INVESTIGATION OF THE GEOCHEMICAL BEHAVIOUR AND SOIL TO FOOD-CHAIN TRANSFER OF VARIOUS MAN-MADE RADIOISOTOPE

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Hypothesis 1

The mobility of radionuclides in STS soils governs their transfer into livestock tissues, with ^{90}Sr (mobile) showing greater uptake into bone, while $^{239+240}$Pu and ^{241}Am (strongly bound) primarily enter liver and skeleton through soil ingestion.

Findings showed strong site-specific geochemical contrasts: ^{90}Sr was highly mobile at Degelen, while transuranics and ^{241}Am were less mobile but still entered animals via incidental soil intake.

Hypothesis 2

Pathway of intake (forage, water, or soil) is a stronger determinant of radionuclide distribution in sheep tissues than total radionuclide burden in the environment.

Finding demonstrated that ^{137}Cs and ^{90}Sr burdens were greatest when intake came via contaminated waters/vegetation, while actinides entered mainly through soil ingestion, regardless of overall site contamination levels.

Hypothesis 3

Livestock management interventions that restrict access to contaminated watercourses and reduce soil ingestion can significantly lower radionuclide burdens in edible tissues and offal.

Findings highlighted the key management insights were: (i) hydrologically connected areas are critical control points for ^{137}Cs and ^{90}Sr, and (ii) soil ingestion drives actinide uptake into liver and bone.

Hypothesis 4

Spatial heterogeneity in radionuclide accumulation by vegetation at the STS leads to large variability (15–75 fold) in potential livestock intake, necessitating site-specific monitoring rather than uniform risk assumptions.

Findings showed extreme variability in accumulation coefficients, which directly influences radionuclide transfer into animals and highlights the need for targeted, localized assessment.

Abstract

The Semipalatinsk Test Site (STS) in northeastern Kazakhstan remains one of the most radiologically contaminated regions globally, posing persistent risks to food safety and environmental health. This study investigates the transfer and bioaccumulation of artificial radionuclides — $^{239+240}$Pu, ^{241}Am, ^{137}Cs, and ^{90}Sr — across interconnected soil–water–plant–animal systems under local livestock husbandry conditions. The research integrates three components: (i) spatial and speciation analysis of radionuclides in key environmental compartments of the STS, (ii) controlled feeding trials assessing radionuclide distribution in ram tissues, and (iii) development of a predictive framework for radionuclide concentration in animal products to define radiological safety limits.

Results revealed strong geochemical contrasts across test sites. At Degelen, ^{90}Sr was highly mobile, with >50% in exchangeable form, whereas ^{137}Cs and ^{241}Am were strongly fixed within arid Experimental Field soils. Transfer coefficients (Ff) for ^{137}Cs ranged from 1.5×10^{-3} – 2.1×10^{-2} d kg^{-1} and for ^{90}Sr from 3.3×10^{-4} – 4.8×10^{-3} d kg^{-1}, while actinide F*f* values were typically 10^{-5} – 10^{-4} d kg^{-1}. Concentration ratios varied up to 15-fold for transuranics and 75-fold for ^{137}Cs and ^{90}Sr, demonstrating high spatial heterogeneity. In rams, ^{137}Cs was most abundant in muscle and kidneys, ^{90}Sr accumulated almost exclusively in bone, and $^{239+240}$Pu and ^{241}Am were concentrated in the liver and skeleton, confirming soil ingestion as the dominant actinide intake pathway. For example, $^{239+240}$Pu and ^{241}Am Ff values for liver exceeded 3×10^{-3}, whereas muscle tissue remained below 10^{-4}.

The methodological framework established links between environmental transfer, dietary concentration ratios, and internal exposure pathways, enabling estimation of product-specific activity levels and derivation of safe soil limits. Key implications include: (1) restricting livestock access to contaminated streams to reduce ^{137}Cs and ^{90}Sr in meat and bone, (2) minimizing soil ingestion to lower actinide burdens in edible organs, and (3) emphasising site-specific monitoring due to heterogeneous contamination patterns.

This study provides STS-calibrated transfer coefficients and a quantitative risk assessment model for radionuclide uptake in animal products. The framework strengthens food-chain safety management and contributes regionally validated data to international radioecological databases.

Kivonat

A Kazahsztán északkeleti részén fekvő Szemipalatyinszki Kísérleti Telep (Semipalatinsk Test Site, STS) a világ egyik leginkább radioaktív módon szennyezett területe, amely tartós kockázatot jelent az élelmiszer-biztonságra és a környezet-egészségügyre. A jelen kutatás az antropogén eredetű radionuklidok — $^{239+240}$Pu, ^{241}Am, ^{137}Cs és ^{90}Sr — talaj–víz–növény–állat rendszeren belüli átvitelét és bioakkumulációját vizsgálja a helyi állattenyésztési feltételek mellett. A kutatás három fő elemet integrál: (i) a radionuklidok térbeli eloszlásának és kémiai formáinak elemzését az STS kulcsfontosságú környezeti komponenseiben, (ii) kontrollált etetési kísérleteket a radionuklidok eloszlásának meghatározására juhszövetekben, valamint (iii) egy prediktív modell kidolgozását az állati eredetű termékek radionuklid-koncentrációjának becslésére és a sugárvédelmi határértékek meghatározására.

Az eredmények erős geokémiai különbségeket tártak fel az egyes kísérleti helyszínek között. A Degelen-hegységben a ^{90}Sr nagy mobilitást mutatott (>50% kicserélhető formában), míg a ^{137}Cs és a ^{241}Am erősen kötődött a száraz, kísérleti mezők talajához. A ^{137}Cs átviteli együtthatói (Ff) $1{,}5\times10^{-3} - 2{,}1\times10^{-2}$ d·kg^{-1} között, a ^{90}Sr esetében $3{,}3\times10^{-4} - 4{,}8\times10^{-3}$ d·kg^{-1} között változtak, míg az aktinidák esetében az Ff értékek jellemzően 10^{-5} – 10^{-4} d·kg^{-1} tartományban maradtak. A koncentrációs arányok akár tizenötszörös különbséget mutattak a transzurán elemek, és hetvenötszöröst a ^{137}Cs és ^{90}Sr esetében, ami nagyfokú térbeli heterogenitást jelez. A juhokban a ^{137}Cs főként az izomban és a vesében, a ^{90}Sr szinte kizárólag a csontban, míg a $^{239+240}$Pu és ^{241}Am elsősorban a májban és a csontvázban halmozódott fel, megerősítve, hogy a talaj lenyelése az aktinidák fő beviteli útja. Például a $^{239+240}$Pu és ^{241}Am májban mért Ff értékei meghaladták a 3×10^{-3}-at, míg az izomszövetben 10^{-4} alatt maradtak.

A kidolgozott módszertani keretrendszer összekapcsolja a környezeti transzfert, a táplálkozási koncentrációs arányokat és a belső expozíciós útvonalakat, lehetővé téve a termékspecifikus aktivitási szintek becslését és a biztonságos talajhatárértékek meghatározását. A fő gyakorlati következtetések: (1) az állatok hozzáférésének korlátozása a szennyezett vízfolyásokhoz a ^{137}Cs és ^{90}Sr csökkentése érdekében a húsban és csontban, (2) a talajbevitel minimalizálása az aktinidák ehető szervekben való felhalmozódásának mérséklésére, valamint (3) a helyspecifikus monitorozás előtérbe helyezése az eltérő szennyezettségi mintázatok miatt.

A kutatás elsőként szolgáltat STS-re kalibrált átviteli együtthatókat és kvantitatív kockázatbecslési modellt az állati eredetű termékek radionuklid-felvételére. Az eredmények hozzájárulnak az élelmiszerlánc-biztonsági irányelvek megerősítéséhez, valamint a nemzetközi radioökológiai adatbázisok és kockázatmodellek regionálisan validált bővítéséhez.

Хураангуй

Казахстаны хойд зүүн хэсэгт орших Семипалатинскийн туршилтын талбай (СТС) нь дэлхийн хамгийн цацраг идэвхт бохирдол ихтэй бүс нутгийн нэг хэвээр байгаа бөгөөд хүнсний аюулгүй байдал болон хүрээлэн буй орчны эрүүл мэндэд урт хугацааны эрсдэл дагуулсаар байна. Энэхүү судалгаагаар $^{239+240}$Pu, ^{241}Am, ^{137}Cs, ^{90}Sr зэрэг хиймэл радионуклидуудын хөрс–ус–ургамал–амьтан хоорондын дамжуулалт ба биологийн хуримтлалыг мал аж ахуйн орон нутгийн нөхцөлд судлав. Судалгааны хүрээнд дараах гурван чиглэл багтсан: (i) СТС-ийн гол хүрээлэн буй орчны хэсгүүд дэх радионуклидын тархалт ба химийн хэлбэрийн судалгаа, (ii) хонь ашиглан хийсэн хяналттай тэжээлийн туршилтаар эд эрхтэнд радионуклидын хуваарилалтыг тодорхойлох, (iii) амьтны гаралтай бүтээгдэхүүн дэх радионуклидын агууламжийг тооцох таамаглалын загвар боловсруулж, цацрагийн аюулгүй байдлын хязгаар тогтоох.

Үр дүнгээс харахад талбай бүрт геохимийн шинж чанарын ялгаа тод илэрсэн. Дегеленийн хэсэгт ^{90}Sr өндөр хөдөлгөөнтэй (солилцооны хэлбэрээр >50%), харин ^{137}Cs ба ^{241}Am нь хуурай “Туршилтын талбай”-н хөрсөнд хүчтэй холбогдсон байв. ^{137}Cs-ийн шилжилтийн коэффициент (Ff) 1.5×10^{-3}–2.1×10^{-2} d kg^{-1}, ^{90}Sr-ийнх 3.3×10^{-4}–4.8×10^{-3} d kg^{-1}, харин актинидуудынх 10^{-5}–10^{-4} d kg^{-1}-ийн хооронд байв. Хуримтлалын харьцаа актинидуудад 15 дахин, ^{137}Cs ба ^{90}Sr-д 75 дахин ялгаатай байсан нь орон зайн өндөр хувьсамтгай байдлыг харууллаа. Хонины биед ^{137}Cs нь булчин ба бөөрөнд, ^{90}Sr нь бараг бүхэлдээ ясанд, харин $^{239+240}$Pu болон ^{241}Am нь элэг ба араг ясанд төвлөрч байсан нь хөрс залгих үйл явц актинидын гол шингээлтийн зам болохыг батлав. Жишээлбэл, элэгний $^{239+240}$Pu ба ^{241}Am-ийн Ff утга 3×10^{-3}-оос дээш, харин булчингийнх 10^{-4}-өөс доош байв.

Боловсруулсан арга зүйн хүрээ нь хүрээлэн буй орчны дамжуулалт, хоол тэжээлийн агууламжийн харьцаа болон дотоод туяа шингээлтийн замуудыг уялдуулж, бүтээгдэхүүн тус бүрийн идэвхт түвшин, аюулгүй хөрсний хязгаарыг тооцох боломжийг бүрдүүлэв. Үүнээс дараах гурван гол дүгнэлт гарсан: (1) Дегеленийн бохирдсон горхинд мал нэвтрэхийг хязгаарлах нь мах ба ясан дахь ^{137}Cs, ^{90}Sr-ийн агууламжийг бууруулна, (2) хөрс залгих хэмжээг багасгах нь идэшний эрхтэнд актинидын хуримтлалыг бууруулна, (3) бохирдлын хувьсамтгай байдал өндөр тул ерөнхий бус, талбай тус бүрт чиглэсэн хяналт шаардлагатай.

Энэхүү судалгаа нь СТС-ийн нөхцөлд тохируулсан шилжилтийн коэффициент болон амьтны гаралтай бүтээгдэхүүн дэх радионуклидын шингээлтийг тооцох тоон эрсдэлийн үнэлгээний загварыг санал болгож байна. Энэ нь хүнсний сүлжээний аюулгүй байдлын удирдлагыг сайжруулж, бүс нутгийн хэмжээнд баталгаажсан өгөгдлийг олон улсын радиоэкологийн мэдээллийн санд нэмэрлэх чухал хувь нэмэр болж байна.

CHAPTER 1.
INTRODUCTION & BACKGROUND

1.1. Background and Rationale

The environmental and public health legacy of nuclear weapons testing remains one of the most intense and longest-lasting environmental and health crises of the modern era. As the spread of nuclear technologies around the world in the middle of the 20th century was fueled by geopolitical rivalry and arms race during the Cold War period, several large world powers carried out comprehensive nuclear weapons testing programs. Even though these tests were generally justified in terms of national security and scientific advancement, they left a lasting legacy of radioactive contamination that continues to affect, people, and food chains to date (Madison Williams-Hoffman et al., 2025; M.P. Johansen et al., 2019; I. Gorlachev et al., 2020; Carlisle E W Topping et al., 2019). One of the most affected regions is the Semipalatinsk Test Site (STS), which was operated in northeastern Kazakhstan and served as the Soviet Union's primary nuclear test site (Bernd Grosche, 2015; Jargin SV, 2024; Magdalena E. Stawkowski, 2016; Karlygash Kuralbayeva et al., 2025).

Between 1949 and 1989, the Soviet Union conducted some 456 nuclear tests at the STS, which included 116 atmospheric bursts, 340 underground bursts, and some surface bursts. Such a range of test types was subject to unleashing a complete range of radionuclides into the surrounding environment (B. I. Gusev et al., 1997; Tina M. Carlsen et al., 2001; IAEA, 1998a; Stanley D. Brunn, 2011; Robert S. Norris and Thomas B. Cochran, 1996). Atmospheric tests, in their turn, created large-scale fallout, spreading radioactive matter on vast territories by winds and precipitation. Surface tests created lasting imprints on the soil, whereas underground tests often caused radionuclides to be transported by subsurface waters (Gerald M. Stokes and Stephen E. Schwartz, 1994; Burton G. Bennett, 2002; Harold L. Beck and Burton G. Bennett, 2002; Steven L Simon et al., 2004; Q.H. Hu et al., 2008). Radionuclides used in these activities were of the long-lived types including plutonium-239 and -240 ($^{239+240}$Pu), americium-241 (^{241}Am), cesium-137 (^{137}Cs), and strontium-90 (^{90}Sr) which are all of significant radiological hazards and environmental persistence (Remus Prăvălie, 2014; André Bouville, 2020; IAEA, 1998a; Kadyrzhanov et al., 2005; A.Ye. Kunduzbayeva et al., 2022; G. Lujaniene et al., 2002).

Such anthropogenic radionuclides contain a range of physicochemical properties that govern their mobility, availability, and biological uptake potential. ^{137}Cs, for instance, is highly soluble like potassium and readily absorbed by animals and plants, which often accumulate in muscle tissue (Anna Burger and Irene Lichtscheidl, 2018; B. S. Manisha Singh et al., 2022; Stara, J. F, 1965; V.V. Prorok et al., 2016). ^{90}Sr, which is highly soluble like calcium, forms bone and teeth depots (Zhen Zhou et al., 2023; N. P. Dikiy et al., 2016). Transuranic elements $^{239+240}$Pu and ^{241}Am exhibit elevated particle attachment and lower soil mobility but also possess a long-term risk of their confinement in liver and bone tissue (M.P. Johansen et al., 2019; Haitao Zhang et al., 2022; F. Ward Whicker et al., 1990; G. Sokolik et al., 2002; Andreozzi, U et al., 1983). The environmental persistence of these radionuclides in soil, water, and plant matrices remains a problematic set of concerns for land use, agriculture, and human health of the region (UNSCEAR, 2008; Yamamoto et al., 1994; Guogang Jia and Leandro Magro, 2021). One of the most vulnerable pathways of radionuclide transfer is the terrestrial food system. In the region of the STS, which encloses over 18,000 square kilometers of semi-arid steppe, livestock-oriented agriculture remains a central component of rural livelihood (N.V. Larionova et al., 2018; N.V. Larionova et al., 2021; Andrey Panitskiy et al., 2023; Baigazinov, Z. and Lukashenko, S, 2014). In the region, inhabitants rely considerably on pastoral systems, and cattle, sheep, horses, and goats constitute the core of the rural economy. Such animals are grazed on pastures that might still harbor traces of remaining contamination. In most instances, inhabitants ingest homegrown livestock products, namely meat and milk, without comprehensive radiological safety analysis. Such practices introduce a direct internal radionuclide exposure path of the inhabitants at the local level and possibly for other consumers at wider markets (B.A. Almayahi et al, 2014; Hasan M. Khan et al, 2010; Tetsuya Nakamura et al., 2020; Natalia SEMIOSHKINA1 and Gabrielle VOIGT, 2006).

Despite official control of access to most highly contaminated regions of the STS, including the "Experimental Field" and "Degelen" enclosures, significant cross-boundary animal movement persists. Most farms remain located in inadequately remediated or unsatisfactorily assessed areas, and fences or ditches used to mark exclusions zones prove unsuitable. Furthermore, economic reliance on livestock makes community relocation or abandonment of ancestral grazing grounds difficult. This socioeconomic reliance helps to disseminate the risk of chronic low-dose radionuclide exposure throughout animals and human beings (N.V. Larionova et al., 2018; Andrey Panitskiy et al., 2023; Magdalena Stawkowski, 2016; Jillian Keenan, 2013).

Another critical element of this question is the lack of empirical data on radionuclide behavior in agricultural animals under realistic conditions of exposure. Even though much work has concentrated on environmental contamination concentrations at the STS, less time has been devoted to measuring the degree of radionuclide absorption, metabolism, and tissue storage in livestock species of differing kinds. This lack of data complicates researchers' and policymakers' ability to estimate internal dose to man through consumption of foods with a reasonable degree of precision. Furthermore, radionuclide transfer from plants and soil to animal tissue is a complex, species-related phenomenon subject to a variety of factors, including animal metabolism, feeding characteristics, soil quality, and seasonal variations in the nature of pastures (S. Geras’kin et al., 2013; Brenda Howard, 2021; B.J. Howard et al., 2009).

Predictive radionuclide transfer models and human exposure customarily used for prediction-such those used by the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP)-must be provided with realistic transfer coefficients and concentration ratios (W.E. Bolcha et al., 2016; N. Petoussi-Henss et al., 2020). These are required to convert levels of environmental contamination to radionuclide activities in animal products. However, these models often assume generic values derived from experiments carried out in temperate ecosystems or controlled laboratory studies, which might be inappropriate for the unique environmental conditions of the Kazakh steppe's arid and semi-arid ecosystems. Local empirical data are thus required for the construction of more realistic predictive models and novel, region-specific risk assessment (N V Larionova et al., 2021; Zh.A. Baigazinov et al., 2020).

Apart from scientific and health considerations, there are gigantic policy and regulatory dimensions to the problem. As a post-Soviet bequest, Kazakhstan not only inherited the material infrastructure of the STS but also the responsibility for managing its long-term environmental and public health legacy. In spite of global cooperative measures that have created much of a mapping and securing of the most hazardous areas, the system of ag safety for contaminated areas is not well-refined. Small-acreage farmers frequently lack access to radiological laboratories, and little expertise on best livestock husbandry for contaminated conditions typically accompanies them. A scientific justification of these remediations that is legitimate must be grounded on scientific studies in the field (Tina M. Carlsen et al., 2001; IAEA, 2023).

Against this backdrop, the present study was conceptualized to fill a significant lacuna in the radionuclide transfer knowledge of animals grazed in contaminated pastures. Through a focus on realistic exposure conditions at the STS, the study seeks to yield plausible data on distribution and accumulation of major radionuclides by the most grazed animal species. This involves controlled feeding studies on contaminated soil, forage, and water samples originating from representative STS locations. Specified organs and tissue of interests-such as liver, muscle, bone, kidney, and fat-are comprehensively analyzed by radiometric and spectrometric methods for the measurement of radionuclide activity concentrations and calculations of transfer coefficients (N Semioshkina et al., 2006).

Furthermore, the work considers the relative significance of each of the principal modes of exposure-namely, feeding on contaminated feedstuffs, ingestion of soil during grazing, and consumption of contaminated water. Each of these factors is a necessary counterpart to developing a full radionuclide intake scenario and for distinguishing most significant internal contamination pathways. By delineating these pathways, the work can elucidate optimum methods of radionuclide exposure reduction, for instance, through supplementation of the feeding stuff, soil cleansing, or purification of the water, which can reduce radionuclide accessibility (Tina M. Carlsen et al., 2001; IAEA, 2010).

Usage of this work extends beyond the frontiers of Kazakhstan. Other past nuclear test sites, those at Nevada (USA), Lop Nor (China), Novaya Zemlya (Russian Federation), and Maralinga (Australia), have similar issues (Vitaly I. Khalturin et al., 2005; Melvin W. Carter and A. Alan Moghissi, 1977; Togzhan Kassenova, 2017; Mamyrbekov A. et al., 2024; Vipin Gupta, 2015). Besides, other locations facing nuclear tragedies, for instance, Chernobyl and Fukushima, similarly exhibit similar issues (Georg Steinhauser et al., 2014; L. Sihver and N. Yasuda, 2018). In all these cases, understanding of radionuclide behavior through agroecosystems and their points of entry into the human food system is essential for planning science-informed policies and community health protection. This work's method and findings are thus of national and international significance (UNSCEAR, 2000a; R O Gilbert et al., 1988).

By way of conclusion, the STS constitutes a unique and time-dependent case study of environmental pollution and safety of the food chain. Its history, geographical size, and on-farm continued application for rearing livestock constitute a thorny and complex risk environment. Resolution of the dilemma requires a multidisciplinary agenda that integrates radioecology, veterinary medicine, epidemiology for public health, and environmental policy. Our work adds to that endeavor by presenting a scientifically valid and contextually appropriate analysis of radionuclide transport into livestock products. Our work provides needed data, approaches, and recommendations for country regulations and world's best practices in the management of the radioactive legacy of nuclear weapons testing.

1.2. Research Problems

Despite a number of decades of environmental observations and radiological work at the Semipalatinsk Test Site (STS), critical scientific gaps remain in the fate and behavior of manmade radionuclides in agricultural ecosystems. By far most of the literature to date has focused on radionuclide measurement of concentrations in the abiotic environmental media of soil, surface waters, and plants. As valuable background studies for distribution and persistence of contamination, these studies fall short of elucidating all of the ecological and human health risks of internal pathways of contamination-that is, radionuclide bioaccumulation by livestock reared under contaminated conditions and subsequent transfer to human foods (Guogang Jia and Leandro Magro, 2021; N V Larionova et al., 2018).

Livestock agriculture remains a cornerstone of local economic and subsistence activities around most of rural Kazakhstan, especially around the STS. Villagers rely on animal husbandry not only for stable protein (meat, eggs), fat (milk), and other required nutrients (meat, organs), but also for cash, manual and other forms of labor, and for culturally valued activities. Consequently, internal contamination of livestock by consumption of contaminated forage, water, or soil is a direct and very effective pathway for human exposure to long-lived radionuclides such as plutonium-239/240 ($^{239+240}$Pu), americium-241 (^{241}Am), cesium-137 (^{137}Cs), and strontium-90 (^{90}Sr). But very little is known about the properties of these radionuclides entering animal systems, being transported throughout a variety of tissue and organ matrices, and being concentrated ultimately in edible products (e.g., muscle, milk, liver) (Andrey Panitskiy et al, 2023; Aitbek Kakimov et al., 2016; B. J. Howard et al., 2004; Andrey Panitskiy et al., 2023; A.K. Aidarkhanova et al., 2018).

It is correct to point out that the behaviour of nuclides in the tissues of living organisms presents the greatest challenge of all. The analytical dynamics of the aforementioned processes in the body of the organism make their analysis distinct. For example, in muscle tissue, cesium, unlike strontium, is predominantly found. The transfer of cesium to soft tissues is due to its behavioural resemblance to potassium, whereas the transfer of strontium to bone tissue is linked to its behaviour in calcium. The alpha-emitting actinides, plutonium and americium, show a disproportionate affinity for the tissues of the liver and the skeleton because of their favourable chemical properties combined. The processes described above separate the tissue from the body of the organism and are subject to different conditions: the animal's gender, age, state of health, type of nutrition, and environmental conditions, such as the organic matter in the soil, moisture, and even its pH concentration (M.P. Johansen et al., 2019; D M Taylor, 1989; G N Ling, 1977).

Although international organizations such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) have proposed general models and parameters for estimating the transfer of radionuclides in agricultural systems, these have originated from controlled laboratory studies or from agricultural systems in the temperate zones of Europe and North America. Models that derive from these sources do not translate well to the Central Asian, semi-arid open-grazing pastoral systems. The transfer of parameters such as the transfer coefficient (F*f) and the dietary concentration ratio (CR*diet) as critical indicators for measuring the movement of radionuclides into animal products is accepted. However, these indicators are not constant and universal; they vary significantly from one region and species to another, and from one ecological setup to another (Guogang Jia and Leandro Magro, 2021; IAEA, 2010. N Semioshkina and G Voigt, 2021).

The transfer coefficient (F*f) measures the rate of assimilation of a radionuclide, calculated from the concentration of the radionuclide in the animal tissues (Bq kg^{-1} fresh mass) and the absorption of that radionuclide per day (Bq day^{-1}). Similarly, the concentration ratio of radionuclide in the diet (CR*diet) is the ratio of the radionuclide concentration in animal tissues to the concentration of that radionuclide in the diet (Bq kg^{-1} dry mass), which is secondary to the diet concentration and relates to specific bioaccumulation conditions. In any case, these coefficients will almost certainly lack empirical field data, which is likely to lead to erroneous or overly simplistic risk assessments. A model based on data gathered from dairy cattle located in the grasslands of Europe is a prime example, as it is unlikely to predict the transfer of cesium in Kazakh fat-tailed sheep grazing in the dry steppe or consuming soil with varying minerals (N.V. Larionova et al., 2018; B.J. Howard et al., 2009; Mayumi Yoshimura and Akio Akama, 2020).

Thus, the STS site serves as a unique case for forensic evidence science, offering both a challenge and a means to further develop radioecology with a focus on radioecology. Over four decades of nuclear testing have left the site with various comprehensive levels of contamination, ranging from background low-level deposition to hotspots of significantly higher contamination. Diverse environmental settings, such as arid open areas, wet meadows, and rocky highlands, create differing levels of bioavailability of radionuclides. Additionally, in the area, with minimal use of advanced technology, rudimentary forms of farming have been practised, allowing for the investigation of the transfer of radionuclides in more realistic scenarios rather than experiments conducted in controlled labs (Andrey Panitskiy et al., 2023; Madina Dyussembayeva et al., 2025).

It would be assumed that, given the significance of the subject, there should be a considerable number of systematic studies on how the various exposure pathways of water, forage, and soil-ingested radionuclides influence livestock's radionuclide internal zonation. Reliance on retrospective data, which capture contamination levels but lack the timeframe to understand the kinetics of doses, biotransformation, or specific tissue accumulation, results in a lack of comprehensive understanding of the topic. Moreover, the animals have been subjected to a variety of diets including multiple radionuclides without considering some of the described variables as multi-exposure, allowing some studies to estimate artificial transfer coefficients (Irina E. Vlasova et al., 2022; Nailya Chaizhunussova et al., 2025).

The lack of information available has serious consequences for both the assessment of the environment's risk and the construction of public policy on healthcare. “Safe zones” and the contaminated areas around the STS have been attempted to be delineated by IRSE and other Kazakhstan governmental bodies. However, without strong, concrete data on the movement of radionuclide and the food chain, the assigned zones do remain questionable. Farming in restricted areas where soil and vegetation contamination has been classified as “moderate” is still permitted. However, if periods of high controlled bioaccumulation occur, there is a greater chance that the internal doses received by livestock, and hence the doses received by men as a result of consuming livestock products, do not exceed the safety levels (Togzhan Kassenova, 2017; Sergazy Duyssembaev et al., 2013).

Additionally, the lack of set and proven procedures for the assessment of radionuclide transfer into livestock greatly stifles the ability to collaborate and share information internationally. The absence of a unified approach for sampling, analysis, and data evaluation makes the interstudy controllability assessment a dilemma and the international databases disorganised. Local stakeholders, such as farmers, health practitioners, and policymakers, are unable to effectively manage land use, animal husbandry, and the associated health of the population due to a lack of proper evaluation tools and evidence-based analysis (Beimbet Mussin et al., 2025; D Copplestone et al., 2013).

There are also other problems such as chronic exposure which has often been ignored in assessments focusing on the primary aftermath of a contamination incident. In the STS site, many radionuclides associated with facilities, especially transuranic elements such as $^{239+240}$Pu and ^{241}Am, are of particular concern because they are almost physiologically inactive. This activity not only poses a health risk to the animals grazing in the same fields day in and day out, but also raises the risk of chronic elementary contamination. This is especially the case in short-term models or static analysis where assessment times are not adequately defined. These (in a weak sense) controlled models all have in common the fact they remain underobserved and thus wherein the retention and redistribution, along with transference into secondary metabolites such as milk and eggs, is less explored (Andrey Panitskiy et al, 2023; Elina M. Karimullina et al., 2018).

The issue of interspecies differences in radionuclide uptake is equally challenging. Individual species—and even different breeds within the same species—have different efficiencies of digestion, differences in metabolic rates, and different affinities for various elements, particularly stable isotopes of radioactive elements, which impact their assimilation of radioactive elements, and digestive radionuclide turnover rates. For example, the growth and metabolic activities of broiler chickens, for which it is assumed there is a high turnover of radionuclides, are much faster than those of ruminants, which are assumed to retain radionuclides for a long time due to the complex compartmentalized digestion and processes of mineral resorption in the bones, as is the case with sheep and cattle, which are ruminants. Intermediate ruminants, like rams, sheep and horses, in which the digestive anatomy and physiology are supposed to be of a lower level than that of ruminants but more advanced than that of the previously discussed species, are assumed to have a different uptake profile. Thus, as discussed in the work ('Natalia SEMIOSHKINA and Gabrielle VOIGT, 2006'), the results obtained for one species cannot be transferred to another blindly.

These challenges are serious and require systematic and relevant studies on radionuclide transfer into livestock under different conditions and environmental and dietary inputs. Focus and rigour are essential methodology elements, alongside sampling approaches, accredited methods, and clearly stated frameworks. Long-lasting radionuclides, in particular, would benefit from studies with a historical aspect, focused on observing changes in tissue over time (IAEA, 2009).

In addition, the methods should be developed further to distinguish external contamination (for example, radionuclides adhering to the skin or wool) from internal incorporation through metabolic pathways. This differentiation is important for estimating the risk and formulating decontamination methods such as washing the contaminated animals, modifying the diet, or selective culling. Research should also focus on constructing models beyond measurement, utilizing available data to predict different exposure situations and indirectly calculating possible human exposures to set regulatory limits (Andrey Panitskiy et al., 2023; Brenda Howard, 2021).

To encapsulate, the scientific problem this thesis attempts to address hinges upon the critical and compelling need which is the lack of understanding of the environmental and agricultural aspects of the Semipalatinsk Test Site and the transfer of radionuclides to livestock. The international models and transfer parameters that are available are not sufficiently designed for the socio-cultural and radiation context of the region. The lack of location-specific data surrounding the uptake, distribution, and accumulation of radionuclides in livestock makes it impossible to estimate and control the risk to public health due to food contamination. This research seeks to address the lack of foundational information in the region and the need for specific data by providing it through the construction and use of the proposed general framework; the methodology balances local, environmental, and species parameters which enhances regional safety and contributes to the international radioecology discourse.

CHAPTER 2.
RESEARCH OBJECTIVES & THESIS

2.1. Objectives of the Study

The main aim of this particular study is to design, implement, and justify a scientifically sound methodology which can be generalised to assess the content and transfer of artificial radionuclides into livestock products in radionuclide contaminated environments and the subsequent risk arising from their ingestion. More specifically, this work is framed within the Semipalatinsk Test Site (STS) in Kazakhstan, which is, due to 50 years of above ground and underground nuclear explosions, one of the world's most contaminated regions. Addressing the complex dynamics of environmental radionuclide contamination and the agricultural food chain, this research contributes to the fundamental and applied radioecology and risk assessment of food safety of the affected regions in the world (S.I. Spiridonov et al, 2009; P.Ye. Krivitskiy et al., 2022).

The research systematically addresses the gap of agglomerating data on the interaction of radionuclides in livestock at field scale and the authentic context of husbandry practices. This is achieved through cross-disciplinary environmental field sampling and analysis, chemistry and radiochemistry, psychosociology, computational analytics, and experimental animal studies. In this context, to tackle comprehensively the overarching problem, the research is structured along five interrelated objectives, each reflecting a crucial aspect of the problem.

Objective 1: To characterize the levels and forms of radionuclide contamination in soil, water, and vegetation at selected sites within the STS

The baseline radiological status of the environment is fundamental to any constructive considerations of the processes of radionuclide transfer through the food chain. It is for this reason that the first objective of this research is to systematically describe the presence and physicochemical forms of key radionuclides of artificial origin – namely, $^{239+240}$Pu, ^{241}Am, ^{137}Cs, and ^{90}Sr – in selected environmental matrices within the STS.

This characterisation includes elucidating specific test sites (e.g. ‘Experimental Field’ and ‘Degelen’ and ‘4A’ area) that vary in the history of contamination, ecological conditions, and the activity of different radionuclides. The study within the framework of detailed multidisciplinary field surveys, designed to provide high-resolution data on spatio-temporal variations of radionuclide constituents, on soil, water, and living plant biomass at different places and seasons, aimed to obtain data on radionuclide activity concentrations and along with that, their physicochemical speciation in matrices—i.e., what form of the radionuclide is present in the matrix or environment: exchangeable, organo-bound, or residue. Such forms influence the degree of availability of the radionuclide and, therefore, the potential for transfer to plants and animals (B. J. Howard et al. 2004; Brit Salbu, 2007).

This type of characterisation gives the necessary input information for any transfer studies and for risk modelling that follows. It also allows the focus on potential “hotspots” and high-risk areas that might need either intervention or restricted access.

Objective 2: To quantify the uptake and distribution of $^{239+240}$Pu, ^{241}Am, ^{137}Cs, and ^{90}Sr in organs and tissues of sheep (rams) under controlled feeding conditions

The biological aspect of radionuclide transfer is the subject of the second objective. It includes experimental studies intended to replicate conditions for field exposure during grazing or foraging for livestock in contaminated ecosystems. The experimental animals, i.e., rams (sheep) were selected to correspond to the agricultural profile of the STS region. Such animals form the backbone of agricultural production and trade, and, as such, play an important role in food security and human bio-exposure, of which exposure is the most important component (N.A. Beresford et al., 2007; Knut Hove et al., 1994).

Animals are systematically exposed to selected contaminated feeds, waters, and soils derived from designated testing locations. During the period of exposure, an account of daily consumption of feeds and water, and of sample collections of biological matrices, is commenced. Muscles, livers, kidneys, lungs, spleens, hearts, and bones, which are typical constituents of the human diet, are subjected to quantitative analysis of radionuclide content using radiochemical and spectrometric techniques of high sensitivity (B.J. Howard et al., 2009; N.A. Beresford et al., 2007).

This one research question yields concrete examples of the biokinetics of radionuclide deposits within a living animal: how the radionuclide is metabolized and distributed biosynthetically and where they primarily accumulate within the biological systems of the body. It also permits the examination of interspecies differences, the impact of different routes of exposure (ingestion of water, soil, or forage) on tissue burden, and the dwelling times of the radionuclide in the tissues over variable length exposure times.

Objective 3: To estimate radionuclide transfer parameters (F_x and CR_diet) for each radionuclide-animal-organ combination

Building upon the environmental and biological data generated in the first two objectives, the third objective focuses on calculating standardized transfer parameters. These include:

- **The transfer coefficient (F_x)** – defined as the ratio of radionuclide activity concentration in an animal product (e.g., muscle, milk) to the daily intake of that radionuclide by the animal (Bq kg^{-1} per Bq day^{-1}).
- **The dietary concentration ratio (CR_diet)** – calculated as the ratio of radionuclide concentration in animal tissues to its concentration in the entire diet, measured on a dry mass basis.

Defining these criteria is especially important for dose assessment. They have been incorporated into dose assessment models and used to set safe limits for food by international organisations such as the IAEA and the ICRP. As indicated in the previous section, however, these criteria are extremely context sensitive. They differ vastly across species and breeds and age, diet composition, and radionuclide speciation (Andrey Panitskiy et al., 2023).

For the purpose of this study, realistic field conditions are combined with controlled conditions in order to calculate these coefficients so that more accurate and regionally relevant transfer parameters are obtained for inclusion in the international and domestic databases. Such in-depth studies also permit interspecies and interorgan comparisons to be made, identifying the more hazardous and less monitored animal food products.

Objective 4: To assess the relative contribution of contaminated soil, vegetation, and water to the total radionuclide intake by livestock

The importance of understanding the distribution of different intake routes is crucial in planning the response and reduction of risks. This part of the research is dedicated to the characterisation of soil, forage, and water and their individual and collective contributions to the net internal burden of radionuclides in the animals. This is done by having different experimental groups which are put to clinical trial, based on the individual or compounded sources of radionuclides, and then their respective tissue concentrations along with the transfer coefficients are measured (S.C. Sheppard et al., 2010).

One such exposed group may be the animals that are given contaminated forage and the other that is given clean forage along with contaminated water, and a third class that is given a combination of both contaminated soil with feed. The outputs of these groups can be used to determine the primary pathways of exposure for each combination of radionuclide and animal (A. Savinkov et al., 2007).

This is useful in formulating planning on how to carry out the safeguards. Suppose, for example, that soil is the greater contributor than vegetation to the intake of plutonium, then possible actions for implementation may include treatment of soil, soil fencing, or restrictive feeding. On the other hand, if the uptake of the radionuclides stems majorly from the water, then greater emphasis should be put on the provision of clean water or filtration systems should be imposed.

2.2. Significance of the Study

The importance of this study remains embedded within its interdisciplinary relevance and practical application in radioecology, veterinary and environmental health, toxicology, and food safety. This research tackles one of the most difficult problems in environmental safety and public health, namely, the transfer of long-lived artificial radionuclides from contaminated environmental matrices, such as soil, water, and vegetation, to the tissues of livestock raised in nuclear fallout—particularly, the bioaccumulation of radioactive contaminants in food chains (S.C. Sheppard et al., 2010; Andrey Panitskiy et al., 2023).

This research is among the first ones to carry out scientifically robust and context-oriented analysis to define the magnitude of the potential risk arising from residual radioactive contamination in agro-pastoral systems. The Semipalatinsk Test Site (STS), which the research focuses on, is undoubtedly one of the world's most devastated nuclear test sites. The ecological legacy of radiological contamination still lingers, particularly in places where nuclear weapons testing and its application have been ignored, and where radiological containment and restoration processes have been futile. These aspects of the STS make it a natural laboratory for the investigation of radionuclide transfer and the ecological persistence of radionuclides, rest assured though very difficult (Gabriele Voigt et al. 2007; Ainur Serikova et al., 2025).

This research sought to fill a critical gap in knowledge regarding tissue accumulation of plutonium-239/240. americium-241, cesium-137, strontium-90 artificial radionuclides in economically and nutritionally important livestock like sheep. The consequences of such contamination go beyond ecological concern to human health as livestock products meat, milk, and eggs form an important part of the local diet. This is particularly the case in rural Kazakhstan; the STS and surrounding communities still practice subsistence livestock farming which helps sustain their diet and provides a form of economic security. Therefore, tissue contamination of sheep is of great concern as the local population faces chronic internal exposure due to radionuclides in the food chain (S. Geras'kina et al 2013; Natalya Larionova et al., 2024; Halime Başkaya et al., 2014).

The biological behaviour of radionuclides in animal systems, as influenced by environmental parameters, can be better understood through predictive models of radionuclide transfer and concentration ratios. Geometric and biokinetic parameters are integral to improving radiological dose assessments and defining the etiological basis of safety limits. These models also support the development of interim and international food safety regulations and protective intervention levels. The Codex Alimentarius, together with IAEA guidelines and related national policies—particularly among countries with shared histories of cross-border radiological contamination—provide the framework for comprehensive radiological dose assessments (Aitbek Kakimov et al., 2016).

The developed Quality Management System (QMS) provides a foundational framework for policy development and technological innovation, which is invaluable for managing cross-border contamination and standardizing radiological dose assessment methodologies. Historical nuclear incidents such as Chernobyl (Ukraine), the nuclear tests in the Marshall Islands, and the Fukushima Daiichi accident (Japan) have underscored the importance of consistent exclusion zone criteria and coordinated international monitoring. These events and their associated research have contributed to unifying international frameworks for policy development and food safety regulations concerning radiological contamination (Hachinohe and Shinano with ethereal Belyakov 2015, 2020). These techniques have unified the international framework of the research for political and subnet policy exports on radiological food safety.

Additionally, the research contributes to public health policy by practising environmental and food-safety science. Recognising the primary means and rates of radionuclides' bioaccumulation in animals enables focused mitigation. Dietary and grazing strategies, soil management, and husbandry aimed at minimising contamination can be adopted. Also, the research highlights the need for sustained monitoring and historical research in post-nuclear regions to protect populations from covert and lingering radiation hazards (Rania Edrees Adam Mohammad et al., 2025).

The other important aspect is the ethical and social dimensions of science in STS and other impacted areas. Many of these communities are remnants of the legacy of nuclear weapons testing from the Cold War, and lack proper healthcare, environmental restorations, or other socio-economic alternatives. This research is grounded in real-world situations and addresses the communities and public concern, which epitomises the environmental justice framework.

Finally, from an academic and scientific standpoint, the interdisciplinary nature of the study exemplifies the importance of integrative research approaches in addressing complex environmental health challenges. By drawing on methods and insights from chemistry, biology, agriculture, and radiation protection science, it represents a model of cross-sectoral collaboration capable of informing both theory and practice.

2.3. Scope and Limitations

Scope of study

The research targets a specific subset of livestock species that are both culturally and economically important in the STS region. These include:

- Rams (Ovis aries) of the *Kazakh fat-tailed coarse-wooled* breed, a species well-adapted to the semi-arid steppe environment and widely used for meat and wool production;

The selective reasons for the species, which are their prevalence, integration into the local food system, and also physiological differences that contribute to cross taxonomic insights on radionuclide accumulation. Collectively, these species are constituents of the agro-pastoral region of the study area.

The research also focuses on four radionuclides of principal interest: plutonium-239+240. americium-241, cesium-137, and strontium-90. The long half-lives of these isotopes, their persistent contamination in the environment, the importance of radiotoxicology, and their previous detection in STS biological and environmental media are all reasons why these isotopes were chosen. These nuclides are alpha (Pu, Am), and beta-gamma emitters (Cs, Sr), thus posing an integrated radiological risk assessment.

Practical yet contained exposure scenarios were easily obtained through several custom feeding trials. Specifically, under cloistered housing conditions, each group was watered and fed, as well as soil in some cases, with soil, silt, and clay particulates laced with varying concentrations of radionuclides and/or radionuclide-bearing animals. Each group was evaluated for a span of several days to several months in order to quantify cumulative radionuclide retention in the short and long term. The designed experimental conditions and measured radionuclide concentrations were based on real-world conditions for the feeding strategies employed and radionuclide uptake rates on the STS.

Muscle, liver, kidneys, lungs, bone, wool, fat, and skin were classified as biological samples and evaluated using approved gamma spectrometry techniques to determine radiochemical variations in activity concentration. Transfer coefficients and concentration ratios were derived from the obtained data, forming the basis for assessing internal exposure risks to radionuclides through animal-derived food products.

Limitations

Its design may be comprehensive, but the study still has important limitations. First and foremost, stable experimental conditions fail to replicate natural grazing behaviour and the associated variability. Under more natural conditions, livestock can and do wander freely over large, diverse, and uneven terrain and can partake of a far more complex and oscillating diet than that provided under experimental regimes. This impacts the ability of the research to be extrapolated to more ecological contexts and may be an underestimate of the actual radionuclide intake in actual situations.

The inhalation pathway, a possible significant route of internal contamination in dusty or dry conditions, is neglected in the present study. Ingestion of contaminated feed, water and soil dominates the exposure route under typical agricultural conditions. Inhalation of soil dust, particularly, may be significant for grazing animals, resulting in an additional uptake of radionuclide. More work is required to assess the impacts of aerosol exposure.

The winter condition was also not analysed in the context of seasonal change as the study was confined to airborne radionuclide mobility in placelike radioecology of the summer. Also, the movement of precipitation, during its different seasonal stages, the amount of soil moisture, the development stages of vegetation as well as the growth cycle and stages of soil cover all affect the availability of the radionuclide. Each one (in-season for example) as well as in inter-season (the peak biomass), soil moisture regime, and wet (for example) during bioavailability of radionuclide of vegetation cover).

The study also did not remain longitudinal in the sense of different levels of exposure in the full sense. Low-level, chronic exposure of multiple generations of animals and the impact on reproduction, immune and body burden, as well as functioning ovaries animal systems, was not assessed. Analogously, the potential for radionuclide redistribution in animals after the cessation of exposure was not assessed.

Moreover, the research investigates specific isotopes without assessing any potential synergistic or antagonistic interactions between several radionuclides, or with other environmental contaminants. This specific characterization is critical to any systematic examination, but may ignore multifaceted relationships that are nonetheless important for biological uptake and retention.

Finally, the conclusions drawn from this case are grounded in the particular geographic and ecological context, hence may lack wider applicability. Although the approach is heuristic, and the findings may be applicable to other comparable sites (e.g., Chernobyl, Fukushima), any contaminated location is distinct with regard to soil chemistry, climate, flora, and animal husbandry. This means that specific regional calibration of models and transfer parameters are needed to ensure any reliable application at different places.

CHAPTER 3.
SAMPLING SITE & CHARACTERIZATION

3.1. Study area

The area roughly 18,000 square kilometers in size in the Kazakh Steppe lying close to Semey, previously known as Semipalatinsk, houses the Semipalatinsk Test Site (STS) which is more commonly known as “The Polygon.” Between the years 1949 to 1989, the region under the USSR was the venue for 456 nuclear tests, of which 116 were carried out in the open atmosphere, 340 were underground while the rest were strategically placed at ground level (Figure 1).

Figure 1- Schematic Map of the Semipalatinsk Test Site and Experimental Testing Areas Where Nuclear Tests Were Conducted

The atmosphere in which these occurrences took place was marked by harsh winters as well as hot summers which drastically affected the way in which nuclear waste was spread out. The Sub Polar region is mainly a frozen tundra characterised by sparse bushes as well as frozen ground which lasts at least 7 months during the year. Although the air temperature in the region during the month of January can sink as low as -45 C at times, in the area of Semipalatinsk, the temperature can hit the warmest in the month of July, which it does more often than not, is over 35.

The climatic conditions of the Degelen mountain area, considering its mountainous terrain, slightly differ from the climate conditions of the rest of the Semipalatinsk Test Site (STS) area. According to measurements taken at a weather station located in an open area, the snow cover can reach a height of 60 cm. The annual amount of precipitation in this region amounts to 400 mm.

The movement of winds was also crucial in the spread of the radioactive fallout. In winter, winds from the south-west dominate, and in summer, there is predominance of north-west winds. However, this region is also subjected to sudden changes in the velocity and direction of wind of great range in the order of hours. Under these conditions, radioactive clouds from the atmospheric tests spread all over the regions of Kazakhstan, and even to remote parts of the Soviet Union and neighbouring countries, far beyond the boundaries of the testing site.

The soils are poorly fertile and the semiarid steppe landscape has grass, sagebrush, and a few shrubs. It receives limited precipitation of 250 to 300 mm within a year, which undermines agricultural productivity. In spite of that, pastoralism, especially the grazing of sheep, cattle, and horses, has been widely practised. Concerns about the possible contamination of soil, water, and vegetation with radionuclide residues, such as cesium-137 and strontium-90. as well as radioactive plutonium, were prominent after testing was completed in 1989 and the site was also closed in 1991.

The consequences of the STS on locals are alarming. The loss of life in STS villages is attributed to the first Soviet nuclear tests. Although it is common to claim that 200.000 civilians — surrounded by a 100+ km quarantine perimeter — had direct exposure to radiation is an exaggeration, it is reasonable to assert that the outcome of the tests was a definitive mark on the ill-planned conduct of that period. The total figures — 200.000 civilians and an incalculable number of soldiers in the fallout zone — qualify the situation as one of the worst in nuclear history. The fate of those who were not born damaged is the most painful to estimate.

Within the STS, a few clean zones host research centres and serve as sites of obsolete agricultural activities and even solar energy collection. Other areas are still being researched within the framework of transcendental collaborations. Central to the work are: military medicine, nuclear security, the impact of socially and ecologically engineered nuclear fallout, and zone monitoring. The STS is a crucial point in the history of disarmament and in the conduct of nuclear tests. It is a monumental site capturing the humanitarian toll of the Cold War, and of the entire nuclear weapon testing, and the resolve to abolish, or at least restrain, the proliferation of these arms.

3.2. Sampling Sites Characteristics at the STS

There are many different ways of considering radionuclide contamination of livestock products, one of which is the chemical and physical form of radionuclides contained in the soil, since this determines their mobility, and thus the transfer of radionuclides to plants, and thereafter to livestock products.

The Semipalatinsk Test Site (STS), which is about 18,000 km² in area, is comprised of different zones which are contaminated to varying extents, depending on their distance from the points of explosions, the types of soil, the form of the land, the hydrology and the rainfall. Some of the most remarkable engineering sites are the “Experimental Field,” “4A,” “Degelen” and “Balapan” testing grounds, which are all characterised by different radioecological conditions.

Soil Types and Landscape Characteristics

Within the STS, the steppe region is divided into two subzones:

- Lands of the dry steppe zone with chestnut soils, which have moderate amounts of organic matter and are typically classified as loamy to sandy loam.
- The desert steppe zone with light-chestnut soils which is poorer in humus and more susceptible to wind erosion.

The major soil constituents are, on the whole, elements of Quaternary eluvial and deluvial beds. They are of modest depth (30-80 cm), exhibit a range of textures (from sandy loams to loams), and contain a considerable proportion of gravel, and dense subsoils or, within small depth intervals, rock fragments. Precipitation is sparse (250-300 mm) and considerable evaporation takes place, leading to soil processes typically referred to as soil leaching to be restricted and to reduced vertical migration of radionuclides.

Experimental Field (S = 375 km²)

Numerous nuclear surface detonations as well as gauged atmospheric explosions and explosions discharged on 'The Experimental Field'. Research indicates that critical radionuclides like ^{137}Cs, ^{241}Am, ^{239}+^{240}Pu, and ^{90}Sr migrate slowly under the local soil-climatic conditions. Contamination is severely confined, only extending to ~1.5 km², and approximately exceeds background values:

- ^{137}Cs > 2 kBq/kg
- ^{241}Am > 10 kBq/kg

Most radionuclides remain in the upper soil horizons, strongly bound to mineral and organic fractions, limiting their transfer to plants.

Site 4A ($S = 63\ km^2$)

The “4A” site, located in a dry steppe zone with diverse grass cover, demonstrates a different radionuclide profile:

- ^{90}Sr is the dominant contaminant, mostly in exchangeable and water-soluble forms, which increases its mobility and bioavailability.
- ^{137}Cs is primarily bound (up to 94%) in fixed mineral forms, reducing its migration potential.
- ^{241}Am is present largely in mobile forms, though overall concentrations remain lower than for strontium.
- $^{239+240}Pu$ occurs mainly in strongly bound forms.

Localized contamination at 4A includes small hot spots:

- ^{90}Sr: 50–100 kBq/kg – 0.09 km^2
- 100–500 kBq/kg – 0.09 km^2
- 500–1000 kBq/kg – 0.06 km^2

Degelen Site ($S = 238\ km^2$)

The geomorphology of the site, described as rugged, the presence of meadow soils, and the high moisture content of these soils brings out peculiar conditions at the “Degelen” site which is exclusively used for underground nuclear explosions. Here, the migration of radionuclides is greater:

- ^{90}Sr is the most mobile, with more than half of its content in exchangeable form, enabling its transfer into groundwater and plants.
- ^{137}Cs and ^{241}Am are less mobile, remaining more strongly bound in soil matrices.

Today, the Degelen area is largely fenced and militarily controlled, significantly reducing access by livestock and wildlife.

Balapan Site

At the “Balapan” site, the performance of several underground nuclear tests assumes radionuclide contamination, primarily with radioactive melt glass and the fracture zones adjacent to the boreholes. Encased in melt material, the radionuclides conceptually cannot migrate, which greatly diminishes the surface contamination potential, although some subsurface movement of radionuclide effluent into the water table has been observed.

Animal Access and Risk

While Degelen is secured, Experimental Field and 4A are only partially restricted with earthen ditches and barriers, which cannot fully prevent livestock entry. This poses ongoing risk of radionuclide transfer into the food chain, particularly from mobile isotopes such as ^{90}Sr.

Regional Perspective

Outside the technical sites, contamination is generally low. Since 2009, comprehensive monitoring by the Institute of Radiation Safety and Ecology (IRSE) has confirmed that radionuclide levels across the majority of the STS territory and surrounding settlements do not exceed radiological safety standards (Lukashenko S.N. 2010–2014). However, localized “hot spots” within technical sites remain ecologically hazardous.

Vegetation Characterization

The vegetation cover across the majority of the Semipalatinsk Test Site (STS) is represented by desert-steppe vegetation on light-chestnut soils, characterized by a widespread presence of both steppe elements, such as turf grasses, and desert elements, including semi-shrub sages and, to some extent, saltworts.

Compared to steppe ecosystems, semi-desert ecosystems are characterised by considerably lower diversity. The vegetation in semi-desert regions is characterised by the dominance of sagebrush, with steppe grasses being scarce and making little contribution to the overall community. Low productivity of pasture in semi-desert landscapes is therefore not surprising, averaging 2 to 4 centners per hectare. The situation is different in dry steppe ecosystems, where the diversity of grasses is greater.

The eastern part of the Central Kazakh upland steppe is represented by the Degelen mountain range, within which the diversity of species, genera and families is significantly greater than in the surrounding semi-desert. Moreover, the combined plant communities are rather complex with respect to cenosis. The most important or outstanding example of Degelen's plant life is its unequivocal, clear and well-defined pattern of altitudinal zonation. Grasslands rich in diverse meadow-steppe vegetation are widely distributed and, depending on relief and soil moisture, pasture productivity ranges between 2 and 10 centners per hectare.

The first stage of the movement of radionuclides in biological systems within the ecosystems in question is the "soil–plant" pathway, which is essential for ascertaining the level of radionuclides that can be absorbed by the tissues of the plants as well as the subsequent incorporation into the tissues of herbivorous animals and, ultimately, into human food animal products.

Research in the field has demonstrated that plants that grow directly on the sites of ground nuclear explosions, for example, tend to have the lowest recorded concentration of certain radionuclides like the ^{137}Cs, ^{90}Sr, ^{239} + ^{240}Pu, and ^{241}Am. Such accumulation increases considerably along deposition "trails" of the radioactive fallout, and in areas marked as background, as well. In contrast, the greatest accumulation coefficients (K_acc) have been noted in the vegetation of radioactive watercourses in the Degelen massif, and in the "4A" site of combat test areas with radioactive materials.

The range of variability of accumulation is enormous: for some transuranic elements (^{239}+^{240}Pu and ^{241}Am), the K_acc value difference is 15-fold and for radiocaesium (^{137}Cs) and radiostrontium (^{90}Sr) the difference reaches 75-fold. Quantitative analyses of radionuclide uptake by vegetation for various STS testing grounds have been provided by Larionova and co-authors (2018, 2021).

Surface and Groundwater Characteristics at the STS

Within the border of the Semipalatinsk Test Site, the Tsar is undoubtedly the most conspicuous stream, with numerous tributaries and many small streams emanating from the slopes of the Degelen mountain massif. These include the Karamar and various other small, multi-channeled streams, flowing, in many cases, to areas of shallow and deep nuclear explosions. There are also many natural lakes, as well as other lakes, briny with arthritic salt and other reservoirs formed from scrapes and subsidence, and cavities resulting from explosions and excavation work. These artificial lakes and reservoirs vary in mineralisation and strongly mineralised brines depending on the area, geology, and isolation of the water region.

Groundwater Regime:

Groundwater within the STS is largely formed from atmospheric condensation and is replenished through precipitation falling onto the mass within the STS. The depth to which the groundwater is found is restricted to the topography and type of soil present:

- Valleys surrounded by meadows and meadow-light chestnut soils, and meadow solonchaks, do appear to have somewhat shallow aquifers, ranging from 2-6 metres deep.
- At the circumference of the Degelen massif, where the soil is light-chestnut and poorly developed, the water table is observed to be 10-12 metres deep.
- Within the unsupported light-chestnut soils of small hilly regions, the water table does exceed 10 metres, suggesting a decrease in infiltration and subsurface storage.

The bedrock which is fractured within the Degelen massif also serves as localized aquifers. These fractures, developed from underground nuclear testing and expanded over time, have allowed the movement of radionuclides into the groundwater.

Radionuclide Contamination of Water:

Hydrology studies have revealed high concentrations of radionuclides in surface and groundwater at several STS sites, especially those where underground nuclear tests were conducted:

- Degelen Site: Groundwaters and small streams draining the massif (Uzynbulak, Karabulak, and Baytles) capture substantial tritium, ^{90}Sr, ^{137}Cs, ^{241}Am, and $^{239+240}$Pu.
- Shagan River: Downstream ^{3}H concentrations have increased associated with the Balapan area, where the 1965 ‘Chagan’ nuclear test created a large artificial lake (referred to as “Atomic Lake” or Lake Balapan). This reservoir, which lies in the riverbed, is one of the most contaminated water bodies in the STS, and was formed as a result of the river water being diverted to the lake.
- Technogenic lakes: The lakes formed by the collapse of underground cavities and craters (e.g. Balapan) have been demonstrated to act as local accumulators of radionuclides. The concentration of radionuclides in these lakes is highly variable, depending on the extent of hydrological isolation and the processes of suspended matter settling, dilution, and evaporation.

Quantitative Observations:

- Tritium (^{3}H): One of the most dispersed radionuclides in STS waters, concentrations in the Degelen streams and the Shagan River frequently surpass the background level by 1-2 orders of magnitude. Being a component of the hydrosphere, tritium is an important indicator of test-associated contamination due to its high mobility.

- Strontium-90 (^{90}Sr): Found in the Degelen streams in a form that is soluble and bioavailable in discrete particles, and in some areas of the streams surpasses the national drinking water standards.
- Cesium-137 (^{137}Cs): is less concentrated in water due to absorption to sediments, but is measurable in particles suspended in water, and in deposits on the bottom.
- Plutonium isotopes ($^{239+240}Pu$) and Americium-241 (^{241}Am): whereas the plutonium isotopes are more prevalent, both isotopes are normally present in the water in minimal concentrations, and are strongly accumulated in the sediments of reservoirs and stream beds, around the test centres, and in other areas of stream beds.

Current Risks and Monitoring:

Although the majority of concentrations of radionuclides in open water bodies outside technical zones do not exceed permissible safety standards, there are, however, concentrated areas of concern. Since the 1990s, continuous monitoring by the Institute of Radiation Safety and Ecology (IRSE, Kurchatov) and international associates (IAEA, DOE) has determined that the greatest risk is narrowed down to the Degelen streams and Atomic Lake area with the highest mobility of radionuclides. The Shagan river system as a whole has diluted concentrations of radionuclides, but still has discernible and historical traces of tritium from test explosions.

Main Types of Livestock Activities at the STS

The primary livestock activities in the territory of the test site and its adjacent areas include the breeding of small ruminants, rams, horses and camels. For example, Sheep farming is the main livestock activity in the Semipalatinsk Test Site (STS) area, due to the ecological nature of the area which incorporates steppe and semi-desert pastures that favour small ruminants. The area is characterised by sagebrush, feather grasses, and similarly drought-resistant vegetation which is productive and economically desirable to the livestock sector, especially sheep, along with the conditions of low pasture productivity, semi-desert productivity of 2 to 4 and 10 centners (for mountain-meadow sites like Degelen) per hectare, noted respectively.

Studies conducted on 42 active farms scattered throughout the STS quadrant (approximately 40 percent of 18,000 square kilometres) report a productive herd of over 13,000 sheep and goats, in addition to 2,500 cattle and 1,600 horses. Local pastoralism is primarily sheep and goats in the region with over 250 farmers active along the border.

The most numerous sheep breed in the region is coarse, fat-tailed sheep, which is equally valued for meat and fat, all of which are fundamental for the national diet. Free-range grazing of small ruminants is a common attribute of livestock farming, seasonable pasture according to the cover and forage snow.

For local households, sheep serve as an essential source of mutton, milk, and fat, which are used for both subsistence and trade. In contrast, the family diet typically includes the more readily available cow's milk, goat's milk, and poultry products, while readily accessible mutton and beef are the primary meat products sold to neighbouring towns and districts such as Semey and Kurchatov. Further, wool and sheep skin are utilised for domestic purposes or for minor commercial sales; however, their economic value in comparison to meat production is negligible.

Sheep are of particular importance to the radiological studies at the STS due to the habit of foraging and their unique physiological framework, which renders them sensitive to radionuclide absorption. Grazing animals consume radionuclides through contaminated forages and water; thus, the soil–plant–animal pathway is vital for biosphere assessment in relation to human exposure.

Key conclusions of the analysis of radioactivity (IRSE, Larionova and others 2018, 2021):

- Sheep are most at risk from ^{90}Sr. Strontium is extremely soluble and is taken up by the plants eaten by sheep. Sr is also retained in the bones and milk of sheep.
- Sheep are at risk from muscle concentration of ^{137}Cs. The concentration of ^{137}Cs in muscle depends greatly on the sheep's grazing location.
- While the plutonium isotopes $^{239+240}$Pu and ^{241}Am are less mobile in the soil–plant system, some of the soil enters the excretion of animals, particularly in the liver.

Comparative studies have shown that sheep grazing near technical sites (e.g., Degelen streams, Experimental Field, and 4A) have radionuclide concentrations several times higher than sheep grazing in background territories. However, other than outside these 'hot spots,' concentrations in meat and milk products tend to be within the regulatory limits on safety and quality both nationally and internationally.

Livestock, including sheep, across the STS are maintained on stable pasture conditions, and sheep are provided shelter during the harshest winters. Water is from natural streams, wells, and artificial ponds and reservoirs. Access to highly contaminated zones is officially restricted, but the complete exclusion of grazing is often impractical due to the predominantly unfenced and Whitemarsh wild landscape.

CHAPTER 4.
MATERIALS AND METHODOLOGY

4.1. Field & SAMPLING LOCATIONS

The experiment was conducted on an Institute of Radiation Safety and Ecology (IRSE) Experimental Farm located on the STS territory, and the laboratory investigation was conducted at Department of Radiochemistry and Radioecology at University of Pannonia, Hungary. Two key locations, as shown in Figure 2, were selected for sampling and monitoring: the "P-2" site within the Experimental Field and the Degelen site near an adit with continuous water discharge.

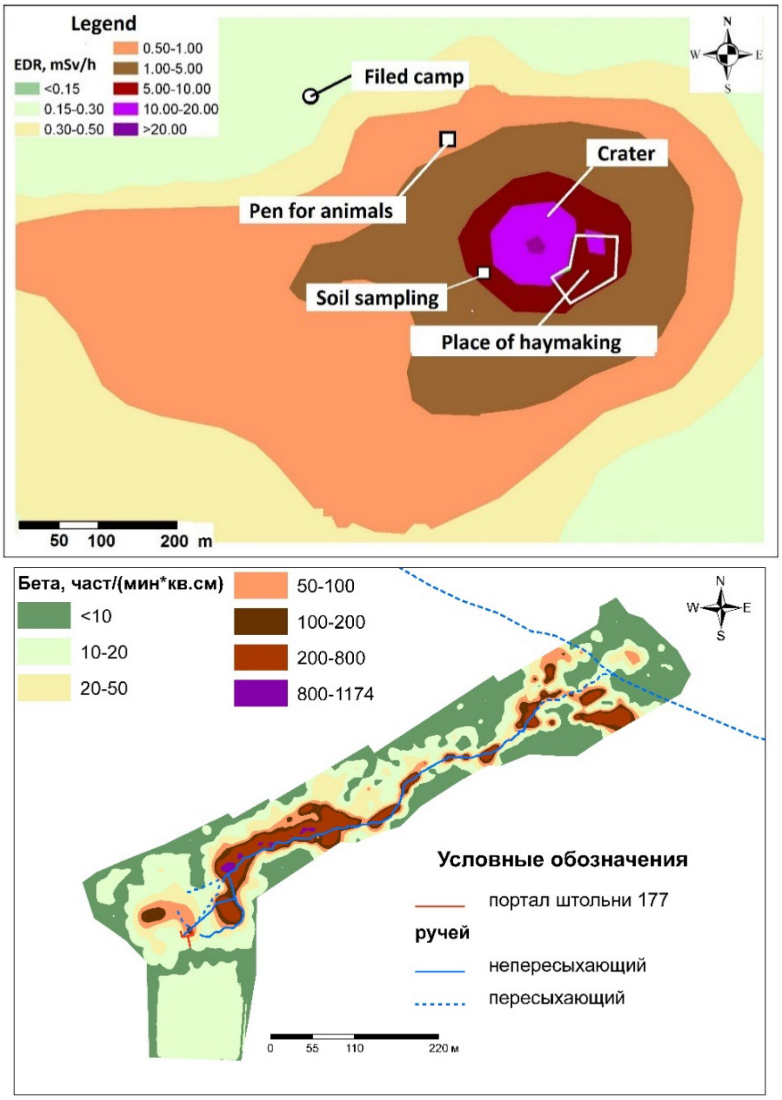


Figure 2- Radiation characteristics of the hay and soil harvesting site

Degelen Site

The dwarfed hilly ranges dubbed 'Degelen' stretch out amidst a network of canyons and are bisected by jagged valleys. Work on Adit #177, which corrects the course of the Uzynbulak stream, is where the focus of the study lies. Blue water wells up through the stone, ricocheting along fractured rock. It cruises through burst cavities created by underground detonations decades prior and oozes along the surface, dolloping with sustenance. The waters on the surface are loaded with tiny particles of rock created by the explosions. The portion of water which is yielded flows unceasingly, yielding waters laden with radionuclides that gradually percolate through the surrounding marshy land. Accordingly, the radioactively dense water which is steadily flowing yields a sustained, seeping source of soil water that augments the surrounding, unusual shrub-filled soil of the spring. The blossoms on top are more harnessed than the soil below, which is dry and devoid of foliage. Primarily, the region devoid of blossoms harnesses most of the soil. Therefore, this region is the most significant to study the migration of radionuclides.

Experimental Field (P-2 Site)

The designated Experimental Field has always served as a central testing area for surface and atmospheric nuclear explosions from 1949 to 1962. The detonations from these explosions resulted in widespread contamination with fallout scattered across the soils and vegetation of the steppe. The P-2 site is a flat, table-land area in a region characterised as the desert steppe zone with weakly developed light chestnut soils and turf grass vegetation. In contrast to the Degelen massif, the area is a desert, and the only source of moisture is precipitation, estimated at approximately 250 mm a year. This moisture is insufficient to cause leaching of the soils, and radionuclides and other materials that are fixed are only mobile when leaching or surface runoff is available in the soil. Still, the conditions under which radionuclides are fixed are favourable, and as a result, the soil available for uptake by the plants is upper and soil fixed within the leaching zone.

4.2. Sample Collection and Preparation

Standardised soil and plant samples were collected at P-2 (Experimental Field) and at Degelen adit №177. The sampling methodology was designed to allow for systematic representation of both contaminated areas and comparative background plots. Each subsample was dried, homogenised, and packaged separately, all under conditions aimed at avoiding undesirable cross-contamination. The samples were all patiently prepared, only to undergo final inspection prior to shipment to an independent lab considering international shipping.

4.3. Research Subjects

Lopushinsky and Kolesnik devoted their research to only one species - sheep, considering them as the most dominant and representing the principal livestock of the Semipalatinsk Test Site (STS) area. The types of animals selected for the experiment were 2-year-old castrated rams of the breed Kazakh fat-tailed coarse-wooled sheep (“Edilbayev”). This is the traditional and most adapted type of sheep in Kazakhstan and is ideal for Kazakhstan’s arid steppe pasture.

The reason these rams were selected is because of their particular physiological characteristics and because they are attainable in that particular region:

- Breed characteristics: The Edilbayev sheep are valued for their resilience, rapid growth, and fat-tail reserves, which provide energy during periods of scarce forage.
- Experimental group details: Animals had an average live body weight of 51 ± 3 kg.
- Uniformity: All selected rams were in good health, of similar age, and demonstrated comparable productivity and exterior-constitutional traits, ensuring reliable comparison of radionuclide uptake.

The radionuclides studied in relation to their transfer to sheep tissues and products included ^{137}Cs, ^{90}Sr, ^{241}Am, and $^{239+240}$Pu. These were chosen because they represent the most ecologically and radiologically significant isotopes present at the STS.

Experimental Design for Studying Radionuclide Transfer in Sheep

The experiment took place in the summer grazing season, with the animals kept in a controlled stable–pasture setup. The rams were organised into groups, and each group was subjected to monitoring of the following controlled intakes:

- Contaminated feed made from forage gathered from the polluted plot test sites.
- Pre-prepared soil particles, representing the grazing radionuclide-loaded slabs which were designed to be incidental.
- Contaminated water sampled from water courses impacted by the testing activities.
- The administered water containing known volumes of a selected group of radionuclides.

Before the start of experimental feeding, all rams were pastured on ‘clean’ steppe lands for the purposes of establishing a radiological baseline. After the animals arrived at the research site, a two-week period of adaptation to the ‘clean’ diet was implemented in order to restore physiological parameters to baseline levels prior to exposure to radionuclides.

The exposure time ranged from 1 to 120 days, which was determined according to the group. Within the framework of the study:

- The amount of feed, soil, and water was individually allocated and recorded for each ram as a daily norm.

- Contamination levels were monitored and assessed in parallel through the collection and analysis of environmental samples (vegetation, soil, water) across prescribed time intervals.

4.4. Sampling and Analysis

During the last stage of the experiment, the chosen subjects underwent a 12-hour starvation protocol followed by a period of gentle slaughter. Alongside the primary biological samples described below, a detail-level recording was maintained:

- Organs: liver, kidneys, lungs, heart, spleen, brain.
- Muscle tissue: thigh and tongue muscles.
- Skeletal system: bones.
- Other tissues: tail fat, wool, skin.

The samples were thoroughly dried, denatured, and sealed following the appropriate laboratory and toxicological methods to be sent for spectrometric analysis.

Initial laboratory results of ^{90}Sr and ^{137}Cs suggest bone and muscle incorporation, whereas $^{239+240}$Pu, ^{241}Am, and some weak indicators of the liver and spleen were more abundant. These results presented here illustrate the transfer pathways of radiocontaminants with the use of small ruminants as sentinels of the deemed areas of radioactive contamination, particularly the area designated STS. The laboratory investigation had been gone with the Department of Radiochemistry and Radioecology at the University of Pannonia (Veszprém, Hungary) where the laboratory were utilised high-resolution gamma spectrometry with radiochemical separation and alpha/beta counting techniques on the selected samples to derive radionuclide concentrations. The samples of primary interest included ^{137}Cs, ^{90}Sr, ^{241}Am, and $^{239+240}$Pu, and also ^{3}H in water samples.

4.5. Control samples

The animals were delivered from Sarzhal village (East-Kazakhstan) which is located more than 200 km to the south of the STS. Traditionally, farm animals in this region are allowed access to grazing all the year round.

Based on radioecological studies in the region of Sarzhal village, artificial radionuclides in soil are largely due to global fallout (Strilchuk, 2013). Analyses of farm products (meat, milk) from Sarzhal (Baigazinov, 2016) have shown that radionuclide activity concentrations were low (Table 1) so it was decided that a reference (or control) group was not required in our study.

Table 1. Activity concentration of the studied radionuclides in the farm products of Sarzhal

Samples	**Activity concentration, Bq kg^{-1}Activity concentration, Bq kg^{-1}**			
Samples	^{241}Am	^{137}Cs	^{90}Sr	$^{239+240}$Pu
meat (n=2)	< 0.02	0.04±0.008	< 0.06	-
Note: FM – fresh mass (here and after) (Baigazinov, 2016)				

4.6. Experiments with rams

Research Subject. The study focused on two-year-old castrated rams of the Kazakh fat-tailed coarse-wool breed ("Edilbaev"), with a live weight of 51±3 kg. The animals were divided into six groups, each consisting of five rams. The studies were carried out in areas of ground nuclear testing.

For the animals in the first group, hay (mixed steppe grass) growing on the radioactively contaminated site "P-2" was used as feed. Throughout the feeding process, the daily intake of feed was meticulously recorded, revealing that, on average, each animal consumed 0.9±0.2 kg of dry feed per day.

The second group of animals was fed pre-prepared soil at a rate of 0.15 kg per head per day, mixed with compound feed by hand immediately before the morning feeding. The soil, harvested from the same site known for its maximum radionuclide content, was collected from the top 5 cm layer, dried (20–25°C), and sifted through a 1.5 mm mesh sieve.

In areas of radioactive watercourses, the third group of animals was fed meadow mixed grass (hereinafter referred to as feed), growing along the radioactively contaminated streambed of a watercourse at the "Degelen" site. It was found through daily monitoring that each animal consumed on average 1.1±0.35 kg (dry weight) of feed per day.

The fourth group of animals was daily provided with water contaminated with radionuclides and fed "clean" feed. The water was collected from the stream alongside which vegetation for the third group of animals was harvested.

The fifth group of animals was fed feed from a radioactively contaminated area and also given contaminated water. Similar to the fifth group, the sixth group of animals was fed contaminated feed and given contaminated water, but their diet also included soil collected from the same site, at a rate of 0.05 kg per day per head. As with the "Experimental Field" site, the soil was collected from the top 5 cm layer, dried (20–25°C), and sifted through a 1.5 mm mesh sieve.

For all animals, vegetation was manually harvested daily, 12–15 hours before feeding. The duration of the rams' stay was set at 7, 14, 28, 56, and 112 days. At the end of each period, one animal was slaughtered.

4.7. Laboratory & Analytical Work

4.7.1. Sampling of organs and tissues of rams

In the analysed rams, biological tissues including muscle, heart, lungs, kidneys, liver, spleen, tongue, ribs, tail fat, and wool were assessed for the radionuclide activities of $^{239+240}$Pu, ^{241}Am, ^{137}Cs, and ^{90}Sr.

In the Republic of Kazakhstan, all slaughtering rituals were carried out in full compliance with the legal system pertaining to agricultural animals, specifically the Ministry of Agriculture: with Farm Animal Slaughter Protocol, dated 8 July 2015, and Order No 11591. The anatomical dissection of organs and tissues adhered to the biological sampling as sanctioned in order 7-1/393 of 30 April 2015 and associated standard 2011 from the Ministry of Health.

4.7.2. Sample Collection and Processing

This section delineates the steps followed to sample the various body elements of the sheep.

Muscle and bone tissue: During the dissection procedure of each of the sheep carcasses, muscle tissue samples were harvested from the thigh and, subsequently, the ribs. Each rib was delicately extracted from the remaining muscle and adipose tissue, and then sectioned into 5–6 cm long pieces. Internal organs: These body parts were collected in their entirety to preserve the radionuclide distribution, as subdivision was found to be inappropriate. These include the lungs, heart, kidneys, liver, tongue and spleen.

After slaughter, wool was removed along with skin and follicles after a period of one week to air at about room temperature. Moistening wool with water eased removal, and it was found that water was oozing out of the container packed with the sheep skin (dermis) that has blood and oozing lymph fluid. As a consequence, the skin was washed with a lot more water (close to room temperature) to lessen the superficial soiling of blood, lymph fluid and tissue/s and fat. More fat and tissue residues were removed with the aid of a scalpel. Distilled water washes were performed and the skin was then packed in sterile gauze and dried in more controlled conditions.

The wool samples underwent additional treatment:

1. After detachment from the skin, raw wool was trimmed and soaked in a detergent solution for 2–4 hours.
2. It was rinsed extensively under running water, followed by a final wash with distilled water to ensure purity.
3. The wool was dried in a laboratory oven at 85 °C, after which residual foreign particles were manually removed if necessary.

This systematic sampling and preparation protocol ensured that all tissues and products derived from the rams were clean, standardized, and ready for subsequent radiochemical and spectrometric analysis.

4.7.3. Preparation and Measurement of Animal Samples for Radionuclide Analysis

Gamma emitting radionuclides

Samples of soft tissue were rinsed first under running water and then homogenised in a laboratory mill to achieve a uniform mixture. For gamma spectrometric analysis, subsamples of around 200 g were set aside. Bone samples were ashed in a muffle furnace at 380 °C and then subsequently ground to a fine powder before analysis.

Gamma spectrometric measurements were performed on a CANBERRA high-purity Germanium (Ge) detector using Genie2000 software. For energy calibration, a certified standard γ-source workbook (OSGI) was employed. For geometry calibration, volumetric standards (OMACH) containing standard radionuclides of ^{137}Cs, ^{152}Eu, and ^{241}Am were used. All measurements were performed in a laboratory which is ISO 17025:2009 accredited. This guarantees that international measurement standards are met.

Radiochemical Separation and Analysis of ^{90}Sr and $^{239+240}$Pu

Upon gamma analysis, the examined tissue samples were dried, carbonised on an electric hot plate, and ashed in muffle furnaces until obtaining a residue that was a light grey or white colour. The muffle ash was then dissolved in concentrated HNO_3, to which H_2O_2 was added as deemed necessary to facilitate complete oxidation. A specific quantity of ^{24}Pu was added as a yield tracer.

The chemical determination of ^{90}Sr was indirect, being performed through measurement of the ^{90}Y daughter radionuclide. After chemical separation of the ^{90}Y, the activity was measured using a beta liquid scintillation counter.

The activity concentrations of the ^{239}+^{240}Pu were then subject to alpha spectrometry after radiochemical purification which included anion-exchange separation and electrodeposition of the actinides on the stainless-steel disks.

4.7.4. Preparation and analyses of soil samples

The weight of selected soil samples was initially 70-80g which were later cured with air for some time. The less than 1.5mm soil fraction was separated through manual sieving, after which the sample was reduced and divided into quarters. One of the quarters was selected and a subsample of 200g was then set aside for gamma spectrometric analysis.

The rest of the sample was gamma spectrometrically measured. The sample was then moistened and finely ground with a pestle. Of the resultant sample, a 10g preserved subsample was used for the subsequent analysis of the plutonium isotopes and the 239 and 240 isotopes. The sample was ashed at a temperature which was between 450 and 500 degrees Celsius. Following acid digestion, the sample was subjected to extraction and chromatography through column filters. The separated isotopes were later retrieved through multiple stages of elution followed by co-precipitation and then membrane filtration. The activity concentrations of ^{137}Cs, ^{241}Am, and 239 plus 240Pu were determined through the same methods as the earlier animal tissue analysis.

Concurrently, the gamma analysis was followed by taking an additional 20-gram subsample which was placed in a closed measuring cuvette (diameter: 70 mm) and sealed in such a way that the calibration geometry was fully covered. The soil ^{90}Sr activity concentration was measured directly by a “Progress” beta spectrometer. Radiochemical separation was not completed, as the anticipated concentration was in the range of kilobecquerels per kilogram (kBq/kg).

Under the specified measuring conditions, the minimum detectable activity (MDA) for ^{90}Sr was 100 Bq/kg. The certified internal document on the procedure for strontium determination provided for strontium analysis by method and ensured that all internal and external quality control aspects were met.

4.7.5. Preparation and analyses of “uncontaminated” hay and wheat bran samples

The preparation of hay and wheat bran samples was carried out according to the method in GOST (2000). Gamma spectrometric analyses were carried out on a Canberra GX-2020 gamma spectrometer according to the standard method (MI 5.06.001.98). The radionuclide 90Sr was determined by radiochemical isolation and measured on a TriCarb liquid-scintillation spectrometer according to an established method.

4.8. Estimation of transfer parameters

The standard parameters used to describe the transfer of radionuclides into farm animal tissues is the transfer coefficient (Ff; d kg-1) (IAEA 2010):

$$F_f = \frac{\text{Radionuclide activity concentration in animal tissue (Bq kg}^{-1}\text{ fresh mass)}}{\text{Daily intake of a radionuclide (Bq d}^{-1}\text{)}}$$

Following the recommendations of Beresford et al. (2007b) and subsequently IAEA (2010) the dietary concentration ratio was also estimated where CRdiet is defined as:

$$C_{\text{Rdiet}} = \frac{\text{Radionuclide activity concentration in animal tissue (Bq kg}^{-1}\text{ fresh mass)}}{\text{Radionuclide activity concentration in the whole diet (Bq kg}^{-1}\text{ dry mass)}}$$

Daily intake of radionuclides for both groups was estimated based on the activity concentration of radionuclides in the contaminated soil and in the solution via their daily consumption with wheat bran and forage (soil – 1,000 g day-1, solution – 10 ml day-1, forage – 13 kg day-1 for mare and 11 kg day-1 for filly).

CHAPTER 5
RESULTS & DISCUSSION

5.1. The transfer of radioisotopes to the tissues

5.1.1 Radionuclide intake by the study animals

To monitor the intake of radionuclides into the bodies of animals daily records were kept throughout the entire experimental period, noting the quantity of food, soil, and water consumed. Additionally, samples of vegetation, soil, and water were collected according to the experimental design. The calculation of the average daily intake of radionuclides into the animals' bodies was based on the specific activities of radionuclides in hay, water, and soil (refer to Table 1), along with the daily consumption rates of hay, water, and soil. As indicated in the table, the daily radionuclide intake by animals varied, primarily due to the amount of hay consumed by each animal and the radionuclide concentrations present in their diet. It is important to note that the harvesting of vegetation for feed was conducted daily before feeding. The results of the calculations for the average daily intake of radionuclides $^{239+240}$Pu, ^{241}Am, ^{137}Cs, and ^{90}Sr into the bodies of sheep are presented in Tables 2–6.

Table 2. Activity concentration of radionuclides in samples of plants, water, and soil

Group 1				Group 2				Group 3		Group 4
Forage (Experimental Field)				Soil (Experimental Field)				Forage (Degelen)		Water (Degelen)
$^{239+240}$Pu	^{241}Am	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{90}Sr
kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	MBq kg-1	MBq kg-1	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}
235±12	50±5	80±8	20±3	83.0±4.0	1.6±0.3	2.8±0.6	13.0±2.0	305±15	65±7	800±135
220±12	45±5	35±4	27±4	53.0±3.0	1.2±0.2	2.4±0.5	22.0±3.0	220±10	73±8	665±115
184±13	10±4	40±4	21±3	85.0±5.0	1.2±0.2	2.6±0.5	18.0±3.0	194±9	67±8	460±10
114±7	35±10	50±10	17±2	64.0±3.0	1.2±0.2	2.4±0.5	20.0±3.0	58±7	68±8	-
35±2	10±3	24±3	13±2	61.0±3.0	1.2±0.2	2.5±0.5	15.0±2.0	54±7	48±5	460±10
30±4	10±4	10±3	13±2	57.0±3.0	1.2±0.2	2.3±0.5	23.0±3.0	47±8	57±7	898±13
29±2	9±3	15±2	8±1	57.0±3.0	1.2±0.2	2.4±0.5	14.0±2.0	50±10	72±10	427±10
51±4	<4	10±2	11±2	58.0±3.0	1.6±0.3	2.9±0.6	22.0±3.0	140±10	60±7	564±10
33±5	55±4	60±6	5±1	67.0±4.0	1.7±0.3	2.9±0.6	13.0±2.0	115±10	64±7	318±10
193±8	17±2	10±2	14±2	55.0±3.0	1.6±0.3	2.7±0.5	22.0±3.0	^{90}±10	69±9	351±10
16±2	<6	8±2	28±4	56.0±4.0	1.3±0.3	2.3±0.5	13.0±2.0	850±20	71±9	444±10
-	<4	10±2	< 11	67.0±5.0	1.6±0.3	2.9±0.6	24.0±3.0	19±9	53±7	624±10
29±5	12±5	16±6	22±4	-	-	-	-	80±10	74±10	477±10
50±5	17±5	10±5	24±6	-	-	-	-	120±10	103±14	460±10
12±2	8±3	10±2	6±1	-	-	-	-	100±10	89±11	437±10
9±1	15±4	5±1	11±2	-	-	-	-	5770±50	110±12	742±15
40±3	10±3	20±2	12±2	-	-	-	-			-

Continue of Table 2.

Group 5 and Group 6						Group 6			
Forage (Degelen)			Water (Degelen)			Soil (Degelen)			
^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{137}Cs	^{90}Sr	^{241}Am	$^{239+240}$Pu
kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}	kBq kg^{-1}
860±100	57±7	17±2	0.72±0.1	1040±100	0.15±0.01	15±0.5	110±12	1.5±0.02	15±1
-	68±8	19±4	1.2±0.2	630±60	<0.001	12±0.5	96±11	0.6±0.01	8±1
48±4	53±7	18±1	2.0±0.4	650±60	<0.001	14±0.5	110±13	0.9±0.03	12±1
78±5	57±7	1.5±0.2	1.5±0.3	1100±110	0.15±0.01	17±1	110±13	1.1±0.03	10±0.2
80±5	63±8	13±3	2.0±0.5	-	0.33±0.03	17±1	110±13	0.9±0.03	16±0.1
950±30	100±12	19±2	1.0±0.3	1200±100	0.082±0.03	-	-	-	-
40±2	92±11	24±2	1.1±0.3	1000±100	0.14±0.003	-	-	-	-
50±4	73±9	46±6	-	-	-	-	-	-	-
26±4	98±12	6±1	-	-	-	-	-	-	-
48±6	150±18	6±1	-	-	-	-	-	-	-
10±3	89±11	3±1	-	-	-	-	-	-	-
11±2	26±4	4±1	-	-	-	-	-	-	-
7±3	30±4	0.8±0.3	-	-	-	-	-	-	-
18±4	74±9	0.9±0.4	-	-	-	-	-	-	-
850±100	13±2	34±1	-	-	-	-	-	-	-
<1.4	38±5	2.2±0.6	-	-	-	-	-	-	-

Table 3. Average daily intake of $^{239+240}$Pu into the body of sheep, kBq per day

Source of intake	Duration of keeping rams in the experiment, days					
	3	7	14	28	56	112
Group 1						
forage	0.21±0.04	0.21±0.04	0.19±0.04	0.14±0.03	0.093±0.02	0.082±0.02
Group 2						
soil	-	9500±1600	9500±1600	9500±1600	9500±1600	9500±1600
Group 5						
forage	-	0.019±0.004	0.020±0.004	0.015±0.003	0.022±0.004	0.015±0.003
water	-	0.00015±0.00003	0.00015±0.00003	0.00015±0.00003	0.00015±0.00003	0.00015±0.00003
Group 6						
forage	-	0.019±0.004	0.020±0.004	0.015±0.003	0.022±0.004	0.015±0.003
water	-	0.00015±0.00003	0.00015±0.00003	0.00015±0.00003	0.00015±0.00003	0.00015±0.00003
soil	-	0.61±0.2	0.61±0.2	0.61±0.2	0.61±0.2	0.61±0.2

Table 4. Average daily intake of ^{241}Am into the body of sheep, kBq per day

Source of intake	Duration of keeping rams in the experiment, days					
	3	7	14	28	56	112
Group 1						
forage	0.045±0.009	0.043±0.009	0.032±0.006	0.027±0.005	0.025±0.005	0.021±0.004
Group 2						
soil	-	0.21±0.03	0.21±0.03	0.21±0.03	0.21±0.03	0.21±0.03
Group 6						
soil	-	0.051±0.02	0.051±0.02	0.051±0.02	0.051±0.02	0.051±0.02

Table 5. Average daily intake of ^{137}Cs into the body of sheep, kBq per day

Source of intake	Duration of keeping rams in the experiment, days					
	3	7	14	28	56	112
Group 1						
forage	0.032±0.006	0.034±0.007	0.038±0.008	0.029±0.006	0.025±0.005	0.021±0.004
Group 2						
soil	–	0.40±0.04	0.40±0.04	0.40±0.04	0.40±0.04	0.40±0.04
Group 3						
forage	–	0.37±0.1	0.30±0.1	0.30±0.1	0.42±0.1	–
Group 5						
forage	–	0.95±0.2	0.95±0.2	0.36±0.07	0.33±0.07	0.23±0.05
water	–	0.0016±0.0003	0.0016±0.0003	0.0016±0.0003	0.0016±0.0003	0.0016±0.0003
Group 6						
forage	–	0.95±0.2	0.95±0.2	0.36±0.07	0.33±0.07	0.23±0.05
water	–	0.0016±0.0003	0.0016±0.0003	0.0016±0.0003	0.0016±0.0003	0.0016±0.0003
soil	–	0.75±0.1	0.75±0.1	0.75±0.1	0.75±0.1	0.75±0.1

Table 6. Average daily intake of ^{90}Sr into the body of sheep, kBq per day

Source of intake	Duration of keeping rams in the experiment, days					
	3	7	14	28	56	112
Group 1						
forage	0.021±0.005	0.021±0.005	0.020±0.003	0.018±0.005	0.015±0.006	0.016±0.007
Group 2						
soil	-	2.7±0.7	2.7±0.7	2.7±0.7	2.7±0.7	2.7±0.7
Group 3						
forage	-	80.0±25.0	100.0±30.0	120.0±40.0	200.0±60.0	170.0±50.0
Group 4						
water	-	3.2±1.0	4.2±1.0	7.5±2.0	5.5±2.0	5.1±2.0
Group 5						
forage	-	63.0±13.0	69.0±14.0	65.0±13.0	77.0±15.0	74.0±15.0
water	-	1.1±0.2	1.1±0.2	1.1±0.2	1.1±0.2	1.1±0.2
Group 6						
forage	-	63.0±13.0	69.0±14.0	65.0±13.0	77.0±15.0	74.0±15.0
water	-	1.1±0.2	1.1±0.2	1.1±0.2	1.1±0.2	1.1±0.2
soil	-	5.4±0.3	5.4±0.3	5.4±0.3	5.4±0.3	5.4±0.3

5.1.2. Radionuclide activity concentrations in ram tissues

5.1.2.1. Transfer Parameter of $^{239+240}$Pu

The results of spectrometric measurements of the activity concentration of $^{239+240}$Pu in the organs and tissues of rams from groups 1, 2, 5, and 6 are presented in Table 7. The content of $^{239+240}$Pu in the organs and tissues of animals from the 1st and 5th groups, which were fed contaminated hay, is low. Concentrations of the radionuclide in the spleen, heart, kidneys, lungs, and bone tissue were below the detection capabilities of the equipment and methodologies employed. In the organs and tissues of animals from groups 2 and 6, which were fed contaminated soil, detectable specific activities of $^{239+240}$Pu were identified in almost all analyzed samples.

Table 7. Activity concentration of $^{239+240}$Pu in organs and tissues of the rams

Tissues	Number of days of containment, days				
	7	14	28	56	112
Group 1 (source of radionuclides – steppe vegetation from the epicenters of ground tests) Bq kg^{-1} FM					
muscle	0.012±0.002	0.022±0.002	0.003±0.002	0.003±0.002	0.02±0.002
liver	0.03±0.006	0.1±0.02	0.1±0.02	0.2±0.01	0.3±0.02
lungs	0.03±0.008	0.03±0.007	0.02±0.007	0.04±0.01	0.03±0.01
kidneys	<0.03	0.1±0.02	<0.03	0.1±0.03	0.15±0.07
spleen	<0.04	<0.08	<0.04	<0.1	<0.1
heart	<0.03	<0.03	<0.02	<0.03	<0.04
ribs	<0.1	<0.1	<0.1	<0.1	<0.1
wool	0.4±0.04	0.3±0.04	1.1±0.06	0.4±0.04	0.3±0.04
skin	0.05±0.005	0.1±0.01	0.1±0.02	0.05±0.008	–
Cartilaginous tissue (ear)	<0.2	<0.2	0.2±0.06	<0.1	0.2±0.1
Group 2 (source of radionuclides – soil from the epicenter of a ground nuclear test)					
muscle	4.6±0.1	2.7±0.1	3.0±0.1	9.0±0.3	7.8±0.24
liver	23±1	140±4	830±30	1200±40	3100±100
lungs	3.7±0.2	5.9±0.2	330±10	115±4	74±3
ribs	36±1	40.4±1.2	280±10	610±20	1620±50
tongue	2.2±0.2	3.1±0.4	7.4±1.6	7.4±0.3	9.6±0.40
tail fat	10.1±0.3	4.4±0.3	6.7±0.3	72.3±2.2	28.1±0.8
Group 5 (source of radionuclides – water and meadow vegetation from areas of radioactive water flows)					
muscle	<0.005	0.005±0.002	0.007±0.001	0.007±0.001	0.003±0.001
liver	<0.007	0.013±0.004	0.11±0.008	0.093±0.009	0.14±0.012
lungs	<0.007	<0.007	<0.007	0.026±0.008	<0.01
kidneys	<0.03	<0.02	<0.02	0.058±0.02	0.074±0.02
spleen	<0.02	<0.1	<0.07	<0.07	<0.065
heart	<0.02	<0.01	<0.02	<0.02	<0.022
ribs	<0.08	<0.09	<0.09	<0.08	<0.08
wool	-	0.69±0.04	0.11±0.02	0.27±0.02	0.49±0.04
skin	0.06±0.004	0.055±0.003	0.044±0.009	0.05±0.007	0.085±0.007
tail fat	0.011±0.002	0.0043±0.002	0.01±0.002	0.012±0.002	0.01±0.002
Group 6 (source of radionuclides – soil. water and meadow vegetation from areas of radioactive water flows)					
muscle	0.005±0.001	0.013±0.001	0.0084±0.0008	0.02±0.002	0.0025±0.001

Tissues	Number of days of containment, days				
	7	14	28	56	112
liver	0.09±0.007	0.37±0.02	0.46±0.02	0.91±0.03	1.5±0.05
lungs	0.02±0.009	0.02±0.009	0.023±0.005	0.03±0.005	0.043±0.008
kidneys	0.05±0.02	0.13±0.03	0.091±0.02	0.14±0.02	0.12±0.02
spleen	<0.03	0.079±0.03	<0.04	0.072±0.02	0.26±0.05
heart	<0.01	0.038±0.02	<0.02	0.014±0.008	0.012±0.008
ribs	0.092±0.04	0.087±0.05	0.22±0.06	0.33±0.06	–
wool	1.4±0.05	2.2±0.07	2.0±0.06	2.0±0.06	2.2±0.06
skin	0.24±0.01	0.19±0.008	0.26±0.01	0.1±0.01	0.22±0.01
tail fat	0.017±0.003	0.015±0.003	0.0088±0.002	0.016±0.003	0.018±0.003

Characteristics of the $^{239+240}$Pu Transfer at Various Ingestion Times

The graphs (Figure 3) illustrate the dynamics of the $^{239+240}$Pu transition into the organs and tissues of animals fed contaminated feed and soil. Relative concentrations are expressed as fractions of the maximum activity concentration of the radionuclide in the organs and tissues. For each time period (7, 14, 28, 56, 112 days), the average was calculated from 3 to 6 values.

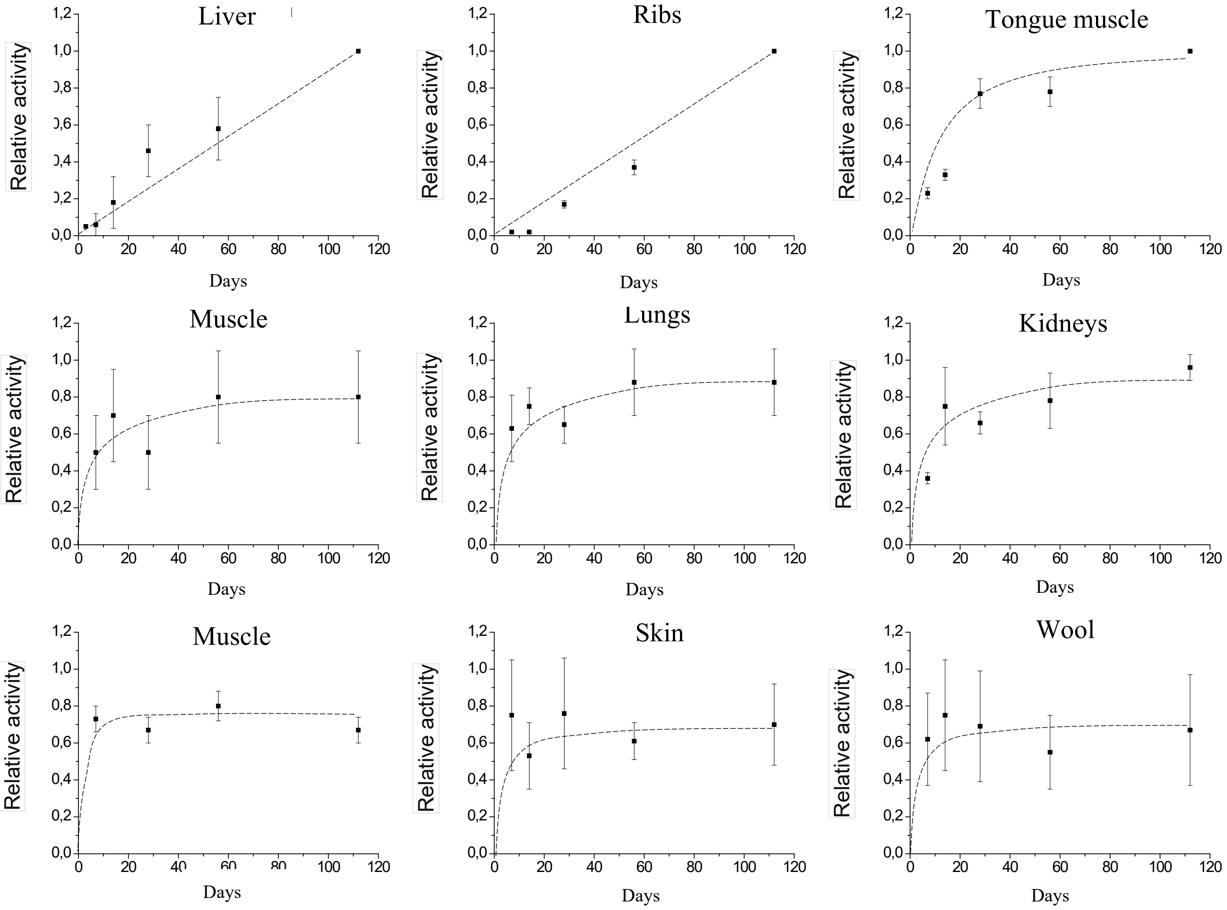


Figure 3- Dynamics of the $^{239+240}$Pu Transition into the Organs and Tissues of Sheep

The graphs demonstrate that with prolonged intake of $^{239+240}$Pu, its concentrations in the liver and bone tissue increase throughout the experiment (up to 112 days). In other organs (tongue muscles, thigh muscles, lungs, kidneys, tail fat), there is a notable slowdown in the growth of radionuclide activity after 28 days of $^{239+240}$Pu entering the body. However, a slight increase in $^{239+240}$Pu activity in the tongue muscles and kidneys is observed on day 112.

Distribution of $^{239+240}$Pu in Animal Organs and Tissues

The distribution of $^{239+240}$Pu in animal organs and tissues is depicted in the histogram (Figure 4). The radionuclide distribution is expressed in relative units (r.u.), represented as fractions of the maximum activity concentration of the radionuclide in each organ.

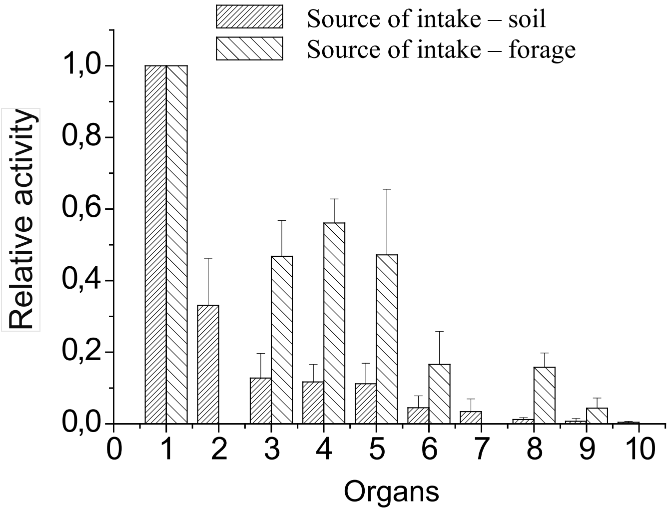


Figure 4- Distribution of $^{239+240}$Pu in the Organs of Rams; (1 – liver, 2 – bone tissue, 3 – spleen, 4 – kidneys, 5 – skin, 6 – lungs, 7 – tail fat, 8 – heart, 9 – thigh muscle, 10 – tongue muscles)

The figure illustrates that the distribution of $^{239+240}$Pu in the Organs of Rams varies when the radionuclide is introduced through soil and feed. Specifically, when introduced through soil, the radionuclide concentration in the liver is up to 8 times higher than in the spleen, kidneys, and skin, whereas with feed, this difference is reduced to up to 2 times. Bone tissue is considered the primary deposition site for 239+240Pu in the body. Numerical values were obtained only from animals fed contaminated soil. In the bone tissue of animals fed contaminated feed, values were below the detection level of the employed equipment and methodologies. Therefore, radionuclide transition coefficients were calculated solely for animals fed soil for 112 days. The skin of animals exhibited the highest radionuclide concentrations. The high Pu content in the skin tissue is likely due to percutaneous absorption. The $^{239+240}$Pu content in the soil at the location where the animals were kept reached 15 kBq kg-1. Particles of $^{239+240}$Pu that land on the skin's surface can penetrate deep into the skin through pores and channels. The activity of $^{239+240}$Pu in the kidneys and lungs is an order of magnitude lower than in the liver and bone tissue but is several times higher than in the spleen, heart, tail fat, and muscle tissue. The concentrations of $^{239+240}$Pu in the lungs vary among animals depending on the source of radionuclide entry. For animals that received $^{239+240}$Pu with their feed, the increase halts on the 7th day, whereas for those exposed through soil, the concentration of the radionuclide continues to rise over time, with a slowdown in accumulation only after 56 days. This effect could be due to the additional inhalation of soil particles into the lungs when animals consumed contaminated soil added to their diet, potentially leading to an increase in $^{239+240}$Pu activity. Overall, the distribution of $^{239+240}$Pu in the Organs of Rams follows this descending order: liver > bone tissue > spleen ≥ kidneys ≥ skin > lungs > tail fat > heart ≥ thigh muscle > tongue muscles.

Transfer Coefficients of $^{239+240}$Pu into Organs and Tissues of Sheep

The transfer coefficients of $^{239+240}$Pu into animal organs and tissues are detailed in Table 8.

Table 8. Transfer Coefficients of $^{239+240}$Pu into Organs and Tissues of Rams

Tissues	$^{239+240}$Pu ($\times 10^{-5}$)		
	Vegetation from areas of radioactive water flows and epicenters of ground tests	Soil from areas of radioactive water flows	Soil from the epicenters of ground tests
liver	>310	>220	>30
ribs	>140	>20	>20
skin	80 (40-110)	34 (30-36)	-
kidneys	150 (110-180)	20 (16-20)	-
lungs	30 (15-30)	>5	>1
heart	<60	1.9 (1.8-2.1)	-
spleen	<160	11 (11-38)	-
tail fat	6 (4-9)	-	0.5 (0.3-0.8)
tongue	-	-	0.08 (0.08–0.1)
muscle	8 (6-11)	1.8 (1.2-2.4)	0.05 (0.03–0.08)
Brain	-	-	-

Note: in the numerator – median, in parentheses – lower and upper quartile

At the selected time intervals, $^{239+240}$Pu concentrations in the liver and bone tissue did not reach an equilibrium state in any group. The transfer coefficients for $^{239+240}$Pu to the liver were only calculated for animals maintained on a contaminated diet for the longest duration (112 days). Comparing the transfer coefficients of $^{239+240}$Pu into the organs of animals fed vegetation from the epicenters of ground tests and zones of radioactive watercourses showed them to be comparable, indicating no significant differences and allowing for an averaging of these data.

5.1.2.2. Transfer Parameter of ^{241}Am

The results of spectrometric measurements of the organs and tissues of rams from groups 1, 2, and 6 are presented in Table 9. In most cases, the content of ^{241}Am in the organs and tissues of animals from groups 1 and 6 was below the detection limit; numerical values were found only in the bodies of animals from group 2.

Table 9. Activity concentration of ^{241}Am in organs and tissues of the rams

Tissues	Number of days of containment, days (Bq kg^{-1} FM)				
	7	14	28	56	112
Group 1 (source of radionuclides – steppe vegetation from the epicenters of ground tests)					
muscle	<0.03	<0.3	0.059±0.02	0.067±0.03	0.069±0.03
liver	<0.09	<0.2	<0.2	<0.12	<0.2
lungs	<0.1	<0.2	<0.2	<0.17	<0.2
kidneys	<0.3	<0.3	<0.3	<0.30	<0.3
spleen	<0.4	<0.8	<0.4	<0.74	<0.8
heart	<0.2	<0.3	<0.2	<0.23	<0.2
ribs	<0.1	<0.1	<0.1	<0.054	<0.1
wool	<0.4	<0.26	<0.6	<0.6	<0.3
skin	0.022±0.007	0.022±0.007	0.034±0.01	<0.02	0.052±0.01
Cartilaginous tissue (ear)	<1	<1	<1	<1	<1
Group 2 (source of radionuclides – soil from the epicenter of a ground nuclear test)					
muscle	0.28±0.07	0.4±0.07	0.5±0.07	0.88±0.1	2.1±0.2
liver	6.9±0.4	14.1±0.5	140±2	210±2	650±4
lungs	5.8±0.3	1.3±0.1	41.4±0.7	21.7±0.4	27.4±0.6
kidneys	4.5±0.3	3.1±0.2	34.5±0.5	39.4±0.5	200±1
spleen	3.5±0.2	1.1±0.2	6.8±0.3	34.1±0.5	130±1
heart	0.89±0.1	0.36±0.1	3.0±0.2	4.5±0.2	14.2±0.4
ribs	4.3±0.3	2.6±0.3	20.1±0.4	53.8±0.9	160.4±1.0
brain	0.25±0.1	0.32±0.1	0.31±0.1	–	0.48±0.1
tail fat	7.1±0.3	3.1±0.2	3.9±0.2	5.2±0.3	4.4±0.2
tongue	0.34±0.1	0.41±0.1	1.6±0.2	2.2±0.2	5.2±0.2
Group 6 (source of radionuclides – soil, water and meadow vegetation from areas of radioactive water flows)					
muscle	<0.04	<0.3	<0.2	<0.3	<0.04
liver	<0.2	<0.3	0.56±0.2	<0.3	0.42±0.2
lungs	<0.2	0.45±0.2	<0.3	<0.3	<0.2
kidneys	<0.6	0.57±0.2	<0.2	<0.3	<0.6
spleen	<1	0.68±0.2	<0.3	<1	<2
heart	<0.4	<0.5	0.54±0.2	<0.4	<0.3
ribs	<0.2	0.51±0.2	<0.5	<0.4	<0.9
skin	<0.1	<0.1	<0.1	<0.1	<0.4
tail fat	<0.1	<0.1	<0.1	<0.2	<0.1

Figure 5 illustrates the dynamics of the ^{241}Am transition into the organs and tissues of animals.

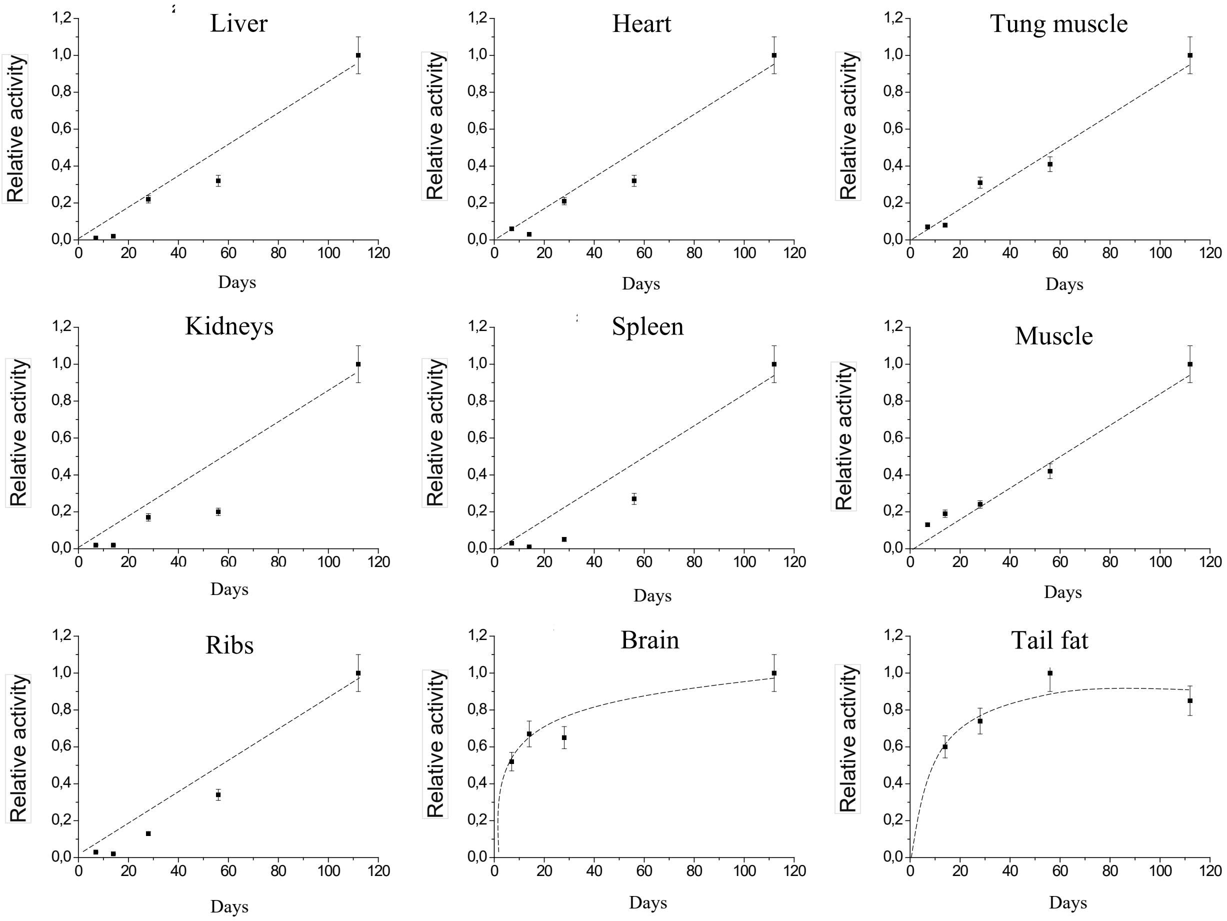


Figure 5- Dynamics of the Transition of ^{241}Am into Animal Organs and Tissues

Quantitative data on the activity concentration of ^{241}Am in organs and tissues are scarce. Despite this, the available data allow tracing the dynamics of the ^{241}Am transition into specific organs and tissues of the rams. It is observed that, in addition to the liver and bone tissue, which are commonly considered the main deposition sites for ^{241}Am, an increase in the radionuclide concentration occurs in the kidneys, spleen, femoral muscle, heart, and tongue muscles. In the brain and tail fat, the growth of activity slows down after 28 days. The difference between the minimum (on day 7) and maximum (on day 112) activity of the radionuclide in the liver was 100 times; in the kidneys, bone tissue, and spleen – 40-45 times; in the heart and tongue muscles – 15 times; in the femoral muscle and lungs – 5-8 times; in the brain and tail fat – 1.5-1.9 times.

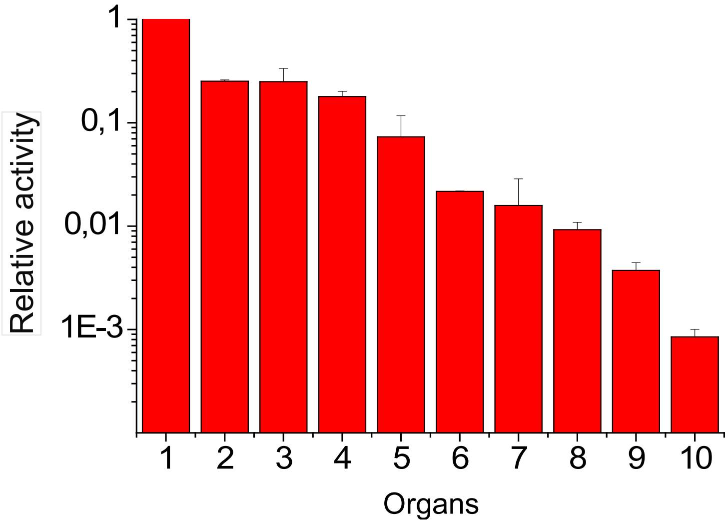


Figure 6- Distribution of ^{241}Am in the Organs of Rams. (1 – liver, 2 – bone tissue, 3 – kidneys, 4 – spleen, 5 – lungs, 6 – heart, 7 – tail fat, 8 – tongue muscles, 9 – thigh muscles, 10 – brain)

The highest concentrations of ^{241}Am are found in the liver, with the lowest in the femoral muscle and brain. The group of organs and tissues with higher concentrations of the radionuclide includes the bone tissue, kidneys, spleen, and lungs, while the group with lower concentrations includes the tail fat, heart, and tongue muscles. The coefficient of unevenness is 250 (for muscle tissue).

The transfer coefficients obtained for animals that were fed soil from the epicenters of ground tests (group 2) are presented in Table 10.

Table 10. Transfer Coefficients (F*f*) of ^{241}Am into Organs and Tissues

Tissues	F*f* of ^{241}Am in sheep tissues upon entry with soil from the epicenters of ground tests ($\times10^{-5}$)	Tissues	F*f* of ^{241}Am in sheep tissues upon entry with soil from the epicenters of ground tests ($\times10^{-5}$)
liver	>310	spleen	>60
ribs	>80	tail fat	2.0 (1.7-2.3)
kidneys	>100	tongue	1.8 (1.0-2.5)
lungs	12 (10-13)	muscle	0.3 (0.2-0.7)
heart	4 (2-7)	Brain	0.15 (0.12-0.15)
Note: numerator – median, denominator – lower and upper quartile			

Available data on the content of ^{241}Am in the organs and tissues of sheep from groups 1 and 6 allow only for estimated parameters of the ^{241}Am transition. The transfer coefficients of ^{241}Am into muscle tissue will be less than 4.0×10^{-3}. It is also suggested that one of the main storage organs may be the skin of the animals. The transfer coefficient of the radionuclide into the skin varies from 2.6×10^{-3} in the short term to 5.5×10^{-4} in the long term, assuming that the level of ^{241}Am penetration deep into the skin depends on the duration of percutaneous entry of the radionuclide (in areas where animals were located, the content of ^{241}Am in the soil reached from 200 to 1500 Bq kg^{-1}).

5.1.2.3 Transfer Parameter of ^{137}Cs

The results of spectrometric measurements of the organs and tissues of rams from groups 1, 2, 3, 5, and 6 are presented in Table 11.

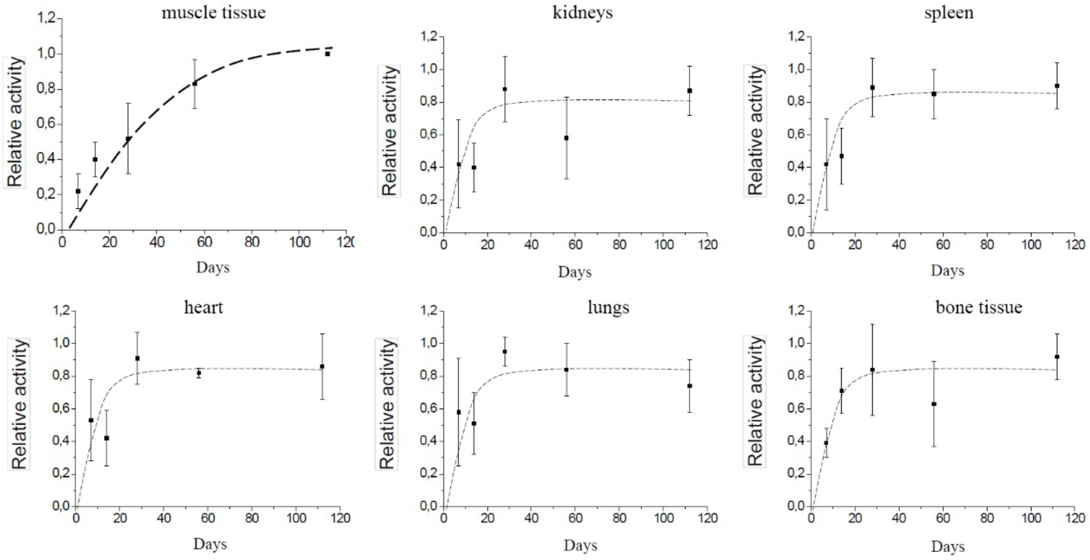
Table 11. Activity concentration of ^{137}Cs in organs and tissues of the rams

Tissues	Number of days of containment, days				
	7	14	28	56	112
Group 1 (source of radionuclides – steppe vegetation from the epicenters of ground tests) Bq kg^{-1} FM					
muscle	0.3±0.06	0.9±0.04	0.9±0.08	0.9±0.09	0.7±0.09
skin	0.1±0.02	0.1±0.02	0.4±0.03	0.43±0.03	11.9±0.2
ribs	0.3±0.08	0.6±0.1	<0.2	0.2±0.05	0.7±0.1
lungs	<0.3	<0.3	<0.3	<0.5	<0.5
liver	0.73±0.2	<0.4	<0.7	<0.3	<0.4
kidneys	<1	<1	<1	<1	<1
spleen	<1	<3	<1	<1	<2
heart	<0.6	<0.8	<0.5	<0.5	<1
cartilaginous tissue (ear)	<3	<3	<2	<3	<3
wool	<1	<0.7	<1	<1	<1
Group 2 (source of radionuclides – soil from the epicenter of a ground nuclear test)					
muscle	2.0±0.2	2.9±0.2	5.4±0.2	9.5±0.3	15.6±0.3
tail fat	0.47±0.2	0.75±0.2	< 0.2	0.34±0.2	0.41±0.2
ribs	< 0.9	< 0.9	< 1.1	1.0±0.4	2.0±0.4
lungs	4.0±0.3	2.4±0.2	5.4±0.4	6.3±0.3	5.4±0.4
brain	0.84±0.2	0.80±0.2	1.6±0.3	2.5±0.3	4.7±0.3
Tungs muscle	4.1±0.3	3.2±0.3	6.1±0.4	7.4±0.4	10.1±0.5
liver	5.1±0.5	3.4±0.4	5.5±0.5	5.4±0.5	6.9±0.6
kidneys	6.5±0.4	5.7±0.4	10.9±0.4	16.8±0.5	16.4±0.5
spleen	3.0±0.3	2.6±0.3	4.9±0.4	5.3±0.4	7.2±0.3
heart	4.3±0.2	3.7±0.2	5.0±0.4	5.5±0.5	6.9±0.4
Group 3 (source of radionuclides – meadow vegetation from areas of radioactive water flows)					
muscle	3.7±0.16	6.4±0.21	8.6±0.23	40±2	–
ribs	3.7±0.57	28.4±1.3	12.0±2.0	11.8±0.6	–
lungs	2.1±0.8	6.9±1.1	6.2±1.2	8.4±1.2	–
liver	4.6±1.1	9.0±1.1	15.2±1.2	12.4±1.3	–
kidneys	8.2±1.4	18.2±2.1	14.9±2.0	31.2±3.4	–
spleen	9.0±2.1	5.1±2.2	7.1±2.0	13.5±2.9	–
testicles	4.1±1.1	5.7±1.1	7.1±1.1	11.9±1.9	–
heart	4.2±1.0	10.2±1.3	14.4±2.0	11.6±1.7	–
wool	2.8±0.2	< 0.2	< 0.5	0.68±0.1	–
Group 5 (source of radionuclides – water and meadow vegetation from areas of radioactive water flows)					
muscle	5.2±0.8	10.1±0.6	11.2±0.8	15.3±0.9	16.4±0.2
tail fat	<0.2	<0.3	<0.2	<0.2	<0.2
skin	0.78±0.1	0.48±0.1	0.84±0.1	2.1±0.2	0.96±0.05

Tissues	Number of days of containment, days				
	7	14	28	56	112
ribs	2.8±0.2	5.2±0.8	-	6.5±0.5	4.6±0.4
lungs	8.1±1.1	8.0±0.5	<0.7	9.2±0.8	5.9±0.4
liver	10.6±1.1	2.2±0.6	1.9±0.6	14.6±0.9	9.1±0.3
kidneys	20.2±1.6	3.2±0.6	5.7±0.4	28.3±1.0	16.2±1.3
spleen	8.5±1.1	2.2±0.6	9.5±0.4	12.0±1.2	8.0±3.2
heart	10.1±1.0	10±0.5	3.0±0.2	14.1±0.9	7.2±0.6
Group 6 (source of radionuclides – soil, water and meadow vegetation from areas of radioactive water flows)					
muscle	3.0±0.5	4.1±0.5	7.9±0.63	13.7±0.8	14.9±0.8
tail fat	<0.3	<0.3	<0.2	<0.3	<0.2
skin	0.65±0.07	3.1±0.2	1.7±0.1	0.51±0.1	0.57±0.06
ribs	1.2±0.3	2.4±1.2	4.2±0.4	3.2±0.2	3.1±0.3
lungs	1.7±0.5	<0.8	7.8±0.7	5.3±0.4	4.9±0.7
liver	2.8±0.6	2.7±0.6	6.9±0.7	9.6±0.8	5.9±0.6
kidneys	3.6±0.6	6.0±0.4	21.2±0.9	13.3±1.5	16.2±0.8
spleen	1.2±0.6	3.2±0.5	8.2±0.7	7.8±0.4	6.6±0.9
heart	2.2±0.5	2.1±0.5	9.1±0.7	7.7±1.0	6.5±0.6

In all samples from the liver, lungs, kidneys, spleens, ear cartilage, and hair of animals from group 1-unlike all other groups-numerical values of ^{137}Cs were not achieved with the methodological hardware used. Nevertheless, the data allow us to estimate the levels of transfer of ^{137}Cs from steppe vegetation into the organs and tissues of animals.

The figure (Figure 7) shows the dynamics of the transition of ^{137}Cs into the organs and tissues of animals. Data are presented as relative concentrations of ^{137}Cs (with ^{137}Cs activity in the heart taken as unity).


muscle tissue

kidneys

spleen

heart

lungs

bone tissue

Figure 7- Dynamics of the Transition of ^{137}Cs into Animal Organs and Tissues

The research results indicate that under conditions of long-term daily intake of ^{137}Cs through various environmental components, the concentration of ^{137}Cs in organs increases to a certain value, after which a dynamic equilibrium occurs between its accumulation and elimination. Consequently, no further increase in ^{137}Cs activity in organs is observed. Thus, the equilibrium state for the kidneys, tongue, liver, spleen, testes, lungs, and tail fat occurs as early as the 7th day. Although the increase in the concentration of ^{137}Cs in the bone tissue, brain, and skin of animals is weakly expressed, it can be stated that the equilibrium state in these organs occurs on the 56th day. The concentration of ^{137}Cs in muscle tissue continues to increase at the selected time intervals of the experiment (up to 112 days); the equilibrium state of ^{137}Cs has not been established. However, a significant slowdown in growth is noted by day 112 of the experiment.

Distribution of ^{137}Cs in Animal Organs and Tissues

The distribution of ^{137}Cs in the organs and tissues of animals is shown in Figure 8.

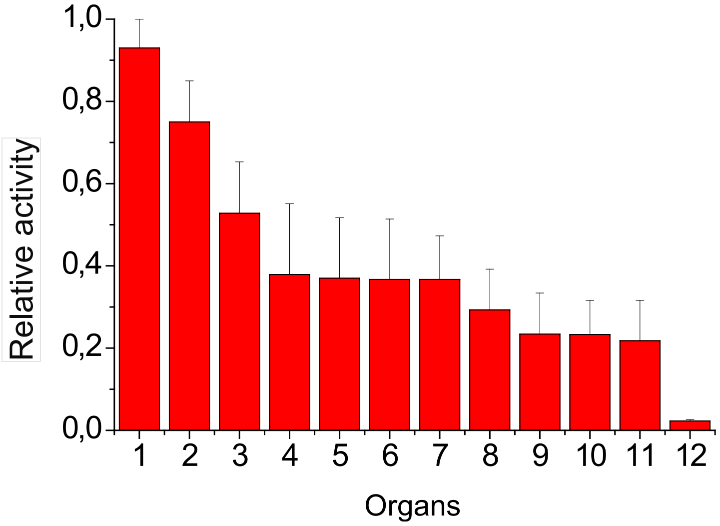


Figure 8- Distribution of ^{137}Cs in the Organs of Rams. (1 – thigh muscles, 2 – kidneys, 3 – tongue muscles, 4 – liver, 5 – heart, 6 – testes, 7 – spleen, 8 – lungs, 9 – skin, 10 – bone tissue, 11 – brain, 12 – tail fat)

The figure indicates that, in general, ^{137}Cs is distributed fairly evenly throughout the body, unlike tropic radionuclides. The difference between the highest and lowest activity of ^{137}Cs in the body ranges from 3 to 25 times. With long-term intake (more than 56 days), the highest concentrations of ^{137}Cs are found in muscle tissue and kidneys, with the lowest in skin and tail fat. The activity of ^{137}Cs in bone tissue is 4 times lower than in muscle tissue.

It should be noted that the nature of the distribution of ^{137}Cs activity among organs and tissues can change depending on the duration of the radionuclide's entry into the body. Thus, if in a shorter period (1–2 days) the highest activities of ^{137}Cs were found in the kidneys and liver, then with longer intake (from 8 weeks or more), the concentration of the radionuclide increases in muscle tissue and becomes 2–3 times higher than in other organs and tissues.

With prolonged intake, the activity of ^{137}Cs in the body decreases in the following order: muscles > kidneys > tongue > liver > heart > spleen > testes > lungs > bone tissue > brain > skin > tail fat > wool.

The distribution of ^{137}Cs in organs and tissues does not depend on the form and source of radionuclide entry into the body. Overall, with long-term intake of ^{137}Cs, its distribution follows a certain pattern, allowing the prediction of the radionuclide's content in one organ based on its content in another.

The analyses established that the distribution of ^{137}Cs in the kidneys, heart, liver, lungs, spleen, testes, and tongue does not depend on the duration and form (via food, water, or soil) of intake. Among these organs, the highest concentrations of ^{137}Cs were found in the kidneys, with nearly identical activity in the liver, heart, spleen, and testes, and the lowest concentrations in the lungs.

Transfer Coefficients of ^{137}Cs into Animal Organs and Tissues

The transfer coefficients of *^{137}Cs* into animal organs and tissues are presented in Table 12.

Table 12. Transfer Coefficients of ^{137}Cs into Animal Organs and Tissues, ×0.01

Tissues	Steppe vegetation from the epicenter o a ground test	Meadow vegetation from the area o a radioactive water flow	Soil from the epicenter of ground test
muscle	2.6 (2.6–2.7)	9.0 (8.6-9.4)	3.1 (2.4–3.9)
kidneys	<3	6.8 (6.3–7.4)	4.1 (2.7–4.1)
heart, liver, spleen, tongue, lungs	<2	2.8 (2.0–3.1)	1.3 (0.8–1.6)

Note: numerator – median, denominator – lower and upper quartile

The table indicates that the parameters of the ^{137}Cs transition into the organs and tissues of animals from different groups vary and depend on the source of the radionuclide. It has been established that ^{137}Cs supplied with water transfers more effectively than when supplied with food and soil, with the smallest amount of ^{137}Cs passing through the soil.

The level of ^{137}Cs transition also depends on the type of vegetation. When ingested through meadow vegetation from zones of radioactive watercourses, ^{137}Cs transitions more significantly than with steppe vegetation from ground-based testing sites.

5.1.2.4 Transfer Parameter of ^{90}Sr

The results of spectrometric measurements of organs and tissues of rams from groups 1, 2, 3, 4, 5, and 6 are presented in Table 13.

Table 13. Activity concentration of ^{90}Sr in organs and tissues of the rams

Tissues	Number of days of containment, days				
	7	14	28	56	112
Group 1 (source – Steppe vegetation from the epicenter of a ground test) Bq kg^{-1} FM					
muscle	<0.12	<0.12	0.29±0.08	0.2±0.07	0.23±0.06
skin	1.0±0.17	1.1±0.12	2.7±0.3	0.57±0.13	2.0±0.2
ribs	40±14	70±10	70±13	100±13	140±11
wool	12.3±1.2	10±2.7	32.0±1.9	21.9±1.8	16.3±1.6
Group 2 (source – soil from the epicenter of a ground nuclear test)					
muscle	0.13±0.05	< 0.07	< 0.10	0.21±0.10	< 1.1
ribs	20±6	60±3	55±20	160±20	210±30
Group 3 (source – meadow vegetation from areas of radioactive water flows)					
muscle	8±0.1	11±1	33±2	47±3	30±3
ribs	2200±50	4600±80	3600±70	–	18300±160
lungs	22±3	32±3	120±4	161±4	52±3
liver	13±2	8±4	45±3	73±3	32±3
kidneys	31±3	25±4	66±4	141±3	60±4
spleen	13±3	25±4	40±4	82±2	26±2
testicles	22±3	30±3	55±3	234±5	50±4
heart	12±3	17±4	34±3	75±2	30±2
wool	193±7	82±6	691±15	2520±20	852±13
Group 4 (source – water)					
muscle	1.5±0.1	2±0.2	2±0.2	4±0.4	6±1
ribs	600±55	700±40	1300±50	2200±100	7900±100
lungs	< 5	< 5	9±2	7±2	18±2
liver	< 4	< 5	3±1	<3	7±2
kidneys	< 4	< 4	7±2	10±3	19±3
spleen	< 5	< 6	5±2	10±2	23±4
testicles	< 5	< 5	13±4	8±1	11±2
heart	< 6	< 5	< 3	5±1	15±4
Wool	162±7	91.4±6.4	192±7	584±19	928±19
Group 5 (source – water and meadow vegetation from areas of radioactive water flows)					
tail fat	12±1	12±1	25±1	–	–
ribs	5510±80	7110±60	15630±100	16430±80	27180±140
wool	860±10	1270±10	350±4	840±8	1580±10
Group 6 (source – soil. water and meadow vegetation from areas of radioactive water flows)					
tail fat	59±1	14±0.4	–	–	–
ribs	4560±110	–	9880±60	14570±130	30020±120
wool	439±5	840±12	550±5	1431±11	1344±10

Note: "–" indicates a sample was not analyzed.

Considering the low levels of transfer of ^{90}Sr into the "soft" organs and tissues of animals, as well as the low concentrations of the radionuclide in the daily diet, analyses of samples from the liver, kidneys, heart, spleen, lungs, and testes of animals from the 1st, 2nd, 5th, and 6th groups were not carried out.

One objective of the study was to investigate the dependence of the distribution of ^{90}Sr in bone tissue on its content in wool. These results will enable the determination of the radionuclide concentration in the body of animals without euthanizing them. Consequently, special attention was paid to the determination of ^{90}Sr in wool and bone tissue.

Features of the ^{90}Sr Transition at Different Arrival Times

The graphs (Fig. 9) indicate that the activity of ^{90}Sr in "soft" organs and tissues increases during the first month, after which it stabilizes for the remainder of the experiment, while its concentrations in bone tissue continue to increase until 112 days.

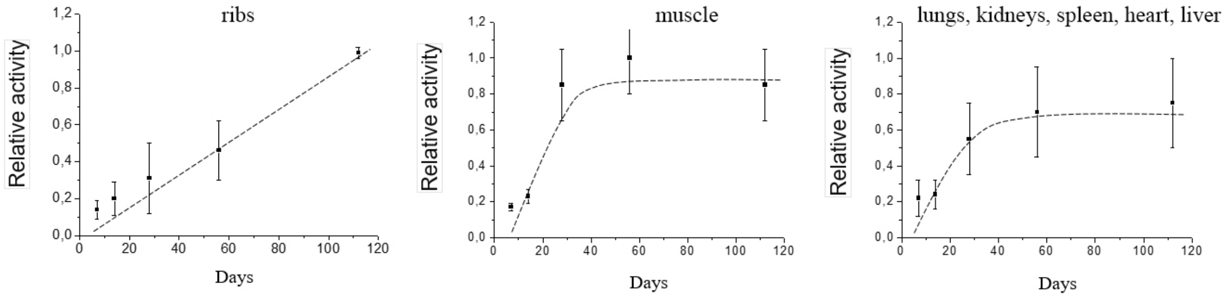


Figure 9- Dynamics of the transition of ^{90}Sr into organs and tissues of sheep

As expected, the main concentrations of ^{90}Sr were found in bone tissue and wool. Its content in "soft" organs was 2–3 orders of magnitude lower than in bone tissue (Fig. 10).

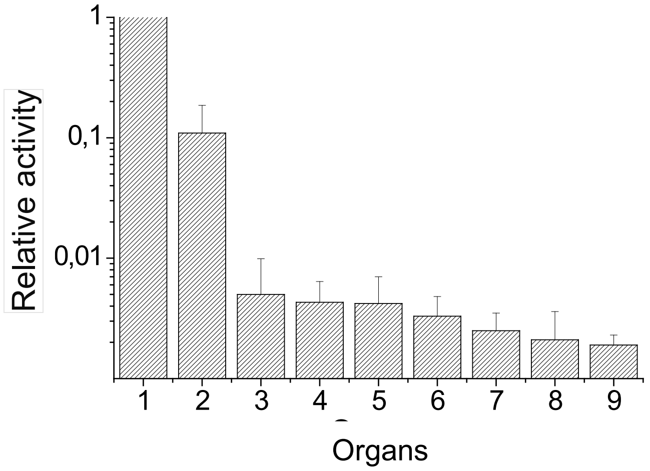


Figure 10- Distribution of ^{90}Sr in the Organs of Rams. (1 – bone tissue, 2 – wool, 3 – lungs, 4 – testes, 5 – kidneys, 6 – spleen, 7 – heart, 8 – liver, 9 – femoral muscle)

Analysis of the research results suggests that the distribution of the activity concentration of ^{90}Sr in "soft" organs follows a weakly defined pattern. The highest concentrations were recorded in the lungs and testes, with a subsequent decrease in the order: kidneys > spleen > heart > liver > femoral muscle. This distribution pattern of the activity concentration of ^{90}Sr in organs and tissues is observed in most experimental animals and does not depend on the type and timing of radionuclide entry into the body.

It has been established that the distribution of ^{90}Sr in bone tissue and wool shows a certain dependence (Fig. 11).

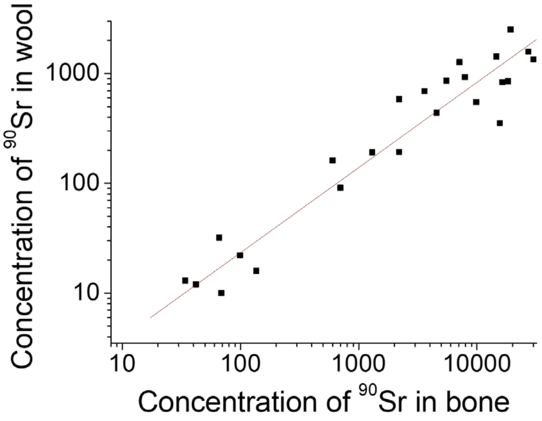


Figure 11- Correlation of Activity concentration of ^{90}Sr in Animal Bone Tissue and Wool. (r=0.8±0.14, tr=5.7)

The critical level of significance was set at p=0.05. For the number of degrees of freedom k=21, the value of the t-Student criterion is t(0.05)=2.08. Thus, tr>t(0.05), indicating the high statistical significance of r and the reliability of its deviation from zero. The signs are positively correlated; an increase in the activity of ^{90}Sr in wool characteristically accompanies an increase in the activity of the radionuclide in the bone tissue of sheep.

Based on the similarity in the distribution of ^{90}Sr in the organs and tissues of animals, two groups can be distinguished: the first includes lungs, kidneys, spleen, and testes; the second includes femoral muscle, heart, and liver (Fig. 5). This classification allows for the calculation of transition coefficients not for individual organs and tissues but provides an average for the group. The transfer coefficients of ^{90}Sr into the organs and tissues of animals from various groups are presented in Table 14.

Table 14. Transfer Coefficients of ^{90}Sr into Animal Organs and Tissues, ×0.01

F_f	water	Meadow vegetation from the zone of a radioactive watercourse	Soil from the epicenter of a ground test
ribs	>15000	1100 (970–1100)	670 (570–780)
lungs, kidneys, spleen, testicles	15 (11–17)	3.3 (2.8–4.3)	–
muscle, heart, liver	4.3 (3.9-4.8)	1.8 (1.6–2.8)	0.6 (0.05–0.8)

Note: in the numerator – median, in parentheses – lower and upper quartile.

Data analysis revealed that the transition of ^{90}Sr into the organs and tissues of animals, when the radionuclide enters the body through various natural components (soil, water, feed), varies significantly.

The bioavailability of ^{90}Sr for animal bone tissue supplied with water is an order of magnitude higher than when supplied with food and soil. If ^{90}Sr enters the body of animals with water and feed together, the coefficient of ^{90}Sr in bone tissue is close to the average of individual values. It should also be noted that, according to none of the time intervals, was an equilibrium state of ^{90}Sr in the bone tissue of animals established.

SUMMARY

This thesis aimed to create evidence for the movement of long-lived artificial radio-nuclides ($^{239+240}$Pu, ^{241}Am, ^{137}Cs, ^{90}Sr) from contaminated environments into meat products on the Semipalatinsk Test Site (STS). It integrated (i) a characterisation of the soils, waters and vegetation of a site and of its representative test areas, (ii) controlled feeding studies with rams to measure the distribution in edible tissues and uptake, and (iii) a practical approach to estimating product concentration, deriving soil boundary intake criteria and apportioning soil, water and forage intake from residual stock for grazing systems. All together, these elements delineate practical operational transfer parameters and provide a working boundary for radiological assessment of the food chain at and around the STS.

The test areas analysed vary greatly in both radioelements' geochemistry and mobility. At Degelen, ^{90}Sr is mobile (primarily in hydro chemically exchangeable forms) and ^{137}Cs and ^{241}Am are more strongly bound. Adit and stream hydrologic connectivity maintains transport to riparian vegetation and to livestock watering troughs. The opposite is true for the Experimental Field (P-2) which is arid and where radionuclides are more strongly retained in surface soils and less available to plants since leaching is absent. Compartmentalised contamination is provided by technogenic lakes and fracture controlled groundwaters. The STS vegetation's accumulation coefficients are highly variable. For transuranics the variation is about 15-fold and for ^{137}Cs and ^{90}Sr about 75 fold which underscores the site and matrix specific transfer need.

Transfer was quantified using the transfer coefficient F_f ($d \cdot kg^{-1}$) and the transfer ratio CRdiet that relates dietary concentration to tissue activity and daily intake. Controlled groups were designed to partition intake from contaminated forage, water, and soil (and their combinations) over which daily consumption was monitored to calculate radionuclide intakes. These defined measures, alongside world standards, facilitate inter-comparison of work within STS and beyond.

Across radionuclides, tissue distributions followed biologically consistent patterns that were modulated by intake route:

- ^{137}Cs showed an equal distribution in the body throughout the period of study. However, after eight weeks of study, it was observed that higher concentrations of Cesium-137 were present in the muscles and kidneys. Measured concentrations (as reflected in the median F_f values) for muscle tissues showed the strongest association with the intake of waters/meadow vegetation associated with the radioactive watercourses ($\approx 9.0 \times 10^{-2}$), were intermediate for steppe vegetation ($\approx 2.6 \times 10^{-2}$), and were lowest with the ground-test soils ($\approx 3.1 \times 10^{-2}$). Other organs such as the heart, liver, spleen, tongue and lungs demonstrated lower Ff values (the ratio of caesium concentration in an organ to that in the blood circulating in the organ) than muscle and kidneys.

- ^{90}Sr unlike ^{137}Cs, was observed to be predominantly located in the bones and wool, with the activities of "soft" tissues in organs being 2-3 orders lower. There was extreme transfer to ribs, especially with the influx of ^{90}Sr via water (^{90}Sr concentrations were in excess of 15000×10^{-2}), and to a lesser degree with radioactive watercourse associated meadow vegetation ($\approx 1100\times10^{-2}$) and ground-test soils ($\approx 670\times10^{-2}$). The ratio of soft tissue to bone was not reached during the study period.
- The distribution of $^{239+240}$Pu followed the classical affinities of actinides within reticuloendothelial and mineral tissues: liver $>$ bone $\gtrsim$ spleen $\geq$ kidneys $>$ lungs/heart/muscle. Transfer to liver remained elevated (e.g., $>3.1\times10^{-3}$ in $\times10^{-5}$ units tabled as “>310"). Muscle Ff was much lower and route sensitive ($\approx$8, 1.8, and 0.05 in $\times10^{-5}$ for vegetation from epicentre, watercourse, watercourse soils, and ground-test soils, respectively). Steady state in liver and bone was not reached in the experimental durations.
- The distribution of ^{241}Am, for example, was also elevated in the liver (and bone), with considerable transfer to kidneys and spleen, and very low for skeletal muscle and brain. From soil-borne uptake, $F\,f$ values ($\times10^{-5}$) within ground-test epicentre for soil were liver >310; kidneys >100; ribs >80; lungs ~12; heart ~4; muscle ~0.3. These results reinforce that soil ingestion dominates the pathway for actinides into the offal portions of the carcass that can be eaten.

Besides empirics, the thesis presents a practical assessment framework that sets forth methodology to (i) compute anticipated radionuclide concentration levels in products, based on measured intakes and transfer parameters, (ii) establish boundary soil criteria that would ensure product compliance with radiological safety standards, and (iii) quantify the contributions of soil, water, and vegetation to daily intake under STS husbandry, within apportioning STS husbandry conditions. This yields a proactive template for decision-making on surveillance, zoning, and risk communication, which can be modified with the addition of new monitoring data.

There are three management-relevant insights to be garnered:

- The hydrologically connected areas (Degelen) are critical control points: restriction of animal access to contaminated streams/springs and associated meadows would disproportionately reduce ^{137}Cs and ^{90}Sr burdens in meat and bone.

- Soil ingestion drives actinide entry: geophagy and feed contamination with surface dust/soil (e.g. geophagy, feed handling, grazing choice, grazing season) are dominant conduits of $^{239+240}$Pu and ^{241}Am in edible offal.
- The heterogeneity of the hot-spot requires focused attention: the 15- to 75-fold variability in plant uptake highlights the necessity for targeted sampling of the vicinity, rather than ranger blanket suborbital sampling, especially adjacent to chronic legacy technical zones and technogenic water bodies where rule-bound assumptions reign, along rigorous streams radiating from centres of chronic oblation.

Limitations and future work. The dry inhalation path (especially soil dust) and long-term redistribution post exposure were neglected, as were winter conditions and the multi-radionuclide interactions. Stubby Transfer Systems should have regional scale correction applied to their unique ecological samples rather than extrapolation. Filling these gaps would provide additional insights for guiding regulations and improving dose estimates.

This research constructs a system that interlinks field-grounded exposures with standardised assessment metrics alongside a practical evaluation toolkit. Such an integration sets the framework needed to manage and screen livestock products within areas impacted by STS. This research indicates that attainable pathway management—especially concerning water access and soil ingestion—can significantly reduce the radionuclide burdens present within meat and offal. Moreover, it demonstrates that the biokinetics of certain radionuclide species, particularly some actinides and fission products, are distinguishable and predictable, and that variability within the environment as a source of geochemical constituents needs to be explicitly integrated into the monitoring and decision frameworks of the assessment. STS-edited transfer parameters and methods are ready for practical onsite risk management, while at the same time, enriching international radioecology data and models.

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