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Practical Matter Article

Impacts of revised dose coefficients for the inhalation of NORM-containing dusts encountered in the Western Australian Mining Industry

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Abstract

The aim of this paper is to evaluate the impact of recent revisions to the dose coefficients published in ICRP-137 and ICRP-141 for members of the ^{232}Th, ^{238}U and ^{235}U decay series on radiation doses received by Western Australian mine workers via the inhalation of insoluble dusts containing long-lived alpha particle emitting radionuclides.

Whilst some dose coefficients for individual members of the decay series have decreased, the nett effect is that the sum of all dose coefficients in all three decay series have increased as a result of the revisions. The increase is inversely related to Activity Median Aerodynamic Diameter.

Assuming the radionuclides in the inhaled dusts are in secular equilibrium, the dose conversion factors (the mean committed effective dose per unit intake of alpha activity) will increase by a factor between 1.9 and 2.9 times.

In 2019, 11 mining operations in Western Australia submitted an annual report of worker radiation exposures to the regulatory authority. The reports indicate that between 35% and 60% of the committed effective doses to workers arises from inhalation of insoluble radioactive dusts. Applying an AMAD of 5 μm and a ^{232}Th decay series to $^{238+235}$U decay series ratio of 10:1, committed effective doses to the workforce are greater by a factor of between 0.74 and 1.26 times from those reported in 2018–19 as a result of the revised DCs published in ICRP-137 and ICRP-141.

Guidance on how to calculate doses from the inhalation of radioactive dusts is provided in the regulatory authority's Guideline '*NORM-5: Dose Assessment*', which will need revision to incorporate the revised dose coefficients. The

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Guideline has been widely distributed outside of Western Australia, and those jurisdictions which have adopted all, or sections of it, into their legal framework for radiation protection may need to consider the impact of the revision.

Keywords: ICRP-137, ICRP-141, naturally occurring radioactive materials, dose coefficients, dose from inhaled dusts, mining industry

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

1. Introduction

The naturally occurring radioactive materials (NORM), thorium-232 (^{232}Th), uranum-238 (^{238}U) and uranium-235 (^{235}U) are members of a small group of primordial radionuclides with half-lives that are comparable to the age of the universe, and are present in concentrations that are not significantly less than when they were created [1, 2]. They are widely distributed in the environment and are present to some extent in all rocks and soils [2–7].

Western Australia (WA) is one of the world's leading contributors to the global commodity market, and according to United States Geological Survey data, ranked amongst the top five countries for the production of eight different major minerals and in the top 10 of a further three minerals [8]. The 2018–19 distribution of the WA mining workforce by commodity being mined is summarised in table 1 [8], from which it can be seen that approximately 103 000 workers were employed on a full-time equivalent basis in the reporting period.

According to Steinhausler [3] 'the mining and extraction industries have been associated with the highest individual occupational exposures to radionuclides'. The federal radiation regulator, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) states 'Although the concentrations of NORM in most natural substances is low, any operation in which material is extracted from the earth and processed can potentially concentrate NORM in product, by-product or waste (residue) streams … has potential to lead to exposures to both workers and members of the public …' [9].

The International Commission for Radiological Protection (ICRP) has identified a range of industries in which NORM may be encountered [10]. Similarly, ARPANSA has identified a range of metal ores and non-metal minerals that may have an association with NORM [9], as signified by the notation [1] in table 1. Estimates for 2018–19 suggest that as many as 17 500 workers, equivalent to 17% of the WA mining workforce, are employed in parts of the mining industry known, or suspected, to be associated with NORM.

Western Australia is endowed with significant uranium deposits, many of which are congruent with established diamond, gold, iron ore and nickel mining operations [11], identified by the notation [2] in table 1. Although there is currently insufficient data to establish the magnitude of individual worker exposures, up to a further 80 000 workers (77% of the workforce) may also be exposed to elevated levels of NORM, if uranium mineralisation is found to extend into the rocks and minerals associated with the established mining operations.

Western Australia has globally significant reserves of 'battery minerals' including lithium, cobalt, graphite, manganese and vanadium, some of which are associated with NORM. Planned expansion of mining and processing of battery minerals [12] has the potential to substantially increase the number of mine workers exposed to NORM.

Thorium-232, ^{238}U and ^{235}U are the parent radioisotopes of complex decay series comprising of different radionuclides, which present potential sources of radiation dose to exposed workers [3, 4, 9, 13]. Because ^{238}U and ^{235}U occur together in natural uranium, the two decay series are treated in combination, and hereinafter are identified as $^{238+235}$U.

Table 1. 2018–19 WA Mining Workforce by Commodity Mined [8].

Commodity Mined (or Activity)	Full Time Equivalent Workforce	Percentage of Workforce
Base metals [1]	2327	2.3
Bauxite/Alumina [1]	7348	7.1
Coal [1]	709	0.7
Construction Materials	716	0.7
Diamond [2]	860	0.8
Gold [2]	25 788	25.1
Iron ore [2]	45 808	44.5
Mineral sands [1]	2115	2.1
Nickel [2]	6449	6.3
Salt	598	0.6
Tin—Tantalum—Lithium [1]	5141	5.0
Other	2259	2.2
Exploration	2815	2.7
Full-time Equivalent Employees in the WA Mining Industry	102 932	

[1]Commodities identified by ARPANSA as having an association with naturally occurring radioactive materials (NORM).
[2]Commodities congruent with known uranium deposits, however insufficient data exists to quantify worker doses.

The significant pathways of exposure are [9, 14–16]:

i. External irradiation from exposure to gamma radiation (γ);
ii. Inhalation of radioisotopes of the gas radon, radon-219 (^{219}Rn), radon-220 (^{220}Rn), radon-222 (^{222}Rn), and their short-lived progeny; and
iii. Inhalation of dust which contains long-lived alpha (LLα) emitting radionuclides.

Mining operations in WA that are associated with NORM and have the potential for radiation exposure to workers to exceed a committed effective dose (CED) of 1 millisievert (mSv) per year are required to comply with the Mines Safety and Inspection Regulations 1995 (the regulations) [17]. The regulations impose strict requirements upon the mining project owners including the preparation of radiation management plans; appointment of appropriately qualified and experienced radiation safety officers; and the submission of annual reports of worker dose assessments to the regulatory authority.

Fourteen WA mining operations are currently required to comply with the regulations and 11 of these submitted an annual report of worker radiation doses to the regulatory authority for the 2018–19 reporting period. The commodities being mined and processed were mineral sands (seven operations); rare earths (two operations); and tantalum-lithium (two operations).

Data for the 2018–19 annual reporting period indicate that workers in the mineral sands and rare earths sectors receive doses of similar magnitude, which are higher than the doses

Table 2. Preliminary committed effective dose (CED) for 11 mining operations from 2018–19 annual reports to the regulatory authority[a].

Source of Exposure	Range (mSv)		Mean (mSv)
	Minimum	Maximum	
External, from γ radiation	0.1	1.5	0.5
Internal, from radon and progeny [a]	0.0	1.3	0.3
Maximum Internal, from LLα	0.2	3.2	0.5
Total CED	0.1	4.4	1.0

[a]Only five operations (representing 20% of the workforce) conducted radon and progeny monitoring in the 2018–19 reporting period. The mean CED is from the five operations, and is not representative of the industry CED. The mean Total CED is not the sum of the means from the three pathways.

received by workers in tantalum/lithium operations. A summary of the preliminary data [1] from the 2018–19 annual reports to the regulatory authority is presented in table 2.

The contribution to CED from the inhalation of LLα varied by the commodity being mined, and ranged from 35% to 60% across the 11 operations.

2. Methods

2.1. Codification of dose calculation methodologies

The regulations stipulate that the assessment of doses is '*done in accordance with a procedure approved by the* [regulatory authority]'. The approved procedures comprise a suite of 14 NORM Guidelines collectively entitled '*Managing naturally occurring radioactive material (NORM) in mining and mineral processing'* [18]. Each NORM Guideline addresses specific components of the system for collecting data; calculating radiation doses; and recording and reporting the derived information.

The Guideline NORM-5 '*Dose Assessment'* [19] (NORM-5) provides a detailed overview of the ICRP Publication 30 series [20] and the respiratory tract model as outlined in ICRP-66 [21]. NORM-5 provides guidance on the calculation of CED and derivation of dose conversion factors (DCFs), based upon a methodology in the International Atomic Energy Agency (IAEA) publication RS-G-1.6 [22].

The ICRP Publication 30 series and Publications 54 [23], 68 [24] and 78 [25], were used as the basis for calculating the CED to mine workers as a result of inhalation of the long-lived members of the ^{232}Th and $^{238+235}$U decay series. In 2015, ICRP commenced publication of the Occupational Intake of Radionuclides (OIR) and indicated that the series of five parts would replace the Publication 30 series and Publications 54, 68 and 78 [26].

Part 1 of the OIR (published as ICRP Publication 130) [27] provides an introduction to the methodology used in the revision of revised DCs for occupational intakes of radionuclides by inhalation and ingestion. The models used include the Human Alimentary Tract Model (published as ICRP Publication 100 [28]), a revision of the Human Respiratory Tract Model, and revised models for the systemic distribution of radionuclides absorbed to blood. OIR Part 2, issued as ICRP Publication 134 in 2016 [29] provided the first set of revised DCs for

[1] An analysis of doses to workers in WA mining operations for the 12 months from April 2018 to March 2019 is currently in production, and therefore the quoted values are subject to change as the analysis is finalised.

radioisotopes of elements of lower atomic number, not relevant to the assessment of doses from NORM.

The ICRP published Part 3 of the OIR as ICRP-137 [30] in 2017. ARPANSA endorsed the revised DCs for the radioisotopes of radon and their progeny contained in ICRP-137 in early 2018 and advised regulators that DCs for the inhalation of dusts containing members of the ^{232}Th and $^{238+235}$U decay series could not be completed until such time as Part 4 of the OIR (ICRP-141) was published [26].

ICRP-141 [31], which included data for radioisotopes of actinium and protactinium became available in December 2019. The revision of the DCs for all of the members of the ^{232}Th and $^{238+235}$U decay was therefore completed, allowing the impacts of the revisions on the WA mining workforce to be evaluated.

The aim of this paper is to evaluate the impact of recent revisions to ICRP committed effective dose coefficients (DCs) for members of the ^{232}Th and $^{238+235}$U decay series on the radiation doses received by WA mine workers via the inhalation of insoluble dusts containing LLα.

2.2. Use of OIR data viewer to calculate DCFs for members of the ^{232}Th and $^{238+235}$U decay series

ICRP-137 and ICRP-141 provide data on individual elements and the half-lives and decay modes of their radioisotopes; information on chemical forms encountered in the workplace; and data on inhalation and ingestion. Tables of CED per intake (Sv Bq^{-1}) are provided, and the electronic annex that accompanies the OIR series of publications [32] was utilised to determine revised DCs for the NORM radionuclides.

The Data Viewer, provided as an electronic annex to the OIR decay series of publications, was downloaded from the ICRP-website [32], and was used to compile a list of updated DCs for each of the radionuclides in the ^{232}Th and $^{238+235}$U decay series.

The OIR Data Viewer 'contains a comprehensive set of committed effective and equivalent dose coefficients, … for almost all radionuclides included in Publication 107 (ICRP, 2008) that have half-lives equal to or greater than 10 min, and for other selected radionuclides' [30]. Therefore, the DCs for some members of the ^{232}Th and $^{238+235}$U decay series do not exist, and could not be considered in the analysis.

Research conducted in the WA mining industry in the 1980's and 1990's evaluated NORM-containing dusts and concluded that they were insoluble, and were removed very slowly from the lung once inhaled [33–38]. Accordingly, the values for DCs cited in tables 3, 4, 5, 6, 7 and 8 from ICRP-137 and ICRP-141 have been selected from the slowest absorption rate, Type S, available in the OIR Data Viewer. A number of DC values (for example lead-212 (^{212}Pb), bismuth-212 (^{212}Bi), radium-224 (^{224}Ra) and radium-228 (^{228}Ra), from the ^{232}Th decay series) were based upon absorption Type F or M in ICRP-30, but were treated as Type S in this evaluation.

The parameter values in the Data Viewer were adjusted to reflect the inhalation pathway and absorption Type S, and, based upon ICRP recommendations for evaluating doses to workers and critical groups [21, 27] and the WA research [34, 39, 40], the impact of revised DCs for AMADs of 1, 5 and 10 micron (µm) were extracted.

The DCs were exported from the Data Viewer into a Microsoft Excel (2016) spreadsheet. Comparisons were made with DCs as published in the ICRP Publication 30 series which were replicated in NORM-5 as DCFs for each of the three AMAD ranges.

The methodology outlined in NORM-5 and IAEA publication RS-G-1.6 [22] was used to calculate a revised DCF for each of the ^{232}Th and $^{238+235}$U decay series, and a table constructed comparing the DCF derived from ICRP-137 and ICRP-141 to the ICRP Publication 30 series.

Table 3. Comparison of committed effective dose coefficients (DCs) for inhalation of 1 μm AMAD particles comprised of radionuclides of the ^{232}Th decay series.

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC (Sv Bq^{-1}) A: ICRP-30 series	DC (Sv Bq^{-1}) B: ICRP-137/141	Change, as a ratio of B : A
^{232}Th	Alpha	S	2.30E-05	1.00E-04	4.35
^{228}Ra	Beta	M	2.60E-06	3.70E-05	14.2
actinium-228 (^{228}Ac)	Beta	S	1.40E-08	1.30E-08	0.929
thorium-228 (^{228}Th)	Alpha	S	3.90E-05	3.50E-05	0.897
^{224}Ra	Alpha	M	2.90E-06	1.60E-06	0.552
^{220}Rn	Alpha	-	-	1.77E-10	-
^{216}Po	Alpha	-	-	-	-
^{212}Pb	Beta	F	1.90E-08	1.10E-07	5.79
^{212}Bi	64.1% beta 35.9% alpha	M	3.00E-08	2.40E-08	0.800
^{212}Po	Alpha	-	-	-	-
^{208}Tl	Beta	-	-	-	-
	^{232}Th decay series: Sum of DCs		6.76E-05	1.74E-04	2.57

Table 4. Comparison of committed effective dose coefficients (DCs) for inhalation of 5 μm AMAD particles comprised of radionuclides of the ^{232}Th decay series.

			DC (Sv Bq^{-1})		
Radionuclide	Particulate Emission	NORM-5 lung absorption class	A: ICRP-30 series	B: ICRP-137/141	Change, as a ratio of B : A
^{232}Th	Alpha	S	1.20E-05	5.40E-05	4.50
^{228}Ra	Beta	M	1.70E-06	2.20E-05	12.9
^{228}Ac	Beta	S	1.20E-08	8.40E-09	0.700
^{228}Th	Alpha	S	3.20E-05	2.30E-05	0.719
^{224}Ra	Alpha	M	2.40E-06	1.10E-06	0.458
^{220}Rn	Alpha	-	-	1.77E-10	-
^{216}Po	Alpha	-	-	-	-
^{212}Pb	Beta	F	3.30E-08	9.40E-08	2.85
^{212}Bi	64.1% beta 35.9% alpha	M	3.90E-08	2.90E-08	0.740
^{212}Po	Alpha	-	-	-	-
^{208}Tl	Beta	-	-	-	-
	^{232}Th decay series: Sum of DCs		4.82E-05	1.00E-04	2.08

Table 5. Comparison of committed effective dose coefficients (DCs) for inhalation of 10 μm AMAD particles comprised of radionuclides of the ^{232}Th decay series.

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC (Sv Bq^{-1})		Change, as a ratio of B : A
			A: ICRP-30 series	B: ICRP-137/141	
^{232}Th	Alpha	S	8.10E-06	2.60E-05	3.21
^{228}Ra	Beta	M	9.80E-07	1.30E-05	13.3
^{228}Ac	Beta	S	7.20E-09	5.10E-09	0.708
^{228}Th	Alpha	S	1.80E-05	1.40E-05	0.778
^{224}Ra	Alpha	M	1.30E-06	6.50E-07	0.500
^{220}Rn	Alpha	-	-	1.77E-10	-
^{216}Po	Alpha	-	-	-	-
^{212}Pb	Beta	F	3.20E-08	6.20E-08	1.94
^{212}Bi	64.1% beta 35.9% alpha	M	3.10E-08	2.10E-08	0.677
^{212}Po	Alpha	-	-	-	-
^{208}Tl	Beta	-	-	-	-
	^{232}Th decay series: Sum of DCs		2.85E-05	5.37E-05	1.88

Table 6. Comparison of committed effective dose coefficients (DCs) for inhalation of 1 μm AMAD particles comprised of radionuclides of the $^{238+235}$U decay series.

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC (Sv Bq^{-1}) A: ICRP-30 series	DC (Sv Bq^{-1}) B: ICRP-137/141	Change, as a ratio of B : A
^{238}U	Alpha	S	7.30E-06	2.00E-05	2.74
thorium-234 (^{234}Th)	Beta	S	7.30E-09	4.90E-09	0.671
^{234m}Pa/^{234}Pa	Beta	-	-	1.70E-10	-
^{234}U	Alpha	S	8.50E-06	2.30E-05	2.71
thorium-230 (^{230}Th)	Alpha	S	1.30E-05	2.50E-05	1.92
radium-226 (^{226}Ra)	Alpha	M	3.20E-06	2.30E-05	7.19
^{222}Rn	Alpha	-	-	4.36E-10	-
^{218}Po	Alpha	-	-	-	-
lead-214 (^{214}Pb)	Beta	F	2.90E-09	1.10E-08	3.79
bismuth-214 (^{214}Bi)	Beta	M	1.40E-08	1.00E-08	0.714
^{214}Po	Alpha	-	-	-	-
lead-210 (^{210}Pb)	Beta	F	8.90E-07	1.50E-05	16.9
bismuth-210 (^{210}Bi)	Beta	M	8.40E-08	8.70E-08	1.04
polonium-210 (^{210}Po)	Alpha	M	3.00E-06	2.80E-06	0.933
	^{238}U decay series: Sum of DCs		3.60E-05	1.09E-04	3.03
^{235}U	Alpha	S	7.70E-06	2.10E-05	2.73
thorium-231 (^{231}Th)	Beta	S	3.20E-10	1.70E-10	0.53
protactinium-231 (^{231}Pa)	Alpha	S	3.20E-05	8.40E-05	2.63
actinium-227 (^{227}Ac)	Beta	S	6.60E-05	1.10E-04	1.67
thorium-227 (^{227}Th)	Alpha	S	9.60E-06	3.30E-06	0.344
radium-223 (^{223}Ra)	Alpha	M	6.90E-06	3.20E-06	0.464
^{219}Rn	Alpha	-	-	-	-
polonium-215 (^{215}Po)	Alpha	-	-	-	-
lead-211 (^{211}Pb)	Beta	F	3.90E-09	1.10E-08	2.82
^{211}Bi	Alpha	-	-	-	-
^{207}Tl	Beta	-	-	-	-
	^{235}U decay series: Sum of DCs		1.22E-04	2.22E-04	1.81

Table 7. Comparison of committed effective dose coefficients (DCs) for inhalation of 5 μm AMAD particles comprised of radionuclides of the $^{238+235}$U decay series.

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC (Sv Bq^{-1}) A: ICRP-30 series	DC (Sv Bq^{-1}) B: ICRP-137/141	Change, as a ratio of B : A
^{238}U	Alpha	S	5.70E-06	1.20E-05	2.11
^{234}Th	Beta	S	5.80E-09	2.90E-09	0.500
^{234m}Pa/^{234}Pa	Beta	-	-	2.00E-10	-
^{234}U	Alpha	S	6.80E-06	1.30E-05	1.91
^{230}Th	Alpha	S	7.20E-06	1.50E-05	2.08
^{226}Ra	Alpha	M	2.20E-06	1.30E-05	5.91
^{222}Rn	Alpha	-	-	4.36E-10	-
^{218}Po	Alpha	-	-	-	-
^{214}Pb	Beta	F	4.80E-09	1.40E-08	2.92
^{214}Bi	Beta	M	2.10E-08	1.40E-08	0.667
^{214}Po	Alpha	-	-	-	-
^{210}Pb	Beta	F	1.10E-06	9.20E-06	8.36
^{210}Bi	Beta	M	6.00E-08	5.70E-08	0.950
^{210}Po	Alpha	M	2.20E-06	1.80E-06	0.818
	^{238}U decay series: Sum of DCs		2.53 E-05	6.41E-05	2.53
^{235}U	Alpha	S	6.10E-06	1.20E-05	1.97
^{231}Th	Beta	S	4.00E-10	1.30E-10	0.325
^{231}Pa	Alpha	S	1.70E-05	4.60E-05	2.71
^{227}Ac	Beta	S	4.70E-05	6.50E-05	1.38
^{227}Th	Alpha	S	7.60E-06	2.10E-06	0.276
^{223}Ra	Alpha	M	5.70E-06	2.20E-06	0.386
^{219}Rn	Alpha	-	-	-	-
^{215}Po	Alpha	-	-	-	-
^{211}Pb	Beta	F	5.60E-09	1.30E-08	2.32
^{211}Bi	Alpha	-	-	-	-
^{207}Tl	Beta	-	-	-	-
	^{235}U decay series: Sum of DCs		8.34E-05	1.27E-04	1.53

Table 8. Comparison of committed effective dose coefficients (DCs) for inhalation of 10 µm AMAD particles comprised of radionuclides of the $^{238+235}$U decay series.

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC (Sv Bq^{-1}) A: ICRP-30 series	DC (Sv Bq^{-1}) B: ICRP-137/141	Change, as a ratio of B : A
^{238}U	Alpha	S	3.50E-06	6.30E-06	1.80
^{234}Th	Beta	S	3.50E-09	1.60E-09	0.457
^{234m}Pa/^{234}Pa	Beta	-	-	1.60E-10	-
^{234}U	Alpha	S	4.10E-06	7.20E-06	1.76
^{230}Th	Alpha	S	5.20E-06	7.80E-06	1.50
^{226}Ra	Alpha	M	1.50E-06	7.20E-06	4.80
^{222}Rn	Alpha	-	-	4.36E-10	-
^{218}Po	Alpha	-	-	-	-
^{214}Pb	Beta	F	4.40E-09	1.00E-08	2.27
^{214}Bi	Beta	M	1.80E-08	1.10E-08	0.611
^{214}Po	Alpha	-	-	-	-
^{210}Pb	Beta	F	9.40E-07	5.10E-06	5.43
^{210}Bi	Beta	M	3.00E-08	3.40E-08	1.13
^{210}Po	Alpha	M	1.10E-06	1.10E-06	1.00
	^{238}U decay series: Sum of DCs		1.64E-05	3.48E-05	2.12
^{235}U	Alpha	S	3.70E-06	6.60E-06	1.78
^{231}Th	Beta	S	3.00E-10	8.60E-11	0.287
^{231}Pa	Alpha	S	8.30E-06	2.30E-05	2.77
^{227}Ac	Beta	S	2.70E-05	3.60E-05	1.33
^{227}Th	Alpha	S	3.90E-06	1.20E-06	0.308
^{223}Ra	Alpha	M	3.00E-06	1.30E-06	0.433
^{219}Rn	Alpha	-	-	-	-
^{215}Po	Alpha	-	-	-	-
^{211}Pb	Beta	F	4.80E-09	9.20E-09	1.92
^{211}Bi	Alpha	-	-	-	-
^{207}Tl	Beta	-	-	-	-
	^{235}U decay series Sum of DCs		4.59E-05	6.81E-05	1.48

Finally, a table was constructed in Microsoft Excel (2016) comparing DCF for AMADs of 1 µm, 5 µm and 10 µm by varying ratios of ^{232}Th decay series to $^{238+235}$U decay series.

3. Results

3.1. Committed effective dose coefficients (DCs) for members of the ^{232}Th decay series

Comparisons of DCs from ICRP-30 (replicated in the NORM-5 guideline) and ICRP Publications 137 and 141 for ^{232}Th decay series radionuclides for AMADs of 1 µm, 5 µm and 10 µm, are presented in tables 3, 4 and 5. Note that:

- ICRP does not cite DCs for radionuclides with half-lives of less than 10 min [30]. Therefore, DCs for thallium-208 (^{208}Tl), polonium-212 (^{212}Po) and polonium-216 (^{216}Po) cannot be included in the tables.
- a DC for ^{220}Rn is published in ICRP-137, but was absent from ICRP-30. Radon is an inert gas, with constant aerodynamic diameter and the DC does not change between the tables.

Tables 3, 4 and 5 illustrate that most of the DCs have increased. Whilst several DCs have decreased, the nett effect for all AMADs is that the sum of all DCs has increased.

3.2. Committed effective dose coefficients (DCs) for members of the $^{238+235}$U decay series

Comparisons of DCs from ICRP-30 (replicated in the NORM-5 guideline) and ICRP Publications 137 and 141 for $^{238+235}$U decay series radionuclides for AMADs of 1 µm, 5 µm and 10 µm, are presented in tables 6, 7 and 8. Note that:

- ICRP does not provide DCs for radionuclides with half-lives of less than 10 min [30]. Therefore, DCs for thallium-207 (^{207}Tl) bismuth-211 (^{211}Bi), polonium-214 (^{214}Po), polonium-218 (^{218}Po) and ^{219}Rn cannot be included in the tables.
- because it has a half-life of 1.17 min, Protactinium-234^{m} (^{234m}Pa) does not have a DC. However, ^{234m}Pa can decay to uranium-234 (^{234}U) via protactinium-234 (^{234}Pa) which has a half-life of 6.7 h, and has DC listed in ICRP-141. The DC for ^{234}Pa is used in tables 6, 7 and 8. A DC for ^{234}Pa was not listed in ICRP-30.
- a DC for ^{222}Rn is published in ICRP-137, but was absent from ICRP-30. Radon is an inert gas, with constant aerodynamic diameter and the DC does not change between the tables.

The data presented in tables 6, 7 and 8 illustrate that most of the DCs have increased, and whilst several have decreased, the nett effect is that the sum of all DCs has increased for all AMADs.

3.3. Calculation of DCF values

The methodology for derivation of DCF in NORM-5 is based upon the IAEA publication RS-G-1.6 [22], and involves summing the DCs for each radionuclide in the decay series, and dividing by the number of LLα radionuclides in the decay series.

Analysis of the radioactivity of dust samples is performed via gross alpha activity analysis (GAAA) as per the regulatory authority's Guideline *NORM 3.4: Monitoring NORM—airborne radioactivity sampling* (NORM 3.4) [41]. GAAA counts all alpha particle emissions from the collected dust sample to provide an activity reading in Bq_{α}.

The beta-emissions from the NORM in the collected dust sample are not detected by GAAA, however their contribution to internal dose is accounted for by including their DCs in calculating the DCF for the entire series. Similarly, where an α-particle emitting radionuclide has a sufficiently short half-life that it is not allocated a DC, its contribution to GAAA must be accounted for by its inclusion in the total number of alpha particle emitters in the decay series.

The ^{232}Th decay series includes six alpha particle emitters, and therefore the values for 'Sum of DCs' cited in tables 3, 4 and 5 are divided six to provide the DCF values for the ^{232}Th decay series in table 9.

The ^{238}U decay series has eight members, and the ^{235}U decay series seven members that decay via alpha particle emission. The specific activity of natural uranium is 12 900 Bq g^{-1} of which ^{235}U contributes 593 Bq g^{-1}, or 4.6% [14]. As outlined in IAEA publication RS-G-1.6 [22], in order to account for the relative contribution of the ^{235}U decay series to the total activity from the combined $^{238+235}$U decay series, the DCs for each member of the ^{235}U decay series is multiplied by 0.046.

Therefore, the combination of the seven alpha-emitting radionuclides in the ^{235}U decay series contribute an equivalent of 0.322 alpha particles to the Bq$_\alpha$ from natural uranium. When added to the eight emitters in the ^{238}U decay series, the combined $^{238+235}$U decay series includes 8.322 alpha emitters.

The DCF data in table 9 for the $^{238+235}$U decay series are calculated from tables 6–8 by:

$$\frac{\text{“}^{238}\text{U decay series: Sum of DCs”} + 0.046 \times \text{“}^{235}\text{U decay series:Sum of DCs”}}{8.322}$$

The data presented in table 9 indicate that the DCF for the three selected AMADs increased by between 1.9 and 2.9 times the NORM-5 values as a result of the revised DCs in ICRP-137 and ICRP-141.

3.4. Calculation of contribution to DCF by thorium to uranium ratio

The DCF values listed in table 9 were then applied to a range of ratios (by mass) of ^{232}Th decay series to $^{238+235}$U decay series in order to represent the contribution made by each decay series and determine an applicable DCF by AMAD.

Examples of the calculated DCF values by the ratio of ^{232}Th decay series to $^{238+235}$U decay series are provided in table 10.

4. Discussion

In order to estimate the radiation dose delivered by inhalation of dusts containing NORM, knowledge of their: concentration; particle size; respiratory deposition; and clearance from the respiratory system is required [42]. DCs will differ markedly according to the parameter values selected, and therefore it is important that the data extracted from the OIR Data Viewer are representative of the particles being inhaled.

As illustrated in tables 3, 4 and 5, the DCs for four radionuclides in the ^{232}Th decay series decreased in ICRP-137 and ICRP-141 compared to those published in the ICRP Publication 30 series. However, correspondingly, the DCs for ^{228}Ra, ^{212}Pb and ^{232}Th increased significantly, ranging from 1.94 times for ^{212}Pb (10 μm particles) to 14.2 times for ^{228}Ra (1 μm particles), resulting in an increase in the sum of all DCs for all AMADs.

As shown in tables 6, 7 and 8, the DCs for the majority of the members of the $^{238+235}$U decay series increased, with only ^{234}Th, ^{214}Bi and ^{210}Po from the ^{238}U decay series and ^{231}Th, ^{227}Th and ^{223}Ra from the ^{235}U decay series decreasing from the DCs in ICRP Publication 30 series to those in ICRP137 and ICRP-141. The highest increases were seen in the DCs for

Table 9. Calculated DCF values by AMAD and decay series.

	DCF by Particle Size ($mSv\ Bq_{\alpha}{}^{-1}$)					
	^{232}Th decay series			$^{238+235}U$ decay series		
Particle Size	A: NORM-5	B: ICRP-137 & 141	Change, as a ratio B : A	A: NORM-5	B: ICRP-137 & 141	Change, as a ratio B : A
1 μm	0.0113	0.0290	2.6	0.0050	0.0143	2.9
5 μm	0.0080	0.0167	2.1	0.0035	0.0084	2.4
10 μm	0.0047	0.0090	1.9	0.0022	0.0046	2.1

Table 10. Calculated DCF values by AMAD and ratio of decay series.

Th : U Ratio	DCF by AMAD (mSv $Bq_{\alpha}{}^{-1}$)		
	1 μm	5 μm	10 μm
All ^{232}Th decay series	0.0290	0.0167	0.0090
10 : 1	0.0256	0.0148	0.0080
5 : 1	0.0234	0.0136	0.0073
2: 1	0.0201	0.0117	0.0063
1 : 1	0.0179	0.0104	0.0057
1 : 2	0.0164	0.0096	0.0052
1 : 5	0.0152	0.0089	0.0049
1 : 10	0.0148	0.0087	0.0047
All $^{238+235}$U decay series	0.0143	0.0084	0.0046

^{210}Pb, ranging from 5.43 times for 10 μm particles to 16.9 times for 1 μm particles; and ^{226}Ra, ranging from 4.80 times for 10 μm particles to 7.19 times for 1 μm particles.

The term '*dose conversion factor*' (DCF) is used in NORM-5 and IAEA publication RS-G-1.6 [22], to represent the mean CED per unit intake of alpha activity arising from inhalation of dusts containing members of either the ^{232}Th decay series and/or the $^{238+235}$U decay series. The DCF is significant as it considers the relative contribution from all the members of the decay series to the CED. Of importance to the use of DCF is that all members of the decay series are in secular equilibrium, and that the activity of one radionuclide is indicative of the activity of all other members of the decay series. The WA research [36] found that the loss of radioisotopes of radon from mineral grains was very low, and that the assumption of secular equilibrium was valid.

DCF is calculated by dividing the 'Sum of DCs' for the ^{232}Th and the $^{238+235}$U decay series by the number of LLα radionuclides in each of the decay series to provide a value of Sv Bq^{-1} per alpha emission.

The nett effect of the revised DCs, as illustrated in table 9, is to increase the DCF values from those published in NORM-5 for the ^{232}Th decay series by between 1.9 times for 10 μm particles to 2.6 times for 1 μm particles; and for the $^{238+235}$U decay series by between 2.1 times for 10 μm particles to 2.9 times for 1 μm particles. The increase in derived DCF is inversely related to AMAD, with the increase becoming larger with decreasing AMAD.

The data presented in table 10 have significance, as ultimately it is this data, or variants of them, calculated in a similar manner, that will be used for calculating the contribution to CED from inhalation of NORM-containing dusts in mining operations in WA. It is important that each mining operation characterises the AMAD of the dust, and the ratio of the ^{232}Th decay series to $^{238+235}$U decay series, as these variables can have a marked effect on committed effective dose calculations.

The need for dust characterisation studies can be determined from table 10. The primary minerals produced in the WA mineral sands industry are ilmenite and rutile, which have a ^{232}Th decay series to $^{238+235}$U decay series ratio approximating 10:1 [15]. At this ratio, the DCF decreases by 69% from 0.0256 $mSvBq_{\alpha}{}^{-1}$ (AMAD = 1 μm) to 0.0080 $mSvBq_{\alpha}{}^{-1}$ (AMAD = 10 μm). Zircon, another major product from the mineral sands industry has a ^{232}Th decay series to $^{238+235}$U decay series ratio approximating 1:1 [15], and at this ratio the DCF decreases by 68% from 0.0179 $mSvBq_{\alpha}{}^{-1}$ (AMAD = 1 μm) to 0.0057 $mSvBq_{\alpha}{}^{-1}$ (AMAD = 10 μm).

The majority of the 11 mining operations that submitted reports used the default AMAD of 5 μm and the ^{232}Th decay series to $^{238+235}$U decay series ratio for ilmenite and rutile of 10:1 in the 2018–19 annual reports to the regulator. As can be seen in table 10, the DCF for these mining operations will be 0.0148 mSv $Bq_{\alpha}{}^{-1}$. In NORM-5 the equivalent DCF is 0.007 mSv $Bq_{\alpha}{}^{-1}$, and therefore the revised DCF is greater by a factor of 2.1 than that generally used to calculate CEDs in the 2018–19 annual reports.

A preliminary evaluation of the data submitted in the 2018–19 annual reports, [2] indicates that the contribution to CED from the inhalation of radioactive dusts across the 11 mining operations ranged from 35% to 60%. Applying the default AMAD of 5 µm and a ^{232}Th decay series to $^{238+235}$U decay series ratio for ilmenite and rutile of 10:1, CEDs to the workforce will increase be greater by a factor of between 0.74 and 1.26 times from those reported in 2018–19 as a result of the revised DCs published in ICRP-137 and ICRP-141.

Table 2 provided a summary of a preliminary review of the CEDs in the 2018–19 annual reports. The maximum CED was 4.4 mSv, from a mineral sands processing operation, which reported dust parameter values of 5 µm AMAD and ^{232}Th decay series to $^{238+235}$U decay series ratio of 10:1. As shown in table 9, the DCF for these parameter values is greater by a factor of 2.1 times, increasing from 0.0080 mSv $Bq_{\alpha}{}^{-1}$ in NORM-5 to 0.0167 mSv $Bq_{\alpha}{}^{-1}$ in ICRP-137 and ICRP-141. As a result of the revised DCs, the contribution to maximum CED from LLα will increase by 3.5 mSv to 6.7 mSv, the CED will increase to 7.9 mSv and the contribution to maximum CED from LLα will increase to 85%.

The regulatory authority has committed to revising the NORM-5 Guideline to accommodate the revised DCs in ICRP-137 and ICRP-141. It is important that current and prospective mines apply the DCs from ICRP-137 and ICRP-141 and derive representative DCFs for their operations. This requirement needs to be communicated to those operations whose workforce may exceed 1mSv as a result of the revised DCs; the emerging battery minerals sector; and those mining operations highlighted in table 1, whose workforces are potentially exposed to NORM, but for which there is insufficient data to establish dose estimates.

It is known that NORM-5 has been adopted by Australian jurisdictions outside of WA [26]. One of the authors (NT) has widely distributed copies of NORM-5 to international jurisdictions [43], some of which may have adopted all, or sections of it, into their legal framework for radiation protection. Therefore, it is of importance that the revision of NORM-5 is brought to the attention of the users in other jurisdictions to allow them to consider possible amendments to their own radiation protection regimes.

5. Conclusions

The revised DCs published in ICRP-137 and ICRP-141 will have a significant impact upon the DCFs used to calculate doses arising from inhalation of NORM-containing dusts by WA mine workers.

Using an absorption Type S for all contributing radionuclides in the ^{232}Th and $^{238+235}$U decay series, DCFs will be greater by a factor of between 1.9 and 2.9 times from those published in NORM-5. The level of the increase is dependent upon AMAD and the ratio of the ^{232}Th decay series to $^{238+235}$U decay series in the inhaled dust.

A scenario which applies an AMAD of 5 µm and a ^{232}Th decay series to $^{238+235}$U decay series ratio of 10:1, would result in the CEDs to the workforce being greater by a factor of

[2] submitted prior to the release of ICRP-141.

between 0.74 and 1.26 times from those reported in 2018–19 as a result of the revised DCs published in ICRP-137 and ICRP-141.

It is known that the concentration, AMAD and radiological characteristics of dusts in mining operations will vary with the mineral being processed, and the physical and metallurgical treatment processes being utilised [44–46]. This analysis has confirmed the importance of mining operations conducting characterisation studies of the NORM-containing dust to which workers are exposed in order to determine site-specific and process-specific parameter values upon which appropriate committed effective dose coefficients can be applied to dose calculations.

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