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Practical Matter Article

A review of radiation doses and associated parameters in Western Australian mining operations that process ores containing naturally occurring radionuclides for 2018–19

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Abstract

Naturally occurring radionuclides (NORs) are encountered in varying concentrations in a wide range of commodities that are mined and processed in Western Australia (WA), including mineral sands, coal, phosphate ores, sandblasting materials, and the production of bauxite, titanium dioxide pigment, copper, zinc, lead, tin, tantalum and the refining of zircon.

Because they have the potential for workers to receive annual doses in excess of 1 mSv, 14 mining operations in WA are required to submit an annual report of worker doses to the regulatory authority. This research provides a summary of the workforce demographics and radiation doses reported by mining operations for the 2018–19 reporting period in order to establish a benchmark against which to compare future worker exposures. The 2018–19 data is compared to that presented in the last peer-reviewed research, published in 1994 in order to evaluate changes in worker dose profiles over the intervening period.

In 1992–93, the collective effective dose received by 1496 workers across seven mining operations was 2824 man.mSv, whereas in 2018–19 it had decreased to 784 man.mSv for 1474 workers in 13 operations. The maximum committed effective dose (CED) decreased by 76%, from 18 mSv (36% of the annual limit) in 1992–93 to 4.4 mSv (22% of the derived annual limit) in 2018–19. The mean CED decreased by 49%, from 1.8 mSv in 1992–93 to 0.97 mSv in 2018–19.

As a result of revised DC's published in ICRP-137 and ICRP-141, the impacts upon the mean CED per unit intake of alpha activity arising from inhalation of insoluble NORs-containing dusts, and contribution to CED from inhalation of radon, thoron and their progeny will require evaluation for individual mining operations in the WA mining industry.

Keywords: radiation exposure, mining, dose coefficients

(Some figures may appear in colour only in the online journal)

1. Introduction

This paper aims to address the absence of peer reviewed information of radiation doses to Western Australia (WA) mine workers in the period since Marshman and Hewson (1994) published an analysis of doses to workers in WA's mineral sands industry (MSI) for the 1992–93 reporting period.

1.1. Legislative framework for radiation exposures in mining in WA

The naturally occurring radionuclides (NORs), thorium-232 (^{232}Th) and uranium-238 (^{238}U) are commonly encountered in mining and mineral processing activities conducted in WA such as the production of mineral sands, coal, sandblasting materials, bauxite, titanium dioxide pigment, copper, tin, tantalum and the refining of zircon [3] (RHSAC 2005, IAEA 2006).

In Australia, a substance that has a head of decay chain (^{232}Th, ^{238}U or a combination of ^{232}Th and ^{238}U) activity concentration >1 Bqg^{-1}, is considered as radioactive (ARPANSA 2017, p 8). In WA, specific provisions relating to the management of naturally occurring radioactive materials (NORM) in mining operations are within the remit of the Mines Safety and Inspection Act (MSIA) 1994 and Regulations (MSIR) 1995 (GWA 1994, 1995). The State mining engineer is the designated regulatory authority under the MSIA.

In accordance with International Atomic Energy Agency (IAEA) recommendations (IAEA 2006, pp 7–11), a graded approach to regulation of exposures to NORM is applied to WA mining operations. In the event that the activity concentration of NORs exceed the radioactive substance criteria, and radiation doses to workers are estimated to be greater than 1 mSv per year, the operation is required to comply with the MSIR, and submit annual reports of worker doses to the State mining engineer for review and comparison against dose limits. Hereinafter such mining operations are referred to as reporting entities.

Regulation 16.18 of the MSIR (GWA 1995, pp 342–343) states: *'The manager of a mine must ensure that an employee … does not receive a dose of radiation exceeding …*

- Effective Dose (ED) in a single year 50 millisieverts (mSv)
- ED over a period of 5 consecutive years 100 millisieverts' (mSv)

In order to ensure compliance with the 100 mSv in 5 year limit, a derived annual limit of 20 mSv is applied. Maintaining worker annual doses below the derived limit is the primary method deployed by reporting entities to demonstrate compliance with the MSIR.

The MSIR requires employees to be classified as either 'designated' (DE) or 'non-designated'. A DE is '*an employee who works, or may work, under conditions such that the employee's annual effective [sic] dose equivalent might exceed 5 millisieverts …'* (GWA 1995,

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[3] WA has abundant uranium deposits (GWA 2013) but has no operating mines.

p 330). DEs '*are then monitored more intensively (including, where appropriate, personal monitoring), and their doses are assessed individually*' (ARPANSA 2005, p 28).

1.2. Sources of exposure to NORs in the WA MSI

As shown by the activity concentrations listed in table 1, NORs are present to some degree in the suite of heavy mineral sands produced by the WA MSI.

As can be seen from the activity concentration data presented in table 1, all of the mineral sands products, with the exception of the ore as mined and rutile, exceed the 1 Bqg^{-1} criteria and are therefore deemed as radioactive. It is also evident that two minerals, monazite and xenotime present the highest source of radiation hazard in the MSI due to their elevated NOR content.

According to ARPANSA (2014); Hewson (1990); IAEA (2006); Koperski (1993) the radiation hazard in the production of mineral sands arises from:

(a) External irradiation from exposure to gamma radiation (γ); and
(b) Internal exposure arising from the inhalation of dust which contains long-lived alpha (LLα) emitting isotopes; radon (^{222}Rn) and its progeny (RnP); and thoron (^{220}Rn) and its progeny (TnP).

The significance of the potential exposures to workers in the MSI were highlighted by Hewson (1990) who reported that in 1987 the maximum potential dose to a worker was approximately 165 mSv, in excess of three times the annual effective dose limit. Inhalation of LLα contributed $\sim$90% of the dose; γ contributed $\sim$10% whilst the contribution from TnP and RnP was negligible.

Sales of monazite from the WA MSI ceased in May 1994 (Hewson and Upton 1996). However, the monazite and xenotime are still present in the ore, and accompany the other minerals, through the various processing circuits, thereby making the risk of exposure to NORs omnipresent in the processing operations.

1.3. Reporting of worker doses

According to Hewson (1989) the requirement for reporting entities to submit annual reports of worker radiation doses was implemented in 1984. However the WA Department of Mines and Energy reflects that '*until the recommendations of the (International Commission for Radiological Protection) ICRP in publications 26 and 30 were adopted into WA mine safety legislation in 1986, sample numbers were low, and quality assurance programs were not in place*' (DME 1993, p 2).

Increased regulatory scrutiny from 1986 onwards led to a standardised reporting format, and the development of an electronic database, the Mines Dose Assessment System (MIDAS), which was used by all reporting entities for the recording of monitoring data and the calculation of worker doses (Hewson 1989, Marshman and Hewson 1994). Analyses of the estimates of the radiation doses received by the workers employed by reporting entities were reported in several peer-reviewed journal articles, for example DME (1992, 1993), Hewson (1990). The last peer-reviewed publication was authored by Marshman and Hewson (1994), at which time all seven reporting entities were operating in the MSI.

In the quarter-of-a-century since the Marshman and Hewson (1994) assessment, the WA mining industry has expanded significantly, in both the commodities being mined, and size of

Table 1. Typical ^{232}Th and ^{238}u concentrations by mass and activity in mineral sands products (after Koperski (1993, p 47)).

	Typical ^{232}Th Content[a]		Typical ^{238}U Content[a,b]		
Mineral	Weight (ppm)	Activity Concentration (Bqg^{-1})	Weight (ppm)	Activity Concentration (Bqg^{-1})	Typical Maximum Activity Concentration (Bqg^{-1}) [c]
Ore as Mined	5–15	0.02–0.06	∼3	∼0.04	0.1
Concentrate	80–110	0.3–0.4	<10	<0.1	0.5
Rutile	>50–350	<0.2–1.4	<10–20	<0.1–0.2	1.6
Leucoxene	80–700	0.3–2.8	20–50	0.2–0.5	3.3
Ilmenite	50–500	0.2–2.0	<10–30	<0.1–0.4	2.4
Zircon	150–250	0.6–1.0	150–300	1.8–3.7	4.7
Xenotime	15 000	60	4000	50	110
Monazite	50 000–70 000	200–280	1000–3000	12–37	320

[a] Head of chain only. Progeny are not included in the cited values. Secular equilibrium is assumed.

[b] The contribution by U-235 is negligible, and has been omitted from the table.

[c] Calculated by adding the maximum activity concentrations for ^{232}Th content and ^{238}U content.

workforce. WA has significant reserves of ‘battery minerals’ including lithium, cobalt, graphite, manganese and vanadium (Ralph *et al* 2020, p 4), rare earths (Lynas Corporation Ltd 2020) and has recommenced the production of the radioactive mineral monazite for the first time since the mid-1990s (Iluka Resources Limited 2020a).

As a result of the expansion, the number of reporting entities has increased to 14, all of which submitted annual reports of worker dose estimates for the 2018–19 reporting year.

The aim of this paper is to summarise the radiation dose profile of the 14 reporting entities for the 2018–19 reporting period, and provide a comparison, where possible, to the 1992–93 information reported by Marshman and Hewson (1994). As new mining projects are commissioned, the number of reporting entities is forecast to increase, and as such, this research will constitute a baseline against which to benchmark doses to the WA mining workforces in the future.

2. Methodology

2.1. Collection and analysis of worker exposure data

The increased regulatory scrutiny noted by Hewson (1989, 1990) was accompanied through 1986 and 1987 by the publication of a series of State mining engineer-endorsed Guidelines that provided the basis for consistent monitoring and dose estimates methodologies by the reporting entities. The Guidelines that were applicable in 1992–93, cited by Hewson (1990, p 6) have been revised, and added to in the intervening period, and are now colloquially referenced as the ‘NORM Guidelines’ (DMIRS 2020).

2.1.1. External dose. NORM Guideline 3.2 promotes, where possible the use of individual monitors for exposure to γ radiation, but also allows for assessments to be conducted based on time and motion studies, if appropriate (GWA 2010c, pp 6–7).

Hewson (1990, pp 5–6) reports that ‘measurement of external radiation … is accomplished using a thermo-luminescent dosimeter (TLD) service provided by the Australian Radiation Laboratory … [to] provide a direct estimate of the dose equivalent due to gamma radiation’.

In 2018–19, reporting entities have a choice of TLD service providers that also offer the use of optically stimulated luminescence (OSL) devices. However, the premise of obtaining the exposure data remains unchanged from that in 1992–93, in that the TLD (OSL) is worn at the worker’s waist level during working hours for a period of between one and three months, at the end of which it is returned to the service provider for analysis.

2.1.2. Internal dose from LLα in dusts. The current version of the Guidelines and those cited by Hewson (1990, p 6) outline the methodologies for the collection of representative samples and the calculation of internal doses from LLα in dusts. Sampling devices, that perform in accordance with International Standards Organisation inhalability criteria, are worn in the workers breathing zone for a minimum of a four-hour sampling period. After a suitable time period (nominally 6 to 7 days) to allow for the decay of TnP and RnP, the collected dust samples are subject to gross alpha analysis (GWA 2010a).

Secular equilibrium of NORs in the low-solubility inhaled dusts is assumed, based upon research summarised by Hartley and Hewson (1993). Internal dose estimates were calculated using the gross alpha analysis results in conjunction with the characteristics of the dust and a worker breathing rate of $20\ \mathrm{l\ min^{-1}}$, equivalent to $1.2\ \mathrm{m^3\ h^{-1}}$.

Unless otherwise approved by the State mining engineer, a default activity median aerodynamic diameter (AMAD) value of five microns was used as the basis of the calculation of internal dose estimate. Most reporting entities used the default value however approval was granted by the State mining engineer to use an AMAD of ten microns by two reporting entities that had embarked upon an extensive particle sizing campaign at their mining operations.

On the basis of location within a processing plant, job type and exposure characteristics, eight similar exposure groups (SEGs) were defined for application across the MSI (Hewson 1990, p 7). Workers are assigned to one (or more) of the SEGs, dependent upon their work activities, and their working periods in each SEG were recorded for dose calculation purposes. The maximum and arithmetic mean internal dose were calculated for each SEG.

Although estimates of internal doses arising from LLα are made in accordance with internationally accepted procedures such as ICRP (1980, 1990, 1994b), they are however, subject to 'a considerable degree of uncertainty' (Marshman and Hewson 1994, p 61).

2.1.3. Committed effective dose (CED). Individual annual worker CEDs are calculated by adding their personal external radiation dose to the mean internal dose for the SEG in which they had been allocated. If the worker had spent time in more than one SEG, their internal dose was calculated by proportioning the mean for each SEG by the time they spent working in each SEG.

2.2. Dose estimates reported for the MSI in 1992–93

Subsequent to the Hewson (1990) analysis, the mining regulatory authority commenced summarising the MSI reports on an annual basis, and made the initial documents publicly available (DME 1992, 1993). However, despite DME (1993) being allocated an ISBN number (0730959252) an extensive search for this and its predecessor DME (1992) by the State Library of WA, the only copies that could be located were those held by one of the authors (MR), which have been used as a template for presentation of the results in this research.

The published summaries de-identified the data and allocated a code to each of the reporting entities, with a view to making the information transparent, allowing the opportunity to benchmark their performance against their industry peers.

The information in DME (1992, 1993) cited data for seven mining operations. As an operation began production its name was de-identified, and a capital letter was used as a replacement identifier. However, in subsequent years, the alpha-coding system was changed to a numeric system (Fetwadjieff 2005, 2006). A search of DMIRS records located the keys to the two allocation processes, enabling the original seven mining operations used in DME (1992, 1993) to be aligned with that used in subsequent reporting periods.

Estimates of internal doses from the inhalation of dusts containing LLα were made 'using standard ICRP-30 assessment protocols' (Hewson 1990, p 6). Despite a cautionary note to the contrary by Mason, Cooper, Solomon and Wilks (Mason 1985, p 610), research by, Hartley and Toussaint (1986), Kerrigan (1988) and Ralph (1988) indicated that the contribution to worker annual dose arising from TnP and RnP was less than 1 mSv, and as a result no sampling was conducted, and their contributions were excluded from dose calculations.

At the time when DME (1992, 1993) were published, the annual limit for CED was 50 mSv, and priority was allocated to assessing doses to those workers receiving above 5 mSv (DEs). However, as a result, detailed analysis of worker doses below 5 mSv did not occur.

2.3. Dose estimates for mine workers in the period between 1992–93 and 2018–19

In 1995, the MSIR (GWA 1995) was proclaimed, bringing the dose limits outlined in section 1 into effect. It is evident from the data from 1986 to 1993, as reported by Marshman and Hewson

(1994), which drew upon DME (1992, 1993), that there is potential for elevated radiation doses in excess of the annual derived limit of 20 mSv in the MSI.

The practice of publication in peer-reviewed journals discontinued after 1994, and the opportunity for operations to benchmark their performance also ceased, until Fetwadjieff (2005) wrote to individual mining operations comparing their dose distribution against other de-identified operations. This practice was repeated the following year (Fetwadjieff 2006), but ceased thereafter. Although some correspondence is in evidence in between the State mining engineer and related stakeholders in government up to 2009, this correspondence was not subject to peer review, nor was it meant for public circulation. Based upon an unpublished report by Tsurikov (2009), the IAEA (2011) compiled a synopsis of the mean doses received by workers in Australian dry [mineral] separation plants (table 29) and airborne dust activity concentrations (table 113) up to 2007–08, but did not conduct a detailed assessment of the data. ARPANSA (2014) included a brief description of the radiation dose profile of the Australian MSI workforce, but did not conduct an in-depth analysis. As a result, Marshman and Hewson (1994) is the most recent peer-reviewed analysis of doses to the WA mining workforce until this research.

2.4. Dose estimates reported for mine workers in 2018–19

In the early 2000s, the MSI underwent a period of consolidation, with two of the mineral sands mining operations (#1 and #2) that reported in 1993 closing. Over the past decade the WA mining industry expanded significantly, and as a result the workforce has quadrupled since the time that the DME (1993) report was published (DMIRS 2019). The expansion has also witnessed diversification in the type of commodity being mined and processed and introduced a number of new mining operations with potential exposure to NORM.

The expansion has resulted in 14 reporting entities in WA currently being required to comply with the MSIR, and submit an annual report of worker radiation exposures to the State mining engineer. The commodities treated at the 14 reporting operations include mineral sands (seven); rare earths (two); lithium/tantalum (three); and downstream processing of mineral products (two). An additional 12 operations (#10, #12, #13, #14, #17, #18, #19, #21, #24, #25, #26 and #27) had commenced operating after the 1993 report, but had either ceased operating, or not required to report in 2018–19 because exemptions had been granted.

The reports were submitted by the reporting entities to the State mining engineer. Data from the 14 annual reports for the 2018–19 reporting period were de-identified and forwarded to the corresponding author (MR), who assessed each report and entered the relevant data into a Microsoft Excel (2016) spreadsheet for the purposes of consolidation and analysis.

Two of the 14 operations (#11 and #14) had provided a report in support of an application for exemption from the MSIR, and had conducted minimal monitoring. Four operations (#20, #22, #23 and #28) were reporting for the first time, and had not conducted the requisite sampling to estimate individual doses, and relied instead on time and motion studies to determine potential (i.e. not actual) doses to groups of workers.

The eight reporting entities that conducted a fulsome assessment of worker dose estimates in 2018–19 did so in accordance with the NORM Guidelines,[4] which reference the ICRP Publication 30 series and Publications 54, 68 and 78 (ICRP 1980, 1988, 1994a, 1997) enabling a direct comparison with the dose estimates reported in DME (1993).

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[4] The dose estimates reported in 2018–19 pre-date the publication of ICRP-141 (ICRP 2019a) and therefore do not reflect the most recent dose coefficients for inhalation of dust containing NORs. Guideline NORM-5 (GWA 2010b) is currently being updated to reflect the revised dose coefficients.

Table 2. Summary of dose estimates from 1986 to 1993 (Marshman and Hewson 1994).

	Committed Effective Dose (mSv)		
Parameter	Maximum	Mean[a]	Comments
External Dose	10.4[b]	2.1	Maximum is ~20% of annual dose limit.
Internal Dose	98[b]	12.3	Maximum is ~twice the annual dose limit

[a] The mean is measured over the eight years from 1986 to 1993.
[b] Reported in 1988.

Three factors were significantly different between the 2018–19 reports and those analysed in DME (1993):

(a) Comparisons are made against the prevailing annual derived limit of 20 mSv.
(b) Forecast changes to the dose coefficients for inhalation of TnP and RnP published in ICRP (2017) stimulated seven reporting entities to investigate the potential contribution from these sources to total worker CED, via time and motion studies.
(c) Production of monazite ceased in May 1994 (Hewson and Upton 1996), and worker doses have steadily declined across the MSI, to the point where the number of DEs has reduced effectively to zero. As a result, a greater emphasis on defining those workers who receive annual doses between 1 mSv and 5 mSv has evolved over the past decade.

3. Results

The most recent peer-reviewed analysis of doses to the MSI workforce was published by Marshman and Hewson (1994), who assessed the annual reports for 1986–93. A summary of their analysis is provided as background to the 1992–93 and 2018–19 analysis in table 2.

A decreasing trend in dose estimates is evident from 1986/87 to 1993 (Marshman and Hewson 1994, p 61). The trend reflects the effectiveness of an industry expenditure to minimise worker doses as a result of '… upwards of $30 million over three years (1987–1989) into engineering works and research programs' (Hewson 1990, p 10).

A summary of the size and radiation dose profile of the workforce employed at the seven mining operations cited in (DME 1993) is provided in table 3, and data from the 14 reports submitted in the 2018–19 reporting period is presented in a similar format in table 4.

The data reported in table 3 for the 1992–93 reporting period (DME 1993) indicated that the mean external dose was 1.5 mSv (maximum 4.9 mSv) and a mean internal dose of 6.3 mSv (maximum of 15.6 mSv). The sum of the doses from external and internal sources suggests a mean CED of 7.8 mSv and a maximum CED of 20.5 mSv.[5]

The data reported in table 4 for the 2018–19 reporting period indicated that the maximum external dose was 1.5 mSv, the maximum internal dose from LLα was 3.2 mSv and the maximum internal dose from TnP and RnP was 1.3 mSv. The maximum reported CED of 4.4 mSv was reported by Site #7.

Table 5 summarises the 2018–19 data that can be directly compared to the data from DME (1993). A rudimentary error analysis was included in two annual reports received in

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[5] The actual maximum dose to an individual worker is not reported in DME (1993). The value cited here is calculated by adding the maximum external and maximum internal doses across the seven operations.

Table 3. Workforce size and committed effective doses from annual radiation reports, 1 April 1992 to 31 March 1993 (DME 1993).

	Site Reference. Former alphabetical references are in parentheses (DME 1992, 1993)						
Parameter	1 (A)[a]	2 (B)[b]	3 (C)	4 (D)	5 (E)	6 (F)	7 (G)
Workforce	177	222	270	226	355	47	199
Designated Employees (DEs)	24	62	67	35	24	0	0
# of Personal Dust Samples	132	344	384	396	479	83	214
Workers in Dose Range (mSv):							
0.0 to <1							
1.0 to <2.0	176	178	222	190	331	43	199
2.1 to <5.0							
5.1–15	1	43	47	33	24	4	0
>15	0	1	1	3	0	0	0
Designated Employee Analysis:							
Maximum External Dose (mSv)	3.4	3.7	3.1	0.8	4.9	—[c]	—[c]
Mean External Dose (mSv)	1.5	1.3	2.1	0.25	2.2	—	—
Maximum Internal Dose (mSv)	2.6	14.5	13.4	15.6	9.9	—	—
Mean Internal Dose (mSv)	1.4	9.5	6.4	8.6	5.7	—	—
Collective Dose (man.mSv)	40	450	550	310	190	—	—

[a] Site 1 ceased operations in 1999 (Iluka Resources Limited 2020b).

[b] Site 2 was placed in care and maintenance in 2013

[c] Sites 6 and 7 do not have DEs, and therefore data were not provided for this Section of the Table.

Table 4. Workforce size and committed effective doses from annual radiation reports, 1 April 2018 to 31 March 2019.

	Site Reference—updated from DMIRS Records						
Parameter	3	4	5	6	7	8	9
Workforce	119	34	14	45	22	30	28
Designated Employees (DEs)	93	0	0	14	20	0	13
# of Personal Dust Samples	117	57	16	44	15	110	95
Workers in Dose Range (mSv):							
$\leq$1.0	31	5	14	14	5	28	Unknown
1.1 to <2.0	63	22	14	0	5	1	
2.1 to <5.0	8	7	0	0	10	1	
5.1–15	0	0	0	0	0	0	
>15	0	0	0	0	0	0	
All Workforce Analysis:							
Maximum External Dose (mSv)	1.44	1.49	0.41	0.40	1.54	0.80	1.13
Mean External Dose (mSv)	0.57	0.70	0.27	0.10	0.82	0.20	0.78
Maximum Internal Dose (mSv)	1.74[a]	0.69	0.61	0.60	3.66[a]	2.06[a]	0.88[a]
Mean Internal Dose (mSv)	0.72[a]	0.53	0.22	0.40	2.50[a]	1.04[a]	0.59[a]
Collective Dose (man.mSv)	149	50.0	6.9	22.5	53.9	15.0	7.6

(Continued)

Table 4. (Continued).

	Site Reference—updated from DMIRS Records						
Parameter	3	4	5	6	7	8	9
Workforce	Unknown	83	340	79	260	120	300
Designated Employees (DEs)		0	0	60	27	15	6
# of Personal Dust Samples	32	70	14	14	75	8	71
Workers in Dose Range (mSv):							
≤1.0	Unknown	Unknown	Unknown	79	Unknown	Unknown	Unknown
1.1 to <2.0				0			
2.1 to <5.0				0			
5.1–15				0			
>15				0			
Designated Employee Analysis:							
Maximum External Dose (mSv)	1.34	1.15	0.11[b]	0.25[b]	0.25[b]	Unknown	Unknown
Mean External Dose (mSv)	1.00	0.35	Unknown	0.03[b]	0.25[b]	0.04[b]	0.0[b]
Maximum Internal Dose (mSv)	0.52	1.35[a]	0.53[a]	0.42	0.27[a,b]	Unknown	Unknown-
Mean Internal Dose (mSv)	0.52	0.18[a]	0.51[a]	0.06	0.27[a,b]	0.07	0.16[b]
Collective Dose (man.mSv)	Unknown	68.1	153	7.9	130	60.0	60

[a] Includes contribution from radon, thoron and their progeny. Static sampling was conducted, and time and motion studies utilised to determine the contribution to internal dose. Revised Dose Coefficients as published in ICRP-137 (ICRP 2019b) were used to calculate doses.

[b] Personal monitoring not conducted. The cited result is estimated from time and motion studies.

Table 5. Direct comparison of 2018–19 data to 1992–93 reporting period (DME 1993).

Parameters	1992–93 data	2018–19 data	Difference (%)
Number of Operations	7	14	+7 (+100%)
Workforce	1496	1474[a]	−22 (−1.5%)
Designated Employees (DEs)[b]	212	248[c]	+36 (+17.0%)
DEs as % of Workforce	14.2	16.8[c]	+2.6%
Workers Exceeding CED 5 mSv	157	0	−157 (−100%)
Mean CED DEs (mSv)	7.3	0	[d]
Maximum External Dose (mSv)	4.9	1.5	−3.4 (−69%)
Personal Dust Samples	2032	738	−1294 (−64%)
Personal Dust Samples per Operation	290	50	−240 (−83%)
Personal Dust Samples per Worker	1.4	0.5	−0.9 (−64%)
Maximum Internal Dose from LLα (mSv)	15.6	3.2	−12.4 (−79%)
Maximum Internal Dose: TnP & RnP (mSv)	[d]	1.3	[d]
Maximum CED (mSv)[e]	18.2	4.4	−13.8 (−76%)
Collective CED to DEs (man.mSv)	1540	0	(−100%)

[a] Best estimate. Several reports did not provide exact workforce numbers, and an approximation has been made, based upon information provided in previous reporting periods.

[b] The definition of a DE is any worker who could receive a dose estimate >5 mSv.

[c] Best estimate. Several sites reported any worker who was involved in the monitoring programme as a DE. Those sites highlighted in table 4 as not conducting personal monitoring nominated zero DEs, as insufficient data had been collected to determine doses at the individual level.

[d] Data for one of the variables was not reported.

[e] From a single site, calculated by adding the maximum external dose and maximum internal dose.

Table 6. Comparison of 2018–19 dose distribution data to 1992–93 (DME 1993).

	Workers in Dose Range	
Dose Range (mSv)	1992–93 data	2018–19 data
≤1.0		176
1.1 to <2.0	1339	91
2.1 to <5.0		26
5.1–15	152	0
>15	5	0

[a] Distribution analysis changed between reporting periods. Refer to discussion 4.2.

the 2018–19 reporting period, however the remaining reporting entities did not attempt to analyse the errors associated with the dose estimates for their workforce. Subsequently, an error analysis cannot be included in this review, and the data is cited as presented *quod est* in the submitted reports.

Table 7. Comparison of inferred 1992–93 (DME 1993) and 2018–19 data.

Parameters	1992–93 data	2018–19 data	Difference (%)
Mean External Dose (mSv)	1.9[a]	0.53[b]	−1.37 (−72%)
Mean Internal Dose from LLα (mSv)	4.7[c]	0.53[b]	−4.17 (−88%)
Mean Internal Dose from Rn and RnP (mSv)	Not reported	0.34[d]	[e]
Mean CED (mSv)	1.89[f]	0.97[b]	−0.92 (−49%)
Collective CED (man.mSv)	2824[f]	784[g]	−2040 (−72%)

[a] Assuming all non-DEs received 0.5 mSv from external radiation.
[b] Excluding the five operations that did not conduct personal monitoring.
[c] Assuming all non-DEs received 0.5 mSv from exposure to LLα.
[d] Seven operations conducted monitoring.
[e] A comparison could not be made.
[f] Assuming non-DEs receive 1 mSv CED, and as per table 5 the 212 DEs received a combined 1540 mSv.
[g] Includes contribution from all 14 sites.

Table 8. Contribution to CED from exposure pathway.

	Mean CED from source (mSv) and (%)			
Site	External	Internal LLα	Internal TnP, RnP	Sum of Mean CED (mSv)
#1	0.57 (44%)	0.42 (33%)	0.30 (23%)	1.29
#7	0.82 (25%)	2.05 (62%)	0.45 (14%)	3.32
#8	0.20 (16%)	0.30 (24%)	0.74 (60%)	1.24
#9	0.78 (57%)	0.34 (25%)	0.24 (18%)	1.36
#15	0.35 (66%)	0.01 (2%)	0.17 (32%)	0.53
#16	0.11[a] (18%)	0.03[a] (5%)	0.48 (77%)	0.62
#22	0.25 (48%)	0.25 (48%)	0.016 (3%)	0.516
Range	16% to 57%	5% to 62%	3% to 77%	—
Mean	39.2%	28.4%	32.4%	—

[a] Estimate from time and motion studies.

The dose distributions cited in the two reports are presented in table 6.

In order to be able to draw comparisons between the two reporting periods for several parameters, inferences have been made from the reported data. Those parameters, and the inferences made to enable a comparison are summarised in table 7.

As outlined in section 2.4, seven sites investigated the contribution of exposure to TnP and RnP to total CED. An analysis of the relative contribution to worker doses by the reporting entities that conducted monitoring of the TnP and RnP exposure pathway, is provided in table 8. As can be seen from table 8, the relative contribution from each exposure pathway can vary significantly between operations.

As can be seen from the data presented in table 5, several parameters could not be compared between the two reporting periods:

- In the 2018–19 reports, no workers received CED greater than 5 mSv, and therefore a comparison of mean and collective doses to DEs could not be made; and
- Doses to workers arising from exposure to radon, thoron and their progeny were not evaluated in DME (1993), but as a result of the increase in DCs published in January 2018 in

ICRP-137 (ICRP 2017), monitoring commenced and the contribution to dose was evaluated at seven operations.

A significant finding of this analysis is that despite no workers exceeding a CED of 5 mSv in the 2018–19 reporting period, 248 workers were categorised as DEs. A definitional change in which workers should be categorised as a DE has occurred in the period from since 1992–93. The change is discussed in section 4.2 of this analysis.

4. Discussion

This paper aims to address the absence of peer reviewed information of radiation doses to WA mine workers in the period since the analysis of doses to MSI workers by Marshman and Hewson (1994).

As can be seen in tables 3–5, and summarised in table 6, the number of operations falling within the remit of the MSIR, and required to submit annual reports has increased from seven operations in DME (1993) to 14 in 2018–19. Two operations (#1 and #2) that submitted annual reports in 1993 were not operating in 2018–19 and 12 operations (#10, #12, #13, #14, #17, #18, #19, #21, #24, #25, #26 and #27) had commenced operating after DME (1993), but had either ceased operations, or not required to report in 2018–19.

Two of the 14 operations (#11 and #14) had applied for exemption from the MSIR, and had conducted minimal monitoring. Four operations (#20, #22, #23 and #28) were reporting for the first time, and had not conducted the requisite sampling to estimate individual doses, and relied instead on time and motion studies to determine potential (i.e. not actual) doses to SEGs.

4.1. Main findings of this study

As can be seen in table 3, 1496 workers were employed in the seven MSI operations in 1992–93. The commodities treated at the 14 reporting operations include mineral sands (seven); rare earths (two); lithium/tantalum (three); and downstream processing of mineral products (two). Despite the increase in the number of operations, the contemporary workforce has declined from the DME (1993) levels to 1474 in 2018–19, a decrease of 1.5%. However, as can be seen in table 4, Operation #11 failed to include worker demographics in the annual report, and therefore the size of the 2018–19 workforce is understated. It is reasonable to conclude that the size of the workforce in 2018–19 is comparable to that in 1992–93.

As summarised in table 6, 212 workers (14.2%) were considered as DEs in 1992–93, 157 of whom exceeded a CED of 5 mSv. In 2018–19, the maximum CED reported was 4.4 mSv, and as a result, the actual number of DEs should be zero. However the reports indicate that 248 workers were considered as DEs, representing an increase in the percentage of the workforce considered as DEs from 14.2% in DME (1993) to 16.8% in 2018–19.

In 2018–19, operations #9, #11, #15, #16, #22, #23 and #28 failed to provide a detailed breakdown of worker dose distribution, hence the entries of ‘Unknown’ in the dose distributions given in table 4 for these operations. Due to the implementation of the derived annual limit, increased attention has been placed upon doses less than 5 mSv in the 2018–19 analysis, hence the stratification apparent in tables 4 and 6. A comparison of the distribution of doses between the two reporting periods is provided in table 6, but the analysis is incomplete because analysis of worker doses below 5 mSv did not occur in DME (1993). However, as shown in table 6, 1339 (89.5%) workers were reported to have received an annual CED of between 0 mSv and 5 mSv DME (DME 1993, p 10), whereas all workers received CED's of less than 5 mSv in 2018–19.

An important difference in the approach to estimating doses is apparent in the two reporting periods: in DME (1993), estimates of CED are provided for all 1496 workers, whilst in 2018–19 estimates of CED are made for only 293 workers (∼20% of the workforce), and no data is presented for the remaining 1181 workers. The reasons for the lack of data are not immediately evident from the information provided by the reporting entities, however it appears that there has been an emphasis on purposive sampling, focussing on those SEGs likely to have the highest exposures, at the expense of others.

As shown in table 5, several parameters can be directly compared between the DME (1993) analysis and this assessment:

- The maximum external dose decreased by 69%, from 4.9 mSv to 1.5 mSv.
- The maximum internal dose from inhalation of dusts containing LLα decreased by 79%, from 15.6 mSv to 3.2 mSv.
- A 65% decrease occurred in the number of dust samples collected across the industry, from 2032 to 706, and the number of samples per mining operation and per worker decreased by 83% and 64%, respectively.
- The maximum CED decreased by 76%, from 18 mSv to 4.4 mSv.
- The mean CED decreased by 49%, from 1.8 mSv to 0.97 mSv.

As can be seen from table 8, the relative contribution from each exposure pathway can vary significantly between operations. In the 2018–19 reports, the maximum dose from inhalation of radionuclides of TnP and RnP was 0.74 mSv, equivalent to the mean dose from inhalation of LLα in the five sites still in operation from 1992 to 1993. The contribution to worker dose arising from this pathway is of increasing significance, and cannot be discounted by the seven operations that did not conduct monitoring in the 2018–19 reporting period. Therefore, it is important that each mining operation monitors each exposure pathway and determine its contribution to CED.

The MSIR introduces the concept of collective effective dose which is defined as 'the total radiation exposure of a group of people calculated by reference to the sum of their individual effective doses' (GWA 1995, p 330). Regulation 16.15 of the MSIR requires 'the manager of a mine must ensure … the collective effective dose (sic) of radiation to employees generally is reduced to levels that are as low as practicable' (GWA 1995, p 339). A discussion on the use of collective dose is beyond the scope of this research, but it is noted that while it is a methodology applied since the 1970s, concerns have been raised over its use for risk assessment purposes (ICRP 2007). Nonetheless, a comparison of collective dose to the workforce between 1992–93 and 2018–19 provides a good overview of the success (or otherwise) of intervention methods implemented in order to reduce radiation doses to the mining industry workforce as a whole.

As summarised in table 5, the collective dose to DEs in DME (DME 1993, p 9) was 1540 man.mSv. In table 7 the collective dose to the workforce in the seven operations was extrapolated to be 2824 man.mSv, whereas in 2018–19 it had decreased to 784 man.mSv from the 13 operations that provided collective dose estimates (as per table 4, Operation #11 failed to include worker demographics in the annual report, and therefore a collective dose to the workforce could not be estimated). Notwithstanding the uncertainties associated with the 2018–19 reports submitted from those operations that conducted minimal personal sampling, the decrease of 2040 man.mSv across the quarter of a century is significant, especially as the two workforces are very similar in size.

A contribution to dose reduction in the MSI operations arose from the engineering control initiatives commenced in the late 1980s, such as such as local exhaust ventilation to restrict the generation of airborne dust; plant redesign to reduce operator exposure periods; and automation of routine operations such as bagging of materials. The engineering controls were supplemented by revised work practises that reduced worker exposure, such as cessation of the ‘beating’ of air tables which liberated large amounts of dust; and the mandated use of respiratory protection for selected tasks (Hartley and Hewson 1990). It is prudent to contend that the lessons learned in exposure controls in the 1990s apply to the contemporary mining industry.

The cessation of production of monazite in May 1994 (Hewson and Upton 1996, p 66), reduced the potential activity concentration of airborne dust in the reporting entities in the MSI (sites #3, #4, #5, #6 and #7 in table 4). The decrease in internal dose reported in 2018–19 is largely as a result of the closure of the two older MSI operations (sites #1 and #2) that did not report in 2018–19, and the introduction of the nine other reporting entities listed in table 4 that treat ores and produce mineral concentrates with activity concentrations less than 10 Bqg^{-1}. Typically the newer reporting entities have airborne dust concentrations much less than those that were encountered in the MSI in the 1990s as witnessed by the mean internal dose reported by the five sites that were operating in 1992–93 and that were still operating in 2018–19, being 0.72 mSv, 36% higher than the mean dose across all 14 operations that reported in 2018–19.

The decrease in the number of personal dust samples per worker increases the uncertainty associated with the reported internal dose estimates, and indicates that an over-reliance of sampling of SEGs, and not assessing individual worker doses is prevalent across the reporting entities.

Only 234 workers were employed in the MSI in 2018–19, with the vast majority (1240, or 84%) of mine workers employed by reporting entities that were processing the lower activity concentration ores and minerals. This is, in all likelihood, the major contributing factor to the overall reduction of CED’s in the WA mining sector.

4.2. Limitations of this study

Marshman and Hewson (1994) drew upon the reports published by the Department of Minerals and Energy (DME 1992, 1993) and the authors counselled ‘the estimates are made using conservative assumptions, to limit the likelihood of understating dose. Accordingly, such estimates should be interpreted and used with caution’ (DME 1993, p 2, Marshman and Hewson 1994, p 61). The same principles were applied in the estimation of doses in the annual radiation reports submitted to the State mining engineer for the 2018–19 reporting period, and therefore similar caution should be exercised, especially the estimates of internal doses from dust containing LLα and from exposure to TnP and RnP.

Although internal dose estimates are made in accordance with internationally accepted procedures such as ICRP (1980, 1990, 1994b), nonetheless, they are based upon an assumption that respiratory protection is not worn, and generalised assumptions about the physical properties of the inhaled dust and the behaviour of radionuclides in the body after inhalation, and therefore, as stated by Marshman and Hewson (1994, p 61) are subject to ‘a considerable degree of uncertainty’.

A difficulty occurs when endeavouring to compare the contemporary data to that published in 1992–93. At the time when DME (1992, 1993) and Marshman and Hewson (1994) were published, the annual limit for CED was 50 mSv, and therefore assessing doses above 5 mSv, representing 10% of the annual limit was understandably, *a priori*. As highlighted in table 6, the focus on assessing doses greater than 5 mSv obviated a detailed assessment of doses less than 5 mSv. However, in the 2018–19 analysis, a greater emphasis has been placed on evaluation of doses less than 5 mSv, and has resulted in the doses being collated in categories of 1 mSv increments.

Although they contemplated the impending reduction of the annual dose limit to 20 mSv, Marshman and Hewson (1994, p 65) could not be aware of its significance a quarter of a century later. The maximum CED reported in 2018–19 of 4.4 mSv, as reported in table 5, is 22% of the derived annual limit of 20 mSv and warrants detailed evaluation, whereas in 1993 it represented 8.8% of the annual limit and would have attracted minimal attention.

Paradoxically, when the annual dose limit was reduced, the criteria for designating employees remained fixed at an annual CED of 5 mSv (ARPANSA 2005, p 28, GWA 1995, p 330), thereby increasing from 10% of the former limit to 25% of the revised derived annual limit. This has led to an inconsistency in the interpretation of which workers should be categorised as DEs across the operations required to comply with the MSIR in 2018–19.

As can be seen in table 4, in 2018–19 some operations reported that they have no DEs, whilst operations #3, #7 and #20 reported that in excess of three-quarters of their workforce are DEs. Several of the 2018–19 annual reports provide clues as to why the inconsistency has occurred—some sites have opted to include any worker who participated in the monitoring programme as a DE, instead of those workers with the potential to exceed 5 mSv. This inconsistency of interpretation needs to be addressed to ensure reports in future years can be assessed effectively.

4.3. Potential impact of revised dose coefficients for NORs

Models of the deposition of inhaled radioactive materials in the respiratory system, and the radiation detriment caused by the inhaled radionuclides, based upon the findings of specialist groups such as the ICRP are used to estimate doses to exposed workers. The protocols for estimating the internal doses received from the inhalation of dusts containing LLα have undergone several revisions in the quarter of a century between the two reports.

By way of example, in DME (1993), dose coefficients (DCs) used to calculate internal doses from the intake of inhaled dusts containing LLα to CED, measured in mSv, were based upon ‘standard ICRP-30 assessment protocols’ (Hewson 1990, p 6). In 2015 ICRP commenced development of series of five volumes of the Occupational Intake of Radionuclides (OIR) to replace the Publication 30 series and Publications 54, 68 and 78 (ARPANSA 2018). The ICRP published Volume 3 (ICRP-137) of the OIR in 2017 and Volume 4 (ICRP-141) in December 2019 (ICRP 2017, 2019a).

The revised DCs published in ICRP-137 and ICRP-141 will have a significant effect upon the assessment of doses to mine workers, with a preliminary estimate suggesting that the mean CED per unit intake of alpha activity arising from inhalation of insoluble NORs-containing dusts may increase by a factor between 1.9 and 2.9 times (Ralph *et al* 2020).

The internal doses from the inhalation of dusts containing LLα reported in 2018–19 predate, and therefore do not reflect the increases in DCs published in ICRP-137 and ICRP-141. Using typical physical and chemical properties of dusts encountered in the MSI, Ralph *et al* (2020) estimated that CEDs will increase by a factor of between 0.74 and 1.26 times those reported in 2018–19, for the same exposure.

As shown in table 5, the maximum CED estimated from DME (1993) was 18.2 mSv, representing 36% of the applicable dose limit of 50 mSv. According to the preliminary investigations by Ralph *et al* (2020) the maximum CED reported in 2018–19 of 4.4 mSv will increase to 7.9 mSv as a result of application of the revised DCs published in ICRP-137 and ICRP-141.

The revised CED of 7.9 mSv is 40% of the derived annual limit, and is equivalent in significance to the maximum estimated CED from the 1992–93 reporting period.

It is prudent to state that the reported maximum internal dose from LLα decreased by 79% from 15.6 mSv in DME (1993) to 3.2 mSv in 2018–19 whilst the mean dose decreased by 88% from 4.7 mSv to 0.53 mSv. Notwithstanding the potential for increases in the future as a result of the revised dose calculation protocols, the decrease in internal doses arising from inhalation of dusts containing LLα is a significant finding of this research.

In 1992–93 the contribution to worker dose arising from inhalation of for TnP and RnP was not considered when calculating CEDs. Applying the DCs from ICRP-30, the concentrations of TnP and RnP that were measured by Ralph (1988) translated into a mean CED of 0.23 mSv, and a measured maximum of 0.39 mSv, and were considered as negligible contributors to CED. The data published in ICRP-137 included significantly increased DCs for TnP and RnP, and as a result seven of the reporting entities have deployed time and motion studies to investigate potential doses arising from this exposure pathway in 2018–19. Using the revised DCs the maximum CED from TnP and RnP was estimated as 1.3 mSv, and the mean was 0.34 mSv. The contribution to total CED from this pathway varied by reporting entity and ranged from 3% to 77% of total CED, with a mean contribution of 32%. These results indicate that, unlike the position adopted in DME (1993) the TnP and RnP exposure pathway is potentially significant, and should not be discounted from CED calculations.

4.4. This analysis in perspective

The final word on this research belongs to those who contributed to the Winn Enquiry '… we believe the aim to keep occupational doses below 20 mSv is achievable within a few years and we urge the industry to accept the challenge in the interests of the health and welfare of its employees' (Winn *et al* 1984, p 50).

The authors contend that notwithstanding the advances made over the past quarter of a century, the advent of the decreased derived annual limit, coupled with the emergence of new operations and revised dose coefficients as published in ICRP-137 and ICRP-141 presents a compelling case for robust evaluation of worker doses arising from exposure to NORM in the WA mining industry.

5. Conclusions

The maximum CED decreased by 76%, from 18 mSv (36% of the annual limit) in DME (1993) to 4.4 mSv (22% of the derived annual limit) in 2018–19. The mean CED decreased by 49%, from 1.8 mSv (22% of the derived annual limit) in DME (1993) to 0.97 mSv (5% of the derived annual limit) in 2018–19.

The maximum external dose received from exposure to γ radiation decreased by 69%, from 4.9 mSv in DME (1993) to 1.5 mSv in 2018–19. The maximum internal dose from inhalation of dusts containing LLα decreased by 79%, from 15.6 mSv to 3.2 mSv.

In 1992–93, the collective effective dose received by 1496 workers across seven mining operations was 2824 man.mSv, whereas in 2018–19 it had decreased by 2040 man.mSv to 784 man.mSv for 1474 workers in 13 operations.

As the WA mining industry became accustomed to lower CEDs, monitoring of potentially exposed workers decreased over time, as indicated by the number of personal dust samples collected across the industry, which declined from 2032 in DME (1993) to 706 in 2018–19, for similar-sized workforces. In some instances, this has resulted in insufficient data being collected in order to fully evaluate potential radiation doses to exposed members of the workforce.

As a result of revised DC's published in ICRP-137 and ICRP-141, the impacts upon the mean CED per unit intake of alpha activity arising from inhalation of insoluble NORs-containing dusts, and contribution to CED from inhalation of radon, thoron and their progeny requires further investigation across the WA mining industry. The revised DCs are likely to have an impact upon existing reporting entities, new projects, and those operations that are seeking, or have been granted exemption from, the MSIR.

Further, there is a possibility that the revised DCs may increase CEDs to the extent that the WA mining industry may witness the re-emergence of workers receiving in excess of 5 mSv per annum. As a result, it is important that a consistent definition of Designated Employee is applied across the industry.

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Declaration of interest

The corresponding author, Mr Ralph, is an employee of the Western Australian Department of Mines, Industry Regulation and Safety.

The corresponding author, Mr Ralph was the author of Ralph (1988) and provided assistance to Mason *et al* (1990).

Mr Chaplyn is the statutorily-appointed Western Australian State mining engineer, the regulatory authority for mining operations under the Mines Safety and Inspection Act 1994 and Regulations 1995. The annual reports on radiation doses to the mining industry workforce are submitted by reporting entities to Mr Chaplyn.

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