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Radioactivity and exposure to radiation in lithium mining in Western Australia

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ABSTRACT

Background: Lithium is a crucial commodity; however, the mining and processing of lithium is associated with exposure to Naturally Occurring Radioactive Material (NORM) from the uranium-238 and thorium-232 decay chains. The sources and pathways of exposure include the inhalation of dust containing alpha-emitting radioactive elements, radon, thoron and their decay products, the ingestion of drinking water containing alpha and beta emitting radioactive elements, and exposure to gamma.

Methods: This study used industry radiation emission and occupational exposure to NORM data from three surface lithium mines in Western Australia (WA) for the period between 2018 and 2024. Samples were collected from the lithium ore, spodumene concentrate, tantalum concentrate, wet tailings and dry tailings to determine radioactivity. Exposure to radiation was compared between the departments including Administration and Support Services, Mining, Crushing & Processing, and Maintenance.

Results: The study found a high mean radiation emission in the tantalum concentrate of 2.169 Bq/g. The radiation exposures for all the departments ranged from 0.262 mSv per year to 0.544 mSv year, which were significantly below the occupational dose limit of 20 mSv per year. The study found that the reverse osmosis plants significantly reduced the radiation levels in the bore water after treatment.

Conclusion: The study demonstrated low levels of radiation exposure with the treatment of bore water using reverse osmosis plants. Based on the study results, proactive control measures to protect workers from exposure to tantalum concentrate and the treatment of bore water should be considered.

1. Introduction

Lithium is a crucial commodity used to produce batteries for electric vehicles, consumer electronics, applications for energy storage, and medical purposes. In health care, it is used for treating acute and chronic depression (Won and Kim, 2017), bipolar disorders and associated mood disorders (Bojja et al., 2022). Lithium is known to be the only drug with anti-suicidal efficacy in bipolar disoder (Won and Kim, 2017). In addition to the therapeutic benefits of lithium, lithium-containing products and materials are critical in industrial products and processes including glass and glass ceramics, high-end lithium greases, air conditioning, the production of synthetic rubber, rubber vulcanization, aluminium electrolysis, and brazing fluxes (Wietelmann and Klett, 2018).

The first electric vehicle (EV) was invented in 1880s by an automaker in Des Moines with a travel capability of 14 miles per hour. Since then, there has been an automotive evolution in the development of the EV range, driven by Tesla and other industrial experts (Saaid et al., 2024). By 2040, EVs are predicted to dominate the global share of road transport by 11–28 %, based on annual EV sales of over 753 thousand in 10 years (Saaid et al., 2024).

The economic and environmental benefits of EVs include minimal fuel use, clean energy, no emission of greenhouse gases and reduction of fossil fuel dependence (Saaid et al., 2024). Due to these benefits, many European countries, USA, China, and Japan have actively promoted EVs through purchase rebates, tax exemptions and tax credits (Saaid et al., 2024). EVs are powered by a compact rechargeable battery pack consisting of thousands of lithium-ion batteries (LIBs) (Saaid et al., 2024), making lithium a critical commodity for EV production. LIBs were first commercialised in 1990s and are also widely used in electronic devices such as drones, mobile phones and laptops, due to their rechargeability, high specific energy and power density and long cycle life (Saaid et al., 2024).

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A rapid surge in the demand for lithium is anticipated in the coming years for powering electric or hybrid vehicles (Opitz et al., 2017; Evans 2010). Azevedo et al. (2022) has predicted the annual global growth of lithium batteries at a compounding rate of approximately 30 % per year. This soaring demand is behind the production growth of 0.41 million metric tons of lithium carbonate equivalent in 2020, to a predicted 2.7 million metric tons of lithium supply in 2030 (Azevedo et al., 2022).

The largest reserves of lithium deposits in the world are hosted in Australia and Chile, with Australia ranking second to Chile (Azevedo et al., 2022). In 2020 Australia, Latin America and China accounted for 98 % of the global production of lithium (Azevedo et al., 2022), and according to the latest statistics review by the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS), lithium is Western Australia (WA)'s third most valuable mineral (Australian Bureau of Statistics, 2022).

A review of the recent data provided by the Australian Bureau of Statistics (ABS) indicated that Australia is the world's biggest exporter of lithium, and in 2020, 46 % of the global supply of lithium was reported to have come from Australia (Australian Bureau of Statistics, 2022). The Australian export of lithium to the global market has primarily been in the form of spodumene concentrate. However, the rising global demand has seen several Lithium mining companies commence the production of lithium hydroxide and the establishment of several commercial exploration and mining companies in WA (Australian Bureau of Statistics, 2022).

Lithium mining is undertaken using conventional open pit mining methods as described in more detail in a previous study (Gbondo et al., 2024). Drill and blast techniques are used to fragment the ore and waste material, while blasted rock is mined using hydraulic excavators to load the haulage trucks which transport the ore to the Run of Mine (ROM) for crushing. The ROM ore passes a main feeder into the primary gyratory crusher and is then passed through a series of screens, directing oversize through the secondary and tertiary crushing circuit. Screens and various internal conveyors ensure that appropriate particle sizes are obtained, before transporting the crushed ore to the beneficiation plant (wet plant). A ball mill is used to grind down material to sub 200 μm, to prepare the ore for the flotation plant.

Cyclone overflow from the grinding circuits is fed to dedicated deslime cyclones and then iron removal circuits, consisting of low-intensity magnetic separators (LIMS) followed by wet high-intensity magnetic separators (WHIMS). Magnetics from the iron removal circuit are discharged either to the final tailings thickener or to the tantalum recovery circuit. The non-magnetic stream is fed to the flotation circuit, where a final spodumene concentrate is obtained after a belt filtration stage.

The tantalum recovery circuit is fed with the magnetic concentrate from the iron removal circuit. The magnetic concentrate receives material via a series of gravity separation units, producing a tantalum concentrate, which is a by-product.

The spodumene, and tantalum concentrates are transported to port operations for shipping, while the waste material is separated into wet tailings and dry tailings. Tantalum concentrate was only recovered at lithium processing operations where its concentrations were reasonable in the ore to make the process financially feasible.

Whilst lithium has unique properties useful to the storage of electricity, the mining and processing of lithium is associated with exposure to radiation, dust, noise, heat stress, solar ultraviolet, whole body and hand-arm vibration and manual handling (Donoghue, 2004). Potential harm from these exposures include respiratory illnesses, occupational noise-induced hearing loss and tinnitus, and heat stroke. Lithium mining and processing has also been associated with melanoma, exacerbated pre-existing spinal disorders, hand-arm vibration syndrome, and musculoskeletal injuries from exposure to solar ultraviolet, whole body and hand-arm vibration and manual handling (Donoghue, 2004; Ross and Murray, 2004; McPhee, 2004).

Human exposure to radiation comes from both natural and artificial sources. Natural radiation emanates from two sources: cosmic radiation (radiation from space), consisting of X-rays, gamma rays and particles; its dose increases with altitude (Shahbazi-Gahrouei et al., 2013), and the decay of naturally occurring radionuclides (unstable elements that release radiation) producing alpha and beta particles and also gamma rays (Shahbazi-Gahrouei et al., 2013; Missimer et al., 2019). According to Missimer et al. (2019), the primary source of natural radiation is Uranium-238, and Thorium-232 decay chains and Potassium-40. The sources and pathways of exposure at a lithium mine are anticipated to be internal exposure due to the inhalation of dust containing alpha-emitting radionuclides, radon (222Rn), thoron (220Rn) and their decay products. Internal exposure to alpha and beta emitting radioactive elements can occur due to the ingestion of contaminated drinking water.

Naturally occurring radiation-emitting elements are unstable and undergo spontaneous transformation into more stable atoms (Martin et al., 2012). These unstable substances are radioactive (emit radiation) and the transformation process to attain atomic stability is referred to as radioactive decay, which produces radiation in the form of charged particles (alpha and beta) and gamma rays (Martin et al., 2012). Alpha particles have high linear energy transfer (LET) and react more with DNA, thereby making them very harmful (VoPham et al., 2017), causing DNA damage and therefore carcinogenesis (Banning and Benfer, 2017). Gamma rays and beta particles are also considered capable of breaking an electron away from an atom and therefore harmful to the DNA due to their high energy (Tuieng et al., 2021; McColl et al., 2015).

The harm from exposure to radiation depends on the exposure duration and the level of radiation individuals are exposed to. The Work Health and Safety (WHS) (Mines) Regulations 2022 (641P) (Government of Western Australia, 2022) stipulates an occupational dose limit of 20 mSv per year for radiation exposure, which is derived from the Radiation Protection Series No.9 (Australian Radiation Protection and Nuclear Safety Agency, 2005). The Exposure Standard (ES) for inhalable dust is 10 mg/m^3 (Government of Western Australia, 2022). Using the formula in the legislation the ES for inhalable dust was adjusted to 7.1 mg/m^3 for work shifts and rosters outside of the 8-h working shift for 40 h a week.

This paper aims to investigate radioactivity (radiation emission) and exposure to naturally occurring radiative materials (NORM) among lithium mine workers in WA. The outcomes of this study will provide further insight into exposures to radiation in lithium mines, contributing to the development of interventions aimed at mitigating these exposures. This will assist in directing focus to prevent potential harm and the allocation of regulatory resources. To our knowledge, there is no previous study conducted in Australia to assess exposure to NORM among lithium mine workers.

2. Material and methods

2.1. Study population/data acquisition

This study used industry occupational exposure data for radiation from lithium mines for the period between September 2018 and August 2024. In WA, mining companies are required to conduct exposure assessments for exposures to NORM, and report the findings to the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS), and the WA Radiological Council. The assessment includes a process referred to as dose assessment (the assessment of exposure levels), which takes into account all exposure pathways and exposure sources. The assessment compares the level of exposure to the exposure limit for radiation.

All mining companies, with NORM in their operations, are required to appoint a radiation safety officer (RSO) to assess exposure to NORM. The RSO is responsible for developing the radiation management plan and undertaking or directing the monitoring activities for the determination of health exposures and potential environmental impact from radiation. The plan details the mining operations, processes, workgroups, hours of work, equipment, the anticipated level of exposure, controls and the mechanism to verify the effectiveness of the controls, and a monitoring plan to quantitatively determine the exposures and environmental radiological impact. The selection of workers from workgroups for the monitoring is through a random process. The Mine Air Quality Officer (a legislatively appointed role in WA) attends the prestart meeting of the workgroups to be monitored on the day, and requests management for random volunteers to wear the monitoring equipment for the shift. The demographics of the volunteers include males and females within the age range of 18–65 years, mainly from WA. No worker was excluded from the exposure monitoring program.

The three lithium mines, Mine A, Mine B and Mine C where the study was conducted, are located in different geographical areas in WA. Although Mine A and Mine C are located in the Southern region and Mine B is located in the Northern region of WA, they are similar in relation to mining and processing operations.

The available dataset used in this study consisted of exposure levels to radioactive dust, gamma, radon and thoron, and ingested water, among lithium mine workers who were involved in surface mining and mineral processing activities for the study period. Exposure to inhalable dust data was also available. For the purpose of this study, mine workers were randomly selected from different departments including Administration & Support Services, Mining, Crushing & Processing, and Maintenance (Table 1). The study subjects provided their written informed consent to participate in this study including the survey and personal monitoring.

2.2. Radioactivity and exposure assessment

Measurements of personal exposure to inhalable dust and radiation were conducted across the three mines in WA. Seventy-one bulk samples of lithium ore, spodumene concentrate, tantalum concentrate, dry tailings and wet tailings were collected to determine the radioactivity (radiation emissions). The bulk sample materials were analysed on sites using X-ray fluorescence (XRF) method, the Malvern Panalytical Zetium XRFs were used for the analyses. As no chemical and thermal processing of the materials take place at the mine sites, the quantity of all radionuclides in the Uranium-238 and Thorium-232 decay chains were considered to remain constant (in the state of secular equilibrium). Therefore, the analyses were performed only for the "head of the chain" elements - uranium and thorium.

Table 1
Departments and functions.

Department	Function
Administration & Support Services	Safe and efficient operation of surface and process plant operations. Ensuring compliance with mining regulations. Overseeing scheduling, planning and budgeting. Management of health and safety, and environment. Cleaning activities across mining operations and village services.
Mining	Setting out drill patterns. Drill and blast activities. Sample collection and geochemical sample preparation. Load and haul activities. Clearing, bench preparation, dump preparation, road construction, emptying floors, pushing up ore stockpiles and feed.
Crushing & Processing	Monitoring and adjusting the day-to-day operation of the plant. Inspections and maintenance. Continuous monitoring of conveyors. Operation of jaw crusher, pulverisers, shakers and riffle splitters. Sampling, reagent preparation and analysis. Quality control of data and reporting.
Maintenance	Maintenance of functional assets to meet operational targets. Continuous improvement of technical business performance. Safe operation of handheld, fixed and plant machinery. Maintaining documentation and service / repair history of plant and equipment.

Water samples were collected from bores (1181) and from post treatment drinking water (270) (through reverse osmosis plants) at consumer points. Bore water sampling was undertaken as per AS/NZS 5667.11.1998 Water quality – Sampling Part 11: Guidance on sampling of groundwaters. The depth of the bores was not taken into consideration for the radiation levels in the bore water. Drinking water sampling was undertaken as per AS/NZS 5667.5.1998 Water quality – Sampling Part 5: Guidance on sampling of drinking water and water used for food and beverage processing. The water samples were submitted to the National Association of Testing Authorities (NATA) – accredited laboratories for the analyses to determine the radiation levels. The NATA-accredited laboratories utilised in-house methods for the analyses.

Personal exposures to concentrations of inhalable dust were determined following the Australian Standard for sampling and gravimetric determination of inhalable dust in workplace atmospheres (AS 3640–2009), which is adapted from the International Standard *ISO 7708:1995, Air quality—Particle size fraction definitions for health-related sampling.* The 7-hole sampling heads were used for the monitoring using the 25mm pre-weighed filters, which were also weighed after monitoring for gravimetric analyses. The assembled filters, cassettes and sampling heads were clipped into the workers' breathing zone. Monitoring was undertaken for a minimum of four hours, with the sampling pump operating at 2 L/min according to the Australian standard.

Emissions of airborne contaminants were monitored across all four departments in mining operations and specifically in active mining areas, within the cabin of mining mobile equipment, at discharge points of fixed processing plants, in maintenance workshops and within laboratory sampling preparation facilities. The lithium mine workers were monitored during their normal 12 h work shifts and asked to keep a diary to record their daily activities.

Independent analyses of the personal monitoring samples were undertaken through the NATA-accredited laboratory. Gravimetric analyses were used for the determination of the inhalable dust's concentration (AS 3640–2009 defines the analytical methods, which are adopted by the NATA accredited laboratory). A NATA–accredited laboratory holds an accreditation number and a compliance reference to ISO / IEC 17,025. Samples submitted to the laboratory for analyses were analysed in batches of 20, and no more than 20 at any given time, and quality controls were in place for blanks, surrogate spikes, laboratory control samples (LCS), matrix spikes and duplicates.

Monitoring for radioactive dust was undertaken as per DMIRS Guideline NORM-3.4: Airborne radioactivity sampling. The Canberra 7401 alpha spectrometers model was used for gross alpha counting (Am-241 check sources were used for checking the alpha spectrometers). The SARAD-1688–2 electronic radon/thoron monitor was used for radon and thoron monitoring.

Monitoring of external gamma radiation was undertaken following the DMIRS Guideline NORM-3.2: Operational monitoring requirements. The RadEye B20, RadEye SPRD, and Colibri TTC gamma radiation monitors were used.

2.3. Statistical analysis

Data analysis was conducted using the IBM SPSS Statistics Version 26 (IBM Corp, 2019). Data has been presented according to radioactivity in material, radiation concentrations in water, concentration of inhalable and radioactive dust, concentrations of radon and thoron and gamma radiation levels. Exposure data were presented according to the departments of lithium mining (Administration & Support Services, Mining, Crushing & Processing, and Maintenance).

Inhalable dust and radiation concentration levels were presented as minimum and maximum (range), and arithmetic mean (AM) ± standard deviation. The arithmetic mean was used to evaluate the exposures, and to determine regulatory compliance to the ES and the occupational dose limit for radiation exposure.

To compare the mean exposure to radiation between departments / sampling locations, we applied parametric statistical tests. If the comparison was assessed between two departments / sampling locations, we used two-sample *t*-test (also known as independent-sample *t*-test). If the comparison was performed between more than two departments / sampling locations, we used a One-Way Analysis of Variance (ANOVA). Because normality is an underlying assumption of the parametric statistical tests, we assessed normality (i.e., whether the outcome variables are normally distributed) for all outcome variables by using Shapiro-Wilk test before data analyses. We also assessed another required assumption of equal variances (i.e., whether the outcome variables equally varied between groups) for the two parametric tests by using Levene's test.

For non-normal (skewed) variables, we applied natural logarithm transformation (LN) to correct skewness. If normality assumption could be assumed after the transformation, we applied the two-sample *t*-test or One-Way ANOVA on LN transformed variables to do the comparisons. If the normality assumption could not be assumed even after the transformation, we then used a non-parametric alternative to the two-sample *t*-test—Mann-Whitney U test—for comparing two departments / sampling locations, and a non-parametric version of One-Way ANOVA—Kruskal-Wallis test— for comparing more than two departments / sampling locations. In our paper, all statistical tests undertaken were two-sided and a p value of <0.05 was only considered as statistically significant (Coakes, 2012).

3. Results

3.1. Summary results

Bulk samples were collected to determine radiation emissions in the lithium ore, spodumene concentrate, tantalum concentrate, dry tailings and wet tailings. Water samples were also collected to determine radiation contents in the bore water (before and after treatment through reverse osmosis plants) for uranium and thorium, gross alpha and gross beta, radium-226 and radium-228. Monitoring was also undertaken for exposure to inhalable dust and radiation in the dust, radon and thoron concentrations and gamma radiation levels.

The annual exposures to radiation from all sources and for all departments (Table 6) were below the regulatory limits set by the WA WHS (Mines) Regulations 2022 (20 mSv per year averaged over a period of five consecutive calendar years, with the provision that the effective dose shall not exceed 50 mSv per year) (Government of Western Australia, 2022). Crushing & Processing recorded the highest annual mean exposure concentration to radiation (0.543 mSv per year) while Mining recorded the lowest annual mean exposure concentration (0.261 mSv per year).

3.2. Radiation emissions in materials

In Fig. 1 we present the radiation emission levels in lithium ore, spodumene concentrate, tantalum concentrate, wet tailings and dry tailings between 2018 and 2024.

The mean radiation emission level of 2.169 Bq/g (min 1.331 Bq/g and max 5.278 Bq/g) in the tantalum concentrate exceeded the regulatory limit of 1 Bq/g set by the WA WHS (Mines) Regulations 2022, (641K Pages 424–425) (Government of Western Australia, 2022). No exceedances were measured for other materials. Tantalum concentrate is a by-product of spodumene production. According to the WA WHS (Mines) Regulations 2022, radioactivity above the 1 Bq/g categorises the material as radioactive (Government of Western Australia, 2022).

3.3. Radioactivity in water

The study found significantly higher radiation levels in the untreated ground water compared to the treated drinking water (Table 2).

Before treatment of the bore water, the mean uranium, gross alpha and gross beta were 7.700 µg/L, 0.886 Bq/L, and 0.765 Bq/L, respectively. These levels were above the trigger values stipulated by the Australian Drinking Water Guidelines, which are 20 µg/L for uranium, 0.5 Bq/L for gross alpha, and 0.5 Bq/L for gross beta (The National Health and Medical Research Council, 2022). The mean uranium, gross alpha and gross beta concentrations of the treated drinking water were within acceptable limits, 0.900 µg/L for uranium, 0.058 Bq/L for gross alpha, and 0.052 Bq/L for gross beta.

3.4. Inhalable dust and radioactive dust exposures

The mean inhalable dust exposures were all below the adjusted ES of 7.1 mg/m^3 stipulated by the WHS (Mines) Regulations (Government of

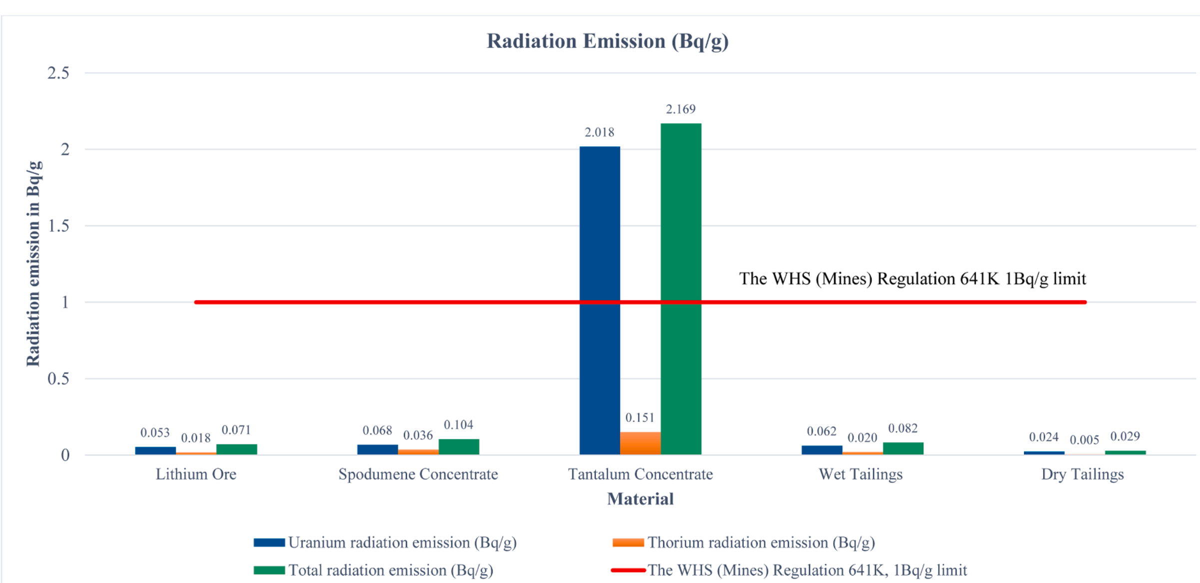

Fig. 1. Radiation emissions in lithium mining (2018–2024).

Table 2
Radiation in water.

Uranium and Thorium (μg/L) (MDL 0.5–50 μg/L, 0.5–30 μg/L)			
Agent Uranium	Number of samples	Range	AM ±SD
Ground water	335	0.500–130.000	7.700±19.200
Drinking water	68	0.001–1.400	0.900±0.300
p-value*			<0.0001
Thorium			
Ground water	87	0.500–50.000	5.400±12.400
Drinking water	37	0.001–0.500	0.400±0.200
p-value*			0.0003
*Based on two-sample T-Test with unequal variance			
Gross Alpha, Gross Beta, Radium-226 & Radium-228 (Bq/L)			
Agent	Number of samples	Range	AM ±SD
Gross Alpha			
Ground water	293	0.014–32.500	0.886±3.571
Drinking water	50	0.016–0.391	0.058±0.055
p-value*			0.0001
Gross Beta			
Ground water	336	0.028–44.100	0.765±3.497
Drinking water	41	0.010–0.114	0.052±0.026
p-value*			0.0002
Radium 226			
Ground water	65	0.017–14.900	0.688±2.469
Drinking water	37	0.035–0.100	0.056±0.024
p-value*			0.0432
Radium 228			
Ground water	65	0.013–19.000	0.748±2.556
Drinking water	37	0.040–0.170	0.101±0.032
p-value*			0.0453

[*] Based on two-sample T-Test with unequal variance

Western Australia, 2022) for all the departments (Table 3) – Administration & Support Services (0.668 mg/m^3), Crushing & Processing (0.669 mg/m^3), Maintenance (1.639 mg/m^3) and Mining (0.431 mg/m^3). Exposure to radiation through inhalable dust was negligible, with most of the results for gross alpha indicating exposures below the limit of detection for all departments (Table 3).

Table 3
Inhalable dust (mg/m^3) and activity levels (Bq/m^3) in dust samples.

Inhalable Dust (mg/m^3)				
Department	Number of samples	% of results below detection limit	Range	AM+-SD
Administration & Support Services	28	0.000 %	0.100–2.427	0.668 ±0.700
Crushing & Processing	13	0.000 %	0.200–1.400	0.669 ±0.368
Maintenance	44	0.000 %	0.063–32.000	1.639 ±5.023
Mining	56	0.000 %	0.086–1.800	0.431 ±0.389
p-value				0.056[a]
[a]Based on Kruskal Wallis test and ANOVA, respectively				
Gross alpha (Activity) in dust (Bq/m^3) (MDL 0.003 – 0.010 Bq/m^3)				
Department	Number of samples	% of results below detection limit	Range	AM+-SD
Administration & Support Services	58	96.600 %	0.003–0.014	0.006 ±0.002
Crushing & Processing	13	100.000 %	0.005–0.014	0.007 ±0.003
Maintenance	67	83.600 %	0.003–0.025	0.006 ±0.003
Mining	92	88.000 %	0.003–0.031	0.006 ±0.003
p-value				0.023[a]

[a] Based on Kruskal Wallis test and ANOVA, respectively

3.5. Gamma, radon and thoron concentrations

Gamma radiation levels (Table 4) were identified in the tantalum processing circuit (AM of 0.199 μSv/hour,) and the tantalum storage area (AM of 0.277 μSv/hour). The gamma mean values were slightly above the background levels (0.040 μSv/hour – 0.210 μSv/hour).

Radon and thoron (Table 5) were also found in the tantalum concentrate processing circuit and tantalum storage area, and inside the reverse osmosis plants. The mean radon concentration levels ranged from 7.346 Bq/m^3 (reverse osmoses plant) to 11.614 Bq/m^3 (tantalum processing circuit), while the thoron mean concentration levels ranged from 10.170 Bq/m^3 (tantalum processing circuit) to 18.062 Bq/m^3 (tantalum concentrate storage area).

The mean radon and thoron concentration levels were identified to be low.

3.6. Exposure to radiation according to departments

Table 6 shows that the radiation exposures for the departments ranged from 0.262 mSv per year (Mining) to 0.544 mSv per year (Crushing & Processing), which are significantly below the occupational dose limit of 20 mSv per year stipulated by the WA WHS (Mines) (2022), 641P, (Government of Western Australia, 2022) and derived from the Radiation Protection Series No.9 (Australian Radiation Protection and Nuclear Safety Agency, 2005).

It should be noted that the radiation exposure of workers in excess of the limit for the members of the general public (1 mSv per year) is considered to be very unlikely at any of the studied sites.

4. Discussion

4.1. Radioactivity in lithium mining

There is no place on earth that is free of radiation emission, as radiation-emitting elements are naturally found in air, soil, water and food, although exposure depends on geological and geographical conditions which vary across the world (Shahbazi-Gahrouei et al., 2013). It must also be noted that minute amounts of uranium have been found in virtually all plants, animals and aquifers (Gerwen et al. 2020). In mining, certain minerals such as gold are associated with considerable concentrations of uranium (Winde et al., 2019). The radiation exposure pathways include the inhalation of radioactive dust and radon, the consumption of polluted groundwater and rivers, the ingestion of food produced with contaminated soil and water, and gamma radiation (Winde et al., 2019).

This study determined radiation emission in lithium mining for lithium ore (0.071 Bq/g), spodumene concentrate (0.104 Bq/g), tantalum concentrate (2.169 Bq/g), wet tailings (0.082 Bq/g) and dry tailings (0.029 Bq/g). Tantalum concentrate was the only material identified in the study to be above 1 Bq/g, which is categorised as radioactive according to the criteria established by the WHS (Mines)

Table 4
Gamma.

Gamma (μSv/hour)			
Location	Number of samples	Range	AM±SD
Tantalum processing circuit	194	0.080 – 1.260	0.199 ± 0.168
Tantalum concentrate storage area	104	0.080 – 1.130	0.277 ± 0.202
P value			<0.001
Background		0.040 – 0.210	

AM = arithmetic mean; SD = standard deviation.
*Difference between two locations was compared by a two-sample t test.

Table 5
Radon and thoron.

Radon (Bq/m³) (MDL 2.000 Bq/m³)				
Location	Number of samples	% of results below detection limit	Range	AM±SD
Reverse Osmosis Plant	134	38.060	2.000–37.700	7.346 ± 8.654
Tantalum processing circuit	1540	9.870	2.000–121.000	11.614 ± 13.200
Tantalum concentrate storage area	736	16.712	2.000–53.162	10.769 ± 11.484
P value				<0.001
AM = arithmetic mean; SD = standard deviation.				
*Difference between three locations was compared by one-way ANOVA.				
Thoron (Bq/m³) (MDL 2.000 Bq/m³)				
Location	Number of samples	% of results below detection limit	Range	AM±SD
Reverse Osmosis Plant	134	39.552	2.000–74.762	15.125 ± 17.772
Tantalum processing circuit	1540	17.468	1.979–96.000	10.170 ± 13.094
Tantalum concentrate storage area	736	22.554	1.286–112.443	18.062 ± 21.235
P value				<0.001

AM = arithmetic mean; SD = standard deviation.
* Difference between the three locations was compared by one-way ANOVA.

Regulations 2022 (Government of Western Australia, 2022).

4.2. Radiation levels in bore water in lithium mining

Ingestion of drinking water presents the main exposure pathway for uranium and its decay products (radium, radon), with research indicating a link between elevated radium and radon concentrations in water with various cancers – bone, lung, breast and blood cancers (Banning and Benfer, 2017). The quantity of radiation-emitting elements released from rocks and sediments into groundwater depends on their concentration in the rocks or sediments and the rate of dissolution, leaching and desorption (Missimer et al., 2019).

Water supply within lithium mining was through the extraction of water from bores which was treated with reverse osmosis plants prior to use for cooking, drinking and ablutions. The results from the study in lithium mining indicated a significant difference between the radiation levels in the bore water before and after treatment. The mean uranium and thorium levels before treatment were 7.700 µg/L and 5.400 µg/L, respectively, while the levels after treatment were 0.900 µg/L and 0.400 µg/L, respectively. The uranium levels after treatment did not exceed the 20 µg/L recommended level in the Australian Drinking Water Guidelines, 2011 (The National Health and Medical Research Council, 2022). A significant difference in the mean gross alpha, gross beta, radium-226 and radium-228 was also identified in the water results before and after treatment. The levels for gross alpha and gross beta in the drinking water (post treatment) were below the trigger values recommended by the Australian Drinking Water Guidelines, 2011, 0.5 Bq/L (gross alpha) and 0.5 Bq/L (gross beta) (The National Health and Medical Research Council, 2022). In the event where these trigger levels are exceeded, the Australian Drinking Water Guidelines request further investigation to identify the nature of the radiation levels and the radiation-emitting elements (The National Health and Medical Research Council, 2022).

The study indicated that the treatment of the bore water through the reverse osmosis plants reduced the gross alpha and gross beta concentrations to acceptable levels as indicated by the Australian Drinking Water Guidelines. This is consistent with findings from research undertaken in 2019 in Florida, United States, which revealed that reverse osmosis is an effective water treatment process to remove radium-226, radium-228, uranium, gross alpha and gross beta (Missimer et al., 2019). Other treatment methods, according to scientific literature, include ion exchange to remove radium-226, radium-228 and uranium (Missimer et al., 2019).

In WA, the regulation of drinking water is managed through a licensing process and the *Advisory Committee for the Purity of Water* (Government of Western Australia, Department of Health, 2023). The *Economic Regulation Authority* issues licensing to larger water service providers such as the Water Corporation, the Bunbury Water Corporation (Aqwest) and the Busselton Water Corporation; with each water service provider required to establish and maintain a binding Memorandum of Understanding for Drinking Water Quality with the Department of Health (Government of Western Australia, Department of Health, 2023). All non-licensed drinking water providers such as mine sites, caravan parks, roadhouses, camps, and small or remote communities are managed directly by the Department of Health (Government of Western Australia, Department of Health, 2023). As such the management of drinking water in lithium mining is regulated directly by the Department of Health.

4.3. Exposure to inhalable dust and radiation in the dust

It is well documented that uranium-bearing minerals contain elements that emit radiation (Doering, 2020). The presence of these elements in several metal ores is a source of environmental radiation impacts, raising radiation protection issues in mining industries

Table 6
Total exposures according to departments.

Dose calculations									
Department	Dust	Gamma	Radon	Thoron	Water - U	Water - Th	Water - Ra-226	Water - Ra-228	Sum - mSv/y
Administration & Support Services	0.170	0.000	0.078	0.000	0.000	0.000	0.004	0.021	0.273
Mining	0.159	0.000	0.078	0.000	0.000	0.000	0.004	0.021	0.262
Crushing & Processing	0.181	0.260	0.078	0.000	0.000	0.000	0.004	0.021	0.544
Maintenance	0.164	0.000	0.078	0.000	0.000	0.000	0.004	0.021	0.267
Comments									
All dose assessments were carried out in accordance with the methodologies stipulated in the approved procedure – DEMIRS Guideline NORM-V, Dose Assessment, 2023									
Dust	Dose coefficients differ for different sites: 0.0114 mSv/Bq for Mine A, 0.0117 mSv/Bq for Mine B and 0.0089 mSv/Bq for Mine C. As the weight ratios between Th and U are different, 1.75:1 at Mine A, 2:1 at Mine B, and 1:5 at Mine C, dose coefficients given in the NORM-V document are also different. Therefore, a reasonable conservative ("middle") value of 0.0114 mSv/Bq was selected for dose assessment.								
Gamma	Gamma was at background level in all areas except at the tantalum processing circuit and tantalum concentrate storage area								
Radon & Thoron	The same value assigned to all workgroups. The background is not allowed to be deducted and levels on a site are about the same as in the camp.								
Water	U and Th were converted from mg/L to Bq/L using conversion factors from Table 15 of the NORM-V Guideline. Dose coefficients taken from Tables 19 and 20 of the same NORM-V Guideline. Water consumption was estimated at ~3L/day, ~185 shifts = ~ 600 L/year.								
Working hours	2000 h per year was used for dose determination.								

(Carvalho et al., 2021). Uranium is a naturally occurring radiation-emitting element widely distributed in the soil, and in higher concentrations in certain rock formations, particularly in Africa, North America and Australia (Gerwen e al. 2020). It is released into the environment through natural water erosion, and from human activity in the forms of mining, milling and uranium processing (Gerwen e al. 2020).

The study results indicated that there was no significant difference in the mean exposure concentrations for inhalable dust between departments. Exposures to inhalable dust for all the departments in lithium mining were below the ES of 7.1 mg/m^3. The highest mean exposure concentration was recorded in the Maintenance Department (1.639 mg/m^3), while the lowest mean exposure concentration was recorded in the Mining Department (0.431 mg/m^3). This can be explained by the activities undertaken by the Maintenance Department on mobile and fixed plants across the mining operations, which is associated with dusty environments. On the other hand, a large proportion of Mining personnel work within enclosed cabins of air-conditioned mobile equipment, which prevents the ingress of dust within their working environment. The mean exposure concentrations for the other departments were 0.668 mg/m^3 (Administration & Support Services) and 0.669 mg/m^3 (Crushing & Processing).

Results from the analyses of the inhalable dust samples for gross alpha indicated very low and negligible exposures as the mean gross alpha exposures for all departments in lithium mining ranged from 0.006 Bq/m^3 to 0.007 Bq/m^3, with most of the results indicating exposures frequently below the limit of detection.

While it is acknowledged that lithium mining is associated with the emission of dust, which was examined in this study through airborne monitoring for inhalable dust and radiation in the dust, the findings indicated low exposures for both inhalable dust and the radiation contents of the dust.

4.4. Gamma exposure in lithium mining

Gamma radiation has sufficient energy to induce the electronic transition of atoms and molecules, causing the electron to escape the atom, a process known as ionisation (Tuieng et al., 2021). Ionising radiation is the cause of the health effects on exposed individuals, based on the level and duration of exposure.

The findings of the study indicated that gamma values were at background levels across all work areas except for the tantalum processing circuit and the tantalum concentrate storage area. However, the mean gamma levels at the tantalum concentrate storage area and tantalum processing circuit were in the range of 0.199 μSv/hour – 0.277 μSv/hour, which indicates the presence of gamma radiation in the processing and storage of tantalum concentrate in lithium mining.

4.5. Radon exposure

Radon is a naturally occurring radiation-emitting gas, classified as a Group 1 carcinogen (cancer-causing substance) by the International Agency for Research on Cancer (IARC). It is formed from the decay of uranium and thorium found in soil and rocks, and is present in the air at various concentrations (Kang et al., 2019; VoPham et al., 2017).

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is the national government agency with the primary authority on radiation protection and nuclear safety.

ARPANSA recommends 200 Bq/m^3 for households and 1000 Bq/m^3 for workplaces as thresholds above which measures must be taken to reduce radon levels (Australian Radiation and Nuclear Safety Agency, 2024). The present study findings revealed that the airborne mean radon concentrations ranged from 7.346 Bq/m^3 to 11.614 Bq/m^3, which are below the recommended radon concentrations levels for workplaces according to ARPANSA (Australian Radiation and Nuclear Safety Agency, 2024). The radon levels in lithium mining fall within the range of 0.735–1.161 % of the recommended levels for workplaces (1000 Bq/m^3) (Australian Radiation and Nuclear Safety Agency, 2024).

Previous research provides an indication of radon exposures in other industries. A study conducted in China in large-scale underground iron ore, coal and copper mines between 2012 and 2013 revealed the presence of radon, with the copper mine having the highest average annual radon concentrations, while the coal mine had the lowest average annual radon concentrations (Fan et al., 2016). It was also observed that across the seasons, radon concentrations were highest in summer and lowest in winter. The high levels in summer were reported to be due to high temperatures which caused the exhalation of radon from rocks (Fan et al., 2016). The average annual exposures for personnel across the mines were 0.8 mSv (coal mine), 2.70 mSv (iron ore mine), and 6.61 mSv (copper mine), and it was observed that the personal exposures depended on the mine type, the work activities, seasons and the individuals (Fan et al., 2016).

The findings of the study undertaken in lithium mining revealed that the radon exposures among lithium mine workers are low and significantly below the recommended guideline value of 1000 Bq/m^3 (Australian Radiation and Nuclear Safety Agency, 2024).

The World Health Organisation considers radon as the second most common cause of lung cancer after smoking. According to a study, even low exposure to radon can cause an increased likelihood of lung cancer (Kang et al., 2019). However, the exposures in lithium mining are well within acceptable levels.

4.6. Total radiation exposure

To determine the total exposure to radiation, exposure from all sources and pathways must be taken into account, which includes exposure to gamma, radon, thoron, airborne radioactive dust and the ingestion of drinking water.

The WA WHS (Mines) Regulations 2022, 641P (pages 428–439) states that "the mine operator of a relevant mine must ensure that a worker at the mine does not receive doses of radiation, arising from mining operations at the mine, that are in excess of the occupational dose limits specified in Schedule 1 of RPS-9 for effective dose and annual equivalent dose" (Government of Western Australia, 2022). RPS-9 is the Radiation Protection Series No.9 developed by ARPANSA. The occupational dose limit (ES) set by RPS-9 is 20 mSv per year averaged over a period of five consecutive calendar years, with the provision that the effective dose shall not exceed 50 mSv in a single year, and when a pregnancy is declared by a female worker, their exposure shall not exceed 1 mSv per year (Australian Radiation Protection and Nuclear Safety Agency, 2005).

The findings of the study revealed that the radiation exposures for the departments were 0.273 mSv per year for Administration & Support Services, 0.544 mSv per year for Crushing & Processing (the highest exposure among the departments), 0.267 mSv per year for Maintenance, and 0.262 mSv per year for Mining (the lowest exposure among the departments). These exposures are significantly below the regulatory occupational limits for radiation exposure for workers and pregnancy declared by female workers. However, it must be noted that the exposures identified in the Crushing & Processing department are approximately half the occupational dose limit for pregnancy. This requires proactive measures to be considered including ongoing monitoring of exposures and the application of control measures such as reducing the time of exposure, access restrictions to the tantalum concentrate production and storage areas and the maintenance of the reverse osmosis plants used to treat the bore water for use.

While there is currently no existing preceding literature on radiation exposures in lithium mining, a similar study undertaken on two open-pit gold mines in Ghana revealed a total effective dose of 0.3 mSv for the workforce, all exposure pathways and sources were taken into consideration (Darko et al., 2010). The findings from the study in the gold mines are consistent with the radiation exposure findings from this study undertaken in lithium mining (Darko et al., 2010).

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2008 report revealed that the global annual average effective dose from natural radiation sources is about 2.4 mSv per year (Tokonami, 2020). On the other hand, exposure to man-made sources of ionising radiation such as mammography exposes the patient to about 0.36 mSv per screening (Tuieng et al., 2021). In comparison to the global average effective dose, the highest annual mean exposure in lithium mining recorded in Crushing & Processing (0.544 mSv per year) is approximately 22.666 % of the 2.4 mSv per year exposure reported by UNSCEAR. Consequently, the authors present that the exposures identified in this study in lithium mining are very low, with the effective treatment of bore water before use.

4.7. Study limitations

The results presented in this study are based on the measurement during day shifts. Due to the constraints of time and resources, data collection was not undertaken during night shifts which is acknowledged as a study limitation. However, the authors believe that the day shift measurements represent true exposures to radiation and inhalable dust among lithium mine workers.

A water consumption rate of 3L/day was assumed for all workers in the dose (exposure) assessment. That was a conservative assumption and is acknowledged as a study limitation.

5. Conclusion

In lithium mining, the radiation content of the bore water presents a potential source of harm, indicated by the elevated concentrations of gross alpha, gross beta, uranium, radium-226 and radium-228. However, the reverse osmosis treatment plants proved effective in the significant reduction of the radiation concentration levels to acceptable levels stipulated by the Australian Drinking Water Guidelines, 2011. It is therefore the position of the authors that bore water in lithium mining is a health concern if not treated before use.

Another health concern identified is the radiation emissions from tantalum concentrate, which met the criteria for its categorisation as a radioactive material according to the WA WHS (Mines) Regulations 2022. This by-product must be handled with the appropriate controls such as reducing the time of exposure for workers and the storage of the material in a location away from frequently occupied workplaces. It is also recommended that exclusion zones and hard barricades be installed around tantalum concentrate storage areas to prevent unnecessary access and exposure to radiation. Further action such as the tying of tantalum concentrate bags and the installation of shelters for tantalum storage must also be taken into consideration to prevent wind blowing the material to other areas of the mine, especially when it is dried up.

While some exposures to radiation are detectable in lithium mining, the findings of this study indicate that with a rigid treatment of bore water before use in lithium mining, and the implementation of controls for tantalum concentrate production and storage, neither lithium mine workers, nor members of the public surrounding lithium mines, are exposed to radiation levels with the potential to cause adverse health effects in WA. It is also clear that, with the same controls, any radiological impact on the surrounding environment is either very minimal or non-existent.

In combination with the regulatory requirements for the management of dust, drinking water and NORM in mining, it is recommended that proactive measures are taken in lithium mining, addressing detailed water monitoring for radiological parameters, and the development of response plans, where required, to manage potential harm and for business continuity in the industry. It is also recommended that reverse osmosis plants be utilised for the treatment of drinking water in remote mines where water from underground aquifers is extracted for use, irrespective of the mineral being mined or processed.

Ethics statement

The study was reviewed and approved by the Human Ethics Research Committee, Curtin University with approval number: HRE2023–0408. All procedures were performed in compliance with relevant laws and institutional guidelines and have been approved by the appropriate institutional committees. The study subjects provided their written informed consent to participate in this study including the survey and personal monitoring.

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CRediT authorship contribution statement

David Gbondo: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Minh Pham:** Validation, Supervision, Formal analysis. **Yun Zhao:** Validation, Supervision, Formal analysis. **Nick Tsurikov:** Validation, Formal analysis, Data curation. **Krassi Rumchev:** Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

There has been no conflict of interest considering the below.

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Data availability

Data will be made available on request.

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