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Comparative Radiological Assessment of a Former Thorium Mine and Oilfield Produced Water Lakes

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Abstract

The mining and mineral extraction industries release numerous pollutants, including naturally occurring radioactive materials (NORM). In this research, a comparison was made between data from a study published by researchers affiliated with the Ministry of Higher Education of Kazakhstan on the radiation hazards of a former thorium and rare earth elements mining site in northeastern Kazakhstan, and other data on radiation hazards recorded in produced water lakes from oil fields. The Kazakh study analyzed 14 samples, taken from a depth not exceeding 20 cm, while the dried-up oil pits used 7 samples taken from a similar depth, the specific activity concentrations for the Kazakh mining site ranged from 445 to 616 Bq/kg for ^{40}K, 23 to 75 Bq/kg for ^{226}Ra, and 55 to 450 Bq/kg for ^{232}Th, respectively. Whereas the values of these measurements of the oil dry pits ranged between 143 to 7441 for ^{40}K, $1.24x10^3$ to $3.2x10^5$ for ^{226}Ra, and 197 to $1.46x10^5$ for ^{232}Th, Bq/kg respectively. Calculated hazard indicators (radium equivalent activity - Raeq, absorbed dose rate - D, and annual effective dose equivalent - AEDE for the mining site ranged from 141 to 766 Bq/kg, 165 to 332 nGy/h, and 0.08 to 0.41 mSv/y, respectively. For the oil-produced water lakes, these values were significantly higher, ranging from 1.74×10^3 to 5.37×10^5 Bq/kg (Raeq), 783 to 2.37×10^5 nGy/h (D), and 0.96 to 290 mSv/y (AEDE). These data demonstrate that the radiological hazard potential (based on activity concentrations) is significantly higher in the oil-produced water lakes. However, in reality, oil and gas workers typically receive very low occupational doses. In contrast, workers at mining sites, despite the lower activity concentration in the bulk material, often receive considerably higher radiation doses. The reasons for this apparent contradiction—the difference between hazard and actual exposure are explored in detail in this paper.

Keywords: NORM, mining, oil and gas, radiation hazard indicators

مقارنة المخاطر الإشعاعية بين موقع تعدين ثوريوم وبحيرات مياه منتجة نفطية

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الملخص

كل مجالات التعدين و إستخراج المعادن تؤدي إلى استخراج ملوثات عديدة، من بين هذه الملوثات ما يعرف بالمواد المشعة طبيعية المنشأ المعروفة بالنورم، في هذا البحث تمت المقارنة بين بيانات بحث تم نشره من قبل باحثين تابعين لوزارة التعليم العالي لدولة كازاخستان حول المخاطر الإشعاعية لموقع سابق لتعدين الثوريوم والعناصر الأرضية النادرة في شمال شرق كازاخستان و بيانات أخرى لمخاطر إشعاعية مسجلة لبعض بحيرات المياه المنتجة الجافة في حقول نفطية.
كان عدد العينات في البحث الكازاخي 14 عينة أخذت من عمق سطحي لا يتجاوز 20 cm، فيما كان عدد عينات البحيرات النفطية جافة السطح 7 عينات أخذت من عمق مماثل. حيث سجل النشاط الإشعاعي النوعي لكل من البوتاسيوم40 (^{40}K) و الراديوم226 (^{226}Ra)و الثوريوم232 (^{232}Th) لموقع التعدين الكازاخي قيم تراوحت بين 616-445 ، 75-23 ، 450-55 Bq/kg على التوالي ، فيما تراوحت قيم هذه القراءات في البحيرات النفطية بين 7441-143 ،- 1051.24 3.2x $x10^3$ ، $1.46x10^5$ 197- Bq/kgعلى التوالي. بالنسبة لمؤشرات الخطر و هي النشاط المكافئ للراديوم (Raeq) و الجرعة الممتصة (D) و الجرعة المكافئة السنوية الفعالة (AEDE) فقد تراوحت لموقع التعدين كالأتي: 766-141 Bq/kg، 332-165 nGy/h، 041- 0.08 mSv/yعلى التوالي ، فيما تراوحت قراءات البحيرات النفطية كالتالي5.37 $1.74x10^3$Bq/kg - $x10^5$، 783 nGy/h 2.37x105 - ، 290-0.96 mSv/yعلى التوالي.
تظهر هذه البيانات أن المخاطر الإشعاعية الناتجة عن البحيرات النفطية أكبر بشكل واضح منها لموقع التعدين ، لكن فعليا و واقعيا يتلقى العاملين في قطاع النفط و الغاز في العموم جرعات إشعاعية ضئيلة جدا، في المقابل يتلقى العاملين في التعدين بشكل عام جرعات إشعاعية معتبرة ، هذا التناقض الظاهر يرجع لأسباب عديدة يفصل فيها هذا البحث.

الكلمات المفتاحية: النورم ، التعدين ، النفط والغاز, مؤشرات الخطر الإشعاعي

1. Introduction

The International Atomic Energy Agency's (IAEA) Basic Safety Standards (BSS) categorize "mining and processing of raw materials involving exposure to NORM," including the oil and gas industry, as practices subject to planned exposure situations. Meanwhile, European Union regulations encompass a "list of 16 industrial sectors involving NORM, featuring the oil and gas industry alongside other mining operations chiefly uranium and thorium mining, and rare earth elements which require radiological evaluation" [IOGP, 2016]. Radiological assessments play a pivotal role in understanding and managing environmental and health impacts associated with radioactive materials.

Environmental radioecology pays special attention to the short, medium, and particularly long-term behaviour, distribution, and effects of radioactive contamination across various ecosystems. NORM has become a growing concern, especially within oil and gas operations and the exploration and processing of rare earth elements, which naturally contain significant quantities of radioactive elements like uranium and thorium, necessitating detailed safety and environmental compliance evaluations.

This research contributes to such evaluations by comparing two major economic sectors: the oil and gas industry and thorium/rare-earth mining. Given that the oil and gas sector serves as the backbone of the economy and daily life in many countries, including Libya, evaluating its collateral health and environmental impacts is vital for a comprehensive assessment of its overall economic and social utility. Such comparisons help leverage international experiences regarding NORM side effects across diverse mining industries, despite variations in mining types, methodologies, and byproducts.

Given the relative scarcity of this research topic both locally and internationally, this study serves as a foundation for a broader series of investigations comparing NORM from the oil and gas sector across different oil-producing countries, as well as contrasting it with other extractive industries like uranium, coal, and phosphate mining.

1.1 The Relationship Between the Oil and Gas Industry and NORM:

Like other mineral elements, NORM exists at varying concentrations within oil and gas hydrocarbon reservoirs, making the petroleum sector prone to occupational NORM enrichment. Natural radioactive materials accompany extracted crude oil, eventually depositing onto the internal walls of pipelines, separation vessels, and storage tanks. These accumulations typically manifest as hard mineral scales, while produced water carries suspended sludges containing unprecipitated radioactive isotopes [IOGP, 2016].

1.2 Scale NORM: Sulfate deposits such as barium sulfate ($BaSO_4$) and strontium sulfate ($SrSO_4$) and carbonate deposits (such as calcium carbonate ($CaCO_3$) represent the primary scales encountered in petroleum facilities. Because radium shares chemical similarities with barium, strontium, and calcium, it co-precipitates with them to form radium sulfate, radium carbonate, or

occasionally radium silicates. The mixing of sulfate-rich seawater with brine-heavy formation water heightens precipitation tendencies. Abrupt pressure, temperature, or pH shifts during fluid ascent further drive scale deposition, severely restricting pipeline conveyance capacity [IOGP, 2008].

1.3 Sludge and Residue NORM: Radioactive particles containing radium that fail to integrate into hard scales settle within sludges, sediments, and produced waters. Other radionuclides, such as lead-210 (^{210}Pb) and polonium-210 (^{210}Po), are found in pipeline debris, bottom sludge of storage tanks, oil-gas separators, dehydration vessels, liquefied natural gas (LNG) storage tanks, and waste pits (IOGP, 2008).

1.4 Gas Processing Facility NORM: Radon is a radioactive gas present in varying proportions within natural gas reservoirs. In the absence of natural gas, radon dissolves into light hydrocarbons and aqueous phases. Upon extraction, it predominantly follows the gas stream. During natural gas fractionation, high concentrations of radon may concentrate within propane streams and, to a lesser extent, ethane streams. Radon-222 (^{222}Ra) decays naturally into multiple radioactive progeny (short-lived radon daughters), alongside longer-lived lead-210 (half-life of 22.6 years) and polonium-210 (half-life of 138 days). Most radon decay products (90–99%) attach to ambient aerosols, airborne dust, or interior equipment surfaces such as scrubbers, compressors, reflux pumps, control valves, and production lines, forming thin radioactive films (IOGP, 2008).

1.5 Seawater Injection Systems NORM: Seawater contains uranium at concentrations reaching parts per billion (µg/L). Utilizing seawater for reservoir pressure maintenance can elevate NORM concentrations. In anaerobic environments like geological formations, sulfate-reducing bacteria promote the absorption of precipitated uranium into bio-fouling sediments. While negligible in many injection setups, systems handling massive volumes of seawater can develop bio-fouling uranium concentrations high enough to pose worker hazards and waste disposal challenges, with uranium concentrations reaching up to ~2% by weight (IOGP, 2008).

1.6 Uranium and Thorium Mining:
Thorium and uranium are naturally occurring radioactive elements distributed within the Earth's crust, frequently co-existing in overlapping geological formations. Although structurally similar, they differ significantly in isotopic composition, radioactivity, environmental behaviour, and nuclear applications. Thorium occurs almost exclusively as Thorium-232 (^{232}Th), whereas uranium consists of a mixture of Uranium-238 (^{238}U) and Uranium-235 (^{235}U) [Lide, 2005]. Both elements undergo alpha decay and serve as parents to long radioactive decay chains [Eisenbud & Gesell, 1997], as illustrated in Figures 1.a & 1.b.
The toxicity of thorium stems primarily from radiological hazards via inhalation, whereas uranium presents both radiological and chemical toxicity particularly nephrotoxicity owing to its heavy metal properties. Radionuclides contributing to gross alpha activity include Radium-226 (^{226}Ra),

Uranium-238 (^{238}U), and Radon-222 (^{222}Ra) along with its progeny like Polonium-210 (^{210}Po), which are linked to severe adverse health outcomes. Chronic exposure to radium isotopes increases risks of anemia, cataracts, bone tumors, and dental necrosis. Gastrointestinal absorption of uranium isotopes induces kidney damage. Furthermore, consuming water with elevated radon levels elevates stomach cancer risks. Beta-emitting radionuclides include Potassium-40 (^{40}K) and isotopes belonging to the uranium and thorium decay series, notably Radium-228 (^{228}Ra) and Lead-210 [Kang & von Hippel, 2001]. Alpha and beta decay are frequently accompanied by gamma radiation.

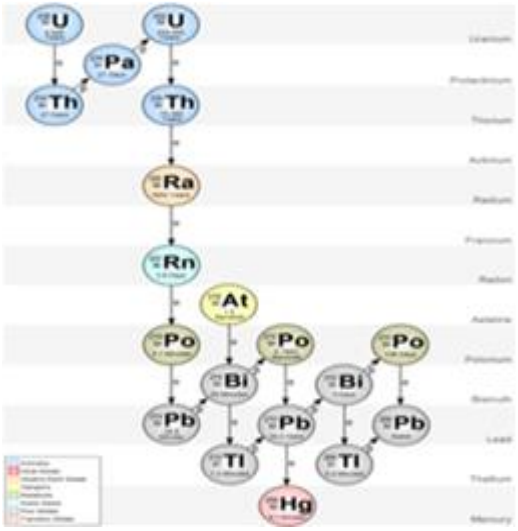


Figure 1.a: Simplified schematic representation of Uranium-238 radioactive decay chain

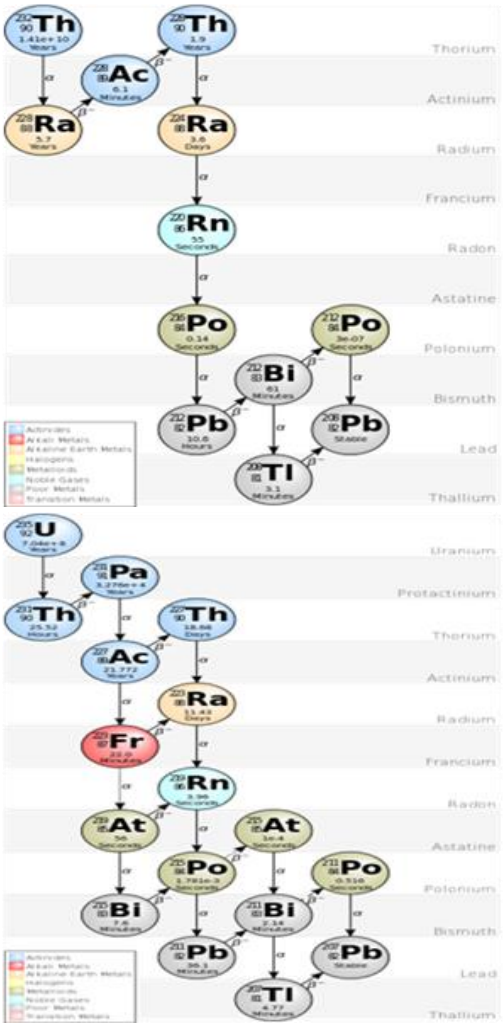


Figure 1.b Simplified schematic representation of Uranium-235, and Thorium-232 radioactive decay chains.

While the radiological inventory across uranium/thorium mining and oil/gas production shares common origins rooted in the natural decay chains of uranium and thorium (with secondary contributions from potassium-40), major differences emerge in:

1. Which isotopes partition into waste streams;
2. Which physical phases (aqueous, solid, or gaseous) dominate;
3. The concentration mechanisms and waste formation pathways; and

4. Hazard patterns and required containment timeframes [IAEA GSR Part 3, 2014].

1.7 Resulting Hazards

From a hazard standpoint, uranium and thorium mining wastes tend to exhibit long-term environmental risk footprints associated with radon release, groundwater and surface water isotope migration, and the persistence of radium and thorium for thousands to tens of thousands of years, mandating extended engineering closures, barriers, and monitoring regimes. Conversely, oil and gas risks are usually localized around specific operational touchpoints (maintenance, scale removal, equipment cleaning, sludge handling) and aqueous release pathways during produced water discharge, with particular emphasis on Radium-226 (^{226}Ra), Radium-228 (^{228}Ra), and radon progeny in gas systems such as Lead-210 (^{210}Pb) and Polonium-210 (^{210}Po) [IAEA, 2021].

1.7.1 Radiological Hazards and Exposure Pathways for Workers, the Public, and the Environment:

Hazards depend on physical state (gas, liquid, solid), radiation type (alpha, beta, gamma), dose pathway (external, internal), and exposure duration. NORM exposure pathways are typically site-specific, depending on proximity to fluid sinks or disposal sites, with external exposure, radon inhalation, and ingestion via water, crops, and animal products playing key roles [UNSCEAR, 2024].

1.7.2 In Uranium Mining and Processing:

1.7.2.a Workers: Critical occupational hazards involve inhaling radon and its progeny in mine environments (especially underground) and dust containing long-lived alpha emitters such as Thorium-230 (^{230}Th), Radium-226 (^{226}Ra), and Polonium-210 (^{210}Po), alongside external gamma radiation originating from radium daughters in mill tailings. The BSS occupational dose limit sets an average effective dose threshold of 20 mSv per year averaged over 5 years, with additional operational constraints [UNSCEAR, 2024].

1.7.1.b Public and Environment: Primary risks relate to radon exhalation from tailings impoundments, potential contaminant migration via ground and surface waters, and the persistence of radium and thorium, rendering engineering containment and hydrological control critical safety elements [UNSCEAR, 2024].

1.7.3 In Oil and Gas Operations:

1.7.3.a Workers: Hazards concentrate during maintenance and cleaning tasks such as scale and sludge removal (external gamma exposure near scales, internal exposure via inhalation of contaminated dust, and potential radon inhalation in gas processing plants). Scales and mineral deposits are documented as the most radiologically significant, while radon decay in gas streams can deposit high concentrations of Polonium-210 (^{210}Po) and Lead-210 (^{210}Pb) inside piping [UNSCEAR, 2024].

1.7.3.b Public and Environment: Aqueous pathways are often paramount near oil and gas installations (particularly during

discharge). Although comprehensive public exposure data are scarce, external gamma dose pathways, particulate/radon inhalation, and ingestion represent the highest potential public exposure routes, with disposal options varying according to contamination levels [UNSCEAR, 2024].

2. Methodology

2.1 Oilfield Samples:

Eight samples were collected from produced water lakes across three adjacent oil fields. These samples were prepared to measure the specific activity concentrations of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in the laboratory. The samples were sun-dried outdoors for two days to eliminate moisture, then placed in an electric oven at 110 ºC for 24 hours to ensure complete residual moisture removal. Dried samples were ground individually using a blender and sieved through a 2 mm mesh screen. One-kilogram samples were stored in Marinelli beakers and tightly sealed with plastic tape.

The beakers were stored for 30 days to allow Bismuth-214 (^{214}Bi) and Thallium-208 (^{208}Tl) to reach secular equilibrium with Radium-226 (^{226}Ra), Thorium-232 (^{232}Th), and their respective progeny. Plastic containers were further secured with secondary plastic wraps to guarantee containment of Radon-220 (^{220}Rn) and Radon-222 (^{222}Rn). Radiological measurements were performed at the Radiation Measurement and Training Center of the Atomic Energy Commission using a High-Purity Germanium HPGe gamma-ray spectrometer with a 40% relative efficiency connected to a multichannel analyzer (MCA). Background radiation interference was mitigated by housing the HPGe detector inside a passive lead shielding enclosure.

Table 1 presents the basic information for the oil samples.

Table 1- The basic information of the oil samples

Sample ID	Collection Date	Detection Date	Counting Duration(h)
Z1	May 2023	Jul 2023	18
Z2	May 2023	Jul 2023	18
Z3	Jun 2023	Aug 2023	18
Z4	Jun 2023	Aug 2023	18
S1	Aug 2023	Sep 2023	18
H1	Sep 2023	Oct2023	18
H2	Sep 2023	Oct 2023	18

2.2 Kazakh Study Samples

Samples were collected from a residential area in Ust-Kamenogorsk (Kazakhstan), also known as Oskemen, the capital of the East Kazakhstan Region situated at the foothills of the Rudny Altai mountains near the confluence of the Ulba and Irtysh rivers. Today, Oskemen serves as a major center for non-ferrous metal mining (lead, zinc, titanium, magnesium). The Kazakh study aimed to evaluate soil radioactive contamination at a former processing facility for monazite, tin, and radioactive ores. The sampling grid covered 480m^2 across 28 total boreholes, collecting 5 depth-incremental samples per borehole 20cm, 40cm, 60cm, 80cm, and 100cm, totaling 140 samples.

Materials were cleared of debris (plant roots, insects, stones, glass, etc.), sieved through a 5mm mesh, and homogenized. Representative samples of at least 1kg were sealed in labeled polyethylene bags. Samples were dried at a maximum temperature of 40ºC spread on polyethylene film, crushed

with a spatula or pestle to break up large aggregates, sieved through a 1mm mesh, and homogenized. A 300g sub-sample was transferred to a 2dcm^3 beaker, mixed with 5:1 of distilled water (1:5 solid-to-liquid ratio), shaken for 2 hours, incubated for 22 hours at room temperature, and filtered through a 0.45µm membrane filter. One liter of filtrate was evaporated to dryness, ashed in an electric furnace at 350^{o}C for 1 hour (in the presence of ethanol), transferred to a pre-weighed counting cell, dried into a uniform layer, weighed, and subjected to gamma-ray spectrometry.

Gamma-emitting radionuclide activity (^{226}Ra, ^{232}Th, ^{40}K) was quantified using an InSpector 1000 gamma spectrometer Canberra, Smyrna, GA, USA [[Kazakh Study , Idrisheva, Z & others].

It should be noted that the comparison was conducted between the seven oil-contaminated samples and only 14 of the 28 surface soil samples (collected at a depth of 20 cm) from the Kazakh site; this is because the oil-contaminated samples were obtained from the surface layer of oil pools. While results from samples collected at greater depths in the Kazakh study will be mentioned, they are excluded from the comparison due to the difference in sampling depth. Furthermore, the Kazakh study assessed alpha, beta, and gamma radiation doses for all samples, whereas the radiological analysis of the oil-contaminated samples focused solely on gamma radiation doses.

2.3 Radiological Risk Assessment:

2.3.1 Activity Concentration (A): Specific activity concentration A was calculated using Equation 1 [Dovlete & Povinec, 2004]:

$$A = \frac{net\ CPS\ samples}{Eff\ I_\gamma W} \rightarrow (1)$$

Where net CPS samples is the net count rate per second, Eff is the detector efficiency at a given energy, Iγ is the ratio of gamma emission intensity to this energy, and W is the sample weight in kg.

2.3.2 The radium equivalent activity (Raeq): The radium equivalent activity (Raeq) in Bq/kg is a widely used radiological hazard index used to assess the risks associated with materials containing ^{226}Ra, ^{232}Th, and 40K. It is determined based on the assumption that 370 Bq/kg of ^{226}Ra, 260 Bq/kg of ^{232}Th, and 4810 Bq/kg of 40K produce the same dose rate. It is calculated as shown in Equation 2 [UNSCEAR 2000]:

$$Raeq = A_u + (A_{Th} \times 1.43) + (A_K \times 0.077) \rightarrow (2).$$

A_u, A_{Th}, and A_k are the radioactivity values for ^{238}U, ^{232}Th, and ^{40}K, respectively, in Bq/kg.

2.3.3 Absorbed Dose Rate (D): Determining the absorbed dose rates (D) of samples in nGy/hr of specific radioactivity concentrations, where 1 Bq/kg of 40K, 238U, and 232Th, respectively, gives an absorbed dose rate of 0.0417 nGy/hr, 0.462 nGy/hr, and 0.604 nGy/hr, respectively, at 1 meter above the ground surface, as shown in Equation 3 [UNSCEAR 2000]:

$$D = (0.462 \times A_U) + (0.604 \times A_{Th}) + (0.0417 \times A_K) \rightarrow (3)$$

2.3.4 Annual Effective Dose Equivalent (AEDE): The concentration of radionuclides in the environment due to terrestrial gamma radiation from 238U, 232Th, and 40K can be measured using the annual effective dose equivalent (AEDE) [UNSCEAR 2000], where:

$$AEDE = D \times 1.23 \times 10^{-3}\ mSv/y \rightarrow (4),$$

where D is the absorbed dose rate (nGy/h), 1.23×10^{-3} = 8760 hr/yr x 0.2 x 0.7 Sv/Gr
8760 is the number of hours in a year, 0.2 is the percentage of time spent outdoors (or occupancy factor) for an average person, and 0.7 is the percentage of the absorbed dose affecting vital organs in the human body, which depends on several factors such as the type of radiation and the type and sensitivity of the human organ [UNSCEAR 2000].

2.3.5 The gamma radiation level index (Iγ) is used to monitor the average annual dose received from exposure to external gamma radiation emitted from the topsoil. It is calculated using the following formula:

$$I_\gamma = \frac{A_{Ra-226}}{300} + \frac{A_{Th-232}}{200} + \frac{A_{k-40}}{3000} \rightarrow (5)$$

where A_{Ra-226}, A_{Th-232}, and A_{K-40} represent the radioactivity [becquerels/kg] of radium-226, thorium-232, and potassium-40, respectively. If the calculated values are greater than or equal to 1, the soil may be considered contaminated [UNSCEAR 2000].

2.3.6 Increased Lifetime Cancer Risk (ELCR): Based on the expected annual exposure (AEDE), the increased lifetime cancer risk (ELCR) can be calculated. This unitless coefficient is used to estimate the probability of developing cancer in humans during the lifetime of an individual exposed to naturally occurring radioactive materials [Bulubasa, G.; Costinel 2021].

$$ELCR = AEDE \cdot DL \cdot RF \rightarrow (6)$$

DL: Life expectancy (70 years as defined by the World Health Organization in 2014). RF: Risk factor for cancer lethality, 0.057 per sievert for random effects of ionizing radiation, as proposed by the International Commission on Radiological Protection (ICRP). The global average is 0.29×10^{-3} [UNSCEAR 2000].

2.3.7 The Annual Gonadal Dose Equivalent (AGDE): is defined as a measure of the genetic significance of the annual dose received by the reproductive organs of a population or those exposed to radiation in general.

$$AGDE = 3.09\ A_{Ra-226} + 4.18\ A_{Th-232} + 0.314\ A_{K-40} \rightarrow (7),$$

where A_{Ra-226}, A_{Th-232}, and A_{K-40} represent the radioactivity [Bq/kg] of radium-226, thorium-232, and potassium-40, respectively. The global average is 300 μSv/y [UNSCEAR2000].

3. Results and Discussion

3.1 The Comparison: As noted, 14 surface soil samples with peak activity values from the Kazakh study were selected for comparison, representing the highest values among 28 readings. Table 2 contrasts radionuclide activities between oilfield samples and Kazakh samples, while Figures 2,3,4 and 5 illustrate hazard indicator comparisons. A striking disparity appears between specific activity concentrations and hazard indicators, which skew significantly higher for oilfield samples. While unexpected

at first glance, NORM in oilfields concentrates intensely within specific operational touchpoints, prominent among them being oilfield evaporation/produced water lakes. In uranium mining, conversely, massive quantities of mill tailings are produced that retain most original ore radioactivity post-extraction, sustaining long-lived isotopes like ^{230}Th and ^{226}Ra, heavy metals, and acid drainage risks. IAEA guidelines indicate mill tailings retain approximately 75% of original uranium ore radioactivity at concentrations approaching raw ore [Nelson, 2015].

Table 2: Comparison of radioactivity concentrations between oilfield samples and Kazakh samples

Radioactivity of oil samples (Bq/kg)			
Sample Code	^{226}Ra	K^{40}	^{232}Th
Z1	$1.33x10^5$	484.7	512.51
Z2	$7.53x10^4$	-	-
Z3	$9.88x10^3$	532.02	197.09
Z4	$8.71x10^3$	143.4	$9.48x10^3$
S1	$1.24x10^3$	240.5	330.056
H1	$3.21x10^5$	$7.44x10^3$	$1.46x10^5$
H2	$7.64x10^5$	329.3	$6.52X10^3$
Radioactivity of Kazakh samples (Bq/kg)			
Sample Code	^{226}Ra	K^{40}	^{232}Th
1	766	450	332
2	376	430	166
3	471	366	206
4	394	352	173
5	290	383	128
6	470	339	205
7	449	395	197
8	616	381	268
9	468	415	205
10	376	444	166
11	509	440	223
12	482	410	211
13	410	405	180
14	398	415	133

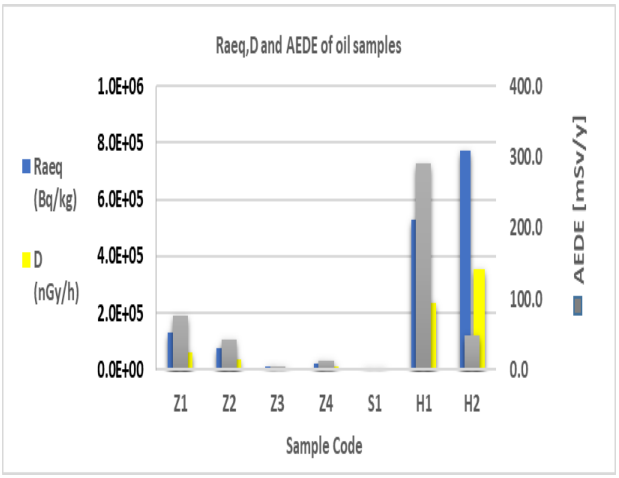


Figure 2 - Radium equivalent activity (Raeq), Absorbed dose rate (D), and Annual effective dose equivalent (AEDE): of oil samples.

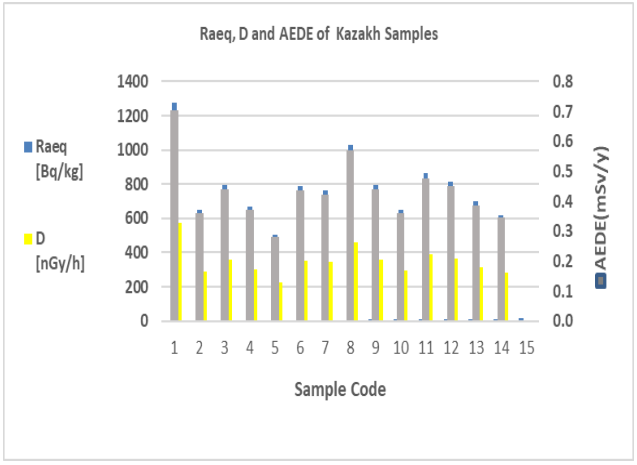


Figure 3- Radium equivalent activity (Raeq), Absorbed dose rate (D), and Annual effective dose equivalent (AEDE): of Kazakh samples

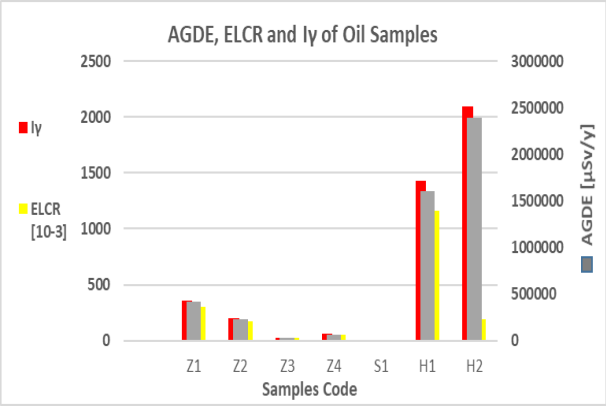


Figure 4- The gamma radiation level index (Iγ), Increased Lifetime Cancer Risk (ELCR) and the Annual Gonadal Dose Equivalent (AGDE) of oil samples

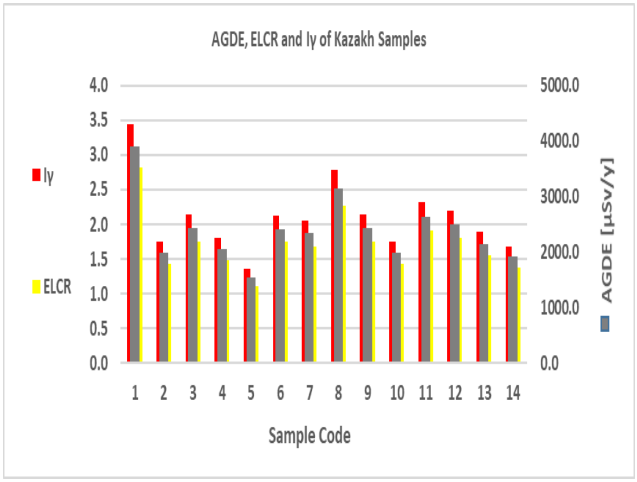


Figure 5- The gamma radiation level index (Iγ), Increased Lifetime Cancer Risk (ELCR) and the Annual Gonadal Dose Equivalent (AGDE) of Kazakh samples

In the oil and gas sector, radioactive waste generally features large volumes of low- to medium-activity produced water juxtaposed against small volumes of scales and sludge exhibiting extremely high activity due to radium co-precipitation with barium and strontium sulfates inside piping and equipment. Scale activities reach 10-100 Bq/g, with sludge potentially reaching hundreds of Bq/g or more [Rowan et al., 2011].

Produced water radioactivity typically ranges around 4Bq/L for ^{226}Ra and 2Bq/L for ^{228}Ra, with potential surges up to 50-fold 200Bq/L depending on fields, salinity, and reservoir geology [Rowan et al., 2011]. Scientific literature reports wide measurement ranges for ^{226}Ra: 0.04-1480Bq/L in produced waters, 1.1-2,015,000Bq/kg in scales, and 10-100Bq/kg in sludge, reflecting basin, operational, and methodological variations [OECD, 1999].



Figure (6) – Instantaneous dose recorded at sampling sites H1 and Z1

3.1.1 Uranium mining: IAEA guidelines confirm that milling residues retain approximately 75% of the original

radioactivity present in the ore, with most chain isotopes remaining at concentrations close to those in the ore—with the exception of the uranium isotopes that are extracted [IAEA 2014 GSR Part 3].
waters influenced by mining activity exhibit dissolved radium levels reaching 8-15Bq/L at specific points, alongside tailings dams and underground drainage [OECD, 1999].

Sample **H1** (Figure 2) recorded a peak instantaneous reading of 33.26 µSv/h, equivalent to 291mSv/y, meaning an individual remaining at that exact spot for a full year would absorb 291mSv. While physically impossible, this is mathematically conceivable. Consequently, oil worker exposure risks are minimal under normal conditions due to the restricted spatial distribution of NORM, low probabilities of encountering such extreme values, and the physical impossibility of prolonged human presence at such spots. Exceptions occur during separator and vessel cleaning, which follow rigorous protocols that decisively minimize exposure; even then, radiation doses rarely reach such extremes. Sample **Z1** registered an instantaneous dose rate of 8.43µSv/h 76mSv/y.

3.2.1Methodological Note: Annual effective dose equivalent values were derived by computing specific activity via Equation 1, determining absorbed dose rate D via Equation 3, and applying Equation 4 to yield AEDE, rather than performing direct conversions from portable instrument instantaneous readings (Figure 2), though both approaches yield consistent trends. This consistency and its underlying nuances are explored in our prior publication [*Atom and Development Bulletin*, Issue 2, 2025, Arab Atomic Energy Commission].

3.2- Knowledge Gaps and Uncertainties:
A shortage of standardized databases tracking radium, lead, and polonium activity by waste stream persists outside the United States, where regular national regulatory reports are available. Many global publications originate from disparate sources utilizing varying measurement methods and detection limits.
Assessments relying solely on Radium-226 measurements may underestimate total activity a phenomenon documented in unconventional gas-derived produced fluids with direct implications for sampling, storage, and analytical protocols.
Comparisons between "radiological risk" and "chemical risk" within identical wastes remain imbalanced: uranium mill tailings contain heavy metals and acid drainage hazards, whereas produced waters feature elevated salinity, heavy metals, and organic compounds that can surpass radiological impacts in certain environmental scenarios. This is highlighted in waste management guidelines addressing radiological and non-radiological facets jointly.
Variations in regulatory frameworks for TENORM in the oil and gas sector across different countries lead to disparities in key management parameters such as designated disposal sites, cleanup thresholds, and measurement requirements [EPA2020]. Based on this information from the US EPA and the data presented in Table 3, it is evident that comparing data from various mining sites worldwide is challenging. For instance, a

granite production site in Shijiazhuang, China, reported an absorbed dose (D) ranging from 57.6 to 280nGy/h and an annual

Table 3 – Comparison of radiation risk indicators with other locations worldwide

Location, Region, Country	**Raeq (Bq/kg)**	**D (nGy/h)**	**AEDE (mSv/y)**
Granite area Xiazhuang, China	121–624	57.6–280	70.7–344
Gold mine. Gauteng, Province, South Africa	76–104 (control soil area) 1668–2812 (tailing)	37.5–49.1 (control) 203.9–1297.3 (tailing)	0.1–1.6
Uranium-rich, Area, Siwalik region, India	ns	52.7–1722	ns
Lomonosovov, diamond deposit, Arkhangelsk, Russia	17–198	9–94	0.01–0.12
Abandoned U Mine, Salamanca, Spain	160–1746 (for soil, for rhizosphere up to 9494)	78–856 (for soil, for rhizosphere up to 4 811)	0.095–1.05 (27.0 for Rhizosphere sample)
Rare earth element mine, Lao Cai, Vietnam	ns	1597–25,057	1.96–30.7
Tin tailing, Perak, Malaysia	0.6–20.9 (soil) 3.2–17.0 (tailing)	1.7–8.9 × 103 (soil) 1.2–7.2 × 103 (tailing)	ns
Pb–Zn deposit, Yunnan, China	78.9–225	36.8–108	0.045–0.133
Former REE processing site, Kazakhstan	141–766 (at 0–20 cm) 127–4064 (at 40–60 cm)	65–332 (at 0–20 cm) 59–1737 (at 40–60 cm)	0.08–0.41 (at 0–20 cm) 0.07–2.13 (at 40–60 cm)
This study	$1.73x10^3$ - $5.37.x10^5$	783.6-$2.37x10^5$	0.96-291
World recommended value	<370	59.0	0.07

Table 4 – Comparison of Annual Gonadal Dose Equivalent with Increased Lifetime Cancer Risk

Location, Region, Country	**AGDE (μSv/y)**	**ELCR × 10^{-3}**
Granite area Xiazhuang, China	ns	ns
Gold mine. Gauteng, Province, South Africa	ns	ns
Uranium-rich, Area, Siwalik region, India	0.06–2.14	0.21–7.49
Lomonosovov, diamond deposit, Arkhangelsk, Russia	65–675	0.15–1.62
Abandoned U Mine, Salamanca, Spain	ns	0.38–4.19 (10.6 for rhizosphere sample)
Rare earth element mine, Lao Cai, Vietnam	ns	0.008–0.124
Tin tailing, Perak, Malaysia	ns	1.2–42.0 (soil) 5.9–34.0 (tailing)
Pb–Zn deposit, Yunnan, China	256–770	0.158–0.463
Former REE processing site, Kazakhstan	459–2306 (at 0–20 cm) 421–11,994 (at 40–60 cm)	0.32–1.63 (at 0–20 cm) 0.29–7.39 (at 40–60 cm)
[[Kazakh Study , Idrisheva, Z & others]		
This study	$1.59x10^4$-2.33x106	3.83-1164.8
World recommended value	300	0.290

equivalent dose ranging from 70.7 to 344mSv/y; however, applying the standard calculation method (Equation 4) as used in this study yields results that do not align. This discrepancy does not necessarily imply the data is erroneous; rather, several possibilities exist. For example, the reported absorbed dose could represent either a long-term average or a direct, instantaneous reading. In contrast, Equation 4 was applied consistently in the cases of the diamond mine in the Russian Federation and the Spanish uranium mine. Consequently, a significant degree of uncertainty is inherent in such comparisons.

4- Conclusion

The principal conclusion of this research is that oil and gas extraction and production can generate high radiation dose rates at exceptional focal points within the broader general radiological landscape of oilfields. However, the practical impact of these doses is strictly limited due to the localized nature and restricted spatial distribution of NORM. Conversely, NORM from uranium or thorium mining presents divergent impacts owing to its wide spatial footprint and the multi-stage extraction and production processes involved.

This study focused on comparing primary data, emphasizing strong methodological and computational similarities across all hazard indices. Although extensive literature—particularly from the IAEA, UNSCEAR, and ICRP details NORM associated with various extractive industries, direct empirical comparisons between original site data from mineral extraction and petroleum production remain scarce internationally and absent locally.

5-Recommendations: As noted in the introduction, this study initiates a series of investigations examining differences and similarities between extractive sectors (such as coal and phosphate) versus oil and gas.

Regarding Libya, the primary focus of these comparisons is to establish a conceptual framework for reviewing occupational radiation doses within the oil sector. While general environmental and occupational impacts appear to be well-documented, rigorous scientific research remains essential to validate existing procedures and policies. At the same time, we acknowledge the complexities of conducting research in this sensitive field; this necessitates a cautious approach to ensure that human health and environmental protection remain top priorities, without compromising production prospects and economic operations which must advance in tandem with health, safety, and sound environmental management.

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