of a β^- or β^+, an anti-neutrino or neutrino, and a recoil nucleus of either $Z+1$ or $Z-1$.

The shape of the energy spectrum of the emitted lepton is given by

$$\frac{d^2 n}{dE dp_e} = (E_0 - E_e)^2 E_e p_e F(Z, E_e) S(Z, E_0, E_e) \qquad (13)$$

where E_0 – the endpoint energy of the decay taken from the ENSDF data in units of electron mass;

E_e and p_e – the emitted electron energy and momentum;

Z – the atomic number;

F – the Fermi function;

S – the shape factor.

The Fermi function F accounts for the effect of the Coulomb barrier on the probability of $\beta^\pm$ emission. Its relativistic form is:

$$F(Z, E_e) = 2(1+\gamma)(2p_e R)^{2\gamma-2} e^{\pm\pi\alpha Z E_e/p_e} \frac{\left|\Gamma(\gamma + i\alpha Z E_e/p_e)\right|^2}{\Gamma(2\gamma+1)^2} \qquad (14)$$

where R – the nuclear radius;

$\gamma = \sqrt{1-(\alpha Z)^2}$, and α – the fine structure constant.

The squared modulus of Γ is computed using approximation B of [17].

2.4.   Program Description

The program is written in the object-oriented C++ programming paradigm using GEANT4 [9], ROOT [18], and the RapidXML library [19] for the Linux operating system. The program is built using the CMake system [20]. The structure of the program is shown in figure 16, the calculation algorithm is given in appendix A.
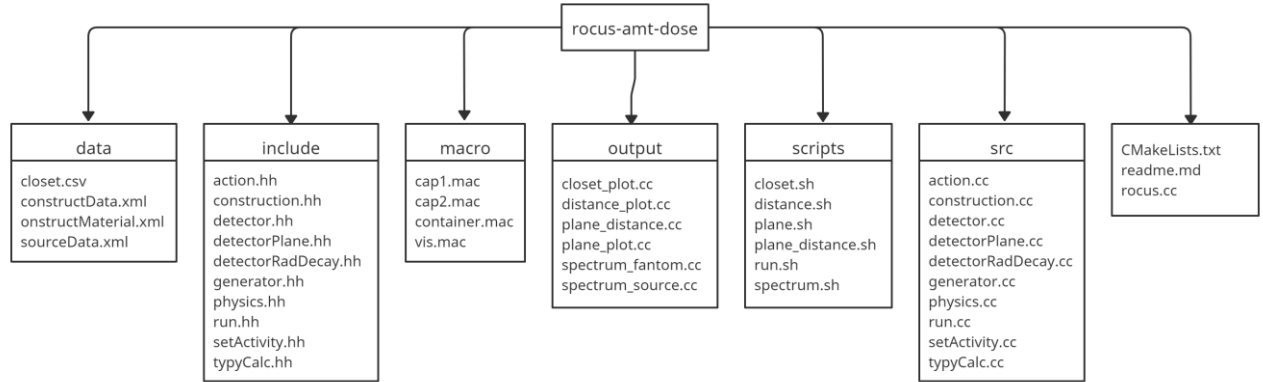
Figure 16 – Program structure

The developed program allows you to perform several calculations defined by the TypeCalculations class. Types of calculations and their description are given in table 3.

Table 3 – Program calculation types

Calculation type	Describtion
0	Calculation of the absorbed dose rate in the phantom of silicon at a distance r from the file «constructData.xml»
1	Calculation of the absorbed dose rate in the phantom of silicon at a distance r from the file «constructData.xml» with visualization
2	Calculation of the absorbed dose rate in the silicon phantom from the distance r_i specified in the «distance.sh» bash-script
3	Calculation of the absorbed dose rate in the plane in the phantom of silicon at a distance r from the file «constructData.xml»

4	Calculation of the absorbed dose rate in the plane in the silicon phantom at a distance r from the file «constructData.xml» with visualization
5	Calculation of the absorbed dose rate in the plane in the silicon phantom at a distance r_i specified in the bash-script «plane_distance.sh»
6	Calculation of the absorbed dose rate in a closet with silicon phantoms at a distance r from the file «constructData.xml»
7	Calculation of the absorbed dose rate in a closet with silicon phantoms at a distance r from the file «constructData.xml» with visualization

After starting the program (./rocus in the build directory), you must enter the calculation number into the terminal, after which the calculation will begin.

Depending on the type of GEANT4 installation, the program works in multi-threaded and single-threaded mode. When working in multithreaded mode, you can set the number of cores to use in the main() method using the SetNumberOfThreads method; by default, the maximum number of cores is used.

Data of materials, sizes of objects and properties of the radiation source are stored in files of the «*.xml» format in a separate directory «data», data is parsed in the classes using the RapidXML library [19], and they are transferred to the class properties.

The source of radiation is described by the following parameters: initial activity A_0 in Ci, half-life $T_{1/2}$ in years, dates of initial activity and the start of the experiment (t_0 and t), a coefficient that reduces the number of simulated particles to speed up k_{dec} calculations, and simulation time t in seconds.

The interaction of the classes used is shown in figure 17.

MyPhysicsList	**ProgressBar**
Describes used models of physics	Used to estimate percents of calculation

SourceActivity
Calculates up-to-date activity of source of radiation

MyPrimaryGenerator
Generates primary particle

SimpleRunAction
Starts run action; used to calculate absorbed dose rate

MyActionInitialization
Starts actions

G4RunManager
Starts run

TypeCalculations
Used to choose one type of calculations from 7 available

MyDetectorConstruction
Describes the geometry of the simulated world

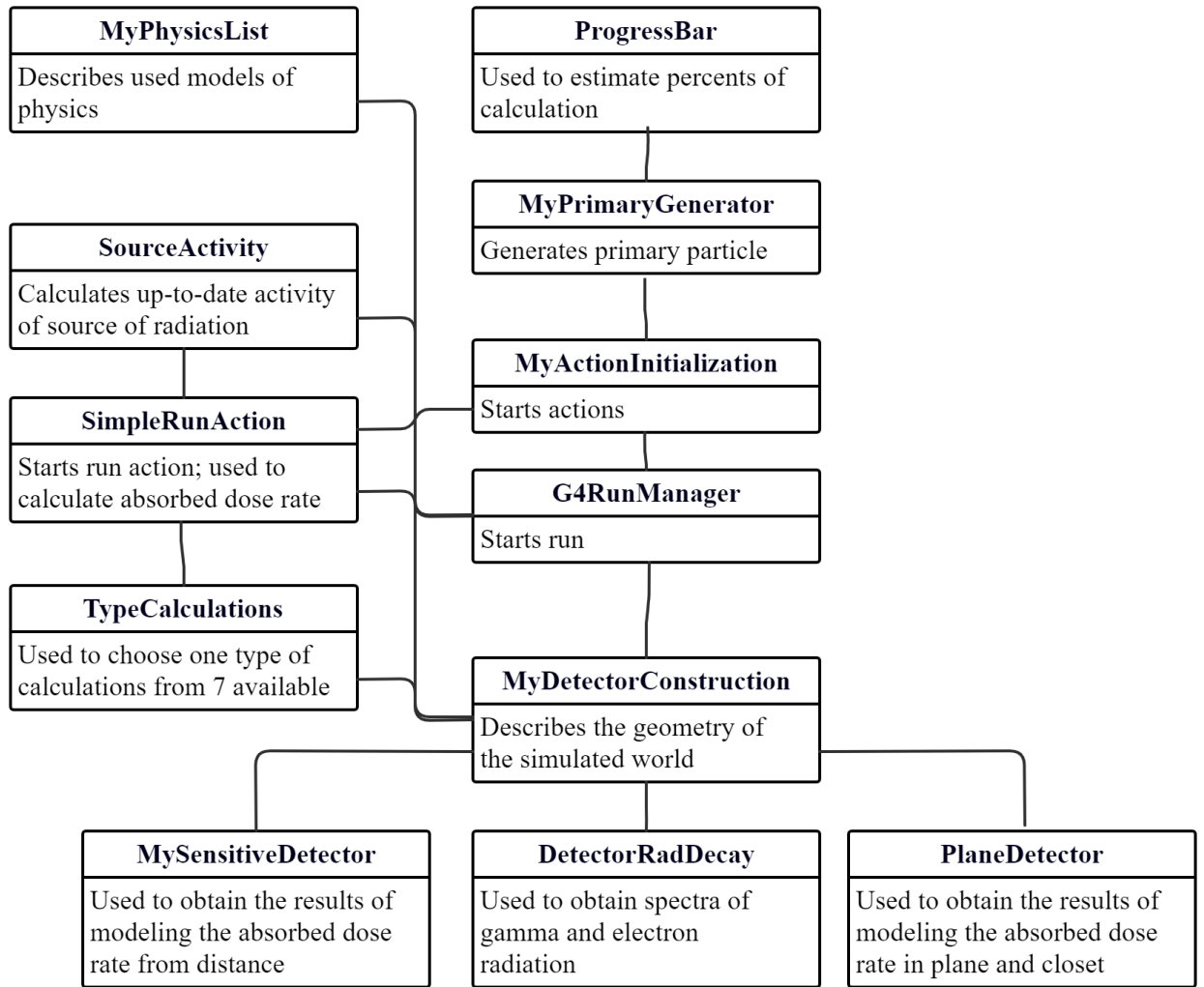| **MySensitiveDetector**	**DetectorRadDecay**	**PlaneDetector**
Used to obtain the results of modeling the absorbed dose rate from distance	Used to obtain spectra of gamma and electron radiation	Used to obtain the results of modeling the absorbed dose rate in plane and closet

Figure 17 – Class diagram

In the SourceActivity class, activity is recalculated in Ci on the date of the experiment according to formula (15):

$$A = A_0 \cdot \exp\left[-\frac{\ln 2}{T_{1/2}} \cdot (t_0 - t) \right].\tag{15}$$

The conversion from Ci to Bq is carried out according to the formula (16):

$$A[Bq] = A[Ci] \cdot 3.7 \cdot 10^{10}.\tag{16}$$

The multiplier $(t_0 - t)$ is defined in years using the STL standard library: the std::tm structure and the std::mktime and std::difftime functions. The std::mktime function converts local calendar time to epoch time as a time_t object. The std::difftime

function returns the difference between the dates of the time_t object in seconds. The resulting value in seconds is converted to years.

In the main() main function, the resulting activity is recalculated by the number of simulated particles according to formula (17):

$$N_{particles} = t[s] \cdot A[Bq] / k_{dec} \qquad (17)$$

The resulting value is passed to the BeamOn method of the G4RunManager class.

To automate the calculations, bash-scripts for launching the program are written, located in the «scripts» directory. The script «distance.sh» starts the calculation of the absorbed dose rate from the distance (calculation of type «2»), the file specifies the starting point of the count r_0, the step in cm h and the number of calculations m. Calculation of the calculation point is carried out according to the formula (18):

$$r = r_0 + ih, \qquad (18)$$

where $i = 0..m$ – calculation number.

There are also bash scripts: «run.sh» – run several calculations of type «0»; «spectrum.sh» – start of calculation of type «0» with acquisition of spectra in the radiation source and phantom; «plane.sh» – calculation of the absorbed dose rate distribution in the plane (calculation of the «3» type), «plane_distance.sh» – calculation of the «4» type with obtaining the distribution of the absorbed dose rate in the plane at different distances, «closet.sh» – the distribution of the absorbed dose rate inside the containers located on the closet (calculation of type «6»).

Visualization of the world geometry is configured by macro files of the «*.mac» format located in the «macro» directory.

For calculation of type «5», the size of the field with increasing distance from the diaphragm changes according to the step function shown in figure 18. The step of placing the detectors is configured in the «constructData.xml» file.
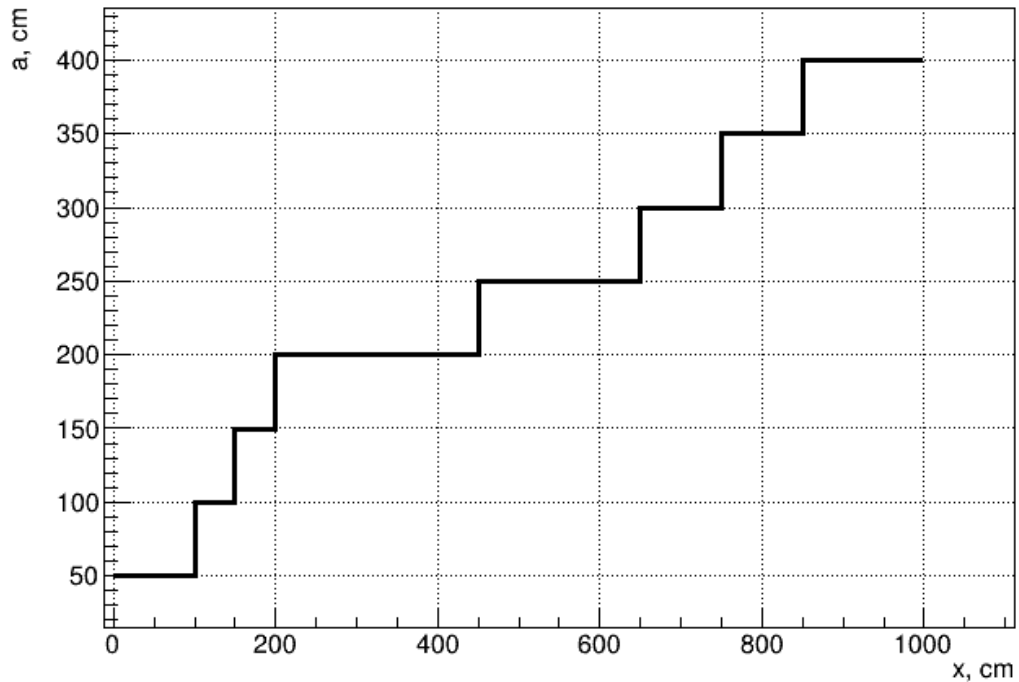
Figure 18 – Step function of field size

For calculation of type «6», the containers on the closet are specified in the «closet.csv» file in the «data» directory. A square matrix is specified, the elements of which take the values «0» if there is no container, and «1» if there is.

The MyDetectorConstruction class describes the geometry of the simulated world, as well as the properties of objects – fields and sensitive volumes (detectors), discussed in section 2.2.

The MyActionInitialization class describes the action to be performed: the particle generator MyPrimaryGenerator is set and the custom action at the SimpleRunAction modeling step.

The MyPrimaryGenerator class specifies the radiation source parameters: source size, particles, angular and energy distributions. The G4SingleParticleSource class is used to generate primary particles. To simulate radioactive decay, the geantino pseudoparticle is replaced by the ^{60}Co ion, which undergoes beta decay.

The MyPhysicsList class describes the physics used – processes, their models, particles, modeling steps for each type of particle. A description of the physics used is given in section 2.3.

In the MySensitiveDetector and PlaneDetector classes, the total particle energy loss in the phantom in J and the phantom mass in kg are read. The PlaneDetector class also passes the phantom volume copy number. The resulting values are passed to an object of the SimpleRunAction class.

In the DetectorRadDecay class, the particle's kinetic energy in keV is transferred to the appropriate std::vector sequential container, depending on whether the particle is a gamma ray or an electron. When the object's destructor is called, the obtained values are output to files of the «*.csv» format.

The SimpleRunAction class processes and displays results depending on the type of calculation. The absorbed dose rate is calculated by formula (19):

$$\dot{D}[rad \ / \ s] = \frac{100 \cdot k_{dec} \cdot E_{deposit}[J]}{m[kg] \cdot t[s]}, \tag{19}$$

where $E_{deposit}$ – total loss of energy by particles in the phantom;

m – phantom mass;

t – simulation time.

Simulation results are displayed in a separate directory «output». Calculation results in the «.csv» format, depending on the type of calculation, are saved in a separate directory. The results of calculating the absorbed dose rate versus distance are displayed in the «distance» directory, the distribution of the absorbed dose rate in the plane to the «plane» directory, the absorbed dose rate in the panel to the «closet» directory, and the spectra to the «spectrum» directory. The resulting figures in the «*.png» format are saved in the «figure» directory.

Processing of simulation results is carried out using ROOT [18]. Scripts were written for plotting spectra in the source («spectrum.cc») and phantom («spectrum_fantom.cc»), the dependence of the absorbed dose rate on the distance («distance_plot.cc»), the distribution of the absorbed dose rate in the plane («plane_plot.cc») and the distribution of the absorbed dose rate in containers located on the panel («closet_plot.cc»). All scripts read data from «*.csv» files.

3. RESULTS OF SIMULATION OF THE RADIATION FIELD OF THE GAMMA FACILITY OF THE ROCUS-AMT UNIT

3.1. Emission Spectra

To check the resulting spectrum formed by the decay of ^{60}Co, the spectra of gamma and electron radiation were obtained in the GIK-9-4 source (figure 19) and the silicon phantom (figure 20).

The spectrum calculation was carried out on May 15, 2019, the activity on this date was $1.025 \cdot 10^{14}$ Bq. For simulation, 10^5 decays of ^{60}Co were carried out.

A study was made of the effect of various physical processes modeled in GEANT4 on the absorbed dose rate (ADR) at a distance of 70 cm from the gamma-ray facility; the result of some physical process.

Table 4 – Effect of Modeled Processes on Absorbed Dose Rate

Particle	Physical process	ADR, rad/s	Effect, %
Gamma	Photoelectric effect	0.5483	5,63
	Compton scattering	0.0144	97,23
	Conversion into e^-e^+ pair	0.5342	2,90
Electron	Coulomb scattering	0.6211	16,64
	Ionization	1.0362	99,63
	Bremsstrahlung radiation	0.6201	19,47
	Conversion into e^-e^+ pair	0.6211	19,64
Total		0.5191	-

Thus, table 4 shows that the greatest contribution to the absorbed dose rate is made by electrons produced as a result of Compton scattering due to ionization in the silicon phantom. The smallest is the formation of e^-e^+ as a result of the interaction of gamma radiation with matter, since, as discussed in section 1, this process is characteristic of particles with higher energy.
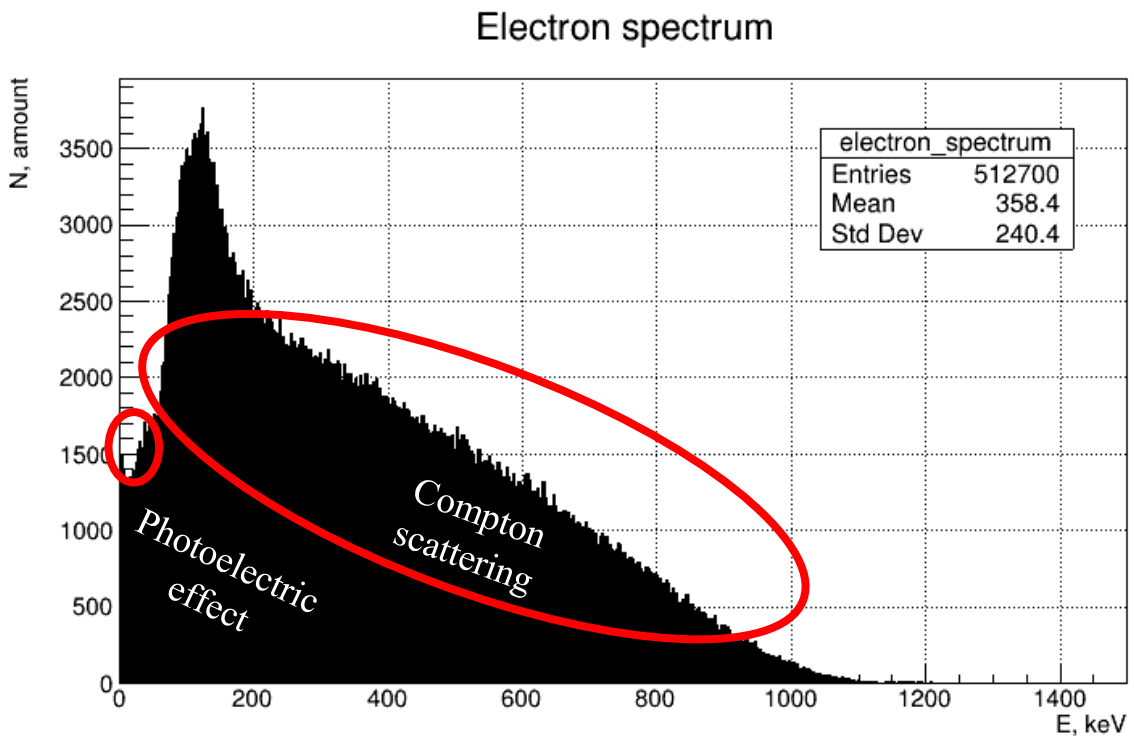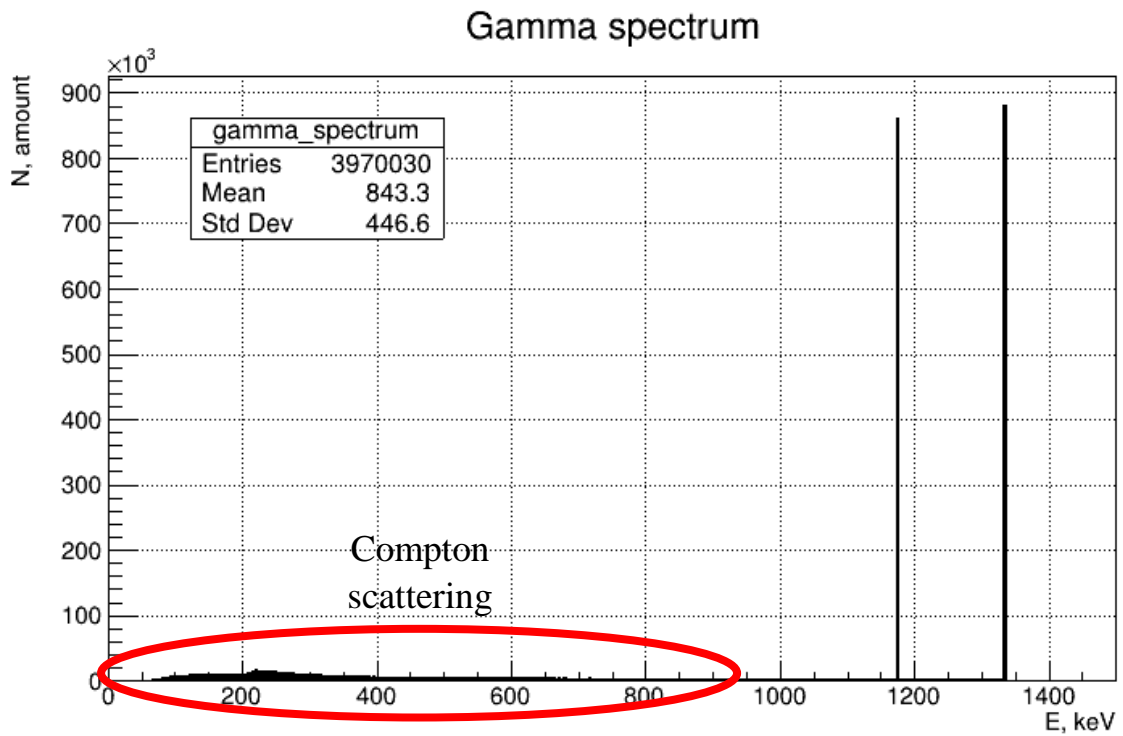
Figure 19 – Emission spectra in the GIK-9-4 radiation source

Figure 20 shows two peaks in the gamma spectrum, 1.17 and 1.33 MeV, which appear as a result of the transition from the excited state to the ground state of the daughter nucleus during the decay of ^{60}Co. Electrons with energies of 0.2-1 MeV are

formed as a result of Compton scattering. The obtained spectra are consistent with the experimental one presented in figure 3.

Figure 20 – Emission spectra in a silicon phantom at a distance of 0 cm from the gamma unit

The silicon phantom is located at a distance of 0 cm from the ROKUS-AMT gamma unit. Compared to the spectrum in the radiation source, the resulting spectrum is significantly weakened due to interaction with the materials of the gamma-ray unit.

3.2. Program Verification

The GEANT4 program uses a statistical Monte Carlo simulation method, so the error in determining the absorbed dose rate depends on the number of part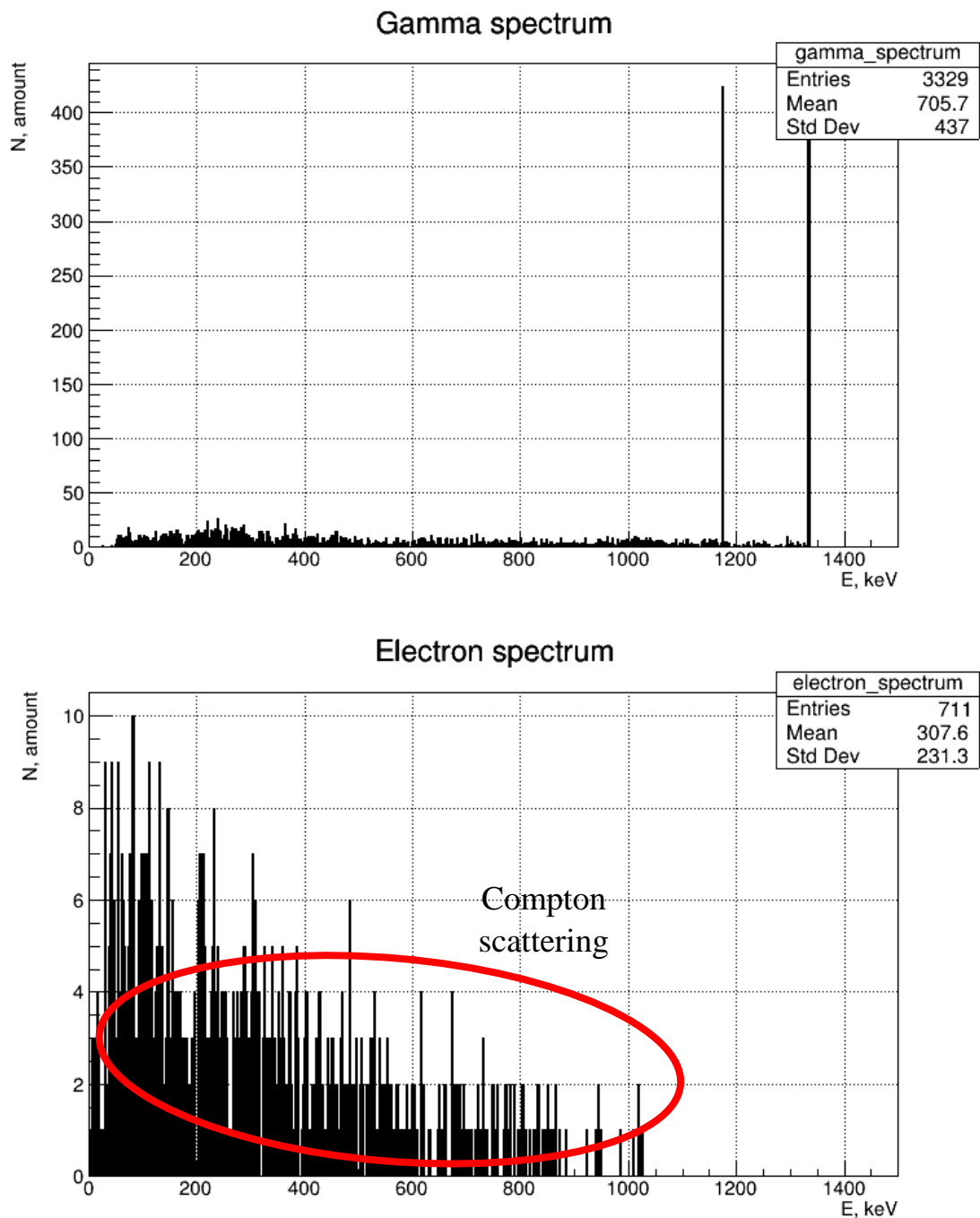icles that passed through the silicon phantom, and therefore also depends on the distance from the radiation source. Figure 21 shows the dependence of the absorbed dose rate at a distance of 630 cm from the aperture of the gamma setup on the number of simulated decays in the radiation source, and figure 22 shows the relative error from the experimental value.
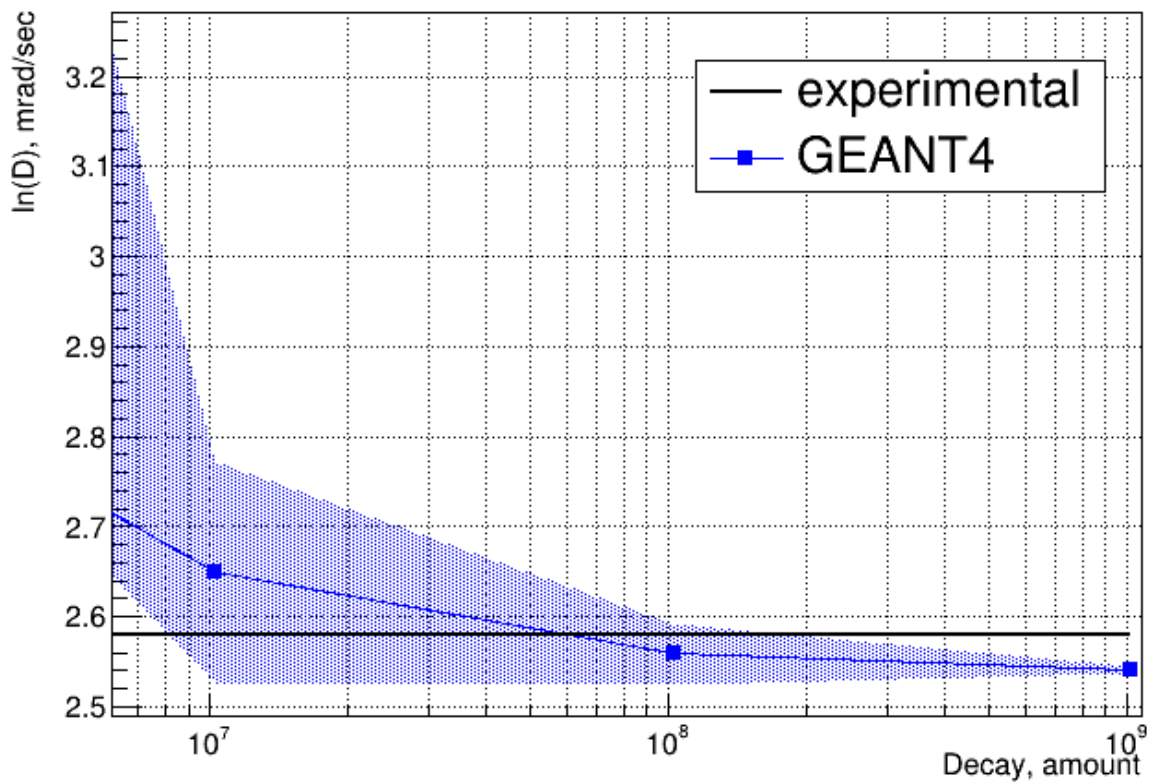

Figure 21 – Absorbed dose rate versus number of simulated decays at a distance of 630 cm

Figure 22 shows that the error decreases with an increase in the number of simulated decays, and when simulating 10^8 decays, the error will be ± 5 %, which is the most optimal considering the calculation time.
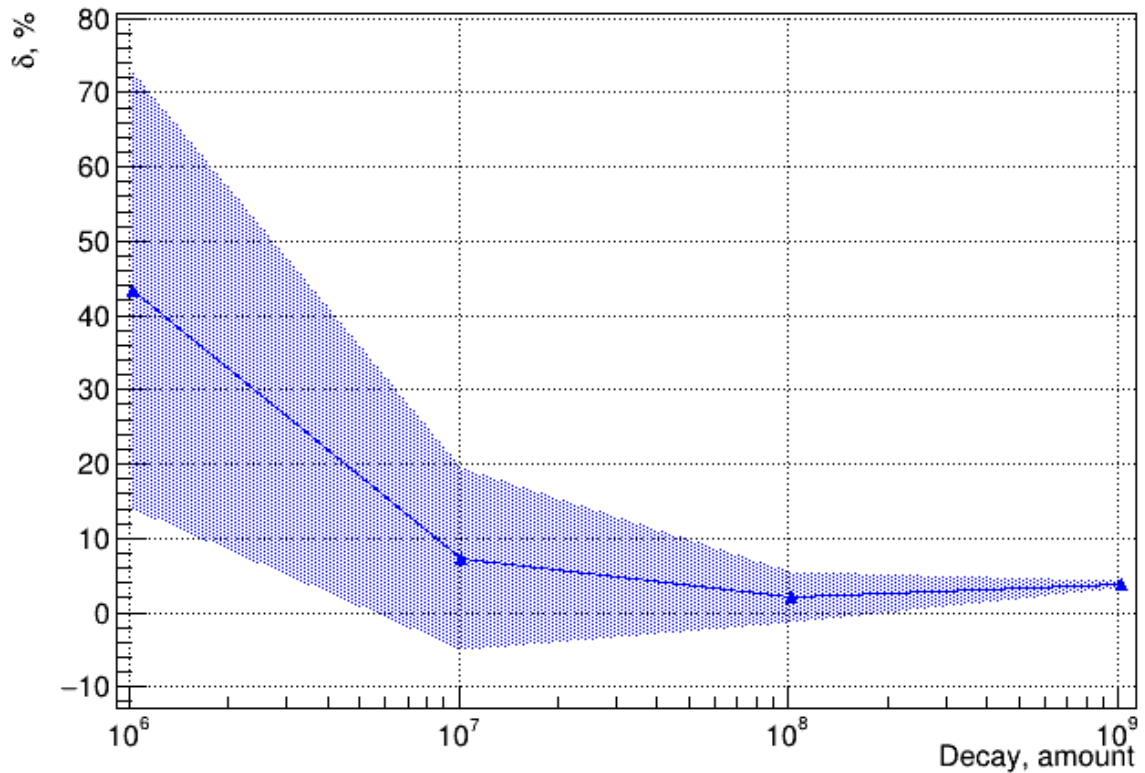
Figure 22 – Relative error of simulation results from experimental data at a distance of 630 cm from the number of simulated decays in the source

Verification of the developed program was carried out by comparing the simulation results with the experimental data obtained during the certification of the «Radian» test gamma complex. To measure the absorbed dose rate, a dosimeter «DKS-101» with an ionization chamber BMK-06 was used, which provides measurement of the absorbed dose rate in water. Formula (20) was used to calculate the absorbed dose rate for silicon:

$$\dot{D}_{Si} = \dot{D}_{изм} \cdot K_{Si}, \tag{20}$$

where $K_{Si} = 0.8987$ – coefficient of proportionality when recalculating the absorbed dose rate for water into the absorbed dose rate for silicon.

An experimental study of the distribution of the absorbed dose rate from distance was carried out on May 15, 2019 with a step of 70 cm along the geometric axis of the gamma radiation beam. The activity of the source on this date was $1.025 \cdot 10^{14}$ Bq. 10^7 decays of ^{60}Co were modeled in GEANT4 for the study, and the

study was carried out 10 times at each point. The results of experimental research and modeling in GEANT4 are shown in figures 23 and 24.
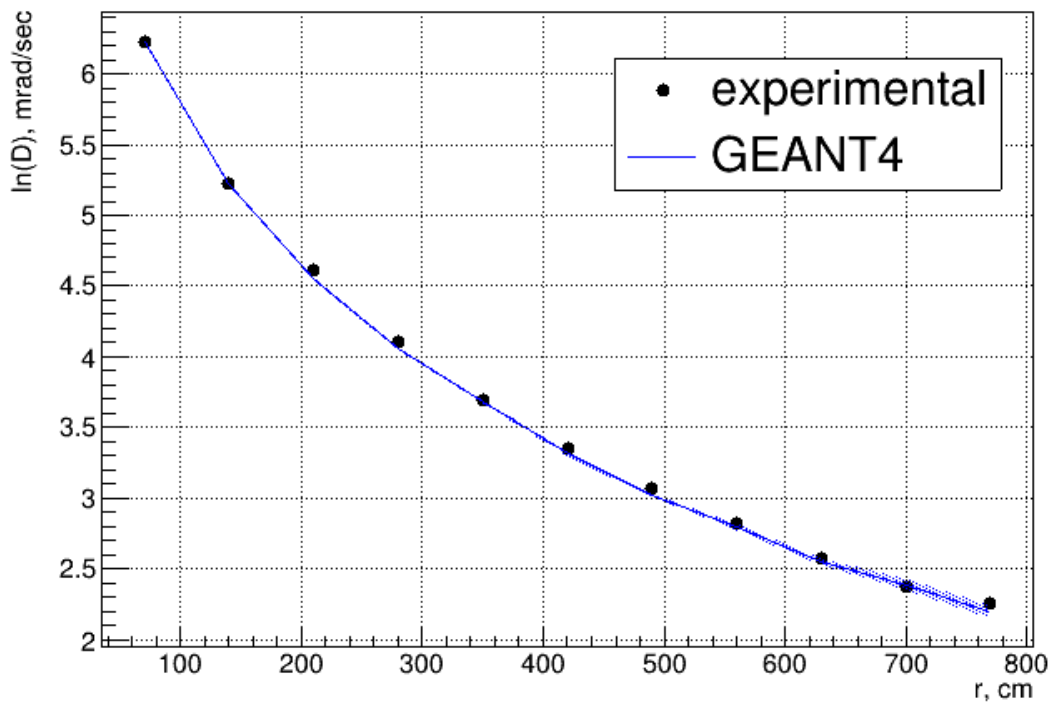
Figure 23 – Dose rate versus distance and deviation from experimental values
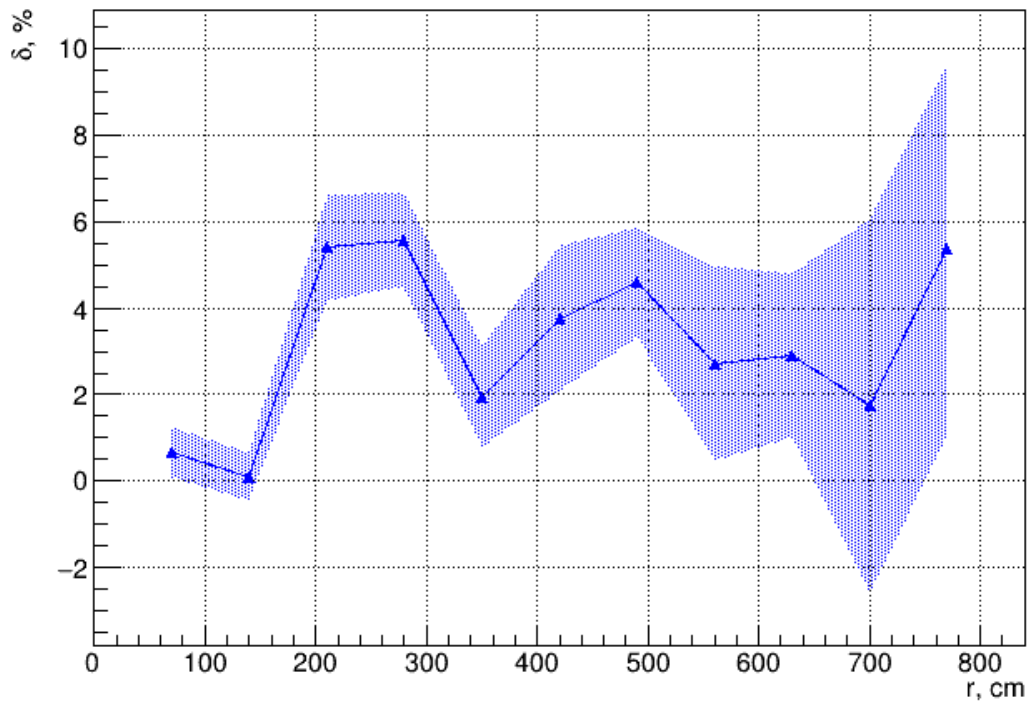
Figure 24 – Relative error in determining the absorbed dose rate at each point

Figures 23-24 show that the obtained values are in good agreement with the experimental ones. The relative error of calculations was up to 10%. An increase in the relative error with distance is associated with an increase in the area of the possible position of the particle, which leads to a decrease in the particles entering the sensitive volume, and in Monte Carlo methods this leads to an increase in the error. The values of the absorbed dose rate decrease from 0.5 rad/s to 0.01 rad/s at a distance 70 cm to 770 cm according to the dependence $\dot{D} \sim 1/r^2$, which is consistent with the theoretical dependence.

An experimental study of the distribution of the absorbed dose rate in the plane at distances of 164 cm and 500 cm was carried out on May 15, 2020. The activity of the source on this date was $8.98 \cdot 10^{13}$ Bq. For the study, 10^7 decays of ^{60}Co were simulated in GEANT4, single measurements were carried out. The results of experimental research and modeling in GEANT4 are shown in figures 25-28.
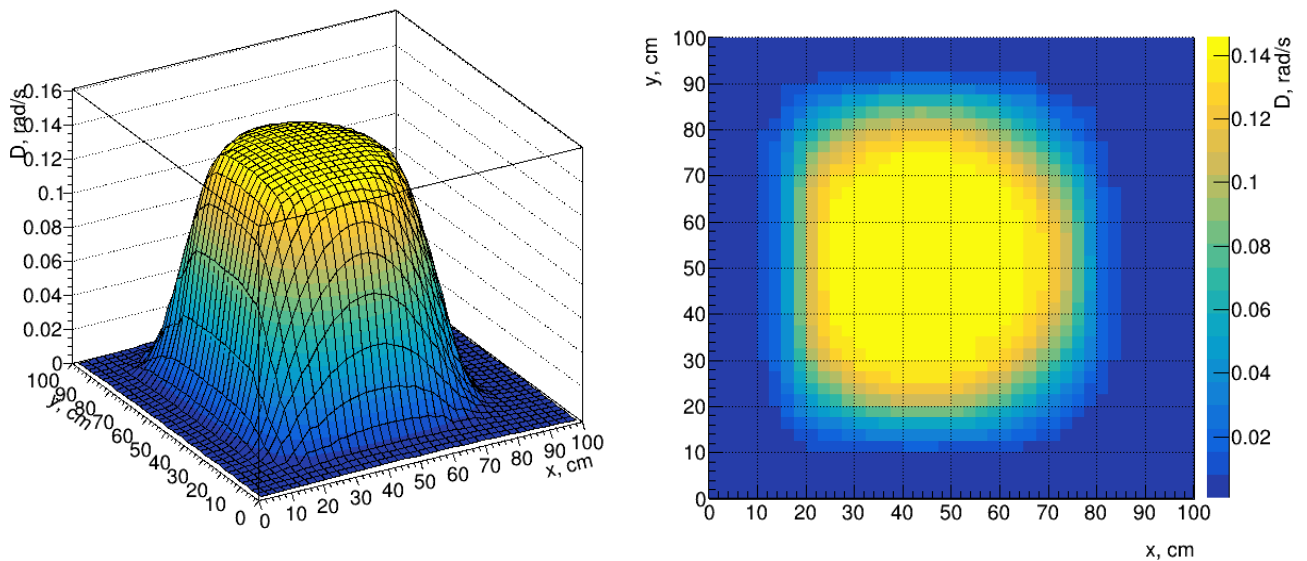
Figure 25 – Dose rate distribution in the plane at a distance of 164 cm from the aperture, experimental data
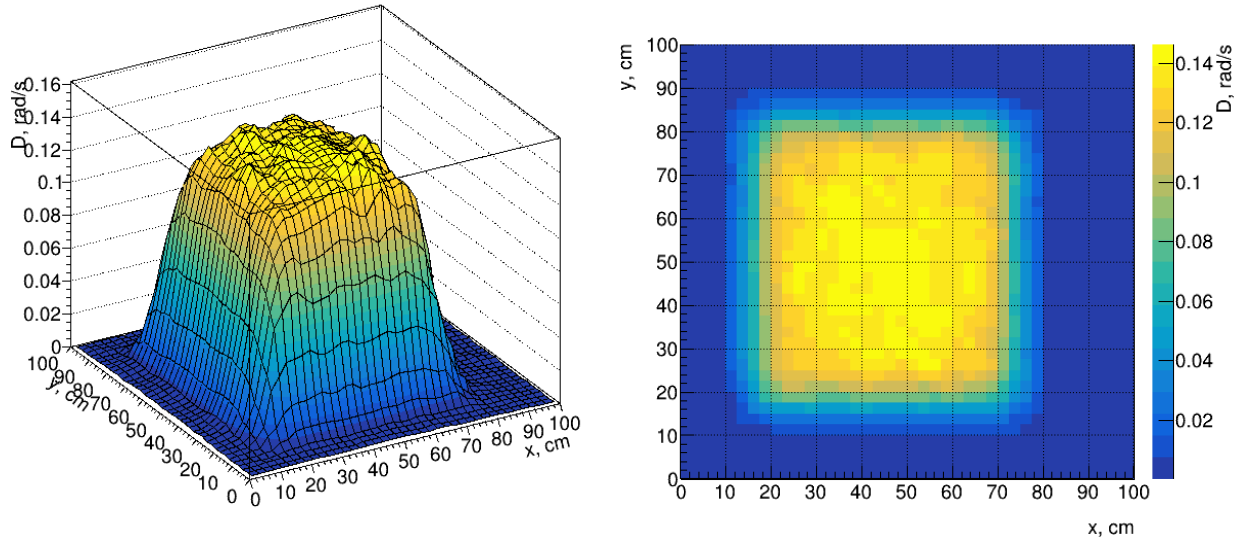
Figure 26 – Dose rate distribution in the plane at a distance of 164 cm from the diaphragm, GEANT4
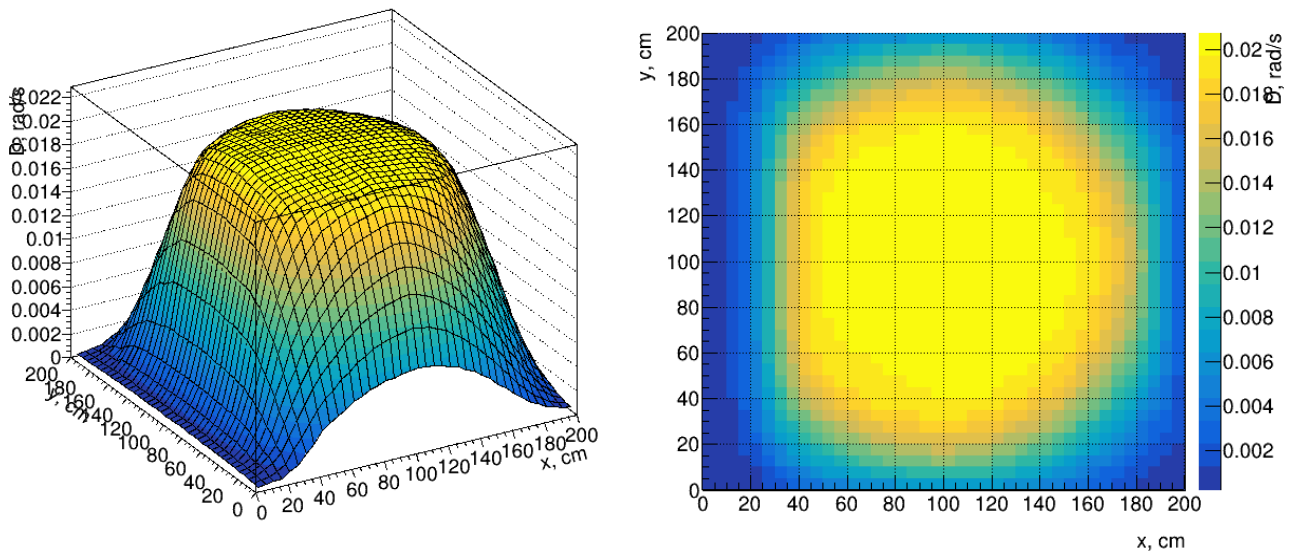
Figure 27 – Dose rate distribution in the plane at a distance of 500 cm from the diaphragm, experimental data
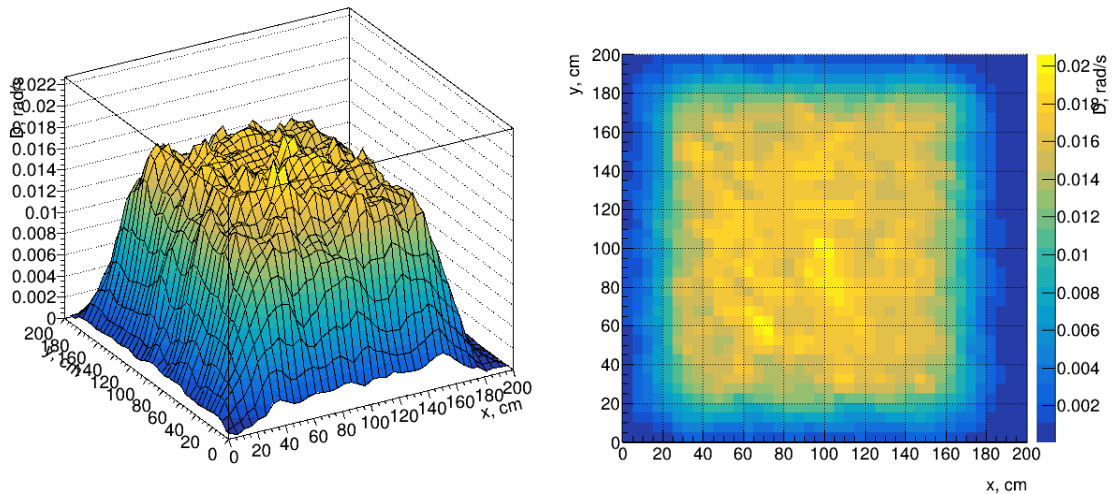
Figure 28 – Dose rate distribution in the plane at a distance of 500 cm from the diaphragm, GEANT4

Figures 25-28 show that the distribution of the absorbed dose rate in the plane coincides with the experimental ones. Deviations are related to the assumptions used in the construction of the model of the radiation head of the ROKUS-AMT gamma-ray unit.

The highest values of the absorbed dose rate are observed along the geometric axis of the gamma-ray beam with a symmetrical decrease with distance from the axis.

As the distance from the gamma installation increases, the size of the resulting radiation field increases, and the absorbed dose rate decreases.

Experimental data and simulation results in GEANT4 of the absorbed dose rate distribution in a closet with containers are shown in figures 29 and 30, respectively. The experimental study was carried out on May 15, 2020, the activity of the source on this date was $8.98 \cdot 10^{13}$ Bq. For the study, 10^7 decays of ^{60}Co were simulated. The relative calculation error is shown in figure 32.

	0.00991	0.00996	0.00994	0.00993	
0.0099	0.01016	0.01037	0.01037	0.01016	0.00987
0.00991	0.01016	0.01037	0.01037	0.01016	0.00995
0.00988	0.01016	0.01037	0.01037	0.01016	0.00995
0.00985	0.01006	0.01016	0.01016	0.01006	0.00987
	0.01006	0.01006	0.01001	0.01001	

Figure 29 – Distribution of the absorbed dose rate (rad/s) in the closet at a distance of 760 cm from the diaphragm, experimental data

	0.00797	0.01011	0.008703	0.009607	
0.007582	0.009055	0.009585	0.008908	0.01155	0.007238
0.007975	0.009207	0.009082	0.007329	0.008444	0.0103
0.009951	0.008082	0.008461	0.008128	0.01122	0.00816
0.009482	0.007583	0.007852	0.01295	0.008831	0.007357
	0.009032	0.009445	0.008904	0.009698	

Figure 30 – Absorbed dose rate distribution (rad/s) in the closet at a distance of 760 cm from the diaphragm, GEANT4

	19.58 %	1.53 %	12.44 %	3.255 %	
23.41 %	10.88 %	7.57 %	14.1 %	13.72 %	26.67 %
19.52 %	9.378 %	12.42 %	29.32 %	16.89 %	3.491 %
0.7216 %	20.45 %	18.41 %	21.62 %	10.47 %	17.99 %
3.741 %	24.62 %	22.71 %	27.5 %	12.22 %	25.46 %
	10.21 %	6.114 %	11.02 %	3.116 %	

Figure 31 – Relative error in calculating the absorbed dose rate in the closet at a distance of 760 cm from the diaphragm

Figures 29-31 show the statistical error in determining the absorbed dose rate in a closet with containers, due to the small number of simulated particles for a given distance. The maximum relative error was 30%.

4. FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING

This Bachelor thesis is aimed at developing a model and program for calculating the absorbed dose rate in a room with a gamma unit.

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

Achievement of the goal is ensured by solving the following tasks:

− development of the general economic idea of the project, formation of the concept of the project;

− organization of the work of the research project;

− identification of possible alternatives for conducting scientific research;

− planning of research works;

− assessment of the commercial potential and the prospects for conducting scientific research from standpoint of resource efficiency and resource conservation;

− determination of resource (resource-saving), financial, budgetary, social and economic efficiency of the study [21].

4.1.   Potential Consumers of Bachelor Thesis

The result of Bachelor thesis is a developed program for modeling the distribution of the absorbed dose rate in a room with a ROKUS-AMT gamma-ray unit when conducting a study of the effect of radiation on electronic components.

The target market for this work is the nuclear industry, research laboratories with the ROKUS-AMT gamma-ray unit, and nuclear medicine centers where the ROKUS-AM gamma-therapy unit is used.

The service market can be segmented according to the degree of need to use this technique. The segmentation results are presented in table 5.

Table 5 – Segmentation results

		The program for calculating the absorbed dose rate in a room with a gamma unit		
		Atomic industry	Science industry	Nuclear medicine
Demand	Strong	███████	███████	
	Weak			███████

4.2. Analysis of Competitive Technical Solutions

Analysis of competitive technical solutions allows you to make timely adjustments to the project in order to more successfully resist competitors. Since the markets are in constant motion, it is necessary to periodically conduct such an analysis. The analysis carried out for the developed program is currently presented in table 6.

Table 6 – Scorecard for comparing competitive technical solutions (developments)

Criteria for evaluation	Criteria weight	Points			Competitiveness		
		$Б_ф$	$Б_{к1}$	$Б_{к2}$	$К_ф$	$К_{к1}$	$К_{к2}$
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Ease of use	0.1	4	2	2	0.4	0.2	0.2
2. Solution accuracy	0.2	4	4	3	0.8	0.8	0.6
3. Memory resource requirement	0.1	2	5	4	0.2	0.5	0.4
4. Functional power	0.1	5	3	2	0.5	0.3	0.2
5. Versatility	0.1	5	4	2	0.5	0.4	0.2
Economic criteria for evaluating efficiency							
1. Competitiveness of the method	0.1	3	3	2	0.3	0.3	0.2
2. Development costs	0.2	5	5	5	1	1	1

3. Estimated service life	0.05	5	4	4	0.25	0.2	0.2
4. Development funding	0.05	2	2	2	0.1	0.1	0.1
Total	1				**4.05**	**3.80**	**3.10**

Analysis of competitive technical solutions is determined by the formula:

$$K = \sum_i B_i \cdot Б_i ,$$ (18)

where K – development competitiveness;

B_i – indicator weight (in fractions of a unit);

$Б_i$ – score of the i-th indicator.

Based on the analysis, it can be concluded that the developed model has the advantage of ease of use, functional power and versatility.

4.3. SWOT Analysis

To conduct a SWOT analysis, we first identify the strengths, weaknesses, opportunities and threats of the project. The result is presented in table 7.

Table 7 – SWOT matrix, first stage

	Strengths of the project: S1. Universality of the method. S2. Low cost implementation of the method. S3. Setting up calculations using XML files.	**Weaknesses of the project:** W1. Availability of computers for use. W2. Dependence of accuracy on the number of simulated decays. W3. Dependence of the calculation rate on the number of simulated decays.
Capabilities: C1. Expanding the capabilities of the calculation model. C2. Using the model for research.		
Threats:		

T1. Lack of demand for new technologies. T2. Probability of developing similar calculation models by other organizations.		

Table 8 provides an interactive project matrix that compares strengths with opportunities and weaknesses with threats, allowing a more detailed look at the development perspective.

Table 8 – SWOT matrix, second stage

Project capabilities	Strengths of the project		
	S1	S2	S3
C1	+	+	+
C2	+	+	+
Project capabilities	Weaknesses of the project		
	W1	W2	W3
C1	+	-	-
C2	+	-	-
Project threats	Strengths of the project		
	S1	S2	S3
T1	+	+	+
T2	+	+	+
Project threats	Weaknesses of the project		
	W1	W2	W3
T1	+	-	-
T2	+	-	-

In the matrix of the intersection of strengths and opportunities, it has a certain result: «+» – a strong correspondence between a strength and an opportunity, «-» – a weak ratio, «0» – if there is any doubt about what to put«+» or «-».

The final SWOT analysis matrix is shown in table 9:

Table 9 – Final SWOT matrix

	Strengths of the project: S1. Universality of the method. S2. Low cost implementation of the method. S3. Setting up calculations using XML files.	Weaknesses of the project: W1. Availability of computers for use. W2. Dependence of accuracy on the number of simulated decays. W3. Dependence of the calculation rate on the number of simulated decays.
Capabilities: C1. Expanding the capabilities of the calculation model. C2. Using the model for research.	1. After optimization to increase the calculation speed, the model will be in demand due to its versatility and convenience.	1. The speed and accuracy of calculations can be increased by optimizing the program code. 2. Expansion of the model's capabilities can be performed without additional equipment.
Threats: T1. Lack of demand for new technologies. T2. Probability of developing similar calculation models by other organizations.	1. The versatility of the method, the convenience of setting up the calculation can cause a demand for the technology.	1. Currently, computer simulation is a cheap research method, which has significantly increased the demand for such technologies.

Thus, at the moment, the advantages of the developed model are such as the accuracy of the data obtained, the possibility of optimizing the model, cost-effectiveness, accessibility, ease of use, the possibility of obtaining data using only a computer.

4.4. Project Planning

The work on the topic includes the following steps:

1. Preparation of terms of reference;
2. Study of the problem, literature review;
3. Scheduling work;

4. Building a model;

5. Writing program code;

6. Obtaining the results of the absorbed dose rate distribution, verification;

7. Registration of the report.

To carry out Bachelor thesis, a working group was formed, which includes a supervisor and a student.

To optimize work, it is convenient to use the classical method of linear planning and control. The result of such planning is the preparation of a linear schedule for the implementation of all work. The calculation of the parameters of the linear schedule requires the determination of the duration of the work. In the absence of time standards for carrying out certain types of work, probabilistic estimates are used. The procedure for compiling stages and works is given in table 10.

Table 10 – List of stages, works and distribution of performers

Main steps	№ works	Content of works	Position of the performer
Task development	1	Preparation of terms of reference	scientific supervisor
Choice of research direction	2	Study of the problem, literature review	scientific supervisor, student
	3	Work scheduling	student
Theoretical and experimental studies	4	Model building	scientific supervisor, student
	5	Writing code	student
	6	Obtaining the results of the absorbed dose rate distribution, verification	scientific supervisor, student
Generalization and evaluation of results	7	Report design	student

4.4.1. Determination of the Complexity of Performing Bachelor Thesis

To optimize the work, we use the classical method of linear planning and control, as a result, we will draw up a linear schedule for the execution of all work.

To determine the labor costs, it is first necessary to set the minimum possible complexity of the stage and the maximum possible, then the expected labor intensity is determined by the formula:

$$t_{ожi} = \frac{3t_{\min i} + 2t_{\max i}}{5} \tag{19}$$

The duration of work in working days is determined as follows:

$$T_{pi} = \frac{t_{ожi}}{Ч_i} \tag{20}$$

where $Ч_i$ – the number of performers performing the same work at the same time at the stage, pers.

4.4.2. Development of the Bachelor Thesis Schedule

Since the project is relatively small, it is optimal to build a tape schedule of work for greater clarity and convenience. The Gantt chart is a horizontal strip chart, on which the work on the topic is presented as long time intervals, characterized by the start and end dates of the work.

Before building a Gantt chart, let's determine the duration of the work of each stage in calendar days. The calculation begins with the determination of the calendar factor:

$$k = \frac{T_{кал}}{T_{кал} - T_{вых} - T_{пр}}, \tag{21}$$

where $T_{кал}$ – the number of calendar days in a year;

$T_{вых}$ – the number of days off in a year;

$T_{пр}$ – the number of holidays in a year.

$$k = \frac{366}{366 - 104 - 14} = 1,478$$

Knowing the coefficient, it is possible to determine the duration of work in calendar days:

$$T_{кi} = T_{pi} \cdot k \tag{22}$$

Using the above formulas, we will issue the calculation in the form of table 11:

Table 11 – Time indicators for an engineering project

Stage	Labor intensity of work			Performers	Duration of work in working days T_{pi}	Duration of work in calendar days T_{ki}
	t_{min}, man-days	t_{max}, man-days	$t_{ожi}$, man-days			
1	4	6	4.8	S.s.	4.8	8
2	7	12	9	S.s.+s.	4.5	7
3	4	6	4.8	s.	4.8	8
4	10	14	11.6	S.s.+s.	5.8	9
5	14	20	16.4	s.	16.4	25
6	7	14	9.8	S.s.+c.	4.9	8
7	7	10	8.2	s.	8.2	13
Total						78

Based on table 11, a Gantt chart was built, which is presented in table 12.

Table 12 – Calendar schedule (Gantt chart) of the Bachelor thesis

№	Type of work	Performers	T_k, cal. days	Duration of work, week								
				March			April			May		
				1	2	3	1	2	3	1	2	3
1	Compiling a task	s.s.	8	▓								
2	Study of the problem, literature review	s.s.+s.	7		▓							
3	Work scheduling	s.	8			▓						
4	Model building	s.s.+s.	9				▓					
5	Writing code	s.	25					▓	▓			
6	Obtaining the absorbed dose rate distribution, verification	s.s.+s.	8							▓		
7	Report design	s.	13								▓	▓

4.5. Project's Budget

The project budget consists of material costs, the basic salary of the Bachelor thesis performers, deductions to off-budget funds and overhead costs.

4.5.1. Material Costs

The calculation of material costs is made according to the formula:

$$C_M = (1 + k_T) \sum_{i=1}^{m} Ц_i \cdot N_{pacxi}, \qquad (23)$$

where m – the number of types of material resources consumed in the performance of Bachelor thesis;

N_{pacxi} – the amount of material resources planned for use in the performance of Bachelor thesis;

$Ц_i$ – the price of a material resource per unit;

k_T – coefficient taking into account transportation and procurement costs, the value of which varies from 15 to 25 %.

Electricity costs are calculated as follows:

$$C = Ц_{эл} \cdot P \cdot F_{об}, \qquad (24)$$

where $Ц_{эл}$ – electricity tariff, for Tomsk for 2022 the tariff is 3.85 rubles/kWh;

P – power of the equipment, the used equipment has a power supply of 180 watts.

$F_{об}$ – equipment use time, use time 496 hours.

Calculations:

$$C = 3.85 \cdot 0.18 \cdot 496 = 343.73 \text{ rub.}$$

Table 13 – Material costs

Name	Quantity, pcs.	Unit price, rub.	$C_м$, rub.
Paper A4	1	250	250
Electricity	89.3	3.85	343.73
Total			593.73

4.5.2. Special Equipment Costs

When performing Bachelor thesis, personal equipment was used. Calculate the amount of depreciation:

$$C_a = \sum_{i=1}^{n} \frac{Ц_{бал} \cdot H_a \cdot g_i \cdot t}{Ф_{эф}}, \tag{25}$$

where $Ц_{бал}$ – the cost of the type of equipment;

H_a – annual depreciation rate;

g_i – the number of pieces of equipment;

t – equipment operation time;

$Ф_{эф}$ – effective fund of equipment operation time;

In work, the special equipment is a laptop worth 50,000 rubles. Depreciation rate 25 %. Equipment use time 62·8/24 = 21 days.

$$C_a = \frac{50000 \cdot 0.25 \cdot 1 \cdot 21}{251} = 1046 \text{ rub.}$$

4.5.3. Bachelor Thesis Performers Salary

The salary of performers of the Bachelor thesis consists of the basic and additional:

$$C_{зп} = З_{осн} + З_{доп} \tag{26}$$

The basic salary can be defined as follows:

$$З_{осн} = З_{дн} \cdot T_{раб}, \tag{27}$$

where $З_{дн}$ – the average daily wage of an employee;

$T_{раб}$ – duration of work.

The average daily wage of an employee is determined by the formula:

$$З_{дн} = \frac{З_м \cdot M}{F_Д} \tag{28}$$

where $З_м$ – the monthly salary of the employee;

M – the number of months of work without vacation during the year (10.4 months, with a vacation of 48 working days, 6-day week);

$F_Д$ – estimated annual fund of staff working time.

Table 14 – Estimated annual working time fund

Working time indicators	Supervisor	Student
Calendar number of days	365	365
Number of non-working days -weekend -holidays	 52 14	 52 14
Loss of working time -vacation -absenteeism due to illness	 48 -	 48 -
Valid annual fund of working time	251	251

Calculation of the average daily salary and basic salary for a supervisor (salary of an associate professor, candidate of science 37,700 rubles):

$$З_{дн} = \frac{49010 \cdot 10.4}{251} = 2030.7 \text{ rub.}$$

$$З_{осн} = 2030.7 \cdot 32 = 64982.4 \text{ rub.}$$

For a student (in calculations, it is assumed that the student's salary is taken equal to the minimum wage of 13,890 rubles):

$$З_{дн} = \frac{18057 \cdot 10.4}{251} = 748.2 \text{ rub.}$$

$$З_{осн} = 748.2 \cdot 70 = 52374 \text{ rub.}$$

Table 15– Basic salary calculation

Performers	$З_{тс}$, rub.	$k_р$	$З_м$, rub.	$З_{дн}$, rub	$T_р$, w.d.	$З_{осн}$, rub.
Scientific supervisor	37700	1,3	49019	2030.7	32	64982.4
Student	13890	1,3	18057	748.2	70	52374
Total						117356.4

The costs of additional wages for the performers of the topic take into account the amount of additional payments provided for by the Labor Code of the Russian

Federation for deviations from normal working conditions, as well as payments related to the provision of guarantees and compensations (when performing state and public duties, when combining work with education, when providing annual paid leave etc.).

$$З_{доп} = k_{доп} \cdot З_{осн}. \tag{29}$$

whwre $З_{доп}$ – additional salary, rub.;

$k_{доп} = 0.14$ – additional salary coefficient;

$З_{осн}$ – basic salary, rub.

Table 16 – Bachelor thesis performers salary

Wage	Supervisor	Student
Basic salary $З_{осн}$, rub.	64982.4	52374
Additional salary $З_{доп}$, rub.	9097.5	7332.4
Total item $З_{зп}$, rub.	74079.9	59706.4
Total	133786.3	

4.5.4. Deductions to Off-Budget Funds

The amount of deductions to off-budget funds is determined by the formula:

$$С_{внеб} = k_{внеб} \cdot З_{общ}. \tag{30}$$

where $k_{внеб}$ – the coefficient of deductions for payment to off-budget funds varies from 30 to 35 %. When calculating, we will assume that $k_{внеб} = 30.2$ % for educational and scientific institutions.

From the previous paragraphs, $З_{общ} = 133786.3$ руб. Then the amount of deductions will be:

$$С_{внеб} = 0.302 \cdot 133786.3 = 40403.5 \text{ rub.}$$

4.5.5. Overheads

Overhead costs are calculated using the formula:

$$С_{накл} = k_{накл} \cdot З_{1-3} \tag{31}$$

where $k_{накл}$ – overhead cost ratio, in the calculation we will take equal to 16 %.

$$C_{\textit{накл}} = 0.16 \cdot 135426.0 = 21668.2 \text{ rub.}$$

4.5.5. Formation of the Bachelor Thesis Cost Budget

Based on the calculations, we will compile a table with the received costs of the Bachelor thesis.

Table 17 – Bachelor thesis cost budget

Costs	Amount, rub.
Material costs	593.73
Special equipment costs	1046
Project executor salary	133786.3
Deductions to off-budget funds	40403.5
Overheads	21668.2
Total	197497.73

4.6. Determination of resource (resource-saving) efficiency of Bachelor thesis

4.6.1. Evaluation of the scientific and technical effect

The assessment of the scientific and technical effect is based on the coefficient of the social and scientific effect:

$$H_T = \sum_{i=1}^{3} r_i k_i \tag{32}$$

where r_i – weight coefficient of the i-th attribute of the scientific and technical effect;

k_i – quantitative assessment of the i-th feature.

Table 18 – Weight coefficients of signs of scientific and technical effect

Signs of scientific and technological effect	Approximate weighting values
Novelty level	0.6
Theoretical level	0.4
Possibility of implementation	0.2

Table 19 – Novelty Level Scores

Novelty level	Characteristics of the level of novelty	Points
Fundamental	Research results open a new direction in this field of science and technology	8-10
New	Known facts, patterns are explained in a new way or for the first time	5-7
Relatively new	Research results systematize and summarize the available information, determine the ways for further research	2-4
Traditional	The work performed according to the traditional method, the results of the research are for informational purposes	1
No novelty	The result was obtained, which was previously known	0

Table 20 – Significance scores of theoretical levels

Theoretical level of the obtained results	Points
Establishment of the law; development of a new theory	9-10
Deep development of the problem: multidimensional analysis of relationships, interdependence between facts with the presence of an explanation	7-8
Development of a method (algorithm, program of events, device, innovation, etc.)	3-6
Elementary analysis of relationships between facts with the presence of a hypothesis, simplex forecast, classification, explanation of versions or practical recommendations of a particular nature	0.6-2
Description of individual elementary facts (things, properties and relationships); presentation of experience, observations, measurement results	0-0.5

Table 21 – Probability of implementation by time and scale of implementation

Implementation time	Points
During the first years	5-10
5 to 10 years	3-4
Over 10 years	0-2
Scale of implementation	Points
One or more businesses	0-2
Industry (Ministry)	3-4
National economy	5-10

The project is evaluated as follows:

- novelty level score– 3

- significance score of the theoretical level – 6

- score on the probability of realization – 5+2=7

$$H_T = 0.6 \cdot 3 + 0.4 \cdot 6 + 0.2 \cdot 7 = 5.6$$

Table 22 – Assessment of the level of scientific and technical effect

The level of scientific and technological effect	Coefficient of scientific and technical effect
Low	1-4
Medium	5-7
Relatively high	8-10
High	11-14

Based on table 22, the level of scientific and technical effect is medium.

4.6.2. Evaluation of the comparative effectiveness of the study

One of the execution options is to write a program not in C ++, but in Python, which is easier to learn, and programs are written faster in it, however, it is an interpreted language, which makes it difficult to debug the program, since it does not give errors immediately, but also the calculation speed is less (Analogue 1). Another

option for performing Bachelor thesis is to write a program without using the GEANT4 library system, but to write your own implementation of the Monte Carlo method (Analogue 2).

The final budget for Bachelor thesis implementation options is summarized in table 23.

Table 23 – Budget options

Project	Budget, rub.	Integral financial indicator of development
Current project	197497.73	0.77
Analogue 1	160127.541	0.63
Analogue 2	255785.394	1

Table 24 – Comparative evaluation of the characteristics of options

Criteria	Parameter weighting factor	Current project	Analogue 1	Analogue 2
1. Ease of use	0.1	4	4	5
2. Solution accuracy	0.3	4	4	3
3. Memory resource requirement	0.2	2	1	1
4. Functional power	0.2	5	2	4
5. Versatility	0.2	5	5	4

$$I_{mn} = 0.1 \cdot 4 + 0.3 \cdot 4 + 0.2 \cdot 2 + 0.2 \cdot 5 + 0.2 \cdot 5 = 4$$
$$I_1 = 0.1 \cdot 4 + 0.3 \cdot 4 + 0.2 \cdot 1 + 0.2 \cdot 2 + 0.2 \cdot 5 = 3.2$$
$$I_2 = 0.1 \cdot 5 + 0.3 \cdot 3 + 0.2 \cdot 1 + 0.2 \cdot 4 + 0.2 \cdot 4 = 3.2$$

Table 25 – Comparative development efficiency

Project	Current project	Analogue 1	Analogue 2
Integral financial indicator	0.77	0.63	1
Integral indicator of resource efficiency	4	3.2	3.2
Integral efficiency indicator	5.19	5.08	3.2
Comparative efficiency of variants	-	1.02	1.62

Based on table 25, we can conclude that the current project is the most effective. The differences from analog 1 are not so big, a feature of analog 1 is the implementation of Bachelor thesis with lower budget costs, however, the functional capacity of the development is much less than the current execution. Thus, it is optimal to leave the current execution.

Conclusions of the section

1.   The analysis of competitive technical solutions showed that the developed model has an advantage in ease of use, functional power and versatility.

2.   The advantages of the developed model, such as the accuracy of the data obtained, the possibility of optimizing the model, cost-effectiveness, accessibility, ease of use, the possibility of obtaining data using only a computer.

3.   The project budget amounted to 197497.73 rubles.

4.   The level of scientific and technological effect is average.

5. SOCIAL RESPONSIBILITY

The result of the Bachelor thesis is the developed program in C ++ using GEANT4 for modeling the distribution of the absorbed dose rate in a room with a ROKUS-AMT gamma unit when conducting a study of the effect of radiation on electronic components. The Bachelor thesis was held in room 302 of building 11 of Tomsk Polytechnic University.

The section discusses dangerous and harmful factors that affect the research process, considers the impact of the object under study on the environment, legal and organizational issues, as well as measures in emergency situations.

5.1. Legal and organizational issues of security

5.1.1. Special (characteristic for the researcher's working area) legal norms of labor legislation

The main provisions on labor protection are set out in the Labor Code of the Russian Federation [22]. This document states that the protection of the health of workers, the provision of safe working conditions, the elimination of occupational diseases and industrial injuries are one of the main concerns of the state.

According to [22], each employee has the right to:

$-$ a workplace that meets the requirements of labor protection;

$-$ compulsory social insurance against industrial accidents and occupational diseases;

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

$-$ refusal to perform work in case of danger to his life and health due to violation of labor protection requirements;

$-$ provision of means of individual and collective protection in accordance with the requirements of labor protection at the expense of the employer;

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

− personal participation or participation through their representatives in the consideration of issues related to ensuring safe working conditions at his workplace, and in the investigation of an accident at work or an occupational disease that happened to him;

− an extraordinary medical examination in accordance with medical recommendations, while retaining his place of work (position) and average earnings during the passage of the specified medical examination;

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

The Labor Code of the Russian Federation states that the normal working hours cannot exceed 40 hours per week, the employer is obliged to keep records of the time worked by each employee [23].

5.1.2. Organizational measures in the layout of the researcher's working area

The rational layout of the workplace provides for a clear order and consistency in the placement of objects, means of labor and documentation. What is required to perform the work more often should be located in the zone of easy reach of the workspace, as shown in figure 32.
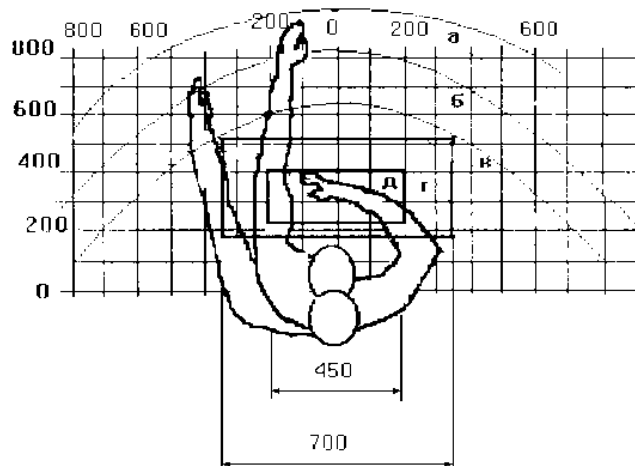
Figure 32 – Hand reach zones in the horizontal plane

а – the zone of maximum reach of the hands; б – the reach zone of the fingers with an outstretched hand; в – zone of easy reach of the palm; г – the optimal space for rough manual work; д - optimal space for fine handwork

Optimal placement of objects of work and documentation within the reach of hands:

− the display is located in zone a (in the center);

− keyboard – in zone г, д;

− the system unit is located in zone б (on the left);

− the printer is in zone a (on the right);

− literature and documentation required for work is within easy reach of the palm – в (left);

− in the drawers of the table - literature that is not used constantly [24].

When choosing a workplace, namely a desk, the following requirements should be taken into account [24], which are presented in table 26.

Table 26 – Requirements for equipping a workplace that provides for long-term work at a PC

Desktop Width	80 to 140 cm
Desktop Height	75 cm
Desktop Depth	60 to 80 cm
Distance from eyes to monitor	50 to 60 cm

Distance of the keyboard from the edge of the table	10 to 30 cm
Seat	Should allow adjustment in height, swivel and angle of the backrest (adjustments should be independent of each other)
Legroom	Width from 30 cm, depth – from 40 cm, with an angle of inclination up to 20 degrees

The monitor should be located at the operator's eye level at a distance of 500-600 mm. According to the standards, the viewing angle in the horizontal plane should be no more than 45 degrees to the normal of the screen. It is better if the viewing angle is 30 degrees. In addition, it should be possible to select the level of contrast and brightness of the image on the screen [24].

It should also be possible to adjust the monitor screen:

− in height +3 cm;

− inclination relative to the vertical 10 – 20 degrees;

− in left and right directions.

If the operator's work involves monotonous mental work that requires significant nervous tension and great concentration, then it is best to choose soft, low-contrast color shades (weakly saturated shades of cold blue or green colors), which do not weaken attention. If the work requires great mental and physical intensity, then warmer shades should be used, which help to increase concentration [24].

5.2. Industrial Safety

5.2.1. Analysis of Harmful and Dangerous Factors

The production conditions at the place of work are characterized by the presence of dangerous and harmful factors, which, by the nature of their occurrence, are divided into the following groups:

− physical;

− chemical;

− psychophysiological;

− biological [25].

Dangerous and harmful factors that may affect personnel when working on a PC are shown in Table 27.

Table 27 – Dangerous and harmful factors in the laboratory № 302 11 of the TPU building

Name of types of work and parameters of the production process	Factors		Regulations
	Harmful	Dangerous	
Calculation of data on a PC	-	Electricity	GOST 12.1.038-82 SSBT. Electrical safety [26],
	Exposure to radiation (HF, UHF, microwave, etc.).	-	SanPiN 2.2.4/2.1.8.055-96. Electromagnetic radiation in the radio frequency range [27].
	-	Fire hazard	GOST 12.1.004-91 SSBT. Fire safety [28].
	Noise, vibration, microclimate	-	SanPiN 1.2.3685-21 «Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans» [25].

The psychologically harmful factors affecting the staff include:

−   neuro-emotional overload;

−   mental stress;

−   physical overload.

5.3.   Justification of Measures to Protect the Researcher from the Action of Harmful and Dangerous Factors

In accordance with the basic requirements for the premises for the operation of a PC [25], they must have natural and artificial lighting. The area per workplace of PC users should be at least 6 m^2.

5.3.1. Deviation of Microclimate Indicators

The air of the working area (microclimate) of industrial premises is determined by the following parameters: temperature, relative humidity, air velocity. The optimal values of the microclimate characteristics are set in accordance with the standards and are given in table 28.

Table 28 – Optimal microclimate parameters

Period of the year	Temperature, ºC	Relative humidity, %	Air speed, m/s
Cold	23-25	40-60	0.1
Warm	22-24	40	0.1

Deviation of microclimate indicators from the norm does not cause damage or health disorders, but can lead to general and local sensations of thermal discomfort, tension in thermoregulation mechanisms, deterioration in well-being and decreased performance [25].

To ensure the established norms of microclimatic parameters and air purity at workplaces and in rooms, ventilation is used.

Ventilation can be carried out naturally and mechanically. The optimal frequency of air exchange in industrial premises is within a fairly wide range: from 3 to 40 times per hour [25].

According to [29], an air exchange rate of 40 m^3/h per person is required in the office. The office in which the work was performed is designed for 7 workplaces, so the ventilation performance will be:

$$L = k \cdot Q = 7 \cdot 40 = 280 \ \frac{m^3}{h} \tag{33}$$

where k – number of persons;

Q – air exchange rate per person.

This performance is provided by a Vents 150 VKO fan with a maximum capacity of 298 m^3/h and a power of 24 W [30].

Thus, the indicator of the microclimate in room 302 of TPU building 11 complies with the established standards [25].

5.3.2. Increased Level of Electromagnetic Radiation

Electromagnetic radiation is a perturbation (change of state) of the electromagnetic field propagating in space.

The screen and system blocks of the computer produce electromagnetic radiation. Its main part comes from the system unit and video cable. The strength of the electromagnetic field at a distance of 50 cm around the screen in terms of the electrical component must comply with table 29.

An increased level of electromagnetic radiation can negatively affect the human body, namely, lead to nervous disorders, sleep disturbance, a significant deterioration in visual activity, weakening of the immune system, and disorders of the cardiovascular system [27].

Table 29 – Permissible levels of electromagnetic field parameters

Name of parameters		Acceptable level value
Electromagnetic field strength	Frequency range 5 Hz – 2 kHz	25 V/m
	Frequency range 2 kHz – 400 kHz	2.5 V/m
Magnetic flux density	Frequency range 5 Hz – 2 kHz	250 nTl
	Frequency range 2 kHz – 400 kHz	25 nTl

There are the following ways to protect against EMF:

− increasing the distance from the source (the screen must be at least 50 cm away from the user);

− the use of near-screen filters, special screens and other personal protective equipment [27].

5.3.3. Insufficient Illumination of the Working Area

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.

According to the standards, the illumination on the surface of the table in the area where the working document is placed should be 300-500 lux. Lighting should

not create glare on the surface of the screen. The illumination of the screen surface should not exceed 300 lux [25].

The brightness of general lighting fixtures in the zone of radiation angles from 50 to 90 ° with the vertical in the longitudinal and transverse planes should be no more than 200 cd / m, the protective angle of the fixtures should be at least 40 °. The safety factor (Кз) for lighting installations for general lighting should be taken equal to 1.4. The ripple factor should not exceed 5%.

Artificial lighting in the premises for the operation of a PC should be carried out:

−   general uniform lighting system.

In industrial and administrative-public premises, in cases of predominant work with documents, the following systems should be used:

−   combined lighting (lamps are additionally installed in addition to general lighting;

−   local lighting designed to illuminate the area where documents are located) [25].

Room area:

$$S = a \cdot b, \tag{32}$$

where a – length, m; b – width, m.

$$S = 6 \cdot 6 = 36 \text{ m}^2.$$

Reflectivity of freshly whitewashed walls with windows covered with white curtains $\rho_C = 70 \text{ %}$, freshly whitewashed ceiling $\rho_\Pi = 70 \text{ %}$. The safety factor, taking into account the contamination of the luminaire, for rooms with low dust emission is equal to $K_з = 1.5$. Coefficient of unevenness for LED strips $Z = 1.1$.

We select Varton 9w LEDs, the luminous flux of which is equal to $\Phi_{ЛД} = 2900 \text{ lm}$.

Choosing fixtures with LEDs such as Diora LPO. This luminaire has two LED strips with a power of 9 W each, the length of the luminaire is 1260 mm, the width is 124 mm.

The integral criterion for the optimal location of luminaires is the value λ, which for LED luminaires with a protective diffuser lies in the range of $1.1 - 1.3$. We accept $\lambda = 1.1$, the distance of the fixtures from the ceiling (overhang) $h_c = 0.5$ m.

The height of the luminaire above the working surface is determined by the formula:

$$h = h_n - h_p, \tag{33}$$

where h_n – lamp height above the floor, suspension height;

h_p – the height of the work surface above the floor.

The smallest permissible suspension height above the floor for Diora two-strip luminaires: $h_n = 3.5$ m.

The height of the luminaire above the working surface is determined by the formula:

$$h = H - h_p - h_c = 3.5 - 1 - 0.5 = 2 \text{ m.} \tag{34}$$

From the formula

$$\Phi_{\text{л}} = \frac{(E \cdot S \cdot K_{\text{з}} \cdot Z)}{N \cdot \eta}, \tag{35}$$

find the number of LED strips N:

$$N = \frac{(E \cdot S \cdot K_{\text{з}} \cdot Z)}{\Phi_{\text{л}} \cdot \eta}. \tag{35}$$

η determined through the room index by the formula:

$$i = \frac{(a \cdot b)}{h \cdot (a + b)} = \frac{6 \cdot 6}{2(6 + 6)} = 1.5. \tag{36}$$

The luminous flux utilization coefficient, showing what part of the luminous flux of the lamps falls on the working surface, for Diora-type luminaires with LED strips at $\rho_{\Pi} = 70 \, \%$, $\rho_C = 70 \, \%$ and room index $i = 1.5$ is equal to $\eta = 0.54$.

Then

$$N = \frac{(E \cdot S \cdot K_{\text{з}} \cdot Z)}{\Phi_{\text{л}} \cdot \eta} = \frac{300 \cdot 36 \cdot 1.5 \cdot 1.1}{2900 \cdot 0.54} = 11.38 \text{ strips} \cdot$$

We accept the number of LED strips 12. In this case, 6 lamps are obtained, that

is, 2 rows of 3 lamps each.

Required luminous flux of LED lamps:

$$\Phi_{\textit{л}} = \frac{(E \cdot S \cdot K_{\textit{з}} \cdot Z)}{N \cdot \eta} = \frac{300 \cdot 36 \cdot 1.5 \cdot 1.1}{12 \cdot 0.54} = 2750 \text{ lm.}$$

From the conditions of illumination uniformity, we determine the distances L_1 and $\frac{L_1}{3}$, L_2 and $\frac{L_2}{3}$ according to the following equations:

$$6000 = L_1 + \frac{2}{3} \cdot L_1 + 2 \cdot 124; \; L_1 = 3451 \text{ mm}, \; \frac{L_1}{3} = 1150 \text{ mm}; \tag{37}$$

$$6000 = 2 \cdot L_2 + \frac{2}{3} \cdot L_2 + 3 \cdot 1260; \; L_2 = 832 \text{ mm}, \; \frac{L_2}{3} = 277 \text{ mm}; \tag{38}$$

Figure 33 shows the plan of the premises and placement of lamps with LED strips in the laboratory № 302-11 of the TPU educational building.
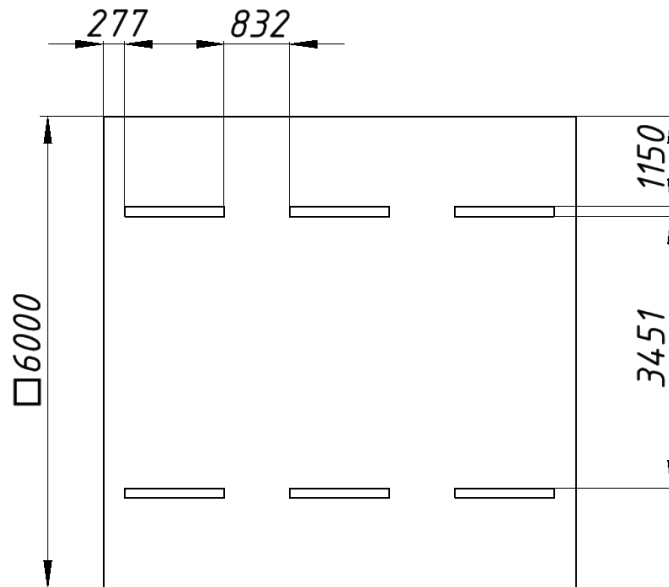
Figure 33 – Plan of the room and placement of lamps with LED strips

We check the fulfillment of the condition:

$$-10\% \leq \frac{(\Phi_{\textit{лд}} - \Phi_{\textit{л}})}{\Phi_{\textit{лд}}} \cdot 100\% \leq 20\%; \tag{39}$$

$$\frac{(\Phi_{\textit{лд}} - \Phi_{\textit{л}})}{\Phi_{\textit{лд}}} \cdot 100\% = \frac{(2900 - 2750)}{2900} \cdot 100\% = 5,2 \%$$

Thus, it is obtained that the required luminous flux does not go beyond the

required range. The power of the lighting installation turned out:

$$P = 12 \cdot 9 = 108 \text{ W.}$$

The calculated number of lamps and the distance between them in the classroom № 302 11 of the TPU educational building corresponds to the actual one.

5.3.4. Exceeding the Noise Level

Noise, being a general biological stimulus, affects not only the auditory analyzer, but also affects the structures of the brain, causing shifts in various functional systems of the body. Among the numerous manifestations of the adverse effects of noise on the human body, the following stand out: a decrease in speech intelligibility, discomfort, the development of fatigue and a decrease in labor productivity, the appearance of noise pathology. Table 30 shows the noise level standards for various types of work.

Table 30 – Noise level standards for various types of work

	Maximum permissible noise level (dB), in the bands of the following octaves (Hz)									Equivalent noise levels, dBA
Scientific work, calculations, design	86	71	61	54	49	45	42	40	38	50
Offices, laboratories	93	79	70	68	58	55	52	52	49	55

The noise level at workplaces while working on a PC should not exceed 55 dB. To reduce the noise level, the ceiling or walls should be lined with sound-absorbing material with a maximum sound absorption coefficient in the frequency range from 63 to 8000 Hz [31]. Curtains on the windows made of dense heavy fabric serve as additional sound absorption.

In laboratory № 302 11 of the educational building of TPU, the noise level complies with sanitary standards [31].

5.3.5. Psychophysiological Factors

Psychophysiological hazardous and harmful production factors are divided into: physical overload (static, dynamic) and neuropsychic overload (mental strain, monotony of work, emotional overload).

The labor activity of workers in the non-productive sphere belongs to the category of work associated with the use of large amounts of information, with the use of computerized workplaces, with frequent making of responsible decisions in conditions of time pressure, direct contact with people of different types of temperament, etc. This causes a high level of neuropsychic overload, reduces the functional activity of the central nervous system, leads to disorders in its activity, the development of fatigue, overwork, and stress.

The most effective means of preventing fatigue during work in production are means that normalize the active labor activity of a person. Against the background of the normal course of production processes, one of the important physiological measures against fatigue is the correct mode of work and rest [25].

To reduce the impact of harmful factors, a framework for the duration of breaks is established. Table 31 shows the total rest time for each category of work [32].

Table 31 – Total break time depending on the category of work and load

Work Category	The level of load per work shift for types of work with a PC			Total time of regulated breaks
	Group A, number of characters	Group Б, number of characters	Group B, hours	at 8-hour shift, min.
I	up to 20 000	up to 15 000	up to 2	50
II	up to 40 000	up to 30 000	up to 4	70
III	up to 60 000	up to 40 000	up to 6	90

In this case, the load level refers to group B, work category III. According to the table, it is required to set breaks, the sum of which for working time will be at least 90 minutes, i.e. breaks of 15 minutes each working hour [32].

5.3.6. Electrical Safety

According to [26], depending on the conditions in the room, the risk of electric shock to a person increases or decreases. You should not work with a computer in conditions of high humidity (relative air humidity exceeds 75% for a long time), high temperature (more than 35 ° C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with ground-connected metal elements and the metal case of electrical equipment. The office belongs to the 1st category in terms of electrical safety, since there are no electrical installations with a voltage of over 1000 V at the workplace.

The computer operator works with electrical appliances: a computer (display, system unit, etc.) and peripheral devices. There is a danger of electric shock in the following cases:

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

Measures to ensure the electrical safety of electrical installations:

- disconnection of voltage from current-carrying parts on which or near which work will be carried out, and taking measures to ensure that it is impossible to supply voltage to the place of work;
- hanging posters indicating the place of work;
- grounding of housings of all installations through a neutral wire;
- coating of metal surfaces of tools with reliable insulation;
- inaccessibility of current-carrying parts of the equipment (conclusion in

cases of electro-shocking elements, current-carrying parts) [26].

When performing this Bachelor thesis, a PC was used. This device is powered by a mains voltage of 220 V at 50 Hz with a rated power input of 0.18 kW. When using this equipment, the requirements for electrical safety [26] were strictly observed.

5.4. Environmental Safety

The work is developing a model of the ROKUS-AMT gamma-ray unit, using a PC.

The impact of equipment operation on the environment is minimal. The greatest harm from them in work is the consumption of electricity. The PC does not emit harmful substances, does not create radiation that can violate the environmental safety of nature. However, its production and disposal are a serious problem. So, in the production of PCs, heavy, alkaline earth metals, mercury, plastic and glass are used, which, without proper disposal at the end of their service, enters nature and remains unprocessed from a century to one and a half thousand years [25].

Activities that allow you to maintain environmental safety while at the workplace [25]:

– correct disposal;

– use of energy-saving lamps;

– use of accumulators instead of saline batteries.

Reducing the level of environmental pollution is possible due to more efficient and economical use of electricity by consumers themselves. This is the use of more economical equipment, as well as an efficient mode of loading this equipment. This also includes the observance of production discipline in the framework of the correct use of electricity [25].

From this we can draw a simple conclusion that it is necessary to strive to reduce energy consumption, to responsibly treat the disposal of various devices, since they can decompose in the environment for up to hundreds of years.

5.5. Fire and Explosion Safety

According to [33], depending on the characteristics of the substances used in the production and their quantity, according to fire and explosion hazard, the premises are divided into categories А, Б, В, Г, Д. Since the laboratory room belongs to category В according to the degree of fire and explosion hazard, i.e. to rooms with solid combustible substances, it is necessary to provide a number of preventive measures.

Possible causes of fire [28]:

− work with open electrical equipment;

− short circuits in the power supply;

− non-compliance with fire safety rules;

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

Fire prevention measures are divided into: organizational, technical, operational and regime [28].

Organizational measures provide for the correct operation of equipment, the correct maintenance of buildings and territories, fire safety briefing for workers and employees, training of production personnel in fire safety rules, publication of instructions, posters, and an evacuation plan [28].

Technical measures include: compliance with fire regulations, norms in the design of buildings, in the installation of electrical wires and equipment, heating, ventilation, lighting, proper placement of equipment [25].

Regime measures include the establishment of rules for the organization of work, and compliance with fire prevention measures. To prevent a fire from short circuits, overloads, etc., the following fire safety rules must be observed [25]:

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

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

− correct maintenance of buildings and territories (exclusion of the formation of an ignition source – prevention of spontaneous combustion of substances,

restriction of hot work);

— training of production personnel in fire safety rules;

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

— observance of fire safety rules, norms in the design of buildings, in the installation of electrical wires and equipment, heating, ventilation, lighting;

— correct placement of equipment;

— timely preventive inspection, repair and testing of equipment.

In the event of a fire, inform the manager, the fire safety authorities of the enterprise and proceed to extinguish the fire with a fire extinguisher.

In the event of an emergency, it is necessary [28]:

— inform the management (duty officer);

— call the relevant emergency service or the Ministry of Emergency Situations by phone - 112;

— take measures to eliminate the consequences of the accident in accordance with the instructions [33].

5.6. Emergency Safety

5.6.1. Analysis of Typical Emergencies During the Study

An emergency situation (ES) is a situation that has developed in a certain territory as a result of an accident, a natural hazard, a catastrophe, a natural or other disaster that may result in loss of life, damage to human health or the environment, significant material losses and violation of living conditions. of people.

During the study, the most probable emergency is a fire. A fire in a work area can be caused by non-electrical and electrical causes. Table 32 discusses possible emergency situations, methods for their prevention and elimination of their consequences.

Table 32 – Emergencies, methods of their prevention and elimination of consequences

№	Emergency	Emergency prevention methods	Elimination of consequences of emergencies
1	Fire	1) check the condition of electrical devices and heating devices;	1) in the event of a fire, call 01,101,112;

		2) comply with fire safety rules in accordance with the requirements of regulatory documentation; 3) conduct training and briefing of employees, develop firefighting skills;	2) use powder and carbon dioxide fire extinguishers as extinguishing agents
2	Electric shock	1) prevent damage to the insulation of current-carrying parts of electrical installations; 2) conduct scheduled inspections of electrical equipment; 3) observe the permissible distance between insulators and wires; 4) follow the rules of safety and technical operation; 5) conduct training and briefing of employees; 6) install protective grounding.	1) turn off the voltage on the damaged installation; 2) fence off the place, put up signs; 3) if there are victims, provide first aid and call an ambulance by calling 112, 103
3	Injury from a fall from a height	1) it is necessary to make sure that computer wires are not in the way of movement, in case of violation, inform the manager; 2) do not use a chair, table, etc. instead of a ladder; 3) prevent the placement of equipment and documentation on shelves and cabinets, access to which is impossible without a ladder; 4) when moving up the stairs, it is always necessary to hold on to the handrail and look under your feet; 5) do not keep your hands in your pockets, because in case of a fall, instinctive movements will help you stay on your feet; 6) never carry objects, holding them in front of you, blocking the view; 7) clean shoes from dirt, ice and other contaminants before entering the building; 8) to train and instruct employees	1) examine the body and head of the victim for open wounds and abrasions; 2) ask to make movements with your fingertips, which will eliminate damage to the spine; 3) movement of arms and legs will eliminate the presence of fractures; 4) to interrogate the victim about violations of general well-being: dizziness, drowsiness, nausea - these signs indicate a concussion; 5) in the absence of serious injuries, a cold compress is placed on the site of the bruise and the victim is escorted home; 6) in case of serious injuries, you must call 03 (103) or 112 and report the incident

Conclusions of the section

This section analyzes the harmful and dangerous factors that may arise in the workplace during research:

− microclimate [25];

− noise and vibration [31];

- electromagnetic radiation [27];

- illumination [25];

- psychophysiological factors [25];

- electrical safety [26];

- fire and explosion safety [28].

Room № 302 11 of the TPU building is assigned to:

- in electrical safety – to class 1 [26];

- for fire and explosion safety - to category B [28].

Possible emergency situations, methods of their prevention and elimination of consequences are also considered.

CONCLUSIONS

1.   A program was written for calculating the absorbed dose rate in a room with a ROKUS-AMT gamma unit using the GEANT4 software package.

2.   It is shown that the obtained spectra of gamma and electron radiation are in good agreement with the known experimental ones. It has been established that the largest contribution 97.2 % to the absorbed dose rate is made by electrons produced as a result of Compton scattering due to ionization with a silicon phantom.

3.   It is determined that the absorbed dose rate decreases with distance according to the dependence $\dot{D} \sim 1/r^2$, which is consistent with the theoretical dependence.

4.   It is shown that the distribution of the absorbed dose rate in the plane at distances of 164 cm and 500 cm is consistent with the experimental data. The highest absorbed dose rate is observed along the geometrical axis of the gamma-ray beam.

5.   Verification showed that the calculation of the absorbed dose rate from a distance along the geometric axis of the gamma radiation beam is carried out with an accuracy of 10 %, the calculation of the absorbed dose rate in containers located on the panel at a distance of 760 cm from the gamma installation, with an accuracy of 30 % at simulation of 10^7 decays of ^{60}Co.

The developed program can be used to determine the absorbed dose rate in experiments on the effect of radiation on electronic components at the «Radian» test gamma complex.

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ФЮРА.14.03.02.005ПБ

Изм.	Лист	№ докум.	Подп.	Дата	**Calculation algorithm**
Разраб.		Kuzmenko A.S.			
Пров.		Timchenko S.N.			
Т. контр.					
Нач.отд.					
Н. контр.					**Block diagram**
Утв.		Vidyaev D.G.			

Лит.	Масса	Масштаб
У		1:1
Лист	Листов	1

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