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Efficiency evaluation of natural radionuclide extraction from oil sludge

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Abstract

This study examines the mechanisms of radionuclide redistribution and phase-specific concentration in the separated low-activity fractions of oil sludge during treatment. Thermal processing of the sludge led to an increase in the specific activity of key radionuclides and promoted their thermochemical redistribution among the solid, aqueous, and oil phases. A diluted sulfuric acid solution containing the non-ionic surfactant OP-10, applied at concentrations exceeding the critical micelle threshold, was employed as a destructive reagent. Radionuclides such as ^{228}Ra and its decay products, ^{228}Ac and ^{228}Th , were predominantly concentrated in barium sulfate and gypsum phases, thereby facilitating subsequent disposal due to the minimal volume of solid residue produced (less than 10 mass%) during thermochemical treatment. Compositional and phase-mineralogical analyses of the initial sludge and its separated fractions were conducted using XRD/EDS and XRF techniques. Natural radionuclides and their progeny were primarily associated with the mineral phase, co-precipitated with barium and calcium sulfates. These results provide a foundation for the development of effective disposal strategies for radioactive oil sludge and contribute to improving sanitary, epidemiological, and environmental safety.

Keywords: oil sludge; thermochemical treatment; radionuclides; NORM; phase separation; barium sulfate; environmental safet.

1 Introduction

Industrial activity related to oil refining and the extraction of oil and gas inevitably exerts anthropogenic pressure on various components of the biosphere. Toxic technogenic waste, particularly oil sludge (OS), represents one of the most hazardous pollutants, affecting almost all environmental media, including surface and groundwater, soil, vegetation, and atmospheric air [1]–[6].

Oil sludge is characterized by a complex physicochemical and mineralogical composition, which is determined by its formation process, the specific composition of the original petroleum product, and various external influences. Additionally, the hydrocarbon content of oil sludge undergoes changes over time, resulting in variability in its phase composition and chemical structure [7].

It is known that crude oil, its refined products, and the waste generated during oil extraction may exhibit increased background radiation due to the presence of natural radionuclides such as $^{228}\mathrm{Ra}$, $^{228}\mathrm{Ac}$, $^{228}\mathrm{Th}$, $^{40}\mathrm{K}$, and their decay products [8]. The primary mechanism by which natural radionuclides are released to the surface during oil extraction is associated with the salts contained in formation waters. These salts often form poorly soluble precipitates due to supersaturation of solutions that occurs during oil extraction processes. This can lead to the formation of a distinct mineral phase or their incorporation into the crystalline structures of natural minerals such as clays, sands, and loams, which serve as the main host rocks for mineral deposits.

Consequently, oil sludge waste consists of intricate mixtures of varying composition, encompassing petroleum hydrocarbons (often high-boiling fractions of oil), dirt, sand, clay, mechanical impurities, silt, water, emulsions, and other constituents. Oil sludge (OS) primarily contains heavy oil residues, with an average composition of 10–56 wt% petroleum products, 30–85 wt% water, and 1.6-46 wt% solid impurities [9]. According to previous studies [10], oil sludge often exhibits increased radioactivity compared to the surrounding background, underscoring the importance of developing processing technologies to reduce radiation levels.

A variety of advanced approaches are currently employed for the treatment of oil residues, encompassing a broad spectrum of both standalone and integrated physicochemical, wave-based, electromagnetic, and electron beam techniques [11]–[15]. Collectively, these methods facilitate the disruption of the structural organization of oil dispersion systems, thereby promoting the separation into distinct lipophilic (oil) and hydrophilic (aqueous–mineral) phases. Furthermore, recent advances in biotechnological methods involving the application of specific microbial strains for the remediation of radioactive oil sludge have attracted growing scientific attention, demonstrating notable potential for sustainable and low-impact decontamination [16]–[19].

Global interest in the development of effective strategies for the treatment of this category of waste is steadily increasing, as it cannot be disposed of in conventional landfills. The substantial accumulation of oil sludge with elevated levels of radioactivity poses both economic challenges and regulatory obstacles for long-term storage. Primarily, such waste raises serious concerns regarding potential environmental contamination and health risks to personnel and surrounding communities [20].

This study investigates a method for the phase separation of oil sludge into three distinct fractions: organic, aqueous, and solid. During this process, naturally occurring radionuclides accumulated over long-term storage in sludge repositories are expected to concentrate primarily within the mineral fraction. The proposed approach aims to reduce the volume of oil sludge requiring prolonged storage, while simultaneously enabling the recovery of value-added products, such as base oil components, and isolating a minor solid residue enriched in natural radionuclides, which may be disposed of using conventional waste management practices.

2 Experiment details

2.1 Preparation of the Working Solution for Oil Sludge Separation

A working solution was prepared consisting of 1% nonionic surfactant OP-10 dissolved in a 10% sulfuric acid solution. OP-10 is synthesized by ethoxylation of a mixture of mono- and dialkylphenols with ethylene oxide. The general structure of OP-10 includes a substituted phenol ring with alkyl groups (R) and a polyethoxylated side chain $–\mathrm{O(CH_2CH_2O)}_n–\mathrm{CH_2CH(OH)}$, where n typically ranges from 10 to 12. This surfactant has a critical micelle concentration (CMC) of approximately 65 mg/L and exhibits high surface activity, making it effective for emulsifying and dispersing hydrophobic components in oil sludge.

2.2 Instrumental methods for analyzing oil sludge and its treatment products

2.2.1 Instrumental Gamma-Spectrometry

Natural radionuclide activity was measured using an *Ortec* gamma-spectrometer equipped with an ultra-pure germanium GMX-20180-S semiconductor detector (Serial No. 41-N31520B) and a multichannel digital analyzer DSpec-502. The energy calibration was carried out using a set of point standard gamma-source samples (PSSS): $^{241}\mathrm{Am}$, $^{137}\mathrm{Cs}$, and $^{60}\mathrm{Co}$. Efficiency calibration was performed using IAEA volumetric standard samples with known radionuclide composition: RGU-1, RGTh-1, IAEA-375, IAEA-444, IAEA-314, and OREAS-121.

The samples were placed in measurement containers on the detector window, and the spectrum registration time ranged from 1 to 18 hours depending on the activity of the sample. The following full gamma-ray absorption peaks were used to calculate radionuclide activities:

- $^{234}\mathrm{Th}$ (63 keV),
- $^{214}\mathrm{Pb}$ (242, 295, 352 keV),
- $^{214}\mathrm{Bi}$ (609 keV),
- $^{224}\mathrm{Ra}$ (241 keV),
- $^{212}\mathrm{Pb}$ (238 keV),
- $^{212}\mathrm{Bi}$ (727 keV),
- $^{208}\mathrm{Tl}$ (583 keV).

The activity of ^{226}Ra was determined using the intensity of 186.2 keV γ-radiation; ^{228}Ra was measured via its decay product ^{228}Ac (911.2 keV); and ^{228}Th was estimated as the average activity of its decay products: ^{224}Ra, ^{212}Pb, ^{212}Bi, and ^{208}Tl.

2.2.2 X-ray fluorescence analysis (XRF)

This method is based on the excitation of characteristic X-ray radiation from sample elements using an X-ray tube with a tungsten anode. The instrument used was the RLP-21 energy-dispersive X-ray fluorescence spectrometer, manufactured by LLP “AspapGeo” (Kazakhstan).

The analysis was conducted according to the certified measurement procedure (MP) “Determination of elemental composition of powdered samples of various materials using a semiconductor detector energy-dispersive X-ray fluorescence device RLP-21.” Automated spectrum processing was performed using proprietary software developed by LLP “AspapGeo.” Quality control was performed using standard samples of black shale (SChS-1, GSO 8549-04), ore (GSO 8079-94), and SG-4 (GSO 10135-2012), analyzed alongside the study samples.

2.2.3 X-ray diffraction analysis

X-ray diffraction (XRD) was carried out using a D8 ADVANCE diffractometer (Bruker, Germany) in $\theta-\theta$ Bragg–Brentano geometry. The device was operated with a copper anode X-ray tube ($\lambda = 1.5406$ Å), at 40 kV and 40 mA. Scanning was carried out over a 2θ range of $5° - 70°$, with a step size of $0.02°$ and a scan speed of 0.5 s/step. Adjustable slits V12 were used to ensure a constant beam size of 12 mm $\times$ 1 cm on the sample. During measurements, the sample holder was rotated at 60 rpm. Phase identification was carried out using the EVA software.

2.2.4 Gravimetric analysis

The change in oil sludge mass during thermal and thermochemical treatments was assessed gravimetrically, based on the relative mass change δm, calculated as:

$$\delta m = \frac{m_0 - m_i}{m_0} \times 100\%,$$

where m_0 is the initial mass of oil sludge, and m_i is the mass of oil sludge after treatment.

3 Results and discussion

3.1 Instrumental methods for analyzing oil sludge and its treatment products

Typically, paraffin-rich petroleum sludge forms when the individual molecular orbitals of straight-chain hydrocarbons aggregate due to proximity, resulting in an induced dipole force that promotes accumulation [21, 22]. Robust molecular aggregation is attributed to these dipole forces, commonly referred to as London Dispersion Forces or Van der Waals interactions [23]. Conversely, when the "heavier" straight-chain

(C20+ hydrocarbon molecules) agglomerate, they often precipitate from suspension within a static fluid, accumulating at the tank bottom as a dense, gelatinous material. Over time, of the gel volatile constituents are expelled due to fluctuations in temperature and pressure, resulting in thickening of the gel [24]. It is presumed that sludge is generated when petroleum or petroleum derivatives physiochemically interact with oxygen, moisture, and mechanical pollutants in a specific environment. This interaction produces distinct sludges with diverse compositions and physical characteristics.

The primary objective in the disposal of oil sludge pits is the dehydration of the upper strata, which constitute a stable water-oil emulsion. The overall stability of such emulsions is largely attributed to the presence of substantially high-molecular-weight polar constituents (such as resins and asphaltenes) in the oil, which adsorb onto the surface of water droplets, creating protective layers that inhibit merging, coalescence, and sedimentation. Inclusion of mineral microparticles from solid rocks and mechanical imperfections in oil sludge exacerbates the process, resulting in enhanced stability of water-in-oil reverse emulsions. Therefore, techniques for manipulating water-oil emulsions to diminish aggregate stability, efficiently disrupt the protective membranes of emulsion droplets, and establish conducive conditions for their coalescence constitute the foundation of dehydration technology. This can be achieved through several techniques, notably thermal treatment and the application of surfactants that alter the hydrophilic-lipophilic balance (HLB) of the system, which results in the phase separation of emulsions into mineral and organic constituents, thereby establishing a distinct phase boundary [25].

The initial task involved determining the component-phase composition and volatile components, specifically water and light hydrocarbon fractions, up to a distillation temperature of 400°C, until a constant weight was attained.

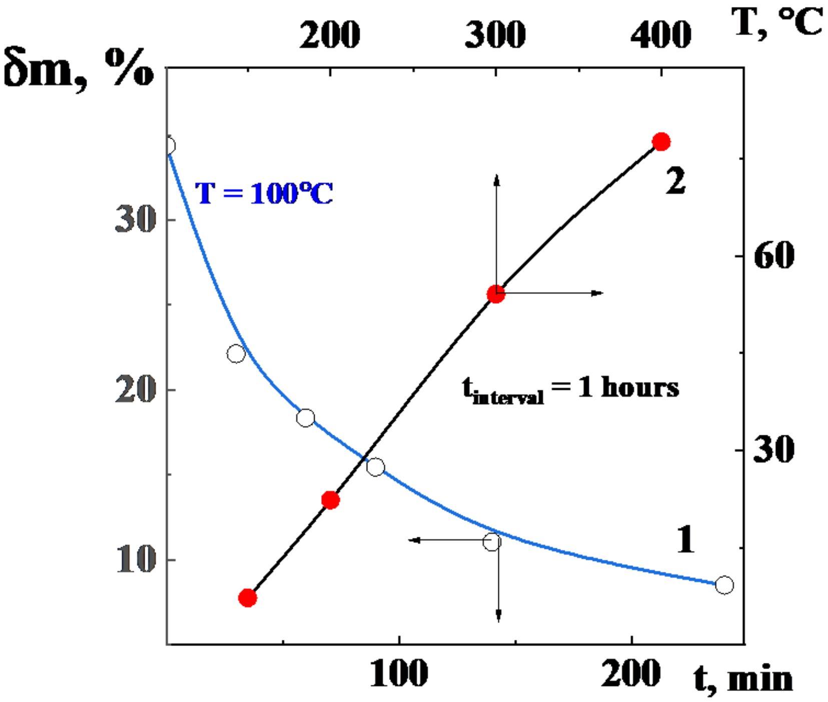


Figure 1: Correlation between the mass loss of the initial oil sludge on time (1) at 100°C and processing temperature (2).

Figure 1 presents the mean thermal analysis data for three samples subjected to heat treatment at a constant temperature of 100°C over time (1) and at varying temperatures, with residual mass measured at one-hour heating intervals (2).

A significant mass loss of the initial oil sludge was evident in both thermal treatment procedures. In the initial scenario (Fig. 1, curve 1), the peak mass reduction of the oil sludge attributable to the evaporation of volatile constituents (water, low-boiling oil fractions) up to 100°C transpires at a heating duration of 150 minutes ($\delta m = 20$ mass. %), with δm stabilizing upon extending the thermal treatment duration to 240 minutes.

In the second mode (Fig. 1, curve 2), the temperature increase from 100°C to 400°C resulted in a substantial weight reduction of the oil sludge, reaching up to 82 mass.%, yielding a solid residue primarily composed of a solid mineral phase exhibiting a gray-brown coloration with black particle inclusions, devoid of residual plasticity, which was retained in the initial processing mode (Fig. 2).

Initial oil sludge

Air-dried oil sludge at room temperature

Dried oil sludge at 100°C. t_{drying} = 240 min

Dried oil sludge at 300°C. t_{drying} = 60 min

Dried oil sludge at 400°C, t_{drying} = 60 min

Figure 2: Photographs of oil sludge depending on drying time and temperature.

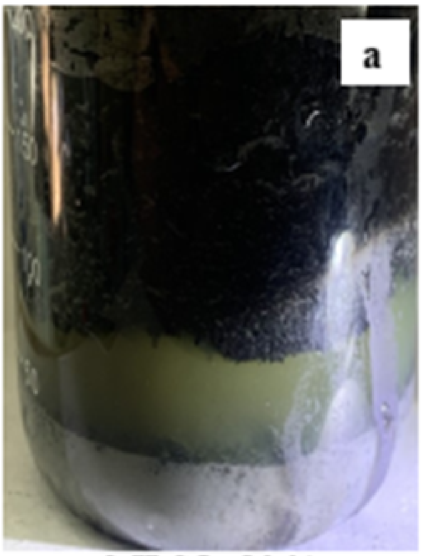
3.2 Phase separation of Oil Sludge

As noted in the introduction, a diverse spectrum of scientific, technical, and technological approaches is currently employed for the treatment of oil sludge to mitigate its adverse environmental effects [11]-[20],[26]. The selection of a particular oil sludge treatment method depends on several aspects, including the origin of the oil deposit development under reservoir conditions and the duration and circumstances of surface storage.

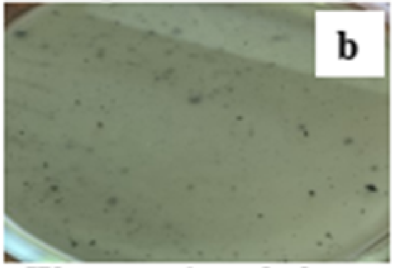
This study used a combined technology for the chemical treatment of oil sludge utilizing a 10% aqueous solution of sulfuric acid consisting of non-ionic surfactants, specifically block copolymers of ethylene oxides, which do not dissociate into ions in solutions and exist in molecular-micellar forms (the primary characteristics of the surfactants are detailed in the Experimental Section).

The interaction of oil sludge with a 10 mass.% aqueous sulfuric acid solution, in the presence of a 1 mass.% surfactant, results in the disruption of the stable water-oil emulsion, which is maintained by natural stabilizers such as asphaltenes and resins present in the oil. Asphaltene-resin aggregates, along with adsorbed salts of divalent and polyvalent metals, organic acids, and other polar oil components, persist in a stable colloidal state. Besides the development of emulsions, the interaction between liquid hydrocarbons and solid particles from oil-bearing rocks (such as clay, sand, dirt, and other mechanical impurities) results in the creation of polydisperse structured mixtures.

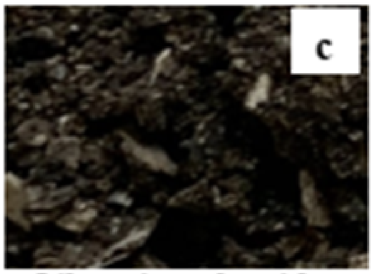
Upon the addition of the working solution at a temperature of 60°C with moderate stirring (60 rpm), the oil sludge separates into three phases (Fig. 3). The components of the oil with a density lower than that of the aqueous solution of sulfuric acid with surfactants (the second layer) and the bottom sediment of the mineral phase with a density higher than that of the aqueous solution $(< 2.4\ \mathrm{g/cm^3})$ transition to the upper part of the solution. Moreover, metal ions (iron, aluminum, magnesium, sodium, potassium, etc.) that do not precipitate in the presence of sulfate anions also transition into the aqueous phase. The mineral phase predominantly consists of sulfates of poorly soluble compounds of barium, calcium, and radium ions, known as radium barium sulfates.



S-H_2SO_4-10 %
Phase separation of sludge oil



Water – mineral phase



Oil – mineral residue

Mineral residue

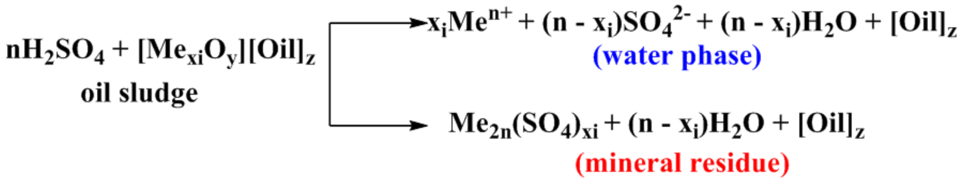
Oil phase

Figure 3: Characterization of oil sludge destruction stages and its separated products.

The phases were further separated into oil, water-mineral, and mineral using a separating funnel. A centrifuge operating at 5000 rpm was employed for the thorough sedimentation of suspended mineral particles from the water-mineral phase (Fig. 3).

The following model might be given in stages to demonstrate the destruction of oil sludge.

1. Reaction between sulfuric acid and metal oxides found in oil sludge's structure:



2. The mechanism by which surfactants facilitate the degradation of oil sludge is attributed to their capacity to enhance the solubility of hydrophobic organic molecules in oil, hence transferring these compounds to the hydrophobic cores of surfactant micelles. The high solubility of surfactants in polar and non-polar solvents and, consequently, their ability to form direct or inverted micelles contribute to the increased efficiency of hydrocarbon removal from the surface of polar particles. The primary mechanism for decomposing oil sludge involves the diminution of interfacial tension by polar and non-polar molecules, resulting in the phase separation of the system and the establishment of a distinct phase boundary.

Thus, it can be concluded that when mixing oil sludge and working solution at a temperature of 60°C, non-ionic surfactant molecules concentrate at the interphase boundary of mixed oil-mineral particles, consisting of asphaltene and resin agglomerates with a mixture of mineral particles and mechanical impurities, and water droplets. This leads to the destruction of the adsorption-structural barrier that stabilizes the colloidal form of oil sludge, which not only reduces the oil content at the phase boundary but also changes the interfacial wettability of the system. Surfactant molecules, adsorbing on the surface of asphaltene-resin particles, facilitate the removal of the oil phase from the solid agglomerates of oil sludge into the hydrophobic core, while water molecules concentrate on the surface of their hydrophilic head. Such separation also leads to the release of the solid mineral phase and mechanical impurities from the volume of oil sludge and to the loss of their aggregate stability with precipitation.

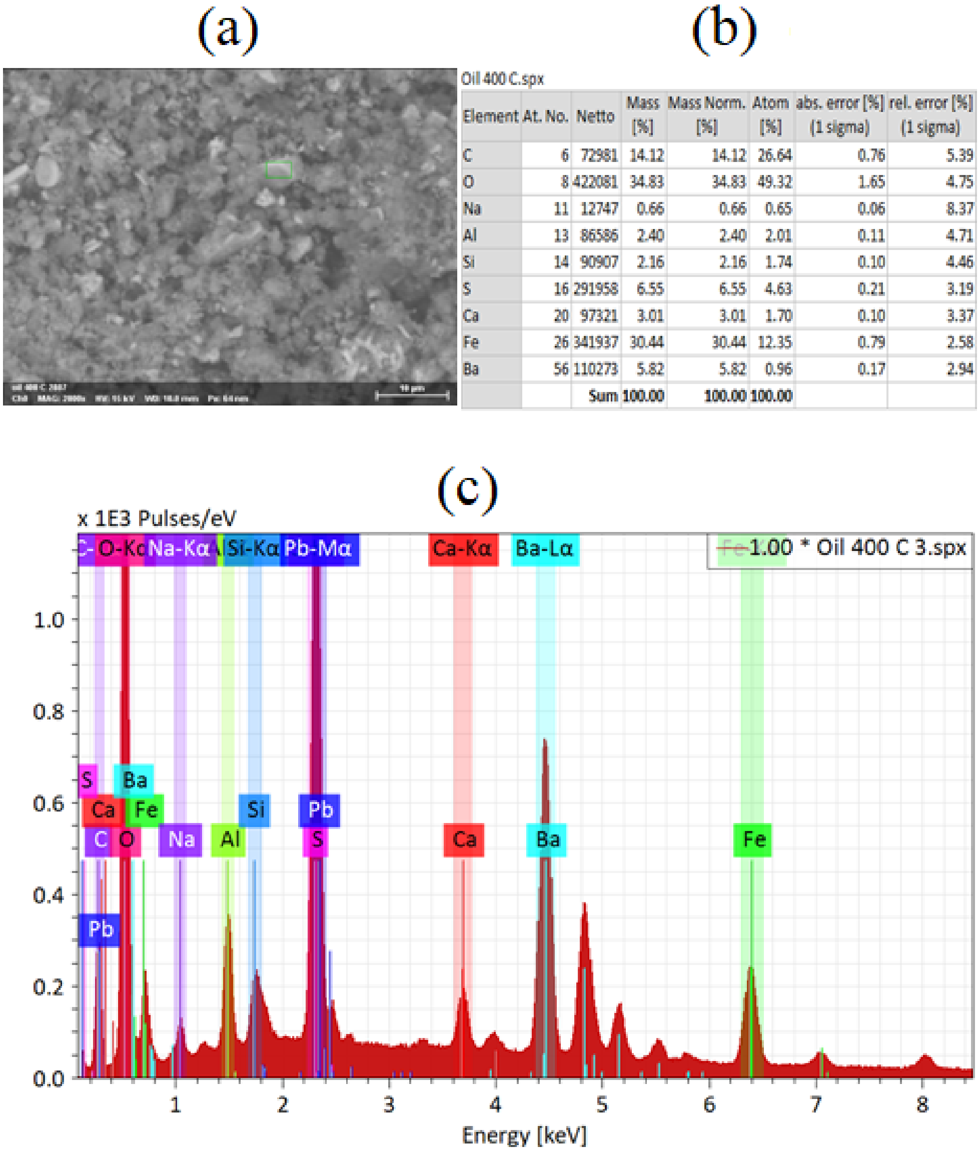
3.3 Analysis of oil sludge after thermochemical treatment

The visual examination of the initial oil sludge and its constituents after thermochemical treatment reveals that the untreated oil sludge is a dark-hued material characterized by high viscosity and significant plasticity (Fig. 2a). Figure 2e shows that the thermally treated oil sludge at 400°C exhibits a pronounced yellow-brown coloration, indicating that the majority of the oil has been combusted from the mineral particles. Figures 2a-d demonstrate that the sediment surface prior to heat treatment at the oil combustion temperature was covered with a substantial coating of oil. After thermal treatment, the oil sludge (Fig. 2e) has a rough, uneven surface with a porous structure.

The thermochemical treatment of oil sludge with an aqueous solution of the nonionic surfactant OP-10 in sulfuric acid results in the formation of three distinct phases, which can be readily separated using a separating funnel (Figs. 3c and 3d).

The mineral content and composition of the oil sludge were analyzed using scanning electron microscopy (SEM), X-ray fluorescence (XRF), and X-ray diffraction (XRD).

Figure 4 displays the scanning electron microscopy (SEM) images and energy-dispersive spectroscopy (EDS) data for oil sludge subjected to thermal treatment at 400°C to ascertain its compositional constituents. The solid residue of the oil sludge, following the evaporation and combustion of volatiles at the maximum heating temperature, mostly comprises silicon and iron oxides, along with barium, calcium, and lead sulfates.



Oil 400 C.spx

Element	At. No.	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%] (1 sigma)	rel. error [%] (1 sigma)
C	6	72981	14.12	14.12	26.64	0.76	5.39
O	8	422081	34.83	34.83	49.32	1.65	4.75
Na	11	12747	0.66	0.66	0.65	0.06	8.37
Al	13	86586	2.40	2.40	2.01	0.11	4.71
Si	14	90907	2.16	2.16	1.74	0.10	4.46
S	16	291958	6.55	6.55	4.63	0.21	3.19
Ca	20	97321	3.01	3.01	1.70	0.10	3.37
Fe	26	341937	30.44	30.44	12.35	0.79	2.58
Ba	56	110273	5.82	5.82	0.96	0.17	2.94
		Sum	100.00	100.00	100.00		

Figure 4: SEM data of oil sludge after thermotreatment at 400°C (a) and its EDS analysis (b, c).

The elemental composition of the oil sludge residue is validated by X-ray diffraction analysis of the mineral-phase composition (Fig. 5). The X-ray diffractogram exhibits high resolution, distinctly revealing peaks corresponding to two modifications (coesite and stishovite), three forms of iron oxide (two types of hematite and maghemite), barium sulfate, and gypsum, along with a minor impurity of lead sulfate. Table 1 presents data on the main parameters of mineral absorption intensity, taking into account the corundum number and their percentage content, calculated using the EVA program.

X-ray diffraction (XRD) data for the thermochemically treated oil sludge indicate a change in the balance of mineral content percentages in the composition of the isolated solid residue (Fig. 6, Table 2). In particular, there is an increase in the content of barium sulfate and calcium from 0.8 mass.% and 1.6 mass.% in the original oil sludge to 23.2 mass.% and 69.3 mass.% in the isolated mineral phase, respectively. In contrast, the content of hematite decreases from 89.2 mass.% to 4.9 mass.% under similar conditions, which confirms the aforementioned model of the destruction of oil sludge stored in the oil tanks.

Table 1: Mineralogical composition of oil sludge thermally treated at 400°C according to XRD data.

Card Number	**Compound Name**	**Formula**	**I/I_c**	**S-Q, mass.%**
83-1249 (C)	Coesite	SiO_2	0.8	3.2
72-2310 (A)	Stishovite	SiO_2	2.2	0.5
73-0603 (C)	Hematite	Fe_2O_3	0.1	89.2
39-1346 (*)	Maghemite-C	Fe_2O_3	1.4	3.7
79-1741 (C)	Hematite, syn	Fe_2O_3	3.2	0.9
76-1579 (C)	Lead Sulfate	Pb_2SO_5	7.6	0.1
78-1833 (C)	Barium Sulfate	$Ba(SO_3)_{0.3}(SO_4)_{0.7}$	2.8	0.8
72-0503 (C)	Anhydrite (gypsum)	$CaSO_4$	1.8	1.6

Table 2: Mineralogical composition of the sediment of thermochemically treated oil sludge according to XRD data.

Card Number	**Compound Name**	**Chemical Formula**	**I/I_c**	**S-Q, mass.%**
72-0503 (C)	Anhydrite (gypsum)	$CaSO_4$	1.8	69.3
78-1833 (C)	Barium Sulfate	$Ba(SO_3)_{0.3}(SO_4)_{0.7}$	2.8	23.2
79-1741 (C)	Hematite	Fe_2O_3	3.2	4.9
76-1579 (C)	Lead Sulfate	Pb_2SO_5	7.6	2.6

3.4 Analysis of the distribution of natural radionuclides in oil sludge

Oil sludge waste generated during petroleum extraction is commonly classified as Naturally Occurring Radioactive Material (NORM) due to the presence of radionuclide progeny from the uranium and thorium decay series. This sludge typically comprises extracted sediments, water, and hydrocarbons that accumulate within storage tanks, pipelines, and other infrastructure associated with oil production operations [29, 30, 31].

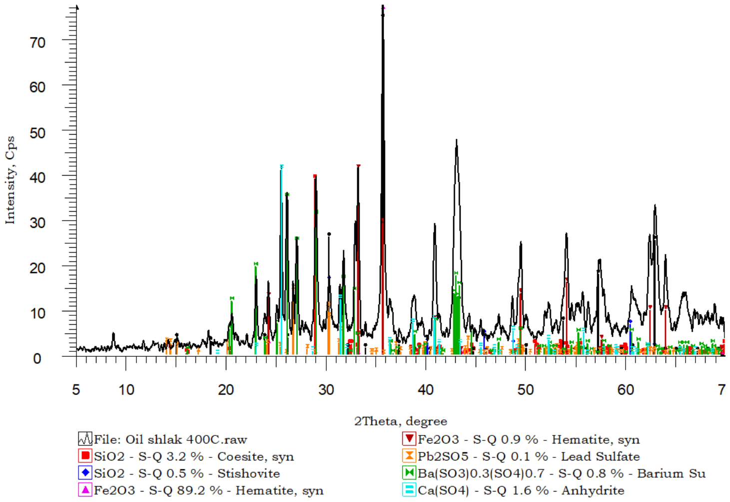


Figure 5: X-ray diffractogram of oil sludge subjected to heat treatment at 400°C.

Extensive research, both domestic and international, has been conducted on the origins, mechanisms, and accumulation dynamics of naturally occurring radioactive substances arising as byproducts of industrial oil production activities.

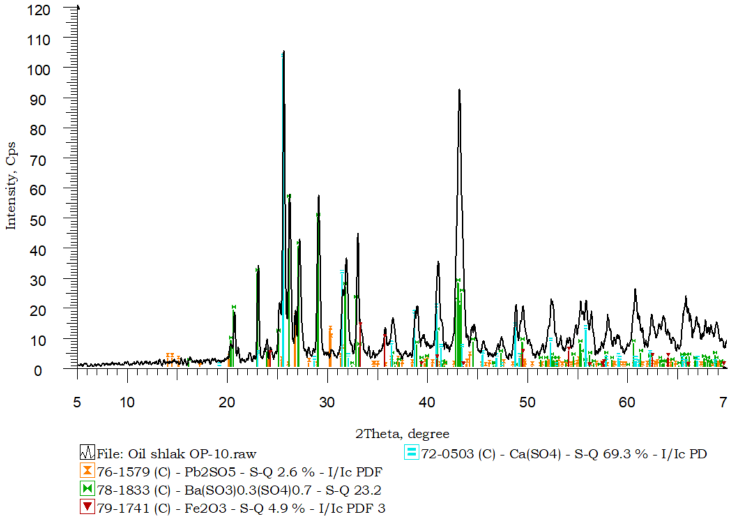


Figure 6: X-ray diffraction pattern of the mineral phase of thermochemically treated oil sludge.

As demonstrated in the preceding section, both thermal and thermochemical treatments of oil sludge lead to the concentration and segregation of sparingly soluble mineral forms into a distinct solid phase. In this context, it is essential to investigate the mechanisms governing the redistribution and phase-specific concentration of radionuclides during the treatment of low-activity oil sludge, as this knowledge is fundamental for developing appropriate strategies for their subsequent storage or disposal.

To eliminate the influence of external variables, ambient conditions were assessed immediately prior to the experiment. The measurements confirmed that environmental parameters, including background radiation levels, remained within the typical range, indicating that the impact of external factors was negligible. Prior to analysis, all samples were thoroughly homogenized to ensure uniform distribution of radionuclides throughout the sample volume.

During the thermal treatment of oil sludge, an increase in the specific activity of the primary radionuclides was observed. This effect is attributed to the loss of volatile and evaporative components from the oil fraction, leading to the concentration of both parent and daughter radionuclides in the dry residue (Fig. 7).

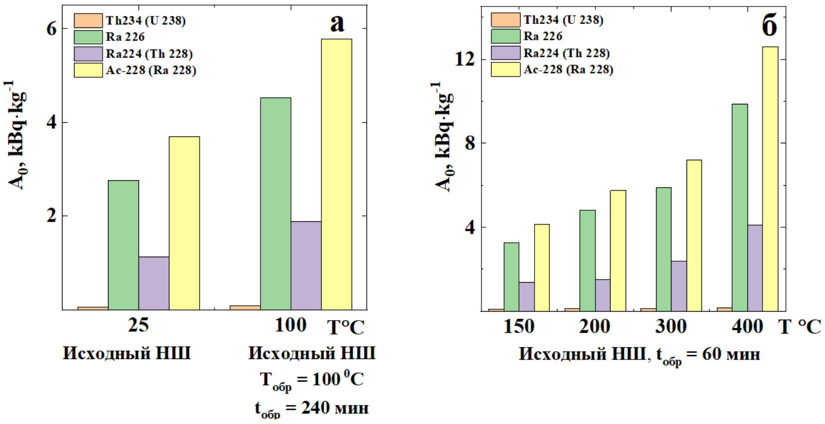


Figure 7: Variation in the specific activity of radionuclides (RN) in oil sludge over time (a) and at different heat treatment temperatures (b).

^{228}Ac is the progeny of ^{228}Ra, which is derived from the thorium series [32]. Actinium exists in secular equilibrium with its parent isotope, and its elevated environmental levels pose a considerable long-term health risk due to the established toxicity of radioactive substances.

The increased concentrations of this radioisotope may serve as a valuable signal of the concomitant elevated presence of ^{228}Ra (Fig. 8). The presence of ^{228}Ac in petroleum sludge is relatively unexplored.

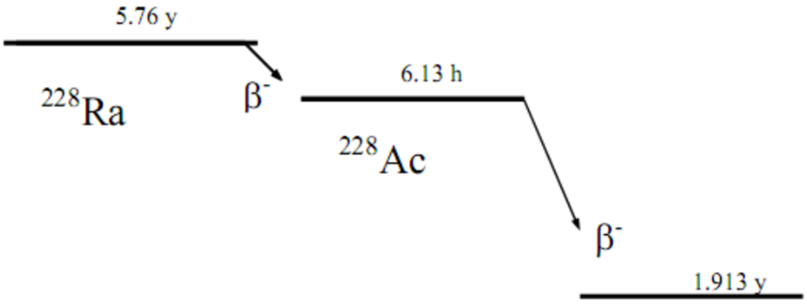


Figure 8: Decay scheme of ^{228}Ac [33].

Thermochemical processing of oil sludge results in the redistribution of specific activity among the solid, aqueous (water–mineral), and oil phases (Fig. 9). Notably, the specific activity of the solid mineral residue consistently exceeds that of the initial sludge, the aqueous phase, and the oil phase by at least an order of magnitude.

This observation suggests that radionuclides such as ^{228}Ra and its decay products, ^{228}Ac and ^{228}Th, are predominantly concentrated within barium sulfate and gypsum phases. This concentration effect facilitates subsequent disposal, as the solid residue constitutes less than 10 mass% of the original sludge volume following thermochemical treatment.

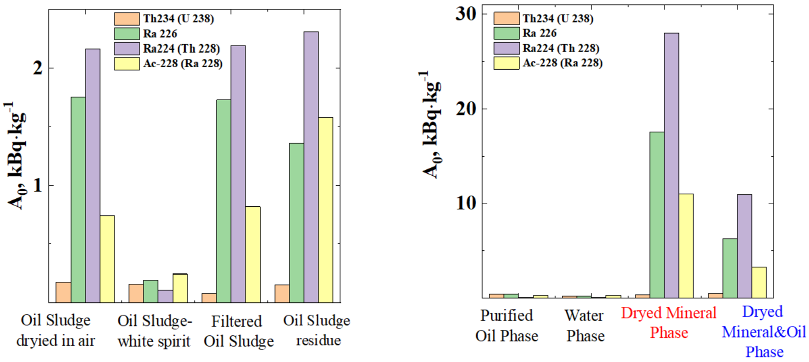


Figure 9: Dependence of the specific activity of radionuclides on the stage of thermochemical treatment (a) and phase separation (b) of oil sludge.

The results obtained from the XRD and gamma-spectrometric analyses are in good agreement with the X-ray fluorescence data (Table 3), thereby confirming the proposed concept of oil sludge decomposition, phase separation, and the preferential concentration of radionuclides and their decay products within the mineral fraction.

Table 3: RFA data of oil sludge and its mineral phases at each stage of treatment.

Probe description	**Fe**	**Th**	**U**	**CaO**	**$BaSO_4$**	**S**
Sludge Oil (T = 400°C)	27.5 ± 0.025%	<0.1 g/t	4.3 ± 0.8 g/t	5.79 ± 0.026%	16.18 ± 0.032%	18.56 ± 0.07
[l]Mineral phase (T_{drying} = 100°C) after first stage of SO treatment	7.64 ± 0.0076%	<0.1 g/t	4.3 ± 0.5 g/t	18.76 ± 0.048%	28.59 ± 0.046%	29.38 ± 0.083
[l]Mineral phase (T_{drying} = 100°C) after second stage of SO treatment	4.93 ± 0.0052%	<0.1 g/t	5.2 ± 0.5 g/t	13.74 ± 0.043%	27.70 ± 0.045%	20.62 ± 0.0684
[l]Mineral phase (T_{drying} = 100°C) after second stage of SO treatment	3.86 ± 0.0049%	<0.1 g/t	6.0 ± 0.6 g/t	8.68 ± 0.038%	34.32 ± 0.057%	20.12 ± 0.076
Residue of water phase evaporation	7.82 ± 0.009%	2.6 ± 1.1 g/t	3.8 ± 0.3 g/t	9.14 ± 0.029%	0.26 ± 0.004%	–

4 Conclusion

The feasibility of a thermochemical process for oil sludge treatment under mild conditions has been demonstrated, resulting in its separation into three distinct phases: oil, water, and solid mineral residue.

A mechanism for radionuclide redistribution and phase-specific concentration was proposed, taking into account their thermodynamic affinities, an aspect critical for solving challenges related to the storage and disposal of radioactive oil sludge. Thermal treatment of oil sludge increases the specific activity of key radionuclides, while thermochemical processing facilitates their redistribution among the solid, aqueous, and oil phases. Radionuclides such as ^{228}Ra and its decay products, ^{228}Ac and ^{228}Th, were found to concentrate predominantly in barium sulfate and gypsum phases.

The obtained results can contribute to ensuring the sanitary, epidemiological and environmental well-being of the population and promote the implementation of effective methods for disposal of radioactive oil sludge.

Acknowledgments

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