International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 38 العدد
Part 1 المجلد

http://www.doi.org/10.62341/ghjy2003

Received	**2026/01/20**	**تم استلام الورقة العلمية في**
Accepted	**2026/02/07**	**تم قبول الورقة العلمية في**
Published	**2026/02/08**	**تم نشر الورقة العلمية في**

Evaluation of Naturally Occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment stations NA/100 and BD/200

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Abstract
This study investigates Naturally Occurring Radioactive Materials (NORM) in produced water and oil-field equipment at two Libyan stations, NA/100 and BD/200. The aim is to quantify radioactivity levels and assess associated environmental and occupational hazards.

Field surveys used Gamma Ray Spectrometers and Dose Meters. Five samples (three sludge, two produced water) were collected from various equipment. These were analyzed using a High Purity Germanium (HPGe) detector to determine activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K.

Results show significantly elevated NORM. Dose rates reached 15.2 μSv/h at equipment like the Low-Pressure Production Separator. ^{226}Ra in produced water exceeded Canadian guidelines (5 Bq/L). Sludge sample S3 from BD/200 showed extreme concentrations: 15500 Bq/kg for ^{226}Ra and 24800 Bq/kg for ^{232}Th.

The calculated radiological indices (Raeq, D, Hex, AEDE) for all samples substantially exceeded worldwide averages. Hazard index (Hex) values were 10-14 times greater than the recommended limit (≤1), indicating a significant radiological hazard from NORM accumulation.

The findings reveal substantial NORM accumulation in the Libyan oil and gas industry, posing serious environmental and occupational

http://www.doi.org/10.62341/ghjy2003

safety concerns that necessitate immediate attention and regulatory control measures.

Key words: NORM, Radiation, Oil and Gas, Safety, Dose, Hazard, Environment.

تقيم المواد المشعة الطبيعية (NORM) في المياه المصاحبة للإنتاج ومعدات الحقول النفطية في المحطات NA/100 و BD/200

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الملخص

تتناول هذه الدراسة المواد المشعة الطبيعية المنشأ (NORM) في المياه المنتجة ومعدات الحقول النفطية في محطتين ليبيتين هما NA/100 و BD/200 وتهدف إلى قياس مستويات النشاط الإشعاعي وتقييم المخاطر البيئية والمهنية المرتبطة بها.

تم إجراء المسوحات الميدانية باستخدام مطياف أشعة غاما وأجهزة قياس الجرعة الإشعاعية. جُمعت خمس عينات (ثلاث رواسب، واثنتان من المياه المنتجة) من معدات مختلفة، وتم تحليلها باستخدام كاشف الجرمانيوم عالي النقاء (HPGe) لتحديد تراكيز النشاط الإشعاعي لنظائر **^{226}Ra** و **^{232}Th** و**^{40}K**.

أظهرت النتائج وجود مستويات مرتفعة بشكل ملحوظ من المواد المشعة الطبيعية. بلغت معدلات الجرعة الإشعاعية **15.2 ميكروسيفرت/ساعة** في بعض المعدات مثل فاصل الإنتاج منخفض الضغط. كما تجاوزت تراكيز **^{226}Ra** في المياه المنتجة الحدود المسموح بها وفق الإرشادات الكندية (5 بيكريل/لتر). وأظهرت عينة الرواسب **S3** من المحطة **BD/200**تراكيز عالية جدًا بلغت **15500 بيكريل/كغ لـ ^{226}Ra** و **24800بيكريل/كغ لـ ^{232}Th** .

وأظهرت المؤشرات الإشعاعية المحسوبة(**Raeq** ، **D**، **Hex**، **AEDE**) لجميع العينات قيمًا أعلى بكثير من المتوسطات العالمية، حيث تجاوزت قيم مؤشر الخطر (**Hex**) الحد

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الموصى به (≤1) بمقدار يتراوح بين 10 إلى 14 مرة، مما يشير إلى وجود خطر إشعاعي كبير ناتج عن تراكم المواد المشعة الطبيعية.

تُظهر النتائج وجود تراكم كبير للمواد المشعة الطبيعية في صناعة النفط والغاز الليبية، مما يشكل مخاطر بيئية ومهنية جسيمة تستدعي اهتمامًا عاجلًا وتطبيق تدابير رقابية وتنظيمية فورية.

الكلمات المفتاحية: NORM، إشعاع، نفط وغاز ، سلامة، جرعة، خطورة، بيئة.

1.0 Introduction

Libyan oil production started in 1961, with about 18,000 barrels being produced each day. By the early 1970s, oil exploration had become the most important industry in Libya. On average, around 1.5 million barrels were produced each day, which played a major role in the country's economy [1]. A common issue in oil production is the presence of Naturally Occurring Radioactive Materials (NORM), such as Uranium and Thorium, which were present in varying amounts in the Earth's crust when it formed. As these unstable radioactive elements decay, they produce other radionuclides that can be carried from the reservoir to the surface during production. These materials can accumulate as scale, sludge, and other byproducts, posing challenges in oil and gas operations [2]. Water is valuable in desert areas, as is well recognized, and there is a growing need for high-quality water. Most places rely on subterranean supplies and streams above [3].

Oil wells produce a lot of water, sometimes an order of magnitude more than the oil they produce. It is one of the most important sources of ground water pollution since the produced waters from oil extraction are typically released back into the environment, particularly if there is a high level of naturally occurring radioactivity [4].

This research aims to quantify the radioactivity concentration and NORM levels within the NA/100 and BD/200 utilizing specialized geophysical instruments. This will determine the prevailing radiation and dose levels in these accessible operational production station areas.

The study includes measuring NORM in the production water pit and estimating radioactivity in both produced water and crude oil

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samples. Additionally, it will assess the radioactivity concentration found in sludge from the pit and production stations, while also estimating potential well-related radioactivity.

2. Techniques and instrumentation

2.1 Field work

The field work was carried out during radiological field surveys and data collection from August 17 to 21, 2022.

For confidentiality reasons, the actual names of the production stations are not used. The stations are referred to throughout this paper by the pseudonyms NA/100 and BD/200.

2.1.1 Radioactivity field survey

For the radioactivity field survey, 10 gamma ray spectrometer and gamma ray dose rate measurements were taken in the field in the proper and convenient points. Gamma Ray Spectrometer model RS 320 and Gamma Ray dose Meter model Automess 6150-AD-2 were used in the field survey.

Gamma Ray Spectrometer model RS 320

It is an industry standard portable handheld gamma ray survey device manufactured by Radiation Solutions Inc. (RSI). Gamma Ray spectrometer model RS 320 has high sensitivity for geophysical and environmental applications. It has different modes of operation, such as survey, assay and scan, and can measure various radionuclides, such as U and Th in ppm, K in % and Total count in C.P.S [5].

Gamma Ray Dose meter model Automess 6150-AD 2

It is dose rate measuring device that can measure photon radiation (X-ray and gamma radiation) with a built-in Geiger-Müller counter tube serves as the detector. It measures maximum dose rate value, accumulated dose range, and dose rate mean value from 0.1 µSv/h up to 999 mSv/h. [6].

The visit was done to the station sites at the end of August 2022. Where measurements of the radioactive background were taken outside the targeted field sites. Three radioactivate measurements in NA/100 station where the measuring locations are Production Separator C-301, Storage Tank and Pit and Seven radioactivate measurements were carried out in different places of BD/200 station

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including High Pressure Production Separator C-011, Low Pressure Production Separator C-021, Dehydrator T-031, Wash Tank D-02, Surge Tank D-01, Pit, and NORM Yard.

Table. 1 Specifications of Gamma Radiation Detection Instruments.

Field	Gamma Ray Spectrometer (RS 320)	Gamma Ray Dose Meter (Automess 6150-AD 2)
Manufacturer	Radiation Solutions Inc. (RSI)	Automess
Type / Function	Portable handheld gamma ray survey device with high sensitivity.	Dose rate measuring device for photon radiation (X-ray and gamma).
Detector Type	Built-in gamma ray spectrometer.	Built-in Geiger-Müller counter tube.
Measurement Range / Units	U and Th in ppm, K in %, Total count in C.P.S	0.1 µSv/h to 999 mSv/h
Main Features	Survey, Assay, Scan. High sensitivity for geophysical and environmental studies.	Measures maximum dose rate, accumulated dose, and mean dose rate.
Applications	Geophysical and environmental radioactivity surveys.	Radiation safety and dose monitoring.
Reference	[5]	[6]

Figure 1. Low Pressure Production Separator C-021 (Personal visit)

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2.1.2 Data collection

Five (5) Samples have been collected as 3 sludge samples and 2 produced water. Table (2) showing the locations and sample types.

Figure 2. Pit (Personal visit)

Table 2. Sample information sheet

Weight (Kg)	Sampling Location	Station Name	Sample Type	No.
1.195	Dehydrator T-031	BD/200	Water Sample	S1
1.200	Wash Tank D-02	BD/200	Water Sample	S2
1.820	Pit	BD/200	Sludge Sample	S3
1.165	Production Separator C-301	NA/100	Water Sample	S4
3.070	Pit	NA/100	Sludge Sample	S5

2.2 Samples analysis instrument

The field samples have been analysed by using a High Purity Germanium detector HPGe P-Type.

High Purity Germanium detector HPGe P-Type

The HPGe is characterized by its higher resolution power and its lower noise than other germanium detectors, this is due to its high purity germanium crystal, fewer impurities and trapping centres. HPGe detectors still need to be cooled to liquid nitrogen temperatures (-196°C) to reduce the thermal generation of charge carriers [7]. The HPGe detector provides information of the number of counts and energy of gamma rays emitted by a mixed source. This

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information is used to identify any unknown radionuclides [8]. HPGe detector can measure the activity of natural radionuclides such as ^{238}U, ^{232}Th, and ^{40}K, using the gamma rays from their decay series [9].

Figure 3. High purity Germanium detector (HPGe) P-Type (Centre of Radiation Measurements and Training).

2.3 Dose evaluation

2.3.1 Radium equivalent dose (Ra_{eq})

Evaluating the hazard from gamma radiation to humans from the samples of a mixture and different amount of ^{238}U, ^{232}Th and ^{40}K is known as the Radium Equivalent dose (Bq/Kg). Is calculated through the following relation [10].

$$Ra_{eq}\,(Bq/kg) = A_U + (A_{Th} \times 1.43) + (A_K \times 0.077) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where A_U, A_k and A_{Th} are the activities of ^{226}Ra, ^{40}K and ^{232}Th in (Bq/kg). Where the recommended value for the radium equivalent reference for the safe limit is 370 (Bq/kg) [10].

2.3.2 Air-absorbed dose rate (D)

The cosmic radiation outdoor absorbed dose rate in air and at the sea level is about 30 nGy/h. The Gamma radiation emitted from Radionuclides that have half-lives similar to the earth age such as ^{40}K, ^{238}U and ^{232}Th series, as well as their decay products, represents the main external source of irradiation to humans [8]. Assuming that ^{137}Cs, ^{90}Sr and the ^{235}U decay series can be neglected as they contribute very little to the total dose from environmental background. The gamma dose rate (D) in the outdoor air at 1m

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above the ground level can be determined using the following equation [10].

$$D\ (nGy/h) = 0.461\ A_{Ra} + 0.623\ A_{Th} + 0.0414\ A_{K} \ \ldots\ldots\ldots\ldots\ (2)$$

Where A_{Ra},, A_{Th} and A_K are the activities ^{226}Ra, ^{232}Th and ^{40}K of in the samples in Bq/kg.

2.3.3 External hazard index (Hex)

The external hazard index can be used to evaluate the potential risk associated with gamma radiation. The external hazard index is determined by the following equation.

$$H_{ex} = C_{Ra}/370 + C_{Th}/258 + C_{K}/4810 \leq 1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

Where C_{Ra}, C_{Th} and C_K are the activities of ^{226}Ra, ^{232}Th and ^{40}K in Bq/kg. The recommended value for the External Hazard Index is less than 1[10].

2.3.4 Annual effective dose

To estimate annual effective doses, account must be taken of (a) the conversion coefficient from absorbed dose in air to effective dose and (b) the occupancy factor.

The conversion coefficient value is published in UNSCER 2000 to be 0.7 (Sv/Gy) and the outdoor occupancy factor is about 0.2 [10].

The outdoor annual effective dose equivalent is given by the following equation:

AEDE

$$(\mu Sv/Y) = D(nGy/h) \times 8760\ (h/y) \times 0.2 \times 0.7\ (Sv/Gy) \times 10^{-3} \ldots\ldots\ (4)$$

3 Results and Discussion

3.1 Results of radioactivity field survey

Using Gamma Ray dose Meter model Automess 6150-AD 2 and Gamma Ray Spectrometer model RS 320 portable survey instruments in the field survey. The measurements of the radioactive background out of the targeted survey stations were taken where the dose rate was (0.12µSv/h) and measurement of gamma ray activity total count was (274 C.P.S).

Seven radioactivity survey measured data were carried out in different places of BD/200 station, The minimum observed

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measurements where in the NORM Yard of BD/200 station of about (0.15 µSv/h) of dose rate and measurement of gamma ray activity total count was (553 C.P.S). While the maximum observed measurements where in Low Pressure Production Separator C-021 was (15.2 µSv/h) of dose rate and measurement of gamma ray activity total count was (61246 C.P.S). These high levels are probably due to accumulation of scale at water drain outlet which finally goes to pit, Also the levels of NORM were considered high at Dehydrator T-031 which was (8.22 µSv/h) for the dose rate and measurement of gamma ray activity total count was (61800 C.P.S) as Figure (4).

BD/200 station mainly most of its production material is gas accompanied with high amount of production water. Probably this high amount of water is the main reason for accumulation of scales. Three measurements were carried out in NA/100 station where the measurements in production Separator C-301 was (0.17 µSv/h) for the dose rate and measurement of gamma ray activity total count was (160 C.P.S). The measurements of the Storage Tank of NA/100 station also taken and results reported were (0.22 µ/h) for the dose rate and measurement of gamma ray activity total count was (182 C.P.S) as Figure (5).

Table 3. Field survey of BD/200 and NA/100 field total count and dose rate

Survey NO	Sample NO	Sample Type	Station Name	Survey Location	(µSv/h)	TC (C.P.S)
V24			BD/200	NORM Yard	0.15	553
V25			BD/200	High Pressure Production Separator C-011 (water drain outlet go to pit)	5.75	37466
V26			BD/200	Low Pressure Production Separator C-021 (water drain outlet go to pit)	15.2	61246
V27	S1	Water sample	BD/200	Dehydrator T-031 (water drain outlet go to pit)	8.22	61800
V28	S2	Water sample	BD/200	Wash Tank D-02	4.03	40065
V29			BD/200	Surge Tank D-01	0.42	2522

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Survey NO	Sample NO	Sample Type	Station Name	Survey Location	(µSv/h)	TC (C.P.S)
V30	S3	Sludge sample	BD/200	Pit (leak)	0.14	986
V12	S4	Water sample	NA/100	Production Separator C-301	0.17	160
V13			NA/100	Storage Tank	0.22	182
V14	S5	Sludge sample	NA/100	Pit (leak)	0.12	274

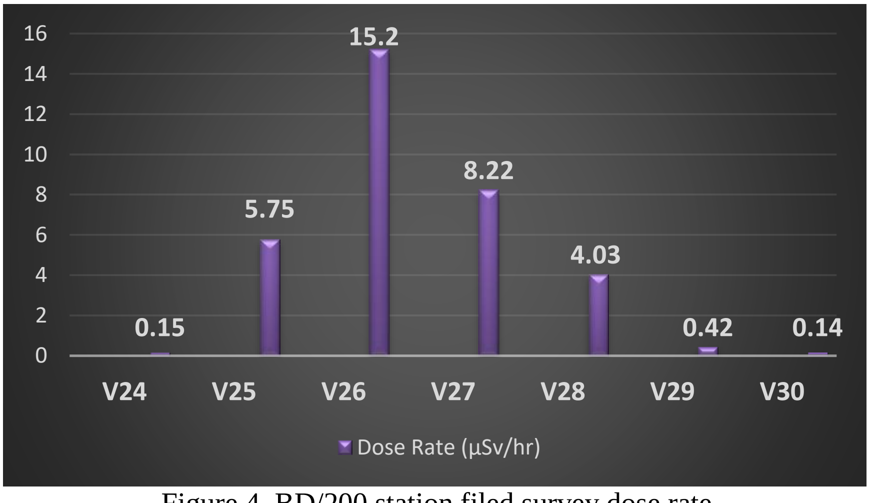

Figure 4. BD/200 station filed survey dose rate

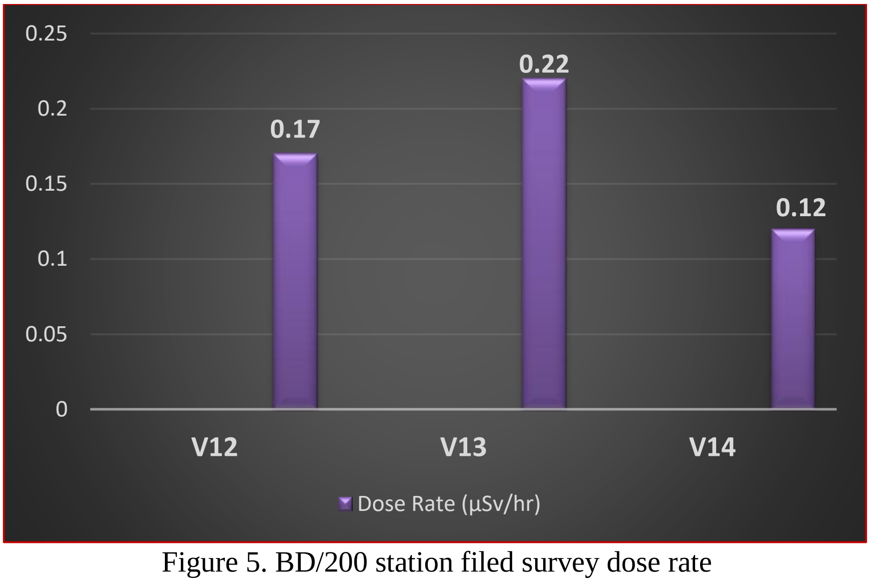

Figure 5. BD/200 station filed survey dose rate

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3.2 Results sample analyses

3.2.1 Produced water samples

Three produced water samples were collected. Two samples were from the BD/200 station field. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were determined using a gamma spectroscopy system with a High Purity Germanium (HPGe) detector. The concentration values for the sample (S1) collected from the Dehydrator T-031 were 924 Bq/L for ^{226}Ra, 86 Bq/L for ^{232}Th, and 4960 Bq/L for ^{40}K. The concentration values for the sample (S2) collected from the Wash Tank D-02 were 1100 Bq/L for ^{226}Ra, 1440 Bq/L for ^{232}Th, and 6030 Bq/L for ^{40}K. One sample (S4) was collected from the NA/100 station Production Separator C-301. The concentration values for this sample were 757 Bq/L for ^{226}Ra, 58 Bq/L for ^{232}Th, and 4870 Bq/L for ^{40}K. Among the produced water samples the highest measurement of ^{232}Th ,^{238}U and ^{40}K was in sample S_2. While the lowest measured activity of ^{232}Th ,^{238}U and ^{40}K was in sample S4. All water samples are greater than the limit guidelines as per Canadian Fluid Control [11].

3.2.2 Sludge samples

Two sludge samples were collected. One sample S3 was from the BD/200 station field. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were determined also by using a gamma spectroscopy system with a High Purity Germanium (HPGe) detector. The concentration values for the sample (S5) collected from the Pit were 15500 Bq/kg for ^{226}Ra, 24800 Bq/kg for ^{232}Th, and 0 Bq/kg for ^{40}K. the other sample was collected from NA/100 station Pit. The concentration values for this sample were 1020 Bq/kg for ^{226}Ra, 607 Bq/kg for ^{232}Th, and 12800 Bq/kg for ^{40}K. In comparison with S3 and S5 samples, sample S3 had higher activates resulting from ^{226}Ra. S3 sample greater than 1100Bq/Kg, which is the exempt value according to the international practices regulations management of radioactive waste [12].

3.3 Dose Results

The radium equivalent dose (Raeq), gamma absorbed dose rate (D), hazard index (Hex), and annual effective dose rate (AEDE) for the samples were calculated using equations 1, 2, 3, and 4. The results are listed in table 4.

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Table 4. Raeq, D, Hex and AEDE of the samples

Sample No	Ra_{eq} (Bq/kg)	D (nGy/h)	Hex	AEDE (µSv/y)
S1	5.05E+03	1.58E+03	9	1.94E+03
S2	4.74E+03	1.65E+03	10	2.03E+03
S3	7.74E+04	2.26E+04	14	2.77E+04
S4	1.94E+03	5.87E+02	3	7.20E+02
S5	4.18E+03	1.38E+03	8	1.69E+03
*WWA	< 3.7E+02	5.70E+01	≤ 1	
*WWR		1.8E+01-9.3E+01		

***(WWA) = worldwide average, *(WWR) = Worldwide range (UNSCERA 2000 Report)**

In table 4, samples S1, S2, S3, S4, and S5 have high radium equivalent dose values of 5.05E+03, 4.74E+03, 7.74E+04, 1.94E+03, and 4.18E+03 Bq/kg respectively. These values are all higher than the safe limit average 3.7E+02 Bq/kg. The lowest radium equivalent dose was 4.74E+03 Bq/kg in sample S2. All the samples show a higher absorbed dose rate than the worldwide average. The hazard index (Hex) for sample S2 is 10 times higher than the worldwide average, and for sample S3 it is 14 times higher. None of the samples fall within the worldwide average limit of ≤1. The highest annual effective dose (AEDE) was 2.77E+04 in sample S3, while the lowest was 7.20E+02 in sample S4. Where Four out of the five samples (S1, S2, S3, S5) exceed the public dose limit according to ICRP Public Dose Limit 1000 µSv/y [13].

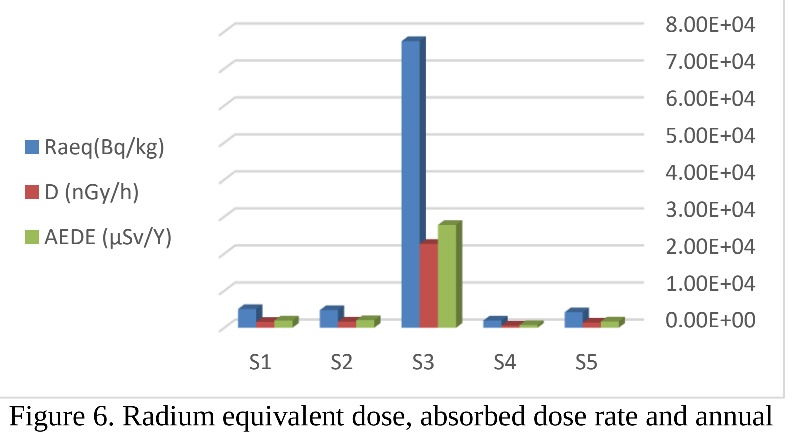

Figure 6. Radium equivalent dose, absorbed dose rate and annual effective dose rate of the samples

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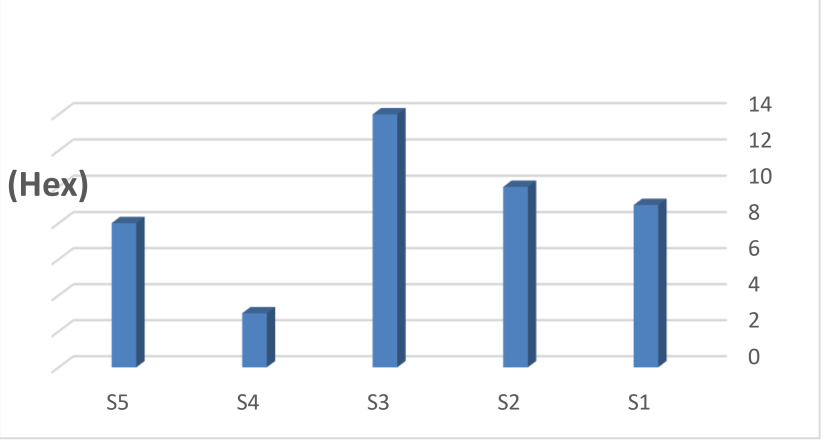

Figure 7. Shows levels of hazard index (Hex) of the samples

4. Conclusion

- Field surveys identified significantly high gamma radiation dose rates and total counts at specific locations within the BD/200 station, particularly at separators and dehydrators, indicating substantial NORM accumulation in scale deposits.
- All analyzed produced water samples contained ^{226}Ra concentrations that vastly exceeded the international guideline limit of 5 Bq/L, identifying produced water as a major vector for environmental radioactive contamination.
- The sludge samples, especially from the BD/200 station pit, exhibited extremely high activity concentrations for ^{226}Ra and ^{232}Th, classifying this waste as radiologically significant and requiring controlled management.
- All calculated hazard indices (Ra_{eq}, D, Hex, and AEDE) for the samples were found to be multiple times higher than the worldwide average and recommended safety limits. This confirms a tangible radiological hazard for workers and the environment.
- The BD/200 station, which handles a larger volume of produced water, showed consistently higher radiation levels and sample activities compared to the NA/100 station, suggesting a correlation between water production volume and NORM accumulation.

5. Recommendation

- The study underscores an urgent need for the implementation of comprehensive NORM management strategies in the Libyan oil

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industry, including regular monitoring, proper labeling of contaminated equipment, safe disposal procedures for radioactive waste, and strict adherence to occupational radiation protection standards.

- Establish strict regulations for managing radioactive waste like sludge and scale, ensuring its disposal in dedicated, secure facilities, and treating produced water to reduce radioactive contamination.
- It is crucial to support further research in this field and to implement a periodic radiation monitoring program.

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