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Assessment of Radon Concentration in Drinking Water and Calculation of Radiation Exposure Dose of Critical Population Groups Living Near the Mothballed Uranium Mine in Northern Kazakhstan

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Normative References

This dissertation references the following standards, guidelines, and regulatory frameworks regarding radon concentrations and radiation exposure limits:

1. Sanitary Rules of the Republic of Kazakhstan for Drinking Water (Radon in Water): The maximum allowable concentration of radon in drinking water is 60 Bq/L, as established by the Order of the Minister of Health of the Republic of Kazakhstan No. 473 dated November 28, 2007. This regulation outlines sanitary-epidemiological requirements for water sources, water supply, and water quality.

2. Sanitary Rules of the Republic of Kazakhstan for Indoor Air (Radon in Air): The maximum allowable concentration of radon in indoor air is 200 Bq/m³, according to the Order of the Government of the Republic of Kazakhstan No. 201 dated February 7, 2012, which defines sanitary-epidemiological requirements for ensuring radiation safety.

3. World Health Organization (WHO), 2009: According to the *Handbook on Indoor Radon: A Public Health Perspective*, the recommended reference level for radon concentration in indoor air is 100 Bq/m³. If this level cannot be achieved due to national circumstances, it should not exceed 300 Bq/m³. For drinking water, WHO recommends a reference value of 100 Bq/L and an annual committed effective dose limit of 0.1 mSv/year.

4. International Commission on Radiological Protection (ICRP), 2007: ICRP Publication 103 sets the annual effective dose limit for public exposure from controllable sources (excluding natural background and medical exposure) at 1 mSv/year.

Definitions

The following terms with their respective definitions are used in this thesis.

Radon	- A naturally occurring radioactive gas that is colorless, odorless, and tasteless. It forms from the decay of uranium in soil, rock, and water and can accumulate indoors, posing significant health risks, primarily lung cancer.
Annual Effective Dose	- A measure of the radiation dose received by an individual in one year, considering the type of radiation and the sensitivity of organs and tissues exposed. Expressed in millisieverts per year (mSv/year).
Becquerel	- The SI unit for radioactivity, representing one radioactive decay per second.
Millisievert	– A unit of effective radiation dose, used to quantify the risk of exposure to ionizing radiation
Inhalation Exposure	- The intake of radon gas through breathing, the most significant route of exposure for indoor radon.
Ingestion Exposure	- The intake of radon through drinking contaminated water, which contributes to internal radiation exposure.

Designations and abbreviations

AED	Annual Effective Dose
Bq/m³	Becquerels per cubic meter
Bq/L	Becquerels per liter
COPD	Chronic Obstructive Pulmonary Disease
EEVA	Equilibrium Equivalent Volumetric Activity
EPA	Environmental Protection Agency (USA)
GAC	Granular Activated Carbon
ICRP	International Commission on Radiological Protection
ISL	In-situ Leaching
ISR	In-situ Recovery
mSv	Millisievert
Rn	Radon
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization

Introduction

Topic Relevance

Since 2009, the Republic of Kazakhstan has been the world's leading producer of natural uranium; Kazakhstan produces about 40% of the world's uranium production. Over the past 50 years, 20 uranium deposits have been developed in Kazakhstan [1]. Currently, more than 240 million tonnes of radioactive waste have accumulated on the territory of the Republic in the form of tailings of enrichment plants, heap leach stacks, tailings-storage facilities of hydrometallurgical plants, dumps of poor and unprocessed commercial ore, which represent a great danger as a source of radioactive and chemical pollution of the environment and have a harmful effect on the health of the population [2].

The main works on conservation and liquidation of uranium deposits in the North Kazakhstan region were completed in 2008 [3]. The mothballed uranium facilities have been transferred under the control of local authorities and remain ownerless and uncontrolled [4]. The mothballed uranium facilities are an unexplored threat to residents of nearby towns and villages. Radon is a potential threat to the population living in the vicinity of mothballed uranium mines.

Radon safety is an important issue of our time. Radon is a natural, inert, radioactive, alpha-emitting, colourless and odourless gas produced by the decay of uranium in the Earth's crust. The combination of these characteristics makes it difficult to detect the presence of radon in homes and drinking water. A report by the United Nations Scientific Committee on the Effects of Atomic Radiation states that radon is the source of about half of the total dose of ionising radiation received by the public from natural sources [5]. According to the U.S. Centers for Disease Control and

Prevention, radon is the second cause of lung cancer and 10-14% of lung cancer cases are due to public exposure to radon decay products in buildings [6].

Because radon is a decay product of uranium in the Earth's crust, high concentrations of radon can often be found near mothballed uranium mines. Therefore, populations located near mothballed uranium mines are at high risk of radon exposure [7]. Their drinking water may contain high concentrations of radon radionuclides, their homes may contain high concentrations of soil air entering through cracks and windows in buildings.

The topic of regulation of radon accumulation in the human body has always been extremely topical in the issue of radiation protection of the population [8]. Assessment of radon intake and calculation of Radiation exposure dose for different population groups is fundamental in the problem of minimization of negative consequences of population exposure, its medical and social rehabilitation.

Purpose of the study

Assessment of radiation situation of Saumalkol settlement and calculation of probable effective dose from radon contact in residential and public buildings, development of recommendations on radiation exposure dose reduction.

Object of the study

The study is aimed at solving the problems of radon safety of the population of Saumalkol settlement living near mothballed uranium mines and radioactive waste storage facilities.

The subject of the study will be residential and public buildings, drinking water and water used in the household of the population of Saumalkol settlement.

Objectives of the study:

1. Assessment of radiation situation in the territory of Saumalkol settlement, located near mothballed uranium mines, on the territory of Northern Kazakhstan;

2. Determination of radon content in residential and public buildings of Saumalkol settlement;

3. Calculation of radiation exposure dose for the population due to radon intake;

4. Development of practical recommendations to reduce the кadiation exposure dose of the population.

Study Material:

In the process of this study, housing facilities in Saumalkol settlement located near mothballed uranium mines in the north of the Republic of Kazakhstan was examined.

Novelty of the study:

For the first time the radiation situation will be assessed and effective radon dose will be calculated for critical groups (populations located near mothballed uranium mines). Special practical recommendations on radon dose reduction for critical population groups will be created.

Research Statement for Defense:

Out of 58 samples, 12 samples of indoor radon exceeded Kazakhstan’s limit of 200 Bq/m^3 and 11 samples exceeded the higher limit of 300 Bq/m^3 recommended by World Health Organization; All 18 samples of water exceeded maximum permissible level 60 Bq/L (Kazakhstan) and 100 Bq/L (WHO). The research calculates annual effective doses (AED) for different age groups. The study builds a series of short-term and long-term recommendations.

Practical Significance:

The practical significance of this research lies in its potential to directly inform public health and environmental protection policies in Kazakhstan and other uranium-mining regions. By identifying elevated levels of radon in drinking water, the study serves as an early-warning system for long-term radiological hazards, which are often underestimated due to the invisible and cumulative nature of radiation effects.

Key practical outcomes include:

- Health Risk Assessment: The research enables the estimation of internal radiation doses received by local populations, thus facilitating targeted health interventions.
- Policy Development: The findings can support the formulation of national and regional policies regarding environmental radiation safety, particularly in post-industrial zones.
- Water Quality Monitoring: The methods applied in the study can be utilized by environmental agencies for ongoing monitoring of drinking water sources.
- Public Awareness: By highlighting radon as a waterborne risk, the research raises awareness about lesser-known yet significant pathways of radiation exposure.

Ultimately, this dissertation contributes to enhancing community health protection strategies and environmental risk management frameworks in areas affected by historical uranium mining operations.

Radon

Radon (Rn), atomic number 86, is a colourless, odorless and tasteless noble gas. It is chemically inert due to its complete valence electron shell, making it unreactive under most conditions [9]. However, radon is highly radioactive, with its most stable isotope, radon-222, having a half-life of approximately 3.8 days [10]. This radioactivity leads to its decay into radioactive polonium and the emission of alpha particles.

Radon gas is directly related to uranium through the natural radioactive decay series of uranium-238 (^{238} U) and uranium-235 (^{235} U). When uranium undergoes radioactive decay, it passes through a series of intermediate decay products, eventually forming radon as a gaseous decay product. In the uranium-238 decay chain, the decay of radium-226 (^{226} Ra) produces radon-222 (^{222}Rn). Similarly, in the uranium-235 decay chain, radon-219 (^{219} Rn), and radium-224 generating radon-220 from thorium-232 is produced [11]. However, radon-222 is the most important isotope because it has a longer half-life of about 3.8 days compared to radon-219, which has a half-life of only 3.96 seconds.

Uranium occurs naturally in various geological formations, such as granite, phosphate rock and shale, which can act as sources of radon gas. As uranium decays over millions of years, radon gas is released and migrates through soil and rock, potentially entering buildings through cracks in foundations, basements and water supplies [12]. Areas with high soil uranium concentrations typically have elevated indoor radon levels [13].

Radon's association with uranium-rich environments makes it an important indicator of uranium deposits. In uranium exploration, radon detection techniques such as soil gas sampling and airborne radon surveys are used to locate potential uranium ore bodies. Radon may be used in the exploration of petroleum or uranium, as a tracer in the identification of NAPL (non-aqueous phase liquid) contamination of the subsurface, in atmospheric transport studies, and as a radiation standard for calibrating radon monitoring equipment in support of environmental surveys of homes and other buildings [14]. As a noble gas, radon can diffuse through rock formations, making it a useful tracer in geochemical prospecting [15].

Due to their common origin, regions with significant uranium mining activity are often at increased risk of radon exposure. The decay of uranium-bearing minerals in tailings and mining waste results in persistent radon emissions that pose occupational health risks to miners and nearby communities. Measures such as ventilation systems, radon-resistant building materials, and regular monitoring are used to reduce exposure [16] [17].

1. Health effects of Radon

Radon exposure has been extensively studied over decades, with long-term research providing critical insights into its health effects. Early studies focused on miners who were frequently exposed to high concentrations of radon in confined underground environments. These investigations revealed significantly higher rates of respiratory diseases, particularly lung cancer, among uranium, gold, and other hard rock miners. The confined spaces in mines, coupled with poor ventilation, created conditions conducive to prolonged radon exposure, offering a clear association between cumulative exposure and adverse health outcomes [17].

One of the most notable studies focused on uranium miners in the Colorado Plateau in the United States. This cohort was monitored over decades, and the findings established a strong dose-response relationship between cumulative radon exposure and lung cancer mortality [18]. Similar studies conducted in Europe, particularly in Germany, Sweden, and the Czech Republic, as well as in China, confirmed the heightened risks associated with occupational radon exposure.

Occupational radon exposure, particularly among uranium miners, is associated with significantly heightened health risks, most notably lung cancer. Studies, such as those conducted on former Wismut miners in Germany, have demonstrated a clear correlation between radon exposure and increased lung cancer mortality[19]. Research by Kreuzer et al. (2017) highlights that even decades after exposure, the risk of lung cancer remains elevated, underscoring the long-term impact of radon on health [20].

Occupational radon exposure poses significant health risks, particularly for workers in underground mining environments. The study on Swedish iron miners highlights an increased mortality risk for cancers other than lung cancer, including stomach and rectal cancers, compared to the general population. Although the study did not find a strong correlation between cumulative radon exposure and these cancers, it suggests potential risks, especially for stomach cancer, which may be influenced by other factors such as the high prevalence of stomach cancer among Finnish workers in the cohort [21].

The study on Czech uranium miners highlights heightened risks of non-lung solid cancers associated with occupational radon exposure. While the primary concern with radon exposure has traditionally been lung cancer, this research indicates that miners exposed to radon and its progeny may also face increased risks for other cancers, such as stomach, liver, and gallbladder cancers [22].

The study "Indoor radon and lung cancer in China" (1990) investigated the relationship between indoor radon exposure and lung cancer risk. While the study focused on residential settings, its findings have implications for occupational environments. Elevated radon levels in workplaces, especially in underground settings like mines, can increase the risk of lung cancer among workers [23].

These findings emphasize the importance of stringent occupational safety measures and continuous monitoring to mitigate the risks posed by radon in workplaces, especially in mining and other industries where radon exposure is prevalent.

Researchers developed the "working level months" (WLM) metric to quantify exposure levels in mining cohorts, a measure that remains pivotal for regulatory frameworks [24]. Beyond lung cancer, mining studies also identified increased incidences of chronic obstructive pulmonary disease (COPD), pulmonary fibrosis, and emphysema, although smoking and exposure to silica dust confounded these findings [25].

As concerns over radon expanded beyond occupational settings, researchers began to investigate its presence in residential environments. In the 1980s, studies revealed that radon could accumulate in homes, particularly in basements and poorly ventilated areas [26]. Residential exposure studies gained momentum, with case-control research conducted in North America, England, Europe, and China. These studies compared lung cancer patients with radon exposure histories to healthy controls, revealing a consistent association between long-term residential radon exposure and increased lung cancer risks. [26]; [27]; [28], [29].

Pooling data from multiple studies became essential to overcome the limitations of smaller, individual research efforts. Large meta-analyses of North American, European, and Chinese residential studies confirmed the correlation between radon exposure and lung cancer. The analyses highlighted that for every 100 Bq/m^3 increase in indoor radon concentration, the risk of lung cancer rose by approximately 16%, with smokers experiencing a significantly amplified risk due to the synergistic effects of radon and tobacco [30]. These studies also underscored the challenges posed by long latency periods, as radon-induced lung cancer often manifests decades after initial exposure.

Although smoking significantly exacerbates the risk, long-term studies confirmed that non-smokers are also vulnerable to radon-induced lung cancer [31], [32], [33]. This finding emphasized radon as a universal carcinogen, capable of causing harm regardless of individual lifestyle factors. Some research also suggested that early-life exposure might increase lifetime risks, given the higher respiratory rates and developing lungs of children [33]. While the evidence remains limited, this possibility has prompted further investigation into radon's effects on younger populations.

Insights from these long-term studies played a pivotal role in shaping international guidelines and public health policies. Regulatory bodies like the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO) established safety thresholds for radon exposure and recommended mitigation strategies for homes and workplaces as 100 Bq/m^3 and in case this level cannot be met due to factors unique to that nation, it should not exceed 300 Bq/m^3[17a]. Public health campaigns emphasized the importance of radon testing, particularly in regions with high geological radon emissions.

Long-term studies also revealed challenges in assessing radon's effects. Confounding factors, such as smoking and occupational exposure to substances like silica dust and diesel exhaust, complicated the interpretation of results. Researchers used advanced statistical methods to isolate radon's effects and refine exposure assessments. Furthermore, while high-level exposure risks were well-documented, understanding the impact of low-level residential exposure required larger sample sizes and longer follow-up periods to achieve statistical significance [34].

Regional variations in radon exposure also added complexity to these studies. Differences in geology, building construction, and ventilation practices influenced indoor radon levels, making it challenging to generalize findings across diverse populations [35], [36]. Despite these challenges, long-term research consistently demonstrated the serious health risks posed by radon and underscored the need for comprehensive mitigation strategies.

Inhalation is the primary route of radon exposure for both the general population and occupationally exposed groups, such as miners[37] Radon gas diffuses into indoor air from soil or water sources. Once inhaled, radon progeny attach to lung tissues, emitting alpha particles that damage DNA and increase the risk of lung cancer [38]. Lung cancer is the most significant health effect associated with long-term radon inhalation. Studies of uranium miners have consistently shown a correlation between radon exposure and increased lung cancer risk, particularly when combined with smoking. Non-cancer respiratory effects, such as chronic obstructive pulmonary disease (COPD), have also been linked to radon exposure, though confounding factors like smoking complicate these findings.

Radon dissolved in water, particularly from groundwater sources, can lead to ingestion exposure [39], [40]. Radon is absorbed through the gastrointestinal tract, with its progeny contributing to internal radiation doses [41]. Although ingestion is a secondary route of exposure, radon in drinking water has been associated with cancers of the digestive system, including stomach and esophageal cancers. However, studies have yielded inconsistent results due to difficulties in separating ingestion effects from inhalation exposure caused by radon release from water [42]. Radon can penetrate the skin during bathing or handling radon-contaminated water. Studies have shown minimal absorption of radon through the skin compared to inhalation [43]. Dermal exposure is considered a minor contributor to radon toxicity [38a]. However, systemic distribution of radon following dermal absorption has been observed, though its clinical significance remains unclear [44].

In many environments, multiple routes of exposure coexist. For example, radon released from water contributes to both inhalation and ingestion risks. According to UNSCEAR (2000), 90% of the radon dosage in drinking water is absorbed by inhalation, not ingestion (UNSEAR 2000). Occupational settings, such as underground mining, often involve combined exposure to radon gas, dust, and other carcinogens, compounding the health risks. Mitigation strategies include improving ventilation in buildings, sealing cracks in foundations, and treating radon-rich water supplies. Public health initiatives emphasize radon testing and education to reduce exposure risks in residential and occupational settings.

Uranium Mining

The 1950s and 1960s saw the commercialization of nuclear power, leading to increased demand for uranium [45]. Countries like the United States, France, and the Soviet Union invested heavily in uranium mining and enrichment facilities[45a]. The development of advanced mining techniques, such as in-situ leaching (ISL), allowed for more efficient extraction[46].

Modern Uranium Mining Techniques:

Open-Pit and Underground Mining

Traditional mining methods, including open-pit and underground mining, remain prevalent in regions with high-grade uranium deposits. These methods, however, are associated with significant environmental impacts, including habitat destruction, water contamination, and the generation of radioactive waste [47].

In-Situ Leaching

ISL, also known as in-situ recovery (ISR), has become the dominant method for uranium extraction in recent decades. This technique involves injecting a leaching solution into uranium-bearing aquifers to dissolve the mineral, which is then pumped to the surface for processing. ISL is less invasive than traditional mining and reduces surface disturbance, but it poses risks of groundwater contamination if not properly managed.

Byproduct Recovery

Uranium is sometimes recovered as a byproduct of other mining operations, such as phosphate or copper mining. This approach can reduce the environmental footprint of uranium extraction by utilizing existing infrastructure.

Kazakhstan's uranium mining legacy

According to the World Nuclear Association (2025), Kazakhstan is the world's largest producer of uranium, accounting for approximately 40% of global production. Other major producers include Canada, Australia, and Namibia [48]. Global uranium reserves are estimated at 6.1 million metric tons, with significant deposits in Australia, Kazakhstan, and Canada [49].

Uranium mining is a cornerstone of Kazakhstan’s economy and a key contributor to the global nuclear energy sector. With vast uranium reserves and advanced extraction technologies, Kazakhstan has dominated the uranium market for over a decade. However, the industry faces challenges related to environmental sustainability, market volatility, and geopolitical dynamics. This article provides an in-depth analysis of the current state of uranium mining in Kazakhstan, supported by modern scientific sources and data.

Kazakhstan holds the second-largest uranium reserves in the world, estimated at approximately 900,000 metric tons, or 14% of global reserves (Ministry of Energy of the Republic of Kazakhstan, 2020). The country's deposits are primarily located in the southern regions, including the Chu-Sarysu and Syr-Darya basins, which are known for their high-grade uranium ores [50].

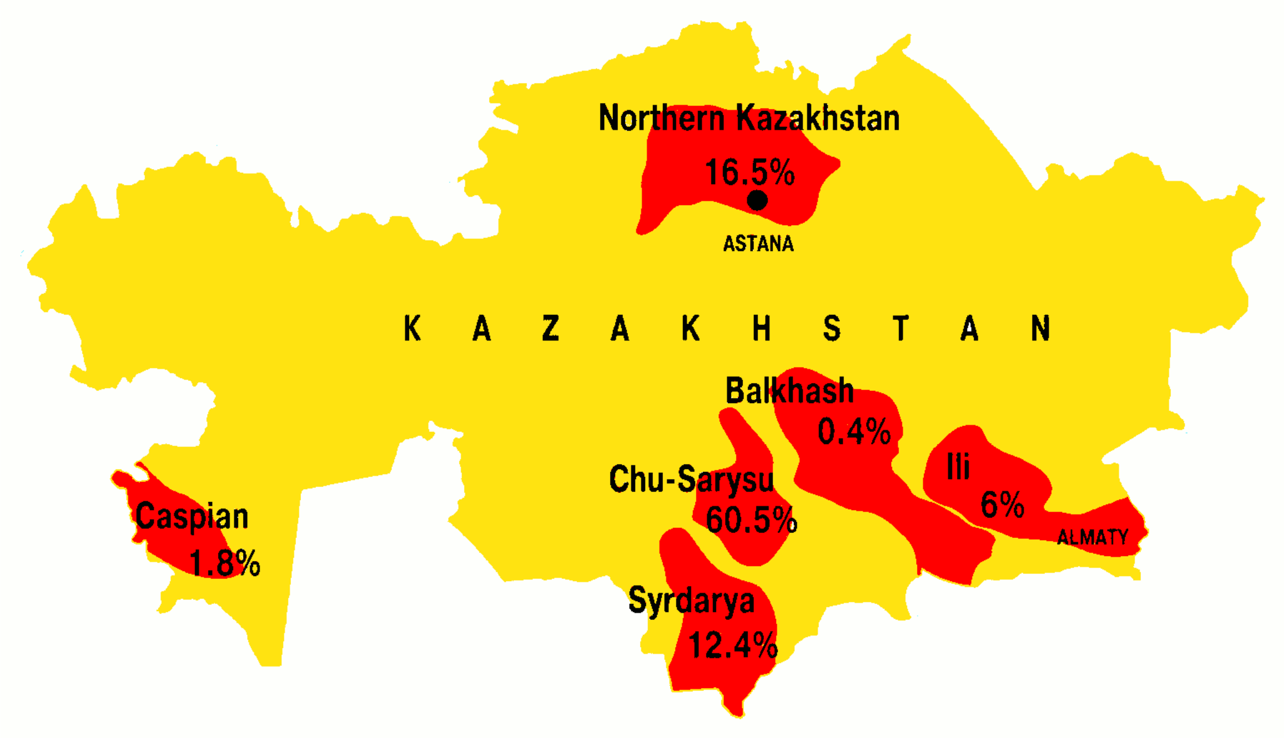

Figure 1.Kazakh uranium reserves[74].

Kazakhstan's dominance in uranium production gives it considerable influence over global uranium prices. The country's production decisions can significantly impact the market, as seen in 2017 when Kazatomprom reduced output to stabilize prices. A 2022 report by the International Energy Agency (IEA) noted that Kazakhstan's strategic role in the uranium market is critical for ensuring global energy security[51].

Nowadays, Kazakhstan primarily employs in-situ leaching (ISL), also known as in-situ recovery (ISR), for uranium extraction. This method involves injecting a leaching solution (typically acid or alkaline) into uranium-bearing aquifers to dissolve the mineral, which is then pumped to the surface for processing [52]. ISL is less environmentally disruptive than traditional mining methods and is well-suited to Kazakhstan's sandstone-hosted uranium deposits. However, Kazakhstan used to extract uranium using Open-Pit and Underground mining.

The development of open-pit and underground mining in the USSR and Kazakhstan is closely associated with the region's industrialization and technological progress. During the Soviet period, both mining methods were systematically developed to extract a range of minerals that supported energy production, construction, and manufacturing. The dual approach facilitated the exploitation of diverse mineral deposits in varied geological settings. Before the collapse of the USSR in 1991, Kazakhstan produced over 70,000 tons of uranium from nine deposits using underground mines and open pits [53].

Kazakhstan's mining history is deeply intertwined with its Soviet past, when large-scale mineral extraction supported the USSR's industrial and strategic goals. Open-pit mining was commonly used to extract near-surface resources such as coal, copper, and uranium, while underground mining methods were developed to access deeper, more complex ore bodies. Soviet engineers implemented extensive tunneling and shaft systems to reach valuable mineral deposits across the region. These mining techniques laid the foundation for Kazakhstan's role as a major mineral supplier within the Soviet bloc [54].

During the Soviet period, uranium mining became a critical component of the national nuclear program. Both open-pit and underground mining techniques were used to extract uranium ore for nuclear energy and weapons development. Large surface operations exploited shallow uranium deposits using heavy machinery, while deeper ore bodies were accessed through underground systems. Kazakhstan’s vast uranium reserves led to the establishment of several dedicated mining towns and facilities that served the USSR’s nuclear ambitions [55].

After the collapse of the Soviet Union, Kazakhstan inherited extensive mining infrastructure along with the environmental and safety challenges it posed. In the decades since independence, the country has made substantial efforts to modernize its mining sector, adopting newer technologies and reinforcing regulations for environmental protection and worker safety. Today, Kazakhstan remains a global leader in uranium production and continues to refine its mining practices through a focus on sustainable development and technological innovation [56].

Benefits and Side effects of legacy mining

Despite the economic benefits that mining brings to local economies—such as job creation and infrastructure development—it also poses serious environmental and social challenges for communities situated near mining sites. Detrimental effects include the loss of vegetation cover, destruction of water bodies, biodiversity reduction, land-use changes, and increased air pollution. These disruptions also contribute to food insecurity, higher living costs, and a rise in social vices and community conflicts [57]. Mining activities in Sierra Leone, for instance, have been shown to degrade arable lands and contaminate water sources, thereby disrupting agricultural livelihoods vital to rural economies [58]. In a study on Burkina Faso, Himmelsbach et al. (2023) observed that industrial gold mining significantly strained local health systems, with communities reporting a surge in patient numbers and emerging diseases[59]. These impacts are not only immediate but often persist long after mining operations end. Similar patterns have been documented in other countries as well, where communities face chronic exposure to pollutants and ongoing socioeconomic stress [60].

Living near an active uranium mine presents distinct environmental and public health hazards. Excavation and drilling generate dust that can carry radioactive particles and heavy metals. These airborne pollutants pose respiratory risks and increase exposure to radon gas—a radioactive decay product of uranium that is strongly linked to lung cancer. Environmental disruption from these operations also includes deforestation, soil erosion, and the contamination of nearby water bodies due to runoff and leaching. These impacts create both short and long-term health risks for nearby residents. Even after uranium mines are closed, residual hazards persist. Exposed tailings and waste rock can emit radon and leach heavy metals into groundwater, causing chronic exposure for local populations. Moreover, the altered post-mining landscapes delay ecological recovery and complicate remediation efforts. Effective strategies, such as long-term environmental monitoring, waste containment, and community health surveillance, are critical to mitigate these enduring threats.

MATERIAL AND METHODS

Study Area:

Figure 1. Map of Saumalkol and Grachevskoye uranium mine

The study was conducted in the Saumalkol village, located in the Aiyrtau district of the North Kazakhstan region. Approximately 5 km from the village, Mining Administration No. 5 was responsible for uranium extraction within a 116-hectare mining allotment. This site comprised multiple uranium deposits, including the Grachevskoe, Kosachinskoe, and Fevralskoe, among others. These deposits form part of the larger Grachevsko-Chaglinsky uranium ore deposit within the North Kazakhstan uranium ore province.

The extracted uranium ore was transported without preliminary enrichment via open gondola railcars, filled to two-thirds capacity to prevent dispersion and spillage. At the central industrial site, partial enrichment occurred through heap leaching before further transport in containers to the Stepnogorsk Hydrometallurgical Plant. The site's water supply was sourced from underground reserves at the Shok-Karagai and Ozerny water intakes. Additionally, Lake Bolshoy Koskol, situated within the mining allotment, served as a reservoir for waste, mine drainage, and industrial water, with discharge regulated through a pipeline system.

Mining Administration No. 5 was decommissioned as part of the Republic of Kazakhstan’s program for the mothballing of inactive uranium mining enterprises and mitigation of environmental impacts from uranium extraction (Program 008, 2001–2010), as outlined in Government Decree No. 1006 of July 25, 2001.

Identifying the annual effective dose (AED) from ingestion and inhalation of waterborne radon in the settlement of Saumalkol is a necessary step in evaluating the radiological health risks that affect the people of Saumalkol. Radon dissolves easily in water, and it can be released into indoor air during household use. Waterborne Radon has a dual pathway of exposure: ingestion through drinking water and inhalation of radon released into the air from water. In most cases when measuring the Total AED that comes from radon the exposure pathways of ingestion and intake of waterborne radon is ignored, however, due to the lack of a centralized water supply system in the town of Saumalkol, residents rely heavily on groundwater sources for drinking, cooking, hygiene, and agricultural purposes. The residents get their water from wells and boreholes reaching depths of up to 40 meters. The settlement is located near a decommissioned uranium mine and has uranium-rich geological formations that may leak radon in to the groundwater. These conditions increase the chance of elevated radon concentrations in groundwater. Raising the risks for chronic exposure among residents. That is the reason why the measuring the AED of ingestion pathway and intake of waterborne radon is a necessary step in identifying the risks of radon exposure in the settlement of Saumalkol.

Identifying the AED from inhalation of radon in air is a critical step in assessing the total radiological burden faced by the people of Saumalkol. Since radon gas can accumulate in poorly ventilated indoor spaces such as: in homes with cellars: it poses a serious health threat through inhalation. Inhalation is the primary pathway through which radon enters the human body, contributing to the majority of radiation dose from natural sources. The lungs are particularly vulnerable, with inhaled radon decay products adhering to lung tissue and increasing the risk of lung cancer. This makes it necessary to evaluate radon levels in indoor air.

Measurement

All the measurements of radon were carried out in accordance with certified methodological guidelines using instruments and measuring devices that passed state verification in 2024.

Radon in water

Volumetric Activity (VA) measurements in water samples were conducted using the circulation method, which involves the transfer of radon along with air from the sample volume to the working chamber of the VA measurement unit during the sparging process.

Taking water samples

Water samples were taken during the August of 2024. Drinking water from wells and boreholes were chosen for this study. Overall, 18 samples of water from 9 different locations in Saumalkol were taken.

Specialized samplers included in the kit were used for water sampling, with the general requirement that the samplers be completely filled with water. For sampling from a stream, well, water pipe, or similar sources, the sampling funnel (tube) provided in the kit was utilized. The plugs were removed from the sampler connections, and the connecting tube with the funnel was attached to the connection located on the sampler cover. The funnel was positioned under the water jet, as illustrated in Fig. 1. Once a steady stream of water emerged from the free connection of the sampler, the connection was sealed with a plug. The tube was then detached from the second connection, and a plug was secured in its place, completing the sampling process. At the end of the sampling, record the sampling time (t1**)** in the measurement protocol.

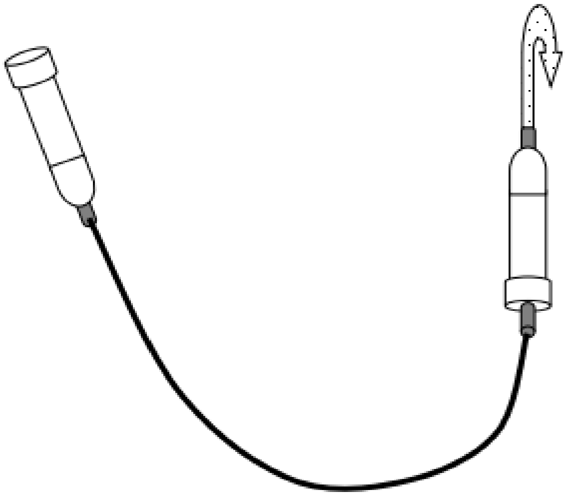

Figure. 2. Scheme of water extraction into the sampler

Figure 3. Scheme of sample measurement. Radon in water

The circuit was assembled according to Fig. 2 in the following sequence: the outlet fitting of the sampler was connected to the ‘INPUT’ fitting of the autonomous blower using connecting tubes from the kit. The ‘OUTPUT’ fitting of the autonomous blower was then connected to the inlet fitting of the measurement unit (located on the front panel of the CU) through the drying cartridge, ensuring the direction of air flow through the cartridge aligned with the arrow indicated on its casing. The outlet fitting of the measurement unit (fitting No. 1 on the rear panel of the CU; fitting No. 2 was sealed with a rubber plug) was connected to the remaining free fitting of the sampler. The autonomous blower was switched on by pressing the ‘MODE 2’ button, with the blower operating for a duration of 5 minutes. Upon completion of air mixing in the system, the measurement starts time (t2) was recorded in the measurement protocol.

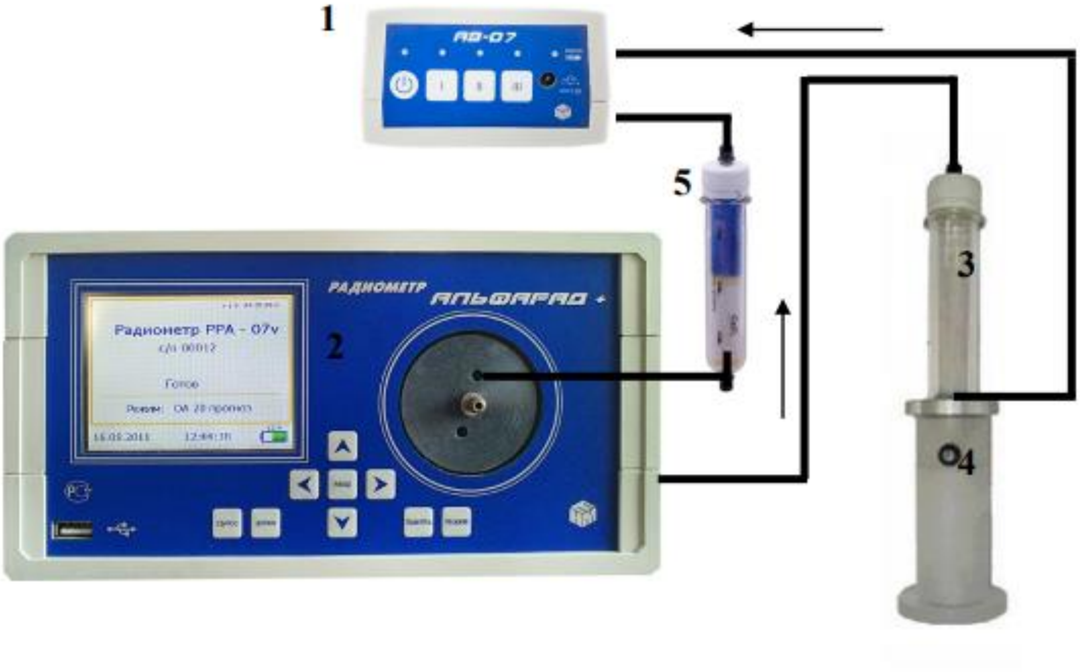

Figure 4. Scheme of sample measurement. 1 - autonomous airblower AV-07; 2 - measuring unit; 3 - water sampler with splitter; 4 - Gas bubbler; 5 - cartridge-drier.

Measurements were performed as follows: from the menu, the option ‘COMPLEX MEASUREMENTS’ was selected, followed by ‘Radon in air’. The elapsed time t in hours representing the duration from the moment of sample collection to the start of measurements, was entered. The measurement was then conducted over a period of 20 minutes. Upon completion, the screen displayed the obtained value of radon volumetric activity in the water, calculated using the specified ratio:

$$\square_{\square\square\square} = \square \times \left(1 + \frac{\square_2}{\square_1}\right) \times \square\square\square\ \square\square\square\ (\square_{\square\square} \times \square)\ \#(1)$$

Q – measured volumetric activity of radon in the sample, Bq·m−3

V2 - volume of measuring chamber, V2=0.94 l;

V1 - volume in the sampler, V1=1.05 l;

t - time elapsed from the end of air sampling to the beginning of measurements, min,
t= t2 - t1;

Radon in Air

The measurements of Radon in Air was done during the August of 2024. The houses for testing were chosen randomly. To enter the houses, the research team asked consent from the house owners. After the consent was given the radiometer was placed in the middle of the living room and then using "EEVA 5" the testing was performed. In the houses with cellars additional tests were made. Overall, 58 samples were analyzed.

The "EEVA 5" mode was selected using the marker and activated by pressing the ‘Enter’ button on the keyboard. In this mode, the following automated processes were carried out: sampling onto the aerosol filter using the built-in blower (180 seconds), automatic movement of the filter to the measurement position via the electric drive of the filter holder (10 seconds), measurement of the filter (120 seconds), and calculation of the equilibrium equivalent volumetric activity (EEVA) of radon, thoron, the air exchange coefficient, and the equilibrium coefficient between decay products of radon (DPR). The total duration of the mode was 5 minutes and 10 seconds. Upon entering the mode by pressing the ‘Enter’ button, a confirmation message appeared on the monitor.

A clean AFA-RSP-3 filter was then installed in the filter holder in the following sequence: the filter clamp was released by turning the front panel of the retractable filter holder, and the filter was removed from the guard ring and placed in the filter holder with the pile side facing the correct orientation. Care was taken to support the filter holder from below while pressing the filter into place to avoid excessive load on the movement mechanism. Once the filter was properly installed, all subsequent steps of the mode were executed automatically after pressing the ‘Enter’ button. The monitor displayed sequential messages indicating the progress of each step, starting with the sampling stage.

RESULTS

Overall, 58 samples of indoor radon were obtained in the settlement of Saumalkol in the summer of 2024. The sampling was done in a span of 1 week. Extreme high values of radon of 30593 Bq/m^3 and 18677 Bq/m^3 were observed.

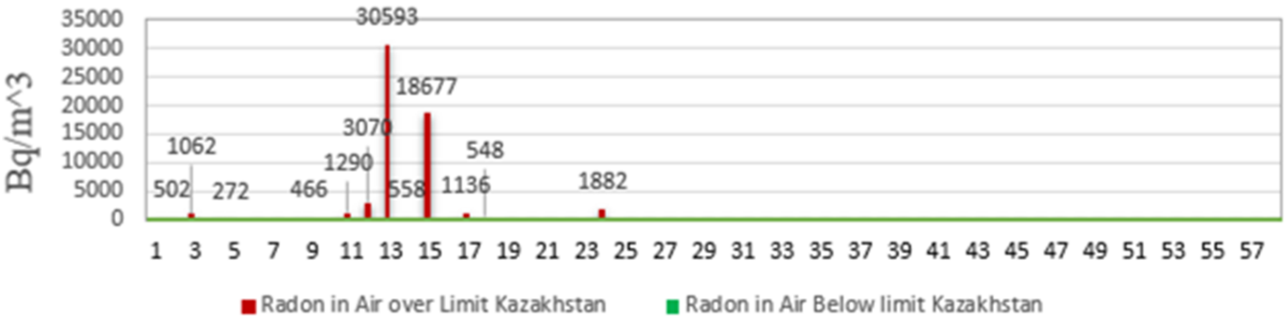

Figure 5.Indoor Radon concentration over the limit of 200 Bq/m^3 in the settlement of Saumalkol

From the 58 samples 12 were above the Kazakhstan's permissible level of radon in air of 200 Bq/m^3.

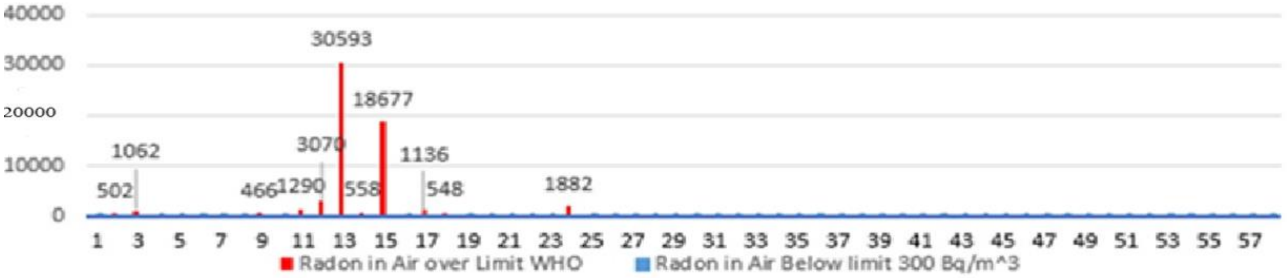

Figure 6. Indoor Radon concentration over the limit of 300 Bq/m^3 in the settlement of Saumalkol

From the 58 samples 11 were above the WHO's recommended permissible level of radon in air of 300 Bq/m^3

Indoor radon concentration

The findings made from the measurements of indoor radon taken in the settlement of Saumalkol taken in the summer season of 2024 shows a significant variability in radon concentrations across the dwellings. First of all, the noteworthy difference between the median of 24 Bq/ m³ and the average indoor radon concentration of 1058

Bq/ m³ indicate that the distribution was positively skewed. This could mean that the average radon concentration was influenced by outliers, and that the indoor radon concentration is unevenly distributed across the dwellings in Saumalkol and localized radon infiltration. Extreme values of radon in some dwellings most notably 30593 Bq/m³ and 18677 Bq/m³ could indicate the presence of local geological structures or vulnerabilities in the houses that could be linked to the proximity of mothballed uranium mines.

Figure 7. Sample measurements of indoor radon in Saumalkol

Overall from the 58 indoor radon samples 12 samples exceeded Kazakhstan's limit of 200 Bq/m³ (Figure 3) and 11 samples exceeded the higher limit of 300 Bq/m³ recommended by WHO (Figure 4). The high amount of exceedances over 20% for the national limit and 19% for WHO's guidelines indicate the need for public health intervention, however, the fact that, the mode and median values were far lower than both benchmarks 200 and 300 Bq/m³ could indicate that most homes in the settlement of Saumalkol are safe. In addition, since the 3rd Quartile is 176 Bq/m³ which is below 200 and 300 Bq/m³ benchmarks this means 75% of homes have safe levels of radon.

From this we can assume that the small fractions of homes that have abnormally high levels of radon affect the average value of indoor radon concentration making the settlement seem at extremely high risk which it is not. But the small population is highly affected by the high indoor radon concentration and require targeted mitigation and long-term monitoring. From the data we obtained we can see that 19% of people affected are potentially exposed to high indoor radon levels that are linked to increased lifetime risk of lung cancer. If we were to assume that the unevenly distributed indoor radon concentration is influenced by localized geological factors, structural factors in the dwellings such as cracks in foundations, floor types, cellars and ventilation all of this factors could be intensified by the presence of mothballed uranium mine. By doing so we can create a link that despite the mine being mothballed uranium decays products remain in the surrounding soil that continue emit radon overtime putting selected houses at risk.

In addition, 18 water samples of drinking water were obtained from 9 different wells, boreholes.

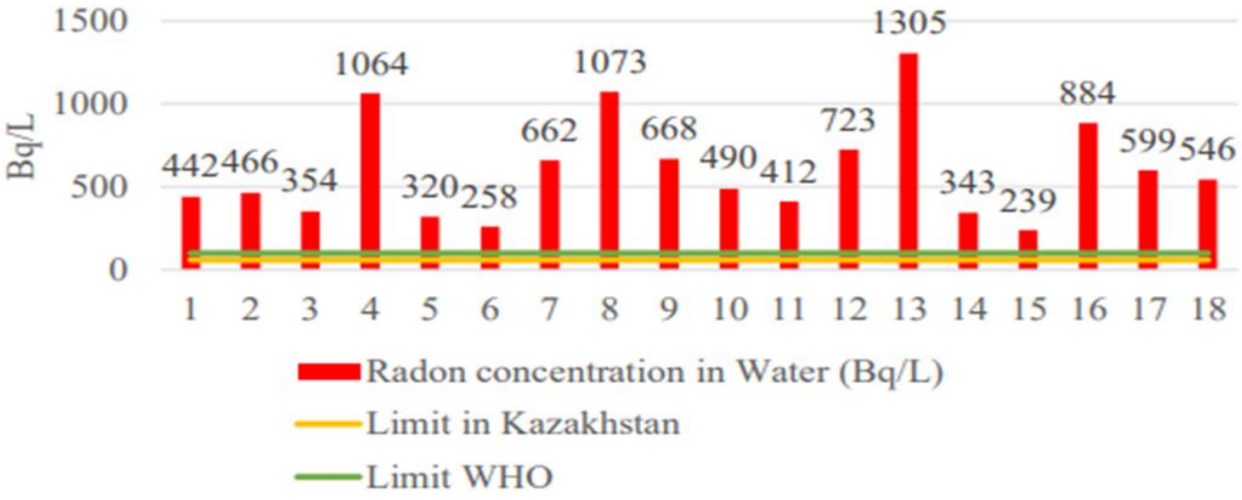

Figure 8. Radon concentration in water in the settlement of Saumalkol 2024

From the obtained 18 water samples all were above the 60 Bq/L radon level for water established in Kazakhstan.

Also, from 18 water samples all were above the 100 Bq/L radon level for water established by WHO.

Radon in Water concentration

The results of the radon concentration samples of drinking water sources from Saumalkol unveil another pathway of radon exposure that should be taken in consideration when measuring the public health risks caused by radon. The fact that all the 18 water samples collected from 9 separate wells or boreholes exceeded both the national limit of 60 Bq/L and the WHO guideline of 100 Bq/L for radon in drinking water (Figure 4) indicate that the local groundwater sources of Saumalkol are contaminated by radon. This is also supported by the fact that the measured concentration of radon in water ranged from 239 Bq/L to 1305 Bq/L, and the average value being 603 Bq/L with multiple cases of water samples exceeding 1000 Bq/L. This uniformly high levels of radon in water could indicate that local groundwater in influenced by hydrological source of radon, that could be possibly influenced by uranium bearing bedrock or sediments that are linked to the mothballed uranium mine. The consistent high levels of radon concentration in water indicate the need for the public health intervention.

Закончено Импульсов 2411
Измерение 06.08.2024 19:11:32
Режим: Радон в воде
$Q_{воды}$ = 546 ± 163 Бк/л
Температура 25 °C
Влажность 42 %
Давление 727 mmHg

Закончено Импульсов 2936
Измерение 06.08.2024 11:34:00
Режим: Радон в воде
$Q_{воды}$ = 662 ± 198 Бк/л
Температура 25 °C
Влажность 47 %
Давление 730 mmHg

Figure 9. Sample measurements of Radon in Water

Annual Effective Ingestion Dose of ingestion of radon in water is obtained by the following formula:

$$\square_{\square\square\square\square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \square \times \square\square\square^{\square\square} \#(2)$$

Where:

$\square^{\square\square}_{\square\square\square\square\square}$ - Radon concentration in water (Bq/L);

$\square_{\square\square\square\square\square}$ - Annual water ingestion rate assumed to be 730 L/year for adults (WHO, 2008);

Currently there are 2 Dose conversion factors that are in used for determining the $\square_{\square\square\square\square\square\square\square\square\square\square}$, one from ICRP 137 and the other from UNSEAR 2000

$\square\square\square^{\square\square}_{\square\square\square\square 137}$ - Dose conversion factor for ingestion 6.9E-10 Sv/Bq: (ICRP 137)

$$\square_{\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \frac{730\square}{\square\square\square\square} \times 6.9\square - 7\frac{\square\square\square}{\square\square} \#(3)$$

or

$\square\square\square^{\square\square}_{\square\square\square\square\square\square 2000}$ - Dose conversion factor for ingestion 3.5E-9 Sv/Bq: (UNSEAR 2000)

$$\square_{\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \frac{730\square}{\square\square\square\square} \times 3.5\square - 6\frac{\square\square\square}{\square\square} \#(4)$$

The Annual Effective Ingestion Dose of ingestion of radon can also be adjusted by changing the value of $\square$ for children and infants

$\square_{\square\square\square\square\square\square\square\square\square}$ - Annual water ingestion rate assumed to be 365 L/year for adults (WHO, 2008);

$\square_{\square\square\square\square\square\square\square\square}$ - Annual water ingestion rate assumed to be 273.75 L/year for adults (WHO, 2008);

Therefore, we can adjust the formulas for children (ICRP 137):

$$\square_{\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \frac{365\square}{\square\square\square\square} \times 6.9\square - 7\frac{\square\square\square}{\square\square} \#(5)$$

And for the infants as (ICRP 137):

$$\square_{\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \frac{273.75\ \square}{\square\square\square\square} \times 6.9\square - 7\frac{\square\square\square}{\square\square} \quad (6)$$

Therefore, we can adjust the formulas for children (UNSEAR 2000):

$$\square_{\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \frac{365\square}{\square\square\square\square} \times 3.5\square - 6\frac{\square\square\square}{\square\square} \#(7)$$

And for the infants as (UNSEAR 2000):

$$\square_{\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \frac{273.75\ \square}{\square\square\square\square} \times 3.5\square - 6\frac{\square\square\square}{\square\square} \quad (8)$$

Annual Effective Inhalation Dose of inbreathing of radon form water is obtained by the following formula:

$$\square_{\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square} \times \square_{\square\square} \times \square_{\square\square\square} \times 10^{-4} \times \square\square\square^{\square\square}_{\square\square\square\square\square\square\square\square\square\square} \#(9)$$

Where:

$\square^{\square\square}_{\square\square\square\square\square}$ - Radon concentration in water (Bq/L);

$\square_{\square\square}$- the equilibrium factor between radon and its progeny assumed to be 0.4 (UNSEAR 2000);

$\square_{\square\square\square}$ - the exposure time to this concentration: 7000 hours; (ICRP 65)

$\square\square\square^{\square\square}_{\square\square\square\square\square\square\square\square\square\square}$- the dose conversion factor of radon via inhalation 9E-6 mSv/Bq*h*m^3;

10^{-4} -the ratio of radon in the air to water; (UNSEAR 2000)

From this we can produce the following equation:

$$\square_{\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square} = \square_{\square\square\square\square\square}^{\square\square} \times 0.4 \times 7000\ \square \times 10^{-4} \times 9\square - 6\ \frac{\square\square\square}{\left(\square\square \times \square \times \square^{3}\right)}\ \#(10)$$

N	Radon concentration in Water (Bq/L)	AED from ingestion of radon from water for adults ICRP 137 (mSv/year)	AED from ingestion of radon from water adults UNSEAR 2000 (mSv/year)
1	442	0,223	1,129
2	466	0,235	1,191
3	354	0,178	0,904
4	1064	0,536	2,719
5	320	0,161	0,818
6	258	0,130	0,659
7	662	0,333	1,691
8	1073	0,540	2,742
9	668	0,336	1,707
10	490	0,247	1,252
11	412	0,208	1,053
12	723	0,364	1,847
13	1305	0,657	3,334
14	343	0,173	0,876
15	239	0,120	0,611
16	884	0,445	2,259
17	599	0,302	1,530
18	546	0,275	1,395

Annual Effective Dose from Radon Ingestion

The calculated Annual Effective Dose (AED) from Ingestion of water with radon in the settlement of Saumalkol shows us that residents who drink water are exposed to radon that are way higher than international safety benchmarks. Using dose conversion factors from both ICRP 137 and UNSCEAR 2000, the estimated AEDs for adult's ranges from 0.120 to 0.657 mSv/year (ICRP 137) and 0.611 to 3.334 mSv/year (UNSEAR 2000), depending on the radon concentration in each water sample. According to ICRP guidance, the public exposure limit from all sources (excluding natural background and medical exposure) is 1 mSv/year, while WHO considers a committed effective dose from drinking water to be 0.1 mSv/year. Based on this knowledge we can observe that all 18 water samples exceeded the WHO's guidelines regardless of the used dose conversion factor, some even exceed the limit of 1 mSv/year. The lowest AED from ingestion 0.120 mSv/year still is considered to be non-negligible health risk that could lead to an increase in the lifetime cancer risks. The highest estimate of AED from ingestion of 3.334 mSv/year is over three times this limit of annual limit. This in combination with the fact that the all of the water samples indicated a high presence of radon concentration indicate for urgent mitigations for drinking water for adults.

The impact of high radon concentration in water is of particular interest when we consider its impact on children and infants. Due to the fact that children and infants consume less water than adults it was expected that they would receive a lower AED from ingestion of radon from water. Children, had the average AED from ingestion dose range from 0.152 mSv/year (ICRP) to 0.770 mSv/year (UNSCEAR), while infants receive an average AED from ingestion of 0.114 mSv/year (ICRP) to 0.577 mSv/year (UNSCEAR). Even the lowest average estimate for children and infants exceeds WHO's guidelines for drinking water. This values are of significant since children and infants are more vulnerable and high exposure to radon is influenced by their heightened radiosensitivity. Earlier exposure to high doses could lead to increase in the lifetime cancer risk.

Table 1. Annual Effective Ingestion Dose of intake of radon in water

N	Radon concentration in Water (Bq/L)	AED from inhalation of waterborne radon (mSv/year)
1	442	0,001
2	466	0,001
3	354	0,001

4	1064	0,003
5	320	0,001
6	258	0,001
7	662	0,002
8	1073	0,003
9	668	0,002
10	490	0,001
11	412	0,001
12	723	0,002
13	1305	0,003
14	343	0,001
15	239	0,001
16	884	0,002
17	599	0,002
18	546	0,001

Table 2. Annual Effective Inhalation Dose of inhalation of waterborne radon

Average Radon concentration in water	603 Bq/L
Average AED from ingestion of radon from water Adults ICRP 137	0,304 mSv/year
Average AED from ingestion of radon from water Adults UNSEAR 2000	1,540 mSv/year
Average AED from ingestion of radon from water children ICRP 137 (mSv/year) Average AED from ingestion of radon from infants ICRP 137 (mSv/year)	0,152 mSv/year 0,114 mSv/year
Average AED from ingestion of radon from water children UNSEAR 2000 (mSv/year)	0,770 mSv/year
Average AED from ingestion of radon from infants UNSEAR 2000 (mSv/year)	0,577 mSv/year
Average AED from inhalation of waterborne radon	0,002 mSv/year

Table 3. Average Radon concentration and AED findings from waterborne radon

Annual effective dose from inhalation of waterborne radon

The inhalation of waterborne radon is most commonly achieved during the use of water with radon during daily activities such as showering, laundering or cleaning. The values of AED from inhalation of waterborne radon were in range of 0.001 mSv/year to 0.003 mSv/year. These values are way below the public exposure limit of 1 mSv/year. From this we can suggest that the inhalation of waterborne radon plays a lower-priority role in the contribution to the total risks of radon. Despite bringing minimal contribution to the total AED from radon the of inhalation of waterborne radon still considered to be an exposure pathway of radon that could amplify the exposure of lungs to radon. However, even the highest estimates of AED from waterborne radon still within the safe exposure limits. From the we can rule out the need for the public health intervention regarding the inhalation of waterborne radon. In other words, the water that is used by the people of Saumalkol is safe for domestic use for most common activities, therefore, it does not constitute the need for change in the lifestyle or is in need for recommendations for mitigation regarding its use for household purposes that are other than drinking.

Annual Effective Inhalation Dose of intake of indoor radon is obtained by the following formula:

$$□_{□□□□□□□□□□\ □□□□□□} = □^{□□}_{□□□□□□} \times □_{□□□} \times □□□^{□□}_{□□□□□□□□□□} \#(11)$$

Where:

$□^{□□}_{□□□□□□}$ - Radon concentration indoor (Bq/m^3);

$□_{□□□}$ - the exposure time to this concentration: 7000 hours; (ICRP 65)

$\square\square\square^{\square\square}_{\square\square\square\square\square\square\square\square\square\square\square}$- the dose conversion factor of radon via inhalation 9E-6 mSv/Bq*h*m^3;

From this we can produce the following equation:

$$\square_{\square\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square} = \square^{\square\square}_{\square\square\square\square\square\square\square} \times 0.4 \times 7000\ \square \times 9\square - 6\ \frac{\square\square\square}{(\square\square \times \square \times \square^{3})}\ \#(12)$$

Annual effective dose from inhalation of indoor radon

As mentioned previously the measurement of the indoor radon concentration resulted in the positively skewed data set. The average indoor radon concentration of 1058 Bq/m³ resulted in the average annual effective dose of 66,678 mSv/year, which far exceeds the ICRP's public exposure limit of 1 mSv/year. But these values are way higher than the median AED from inhalation 1.5125 mSv/year which is over the safe limit of ICRP guidance of 1 mSv/year. However, the 3rd quartile of has the value for AED from inhalation of 10.10 mSv/year a value that is more than 10 times higher than established limit of 1 mSv/year, which means that at least 25% of population has higher annual effective dose that is higher than that. This indicates that at least a quarter of the population of the settlement of Saumalkol are at a significant risk of long term health side effects such as lung cancer. In addition, maximum indoor radon concentration was observed at 30,593 Bq/m³, corresponding to an AED of 1927.36 mSv/year, a value over 1900 times higher than the ICRP-recommended limit of 1 mSv/year for public exposure. A second extreme case, at 18,677 Bq/m³, resulted in an AED of 1176.65 mSv/year. These outliers support the idea that exposure of radon is linked to some local geological structures or impacted by the legacy contamination from the nearby mothballed uranium mine.

From the 12 samples that exceeded Kazakhstan's national limit of 200 Bq/m³, while 11 samples exceeded the WHO's limit of 300 Bq/m³ in these dwellings AED from inhalation excluding the 2 highest outliers ranged from approximately 17.135 to 193.41 mSv/year, indicating chronic exposure that could greatly increase the risk of lung cancer over time. Even among the dwellings with lower radon levels the entire settlement had more than 50% of the AED from inhalation that is higher than 1.513 mSv/year, total there were 31 samples with AED higher than 1 mSv/year; these findings suggest that the residual exposure of inhalation of indoor radon is widespread in settlement of Saumalkol. Furthermore, the data set supports the legacy uranium mining activities have played a role to environmental conditions conducive to radon accumulation indoors, since the given the magnitude and distribution of these concentrations.

Table 4. Annual Effective Inhalation Dose of inhalation of indoor radon

N	EER of Radon in Air (Bq/L)	AED from inhalation of air (mSv/year)
1	50	3,15
2	502	31,625
3	1062	66,905
4	12	0,755
5	272	17,135
6	4	0,2525
7	24	1,5125
8	2	0,125
9	466	29,3575
10	28	1,765
11	1290	81,27
12	3070	193,41
13	30593	1927,36
14	558	35,155
15	18677	1176,65
16	176	11,0875
17	1136	71,5675
18	548	34,525
19	74	4,6625
20	188	11,845
21	4	0,2525

22	29	1,8275
23	181	11,4025
24	1882	118,565
25	113	7,12
26	11	0,6925
27	10	0,63
28	7	0,44
29	8	0,505
30	2	0,125
31	11	0,6925
32	9	0,5675
33	24	1,5125
34	9	0,5675
35	6	0,3775
36	12	0,755
37	1	0,0625
38	20	1,26
39	33	2,08
40	50	3,15
41	6	0,3775
42	34	2,1425
43	24	1,5125
44	25	1,575
45	6	0,3775

46	3	0,19
47	13	0,82
48	3	0,19
49	6	0,3775
50	3	0,19
51	7	0,44
52	1	0,0625
53	11	0,6925
54	26	1,6375
55	25	1,575
56	6	0,3775
57	32	2,015
58	1	0,0625

Table 5. Median Radon concentration, Average Radon concentration, Median and Average Annual Effective Inhalation Dose findings from indoor radon

Median radon concentration in air (Bq/m^3)	Average radon concentration in air (Bq/m^3)	Median AED from inhalation of air (mSv/year)	Average AED from inhalation of air (mSv/year)
24	1058,379±4660	1,5125	66,678±293

Total Average Annual Effective Dose can be calculate using the following formula:

$$\square_{\square\square\square\square\square} = \square_{\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\square} + \square_{\square\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square} + \square_{\square\square\square\square\square\square\square\square\square} \#(13)$$

We can further adjust this equation by changing the value of $\square_{\square\square\square\square\square\square\square\square\square}$ for adults, children and infants, so the equation for adults will be:

$$□_{□□□□□□} = □_{□□□□□□□□□□□\ □□□□□□□} + □_{□□□□□□□□□□□\ □□□□□□} + □_{□□□□□□□□□□\ □□□□□□□} \#(14)$$

And the same can be done for children:

$$□_{□□□□□□} = □_{□□□□□□□□□□□\ □□□□□□□} + □_{□□□□□□□□□□□\ □□□□□□} + □_{□□□□□□□□□□\ □□□□□□□□□} \#(15)$$

And infants:

$$□_{□□□□□□} = □_{□□□□□□□□□□□\ □□□□□□□} + □_{□□□□□□□□□□□\ □□□□□□} + □_{□□□□□□□□□□\ □□□□□□□□} \#(16)$$

Total Average Annual Effective Dose Adults ICRP 137	66,984 mSv/year
Total Average Annual Effective Dose Adults UNSEAR 2000	68,142 mSv/year
Total Average Annual Effective Dose Children ICRP 137	66,832 mSv/year
Total Average Annual Effective Dose Children UNSEAR 2000	67,450 mSv/year
Total Average Annual Effective Dose Infants ICRP 137	66,793 mSv/year
Total Average Annual Effective Dose Infants UNSEAR 2000	67,257 mSv/year

Table 6. Total Average Annual Effective Dose from Radon in the settlement of Saumalkol for infants, children and adults

Minimal AED from ingestion of radon from water ICRP 137	0,120 mSv/year

Maximum AED from ingestion of radon from water ICRP 137	0,657 mSv/year
Minimal AED from ingestion of radon from water UNSEAR 2000	0,611 mSv/year
Maximum AED from ingestion of radon from water UNSEAR 2000	3,334 mSv/year
Minimum AED from inhalation of waterborne radon	0,001 mSv/year
Maximum AED from inhalation of waterborne radon	0,003 mSv/year
Minimum AED from inhalation of indoor air radon	0,063 mSv/year
Maximum AED from inhalation of indoor air radon	1927,36 mSv/year
Minimum Average Annual Effective Dose Adults ICRP 137	0,183 mSv/year
Maximum Average Annual Effective Dose Adults ICRP 137	1928,021 mSv/year
Minimum Average Annual Effective Dose Adults	0,674 mSv/year

UNSEAR 2000	
Maximum Average Annual Effective Dose Adults UNSEAR 2000	1930,698 mSv/year

Table 7. Maximum and Minimum AED values for ingestion, waterborne radon inhalation and indoor radon inhalation

Total annual effective dose from radon in the settlement of Saumalkol

The Total AED from radon exposure is the sum contribution from inhalation of indoor radon, ingestion of radon in water, and inhalation of waterborne radon; this reveals a high exposure levels across all population groups in Saumalkol. The uniformity in high levels of AED values across all the age groups implies a community-wide public health risk.

For adults, the total average AED is 66,984 mSv/year [63] and 68,142 mSv/year [5]. These values are over 66 times higher than the ICRP's recommended dose limit of 1 mSv/year for the general public, representing a significant radiological health hazard. Importantly, similarly high exposures are found in children (66.8–67.4 mSv/year) and infants (66.7–67.2 mSv/year), with only slight variation across age groups and assessment models. The indoor radon inhalation was considered to be a major exposure pathway due to the skewed nature of the dataset resulting in the overly inflated contribution to the total AED for all age groups. In some cases, using the higher dose conversion factor (UNSEAR) for ingestion for both adults and children the average AED from ingestion had higher impact on the Total AED than the median AED from inhalation of indoor radon. The AED from inhalation of waterborne radon was the lowest contributor to the total AED, signifying its minimal contribution to the total exposure to radon. The data in Table 7 highlight the extremely wide range of radon-related AEDs which reflects both the localized variability in environmental conditions and the uneven distribution of radon sources across the settlement of Saumalkol.

Inhalation of indoor air radon presented the most dramatic variability, with AED values ranging from a minimum of 0.063 mSv/year to a maximum of 1930.698 mSv/year. This maximum value is very high, surpassing safe exposure limits by more than 1930 times; suggesting high radon accumulation in specific indoor places; probably due to a combination of geological emission, poor ventilation, and building design. This range underscores the urgent need for individualized household-level assessment and mitigation.

When combining all pathways, the total AED for adults ranged from 0.183 mSv/year to 1928.021 mSv/year (ICRP) and 0.674 mSv/year to 1930.698 mSv/year (UNSCEAR). The lower bounds are well within the international safety thresholds, suggesting some households are within the acceptable limits for radon exposure. However, the upper bounds reflect dangerously high exposure levels consistent with serious health risks, particularly lung cancer, if residents remain in these conditions in the long term.

The wide range of AEDs supports the claim that the radon exposure in the settlement of Saulmakol is unevenly distributed. In some cases, resident’s may experience minimal radon exposure and in other cases they are subjected to severe levels of radon exposure that could negatively impact their wellbeing.

Limitations

One of the main step in identifying the total annual effective dose (AED) that comes from radon is to measure the radon concentration. For the purpose of this study we were able to get 58 samples of indoor radon and 18 samples of water samples.

According to the national census there currently over 11 thousand residents leaving in the settlement of Saumalkol and in order to achieve a proper assessment of the risk that affects the population a larger sample size would be required. A larger sample size could potentially help of us identify more territories that are affected by the high levels of radon. It also would result in larger data set that could change the current difference between our median and the mean. As of now the median of the data affecting the indoor radon concentration is smaller than the mean by a significant margin. This leads to the mean that is heavily impacted by a set of outliers, with a bigger and more balanced dataset, the mean may decrease, leading to a more accurate and potentially lower estimation of the community's average AED. This aligns with WHO recommendations, which emphasize that population wide assessments of indoor radon should be based on statistically representative and geographically diverse samples to ensure robust risk evaluations[17].

One of the fundamental limitations of this case study of assessing the AED from radon exposure in the settlement of Saumalkol is the fact that all of the data samples were taken in the summer period, august 2024. According to the *WHO Handbook on Indoor Radon* [17], indoor radon concentrations should ideally be measured over multiple seasons, including both summer and winter, to account for seasonal variability. Indoor radon levels are known to fluctuate drastically based on weather conditions, building ventilation behavior, and the time of day during which sampling happens. By implementing year-round monitoring, future studies could not only increase the number of observations and samples but also provide a more detailed comprehension of seasonal influences on indoor radon levels in the dwellings. It is possible that the inclusion of winter measurements; when radon accumulation tends to be higher due to reduced ventilation would alter the calculated AED from inhalation, potentially leading to more accurate and representative exposure numbers.

The measurement of indoor radon was conducted using short-term active radon measurements using the Alpharad Plus radiometer, which was employed to obtain 5-minute long indoor radon sampling at each measuring site. As per manufacturers reports the Alpharad Plus radiometer has measurement if uncertainty of approximately ±30%. This level of error, in combination with the short duration of sampling, increases the potential for variability in the recorded radon concentrations particularly as indoor radon levels are highly sensitive to factors such as ventilation, weather conditions, and time of day. These fluctuations may compromise the precision of the estimated annual effective dose (AED) from inhalation.

Although the inclusion of geospatial data in this study could have significantly enhanced the analysis of radon exposure patterns, particularly by finding clusters of elevated concentrations; this approach was not pursued due to ethical considerations. In a small settlement such as Saumalkol, the geolocation of individual sampling points could potentially compromise participant anonymity, as even little spatial data can lead to identification [64]. Given that radon levels are associated with health risks and may carry social or economic implications [65], such data should only be collected under strict ethical protocols, including approval from a research ethics committee and informed consent [66].".

To improve the reliability and generalizability of radon exposure assessments in Saumalkol and similar settlements, future research should aim to increase both the size and spatial coverage of sampling. A larger, statistically representative dataset would reduce the influence of outliers and enable more detailed spatial analysis, potentially identifying localized radon hotspots and refining AED estimates across the population.

Future studies should also adopt a year-round monitoring strategy. Including measurements during both winter and summer would allow for a more accurate estimation of seasonal variability and its impact on indoor radon concentrations. As radon levels tend to rise during colder months, incorporating winter data could lead to a more comprehensive and representative calculation of AED from inhalation. In terms of measurement methodology, it is recommended that long-term passive radon detectors, such as alpha track detectors in addition to short term active measurements. Passive detectors provide time-integrated data over weeks or months and are less sensitive to momentary fluctuations, thereby producing more reliable exposure data. Their use is consistent with international best practices in environmental health research ([17]; [67] Lastly, future studies may consider integrating geospatial data using anonymized or aggregated formats, such as spatial interpolation techniques or grid-based heat maps, to preserve participant confidentiality. This would allow for spatial modeling of radon distribution without compromising personal data protection. Any such approach should follow established ethical guidelines and be approved by the appropriate institutional review boards or ethics committees.

PRACTICAL RECOMMENDATIONS

Short Term:

Mitigate High-Radon Homes. Mitigating homes with high indoor radon levels is a proven method to reduce radiation exposure. Techniques like sub-slab depressurization can lower radon concentrations by over 90%, often bringing levels below the recommended action level of 100 Bq/m^3. A study in Iowa [68] showed significant reductions after mitigation, and Finland's national mitigation program successfully decreased indoor radon levels and related health risks [69].

Implementing such measures in high-radon homes is an effective way to reduce annual effective doses from radon.

Install Point-of-Use Water Treatment (GAC Filters) Install Point-of-Use Water Treatment (GAC Filters). Implementing granular activated carbon (GAC) filters at the point of use is an effective strategy for reducing radon levels in drinking water. GAC filters can remove up to 99% of radon, significantly decreasing the risk of inhalation exposure when water is used indoors. A U.S. Environmental Protection Agency study found that 94% of tested GAC systems achieved over 90% radon removal efficiency, with 84% surpassing 95% efficiency [70]. This method has been successfully applied in homes and small water systems, proving its practicality and effectiveness in reducing radon-related health risks.

Distribute Radon Test Kits and Offer Free Testing Providing free or low-cost radon test kits is an effective public health strategy to identify homes with elevated radon levels and encourage timely mitigation. Early detection is crucial, as radon exposure is a leading cause of lung cancer among non-smokers. Studies have shown that community-based distribution programs significantly increase testing rates and awareness. For example, Wang et al. (1999) found that distributing free test kits through public health initiatives led to a threefold increase in household radon testing[71]. Offering free testing removes cost barriers and helps prioritize high-risk areas for intervention.

Provide Temporary Relocation or Support for Extreme Cases In areas where radon levels are exceptionally high and pose an immediate health risk, temporary relocation or targeted support should be considered until mitigation can be completed. Exposure to extremely elevated radon concentrations can result in dangerously high annual effective doses, especially in poorly ventilated homes. According to Field et al. (2000), prolonged exposure to radon concentrations well above recommended limits significantly increases lung cancer risk [72]. In Canada, temporary relocation has been used in urgent cases where radon exceeded 1,000 Bq/m³ while mitigation was arranged [73]. Offering support in such cases prioritizes public safety and demonstrates a responsible, health-first approach.

Long term:

Implement Year-Round Passive Radon Monitoring. Establishing a system of year-round passive radon monitoring using devices such as alpha track detectors is a sustainable and cost-effective approach for continuous surveillance in radon-prone areas. Unlike short-term testing, passive long-term monitoring provides more accurate assessments of annual average radon concentrations, accounting for seasonal fluctuations. This data is critical for identifying persistent high-radon zones, tracking trends over time, and prioritizing mitigation or public health interventions. Alpha track detectors are widely used for this purpose due to their reliability and affordability. Studies, including Kropat et al. (2014), have demonstrated their effectiveness in national radon surveys and long-term exposure assessments. Countries such as Switzerland and the UK have successfully integrated year-round passive monitoring into national radon control strategies, enabling evidence-based policy development and more targeted resource allocation[74].

Develop Centralized Water Treatment Systems. For communities relying heavily on groundwater with elevated radon levels, implementing centralized water treatment systems such as community-scale aeration tanks is a practical and long-term solution. Aeration is highly effective at removing radon from water by releasing it into the air before distribution, often achieving removal efficiencies of over 95%. This approach ensures consistent water safety across all households, reduces the burden on individual homeowners to install treatment devices, and simplifies maintenance and regulatory oversight. Countries like the United States and Germany have adopted centralized radon removal technologies in public water systems where groundwater is the primary source, showing long-term effectiveness and public health benefits.

Update Building Codes with Radon-Resistant Construction Guidelines. To prevent future radon-related health risks, it is essential to update building codes to include radon-resistant construction guidelines for new buildings. These guidelines should incorporate passive design features, such as radon-resistant barriers, proper venting systems, and soil gas barriers, which prevent radon infiltration at the source. Implementing these measures during construction can significantly reduce the need for costly mitigation efforts later. Studies show that radon-resistant construction techniques are highly effective when applied in regions with elevated radon potential. For example, the U.S. Environmental Protection Agency (EPA) and the Department of Housing and Urban Development (HUD) recommend incorporating radon-resistant features in all new homes built in radon-prone areas. A study by the EPA (2001) found that homes built with radon-resistant features had radon levels significantly lower than those without these measures [75]. Countries like Canada and the United Kingdom have successfully integrated such guidelines into their building codes, resulting in long-term public health benefits and reduced radon exposure.

Conduct Geological and Structural Studies. To address radon risks effectively, it is crucial to conduct detailed geological and structural studies in regions known for high radon potential. These studies can help identify areas with elevated radon concentrations in both soil and groundwater, providing critical data for targeted mitigation efforts. Understanding the local geology, including soil composition, rock formations, and groundwater flow, allows for more accurate predictions of radon movement and concentration, which can inform both mitigation strategies and future development planning.

CONCLUSION

This paper was set out to assess the radiation situation and calculate the probable effective dose (AED) of radon exposure in the settlement of Saumalkol, located in proximity to mothballed uranium mines in Northern Kazakhstan. The research aimed to address an acute environmental health issue by analyzing radon concentrations in both indoor air and drinking water across residential and public buildings, followed by calculating the radiation exposure dose for different population groups, and finally, developing evidence-based recommendations to mitigate exposure.

Through extensive field measurements, including 58 indoor radon samples and 18 water samples, the study demonstrated the presence of alarmingly high radon concentrations in specific areas of the settlement, with some AED values exceeding the recommended safety threshold of 1 mSv/year by more than 700 times. This finding underscores the acute heterogeneity of radon distribution in Saumalkol and its severe implications for public health, particularly concerning lung cancer risks.

The research successfully fulfilled its first objective by providing a detailed radiation assessment of Saumalkol, revealing a wide variability in radon levels both spatially and across different exposure pathways. The second objective was met by determining the radon content in a representative sample of residential and public buildings. The third objective, the calculation of radiation exposure dose for population groups—including adults, children, and infants—was also achieved using both ICRP and UNSCEAR dose conversion factors. Lastly, based on the empirical data, the study proposed targeted and practical recommendations for reducing population exposure, such as increasing building ventilation, utilizing water treatment methods to reduce radon levels, and advocating for regulatory and monitoring frameworks to be instituted by public health authorities. Moreover, the study introduced novel insights by highlighting the necessity for individualized household-level interventions, the seasonal variability in radon accumulation, and the potential benefits of integrating geospatial analytics in future research. Despite certain limitations, such as a modest sample size and seasonal constraints in data collection, the findings provide a strong foundation for both immediate public health action and more comprehensive longitudinal studies. In conclusion, this work has contributed a scientifically robust, context specific assessment of radon risks in a post-industrial uranium region and provided actionable strategies for radiation exposure dose reduction. It serves as an essential step toward ensuring the environmental safety and health security of the Saumalkol population and demonstrates the critical need for sustained monitoring and intervention in radon affected areas.

Key Findings.

Elevated Radon Concentrations in Indoor Air

Indoor radon levels in Saumalkol exhibited significant variability, ranging from 2 Bq/m^3 to 30,593 Bq/m^3. 20% of tested dwellings exceeded Kazakhstan's permissible limit (200 Bq/m^3), while 19% surpassed the WHO-recommended threshold (300 Bq/m^3).Extreme outliers (e.g., 30,593 Bq/m^3) suggest localized geological influences or structural vulnerabilities in certain homes, likely exacerbated by their proximity to mothballed uranium mines.

High Radon Contamination in Drinking Water

All 18 water samples from wells and boreholes exceeded both Kazakhstan's limit (60 Bq/L) and WHO guidelines (100 Bq/L), with concentrations ranging from 239 Bq/L to 1,305 Bq/L (average: 603 Bq/L).

The uniformly high radon levels in groundwater indicate contamination from uranium-rich geological formations, posing a chronic exposure risk to residents.

Radiation Exposure and Health Risks

Ingestion Pathway:

The Annual Effective Dose (AED) from drinking water ranged from 0.120–3.334 mSv/year for adults, exceeding WHO’s safety benchmark (0.1 mSv/year). Children and infants also faced elevated risks, with AEDs ranging from 0.114–0.770 mSv/year, raising concerns about long-term health effects.

Inhalation Pathway:

These concentrations translate into Annual Effective Dose (AED) from inhalation ranging from 0.0625 to 1,927.36 mSv/year.The median AED was 1.5125 mSv/year, and the mean AED was 66.678 mSv/year. 31 homes (53.4%) had AED values from indoor inhalation above 1 mSv/year, meaning over half the households are exposed to chronic radiation exceeding international safety limits.

Total Exposure:

Combined AEDs from all exposure pathways averaged 66.984 - 68.142 mSv/year for adults, with similar risks for children and infants, highlighting a community-wide public health threat.

The findings confirm widespread radon contamination in Saumalkol’s indoor air and drinking water, with critical health risks for residents, particularly those near abandoned uranium mines. Immediate mitigation measures—such as radon-resistant construction, water filtration, and targeted home remediation—are urgently needed to reduce exposure. Future studies should incorporate year-round monitoring and expanded sampling to refine risk assessments and guide public health interventions.

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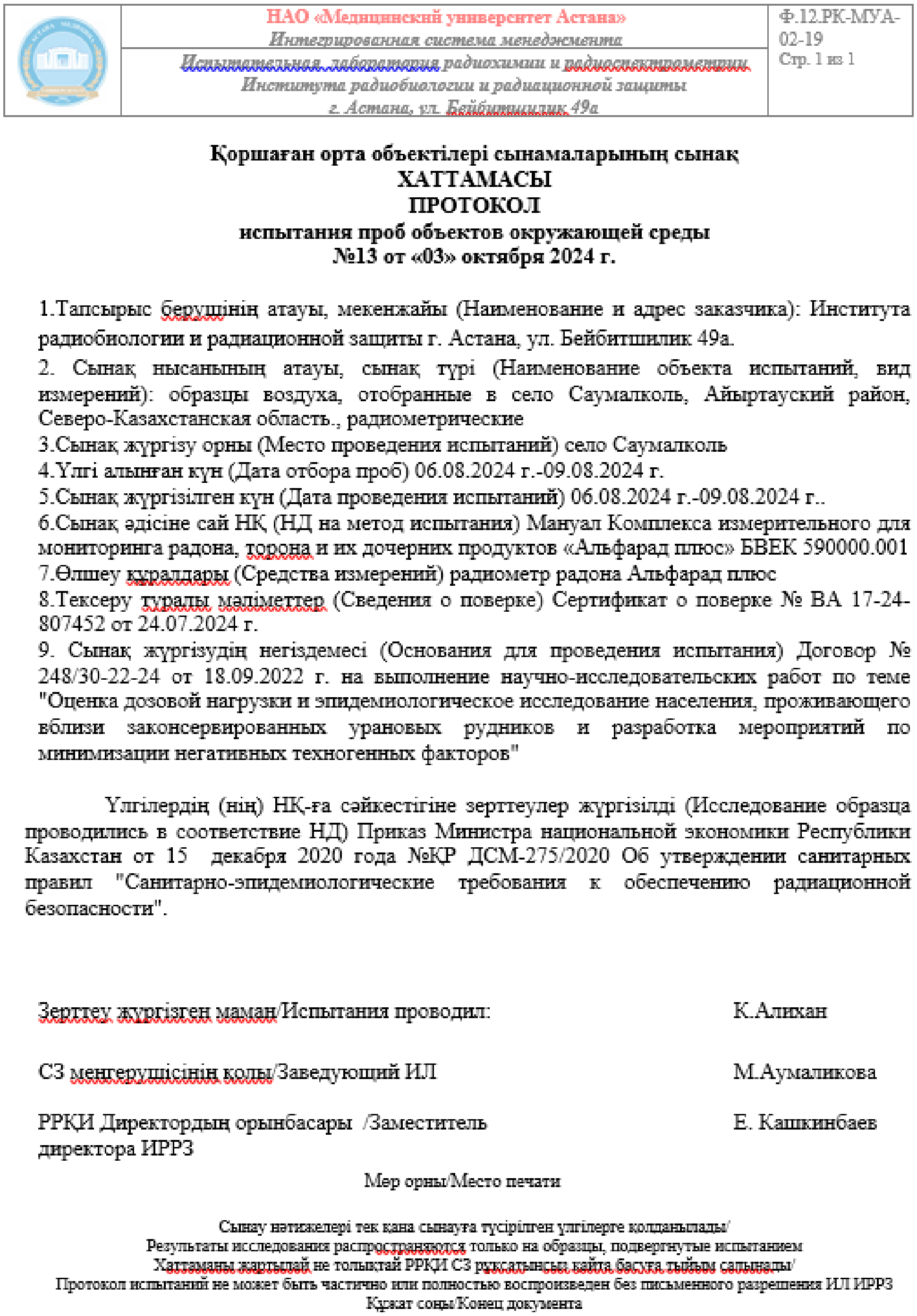
Appendix A

Research protocol in the settlement of Saumalkol



	НАО «Медицинский университет Астана» *Интегрированная система менеджмента*	Ф.12.РК-МУА-02-19 Стр. 1 из 1
	Испытательная лаборатория радиохимии и радиоспектрометрии Института радиобиологии и радиационной защиты г. Астана, ул. Бейбитшилик 49а	

Қоршаған орта объектілері сынамаларының сынақ
ХАТТАМАСЫ
ПРОТОКОЛ
испытания проб объектов окружающей среды
№13 от «03» октября 2024 г.

1.Тапсырыс берушінің атауы, мекенжайы (Наименование и адрес заказчика): Института радиобиологии и радиационной защиты г. Астана, ул. Бейбитшилик 49а.

2. Сынақ нысанының атауы, сынақ түрі (Наименование объекта испытаний, вид измерений): образцы воздуха, отобранные в село Саумалколь, Айыртауский район, Северо-Казахстанская область., радиометрические

3.Сынақ жүргізу орны (Место проведения испытаний) село Саумалколь

4.Үлгі алынған күн (Дата отбора проб) 06.08.2024 г.-09.08.2024 г.

5.Сынақ жүргізілген күн (Дата проведения испытаний) 06.08.2024 г.-09.08.2024 г..

6.Сынақ әдісіне сай НҚ (НД на метод испытания) Мануал Комплекса измерительного для мониторинга радона, торона и их дочерних продуктов «Альфарад плюс» БВЕК 590000.001

7.Өлшеу құралдары (Средства измерений) радиометр радона Альфарад плюс

8.Тексеру туралы мәліметтер (Сведения о поверке) Сертификат о поверке № ВА 17-24-807452 от 24.07.2024 г.

9. Сынақ жүргізудің негіздемесі (Основания для проведения испытания) Договор № 248/30-22-24 от 18.09.2022 г. на выполнение научно-исследовательских работ по теме "Оценка дозовой нагрузки и эпидемиологическое исследование населения, проживающего вблизи законсервированных урановых рудников и разработка мероприятий по минимизации негативных техногенных факторов"

Үлгілердің (нің) НҚ-ға сәйкестігіне зерттеулер жүргізілді (Исследование образца проводились в соответствие НД) Приказ Министра национальной экономики Республики Казахстан от 15 декабря 2020 года №ҚР ДСМ-275/2020 Об утверждении санитарных правил "Санитарно-эпидемиологические требования к обеспечению радиационной безопасности".

Зерттеу жүргізген маман/Испытания проводил:	К.Алихан
СЗ меңгерушісінің қолы/Заведующий ИЛ	М.Аумаликова
РРҚИ Директордың орынбасары /Заместитель директора ИРРЗ	Е. Кашкинбаев

Мөр орны/Место печати

Сынау нәтижелері тек қана сынауға түсірілген үлгілерге қолданылады/
Результаты исследования распространяются только на образцы, подвергнутые испытанием
Хаттаманы жартылай не толықтай РРҚИ СЗ рұқсатынсыз қайта басуға тыйым салынады/
Протокол испытаний не может быть частично или полностью воспроизведен без письменного разрешения ИЛ ИРРЗ
Құжат соңы/Конец документа

Appendix B

Scientific Impact

The research presented in this Master's dissertation was successfully defended and disseminated at a scientific conference, underscoring its relevance and contribution to environmental and public health sciences.

Conference Presentation:

"Assessing Radon Exposure Risks in Saumalkol: Legacy Uranium Mining and Public Health"

Date: April 14, 2025

Event: International Young Scientists Forum

ASTANA MEDICAL UNIVERSITY

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КОММЕРЦИЯЛЫҚ ЕМЕС АКЦИОНЕРЛІК ҚОҒАМЫ

СЕРТИФИКАТ

№: 1396

Көбей Әлихан Саятұлы

«Астана медицина университеті» КеАҚ
Ғылым күндері аясында өткізілген
Жас ғалымдар халықаралық форумына
қатысқаны үшін берілді
14.04.2025 ж.

Проректор
Койков В.В.

Астана, 2025 ж.