Managing the Radiation Exposures of WA Mine Workers from Naturally Occurring Radioactive Materials: An Historical Overview (Part II)

Martin I. Ralph [(a)] , Nick Tsurikov [(b)] and Marcus Cattani [(c)]

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Abstract

Naturally Occurring Radionuclides (NORs)are found in a wide range of commodities that are mined and processed in Western Australia (WA), such as mineral sands, tin, tantalum and the suite of ‘ battery minerals’ which include rare earths, lithium and cobalt.

An intense period of scrutiny was applied to the WA mineral sands industry during the mid- 1980’s to the mid-1990’s. Committed effective doses (CEDs) well in excess of the (then) applicable annual dose limit of 50 mSv were reported, leading to significant capital expenditure across the industry to reduce worker exposures.

Prior to research by Ralph, Chaplyn and Cattani [1] who analysed data from the 2018-19 reporting period, the most recent previous peer- reviewed research into radiation exposures of the WA mining industry workforce was published by Marshman and Hewson in 1994 [2].

Part I of this research [3] provided an overview of the legislative framework that governs the management of radiation exposures from minerals containing NORS in WA, and a synopsis of doses to mine workers in Australia and internationally. This paper completes the record of radiation doses to WA mine workers that commenced with the Winn Commission of Inquiry which reported on radiation exposures to workers in the Western Australian minerals sands industry in the late 1970’s and mid 1980’s, and extends it to the 2018-19 reporting period.

93.5% of the total number of workers across the almost 50 years covered by this research were assessed as receiving annual CEDs of less than five mSv. Exceedances over 50 mSv were frequently reported in the 1970’s and 1980’s, however, the last reported exceedance occurred in 1988. The maximum reported CED was 163.4 mSv, reported in 1987. In the 1990’s the maximum reported CED was 32 mSv in 1994-95;in the 2000’s the maximum reported CED was 15.7 mSv in 2002-03; and in the 2010’s the maximum reported CED was 4.4 mSv in 2010-11, 2011-12 and 2018-19. The last reported CED that exceeded the contemporary derived annual dose limit of 20 mSv occurred in 1995-96.

Exceedances over the derived air concentrations for long-lived alpha emitters in dust continue to be reported in some mining operations, serving as a timely reminder that although doses are below 25% of the contemporary derived annual limit of 20 mSv per year, the potential for elevated CEDs exists because of the omnipresent NORMs in the suite of minerals being processed.

The research concludes that the declining trend of worker doses since the mid-1990’s is to be acknowledged, but cautions that, with the imminent application of revised dose conversion factors for inhaled radioactive dusts, a trend of decreasing worker participation in personal monitoring programmes needs to be addressed.

a) Corresponding author: Edith Cowan University, Western Australia, School of Medical and Health Sciences WA 6027, Australia
Email: miralph@our.ecu.edu.au

(b) Calytrix Consulting Pty Ltd, PO Box 83, Stoneville, Western Australia 6081, Australia

(c) Edith Cowan University, Western Australia, School of Medical and Health Sciences, 270 Joondalup Drive, Joondalup, WA 6027, Australia

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Disclaimer

References to mining operations that are in the public domain have been retained, however the authors have endeavoured to de-identify the names of Reporting Entities and mining project proponents wherever possible.

1 Introduction

As was outlined in Part I of this research [3], the NORs thorium-232 (^{232}Th) and uranium-238 (^{238}U) are widely distributed in the environment and are present to some extent in all rocks and soils [4-11] [1] . Thorium-232 and ^{238}U are the parent isotopes of decay series comprising of different radioactive isotopes, the emissions from which present potential sources of radiation dose to exposed workers [4, 12, 13]. The significant pathways of exposure are [10, 13-17]:

i. External irradiation from exposure to gamma radiation (γ) emitted by most members of each decay series;
ii. Inhalation of dust which contains long-lived alpha (LLα) emitting isotopes;
iii. Inhalation of the radioisotopes of the noble gas radon, ^{220}Rn (known as thoron, Tn) and ^{222}Rn (radon, Rn); and the products of their decay, all of which have short half-lives, and are referenced as thoron (^{220}Rn) progeny (TnP); or radon (^{222}Rn) progeny (RnP).

Contributions from each of the three significant pathways are added, to calculate the committed effective dose (CED) which is compared against legislatively imposed limits.

International expert agencies have identified a range of ores and minerals in which NORs are encountered [5, 10, 11], many of which are mined and processed within Western Australia (WA). In 1992, Hewson, Kvasnicka and Johnson [18] stated that in relation to workers exposure to radiation, the WA mining regulatory authorities were charged with regulating of the order of 60 mining operations, comprising “seven mineral sands separation plants; four synthetic rutile plants; one tin processing and smelting operation; approximately 40 underground non-uranium mines; one zirconia plant; two titanium dioxide pigment plants; one prospective rare earths plant; and four prospective uranium sites”. The number of mining operations with workers potentially exposed to NORMs was more than an order of magnitude greater than any of the other jurisdictions in Australia. The challenge posed to the WA regulatory authorities was exacerbated by the unique radiological properties of the ores treated by the State’s mineral sands industry (MSI) which was reported to be an order of magnitude higher than that encountered in similar MSI operations on the eastern seaboard [19].

As was reported in Part I of this research [3], the WA mining industry has expanded considerably since the early 1990’s, and has recently expanded the portfolio of commercially exploitable minerals [20-22]. The size of the mining workforce is at an historical peak [23], and the cohort of workers potentially exposed to radiation in the course of their work has increased accordingly.

This paper aims to complement the first instalment of the research, by completing the record of radiation doses to WA mine workers from the first broad estimates in 1977, through the period of initial systematic evaluations in 1987, to the most recent research by Ralph, Chaplyn and Cattani [1], who analysed data for the 2018-19 reporting period.

Part I of this research [3] concluded with the findings of the Winn Committee of Inquiry (Winn Inquiry), and the commentary by Hartley and Hewson [24] that “It then became clear that stricter regulation of the [mineral sands] industry

1 - The presence of uranum-235 in the rocks and soils is acknowledged, however its contribution to mine worker doses is negligible when compared to those from ^{232}Th and ^{238}U.

was needed as well as a program to limit the exposure of workers to radioactive dust".

2 COROLLARIES TO THE WINN COMMITTEE OF INQUIRY

The Winn Inquiry was the catalyst for an intense period of change in the regulatory governance of, and research into, the sources and quantity of worker exposures in the MSI, and over time, other mining operations that encounter(ed) NORs.

The findings of the Winn Inquiry had far-reaching impacts, including the establishment of a new tripartite oversight committee, the MRSB formed as a result of the gazettal of the Mines Regulation Amendment Act, 1987 [25]; relocation of regulatory responsibility for radiation protection in WA mines from the Radiological Council (RCWA) to the State mining engineer (SME); and the establishment of a specialized Radiation Secretariat (laterrebadged as the Radiation Safety Section, RSS) within the Mines Inspectorate [2] [24].

2.1 Research activities of the RSS and others, post the Winn Inquiry

In order to address one of the main technical findings of the Winn Inquiry, one of the early research projects undertaken in 1988 by the RSS, was an investigation into the presence of TnP and RnP in four mineral sands processing operations. A summary of the data derived from the 24 samples collected in "representative" areas of the processing plants is presented in Table 1 [26].As can be seen in Table 1, the measured mean CED from inhalation of the combination of TnP and RnP was 0.23 mSv, and ranged from a minimumof 0.04 mSv to a maximum of 0.39 mSv, with a potential maximum of 0.92 mSv.

Reporting of radiation doses to the Interim Mines Radiation Committee (IMRC) became more august [27], and additional research was supported, including: characterisation studies of the particle size of dusts inhaled by the workforce [28]; an analysis of the effectiveness of respiratory protection for reducing worker exposures [29]; investigations into the secular equilibrium of the ^{232}Th series [30], and

Table 1: Summary of TnP and RnP Sampling in the MSI

Source	Range (mWL) [1]			CED (mSv) [2]		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
TnP	0.4	16.0	3.2	0.017	0.69	0.14
RnP	0.05	1.8	0.7	0.006	0.23	0.09
Potential Total CED (mSv) [3]				0.023	0.92	0.23
Measured Total CED (mSv)				0.04	0.39	0.23

[1] mWL = milli Working Level, which has been replaced by the SI unit μJm^{-3} , where 1 WL = 20.8 μJm^{-3}

[2] Assuming: 2000 hours exposure; Breathing Rate = 1.2 m^3h^{-1} ; DC (^{220}Rn) = 3.6 mSvWLM^{-1} ; DC (^{222}Rn) = 10.4 mSv WLM^{-1} (WLM = Working Level Month = exposure at a concentration of 1 WL for 170 hours)

[3] Derived from the sum of the contributions from TnP and RnP

2 - As per Part I of this research, the term Mines Inspectorate is applied to the team of Inspectors appointed to assist the SME in ensuring compliance with the WA mine safety legislation [3].

emanation of Tn from monazite [31]; and uncertainties in the calculation of doses from the inhalation of thorium [32, 33].

In June 1989 the WA Minister for Mines commissioned a Technical Audit of Radiation Safety Practises in the Mineral Sands Industry (the Technical Audit) [34] in order to ascertain the level of progress made in implementing the recommendations of the Winn Committee. The Technical Audit accessed papers that were prepared for the IMRC, including reports by Hewson [35, 36] which continued the reporting of doses established in 1988 [27]. The Technical Audit commended the improvements that had been made in regulatory oversight of the MSI, commenting “most of the recommendations of the Winn Committee of inquiry (Winn Committee) have been implemented”. The authors also provided comment in relation to the scrutiny placed on worker exposures, stating “Comprehensive and detailed requirements have been placed on mines operators to assess and to report on radiation exposures ... In large measure, this improvement is attributable to the drive and initiative of the Radiation Secretariat and its ability to liaise effectively with the industry” [34].

The authors of the Technical Audit, Mason, Carter and Johnson made 23 recommendations to the Minister, the majority of which were administrative in nature [37]. Technical recommendations encouraged the continuation of research to refine the models for dose assessment protocols in the industry, with one recommendation (#8) promoting “personal monitoring for inhaled radioactive dust should be carried out for every shift for those workers who may receive a total committed effective dose of 15 mSv or more in a year” [34]. This impost on the MSI ultimately led to: a significant increase in the number of dust samples collected across the industry; pursuit of methods to reduce exposures to LLα; and research to validate integrated personal dosimeters to replace dust sampling as an assessment technique [38].

Such was the volume of activity at the time that WA felt justified in hosting the First International Symposium on Radiation Protection in the Mining, Milling and Downstream Processing of Minerals Sands in 1993 [39]. During the symposium Hewson and Hartley [40] summarised the findings of completed research projects and provided a status update on a number of projects that were in progress such as thorium metabolism [41] and the use of an integrated personal dose assessment instrument [38]. The symposium provided the platform for the release of further research on particle size characterisation studies [42] and the biological properties of inhaled particles [43].

In his report on the proceedings of the Symposium, Koperski [44] stated “It has resulted in better recognition, on a global scale, of the radiation protection issues relevant to the heavy mineral and downstream processing industries”. As the Symposium Convenor and Chair, Koperski could well be challenged as having confirmation bias when he (proudly) declared “Occupational radiation protection in the MSI in Australia is leading the world”. However, Koperski’s opinion had been foreshadowed in 1988 by Fitch (President of the Australian Radiation Protection Society) who suggested “Western Australian ... health physicists have made a very significant contribution to radiation protection ... they frequently seem to be ahead of us in tackling a variety of radiation protection problems” [45].

Over the following handful of years, the SME introduced the requirement for those mining operations required to comply with the radiation safety regulations in the Mines Safety and Inspection Regulations (MSIR) [46] (hereinafter referenced as ”reporting entities”) to submit a Radioactive Waste Management Plan for their operations [47] and identified other potential reporting entities [48]; whilst supporting further research into the biological properties of inhaled particles [49, 50]; and alternate methods for the measurement of internal doses [51, 52].

Despite the advancements that were being made, research into worker dose assessments seemingly moved into the political realm, as was explored by McIntyre [53] who concludes “Australian occupational health and safety has a very serious problem when unions are in a position to veto the public funding of research regardless of its scientific merits, its values or its international credentials". In the latter half of the 1990's, the momentum for research into dose assessment methodologies appears to have dissipated (G Hewson, personal communicationMay 5, 2021), with the research by Terry into thoron-in-breath as a dose assessment technique [49, 52] signaling the end of the post-Winn Inquiry research phase.

From 1999, it is apparent that, other than the evaluation of radiological hazards in zircon plantsby Hartley [54], the findings of the research conducted between 1988 and 1998 became mainstream, and the little research, where it occurred, was conducted in accordance with the operational needs of specific reporting entities (for example Browne's [55] and Sonter and Hondros' [56] investigations into TnP and RnP).

2.2 Development of the 'NORM Guidelines'

The Winn Inquiry, and later, Meunier [57] and Gandini [58] identified the nurturing of appropriately qualified and skilled radiation safety officers (RSOs) as an issue that would negatively impact the pursuit of improved radiation protection across the MSI. According to Hewson [35], the RSS responded by implementing training programs for the nominated industry RSOs, supplemented by seminars for managers and technical officers in the MSI, which were also attended by members of the Mines Inspectorate. Eventually, and apparently in response to pressure from the union representatives on the IMRC [58], the courses and seminars grew in status and were delivered by the university sector [24], and converted into a formal textbook [12].

A tangible outcome of the development of RSOs was the publication of a series of Guidelines, designed to assist the RSO in implementing a system of radiation protection at their mining operation [35]. A suite of ten Guidelines were endorsed by the IMRC and published between August 1986 and October 1988 [24].

Over time the Guidelines have been edited and condensed, and have entered the radiation protection lexicon, as the "NORM Guidelines" [59]. The NORM Guidelines are cited in ARPANSA Radiation Protection Series No.9.1 [14], and have been distributed to numerous regulatory authorities in jurisdictions outside of Australia, some of which have adopted them into their radiation protection legislation [20].

As a result of the changes to Dose Coefficients (DCs) introduced via the International Commission on Radiological Protection (ICRP) publications 137 and 141, NORM Guideline 5 entitled "Dose Assessment" [60] has been revised by the Mines Inspectorate [3], and the SME has promoted the use of the revised DCs in the estimate of worker doses for the 2019-20 reporting period [61].

The NORM Guidelines have proven to be a valuable resource for industry-based RSOs, and continue to play an important role in providing the basis for consistent monitoring and dose estimate methodologies by reporting entities.

2.3 Reporting requirements

According to Hewson [35], the requirement for reporting entities to submit annual reports of worker radiation doses was implemented in 1984. NORM Guideline #8 entitled "Reporting Requirements" was released in November 1987 [24], too late in the calendar year reporting format of the time to align the annual reports from all reporting entities to the new standard for that reporting period. As a result, the standardisation of annual reports can be considered to have effectively commenced in 1988.

In relation to the period prior to 1988, the Mines Inspectorate reflected that "until the recommendations of the 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" [62]. As a result, the doses reported prior to 1986, and probably including those in 1987, have an elevated level of uncertainty, and should be

3 - At time of writing the public consultation process is drawing to a close and publication of the revised guideline, to be retitled as NORM-V to avoid confusion with previous editions, is imminent.

treated with caution.

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 [2, 35].

Over the passage of time, the original NORM Guideline No. 8 has undergone minor edits, and as a result of restructuring of the hierarchy of NORM Guidelines has been renumbered to NORM Guideline No. 6 [63]. With two exceptions, the information provided in annual reports to the SME have been presented in a (mostly) standardised format since 1988:

- In 1992 it was agreed to change the reporting period from a calendar year to a ‘ radiation reporting year’, from 1st April to 31st March. The first radiation reporting year was 1993- 1994; and
- As a result of the withdrawal of support for the Boswell dose reporting system (refer to Section 2.4), in 2017 the Mines Inspectorate directed that an Executive Summary, which included analysis of dose trends for the previous 5 years, be included with annual reports [61].

The consistency in reporting format has contributed significantly to the capacity for the Mines Inspectorate to assess exposures and to identify trends in worker doses in reporting entities, and assisted the authors in compiling the data for this research.

2.4 Computer-based dose calculation, recording and reporting systems

As was reported by Hewson in 1989 [35], “Another project [by the RSS] involves the development of a computer-based radiationexposure recording and reporting system, so that future investigation of worker exposure trends may be based on reliable data”. The initiative, which had commenced in 1988 [2] as a joint project between the RSS and the Chamber of Mines and Energy of Western Australia was largely driven by the:

- complexities associated with calculating CEDs, particularly doses arising from the inhalation of LLα;
- general lack of technical expertise of industry RSOs to effectively and consistently calculate CEDs, as identified in the Winn Inquiry; and
- requirement for the RSS to audit the dose assessments provided by the reportingentities, which was a laborious and time- consuming exercise.

Marshman and Hewson [2] reported that a database application referenced as the Mines Dose Assessment System (MIDAS) was installed at each of the reporting entities in October 1992. The use of MIDAS ensured that the dose calculation process was consistent across operations, whilst allowing for input of site-specific data such as particle size and ^{232}Th to ^{238}U ratio required for calculating internal dose from inhalation of dusts containing NORM. Marshman and Hewson [2] provide an overview of the structure of the database and highlight that “The acceptance of MIDAS by industry has the following benefits for the appropriate authority [the Mines Inspectorate]:

i. all reporting by companies is in a uniform format which expedites the analysis of annual reports; and

ii. the data in these reports can also be transferred electronically”.

Although the MIDAS data were able to be transferred to the Mines Inspectorate electronically, thereby obviating the need for officers of the RSS to attend the mining operations to audit the dose assessment inputs, the submission of hard copies of annual reports continued into the mid-2010’s. In some part this was due to the need for reporting entities to include data that could not be captured within MIDAS, such as maps of surveyed areas; equipment calibration certificates; and environmental data such as radionuclides in soil or water.

At the time that MIDAS was being developed, the MSI had embarked upon a significant campaign of assessing the particle size characteristics of dusts encountered in processing operations [28, 42], and in order to standardise the calculation and reporting of this complex data, the RSS developed two database routines (Marple and Sierra) based upon the Microsoft DBase IV application, and distributed them for use by reporting entities [64].

In the early 2000's, the Chamber of Minerals and Energy of WA funded the development of a replacement for MIDAS. A software application called Boswell, which utilised the Microsoft Access (2000) platform. was developed by the Mines Inspectorate, and implemented in September 2004, with the expectation that the 2004-05 annual reports would be compiled using dose assessment data extracted via Boswell [65].

The transition to Boswell was not smooth, with new functionality seemingly causing confusion amongst industry-based RSOs [66] and multiple examples of errors still being reported in the late 2000's (C. Bovell, personal communicationDecember 7, 2020), [67]. One such report brings attention to the issues, and their impacts on the reporting process "A summary of Work Category external year doses was unable to be provided due to errors being generated by the Boswell program
... and [the] affected information has been excluded from this report" [67]. Many of the hard- copy annual radiation reports include print-outs or PDF copies of selected sections of the Boswell data, however, due to the errors inherent within Boswell, a number of the annual reports submitted at the time were incomplete.

With the advent of Microsoft Access (2013), in May 2014 the Mines Inspectorate opted to withdraw support for Boswell [68]. Despite the withdrawal of support, several reporting entities continue to use Boswell, in the knowledge that many of the reporting functions are flawed. This has created an additional burden for the Mines Inspectorate on the auditing of dose assessments (C. Bovell, personal communication December 7, 2020). Some reporting entities have developed their own automated calculation processes, but in so doing, the consistency brought about by MIDAS and (to some degree) Boswell has been lost.

The deficiencies in Boswell have served to bring back into sharp focus the issue with the capabilities of the industry-based RSOs, as was identified by the Winn Inquiry [69] and repeated as Item 4.1.1 of the 2006 report by Uranium Industry Framework Steering Group [70]. The significant increase in the number of workers potentially exposed to NORs (as was indicated in Part I of this research [3]) has exacerbated the RSO competency issue as highlighted in a 2019 presentation at an international NORM symposium by Tsurikov [71], who contends that the use of software applications such as MIDAS and Boswell have contributed to the skill decay of contemporary RSOs.

What is apparent, is that nearly four decades after the matter of the number, and competence of, industry RSOs in the WA mining sector was identified by the Winn Inquiry, the issue remains largely unresolved.

2.5 *Management of annual radiation reports submitted by reporting entities*

Since 1986 when the Mines Inspectorate became the regulatory authority (RA) for reporting entities, the Department in which the Mines Inspectorate has resided (the Department) has been responsible for the keeping of records associated with the radiation exposure of mine workers. With the advent of the MSIR [46], the SME is required to store records of the:

- Results of baseline radiation monitoring programs submitted by reporting entities in accordance with MSIR 16.6;
- Radiation management plans (RMPs) submitted in accordance with MSIR 16.7;
- Approval and appointments of RSOs in accordance with MSIR 16.9;
- Dose assessments for an employee, in accordance with MSIR 16.25(4) and

16.25(5); and

- The removal, importation, storage, stockpile management and disposal of radioactive material in accordance with MSIR 16.27, 16.28, 16.30, 16.31 and 16.32.

Prior to commencement of mining operations in WA, a proponent must have a project management plan (PMP) approved by the SME [72]. The PMP is required to indicate whether NORM will be encountered in the orebody, production process or mine tailings in sufficient concentrations so as to be deemed as a reporting entity. Operations meeting the reporting entity criteria must have a RMP approved by the SME before operations can commence. As was addressed in the Part I of this research [3], a reporting entity must also provide annual reports of estimates of radiation doses received by the workforce, as per MSIR 16.24, with the report to follow the format as outlined in NORM Guideline No. 6 [63].

In the period prior to the advent of email, hard copies of the annual reports were received by records management officers of the Department, copied and the originals placed on Departmental files created for the sole purpose of establishing an historical record. The copies were forwarded to technical specialists in the Mines Inspectorate for audit and feedback to the reporting entity.

As technology improved, the records management officers of the Department transitioned to creating PDF versions of the submitted hard copies, and storing them in the Department's bespoke electronic record management system, "Records Manager (2005)" [73]. The electronic PDF copies of the report were brought to the attention of the Mines Inspectorate technical specialists as per the previous methodology.

Since the mid-2010's, submissions have been made via email, or the bespoke Mines Inspectorate computer-based record and communication information management system, the Safety Regulation System (SRS) [74]. Whilst the transition to SRS was occurring, an ad hoc process developed whereby some officers opted to forward electronic copies of the annual reports to the records management officers for retention in Records Manager (2005).

2.6 Reports of WA mine worker dose assessments

Subsequent to the Winn Inquiry, the RSS began a process of consolidating the data from the MSI and providing reports on the status of worker doses to the SME and IMRC [27, 35, 75, 76]. Largely, these reports were for internal stakeholders, but following the commencement of the Technical Audit by Mason, Carter and Johnson [34] in 1989, and increased pressure for transparency from external stakeholders, the RSS commenced a program of reporting on the status of doses in the MSI via peer-reviewed publications.

The first such report was published in 1990 by Hewson [77] who summarised the exposure status of the MSI workforce between 1983 and 1988. Hewson commends the reader to consider the findings of the Winn Inquiry for an analysis of dose assessments prior to 1983. An important factor to consider when conducting comparisons with this first report is that in an endeavour to "ensure that the summary statistics are not biased low", Hewson only analysed doses to designated employees (DEs), who had worked in excess of 500 hours in the applicable reporting period.

The second publication was released as a technical report by the Mining Engineering Division (MED) of the Department [78]. This paper established a reporting template that was followed in the third report by Hewson and Marshman in 1993 [62] and replicated by Ralph, Chaplyn and Cattani in 2020 [1].

The final peer-reviewed publication of doses to MSI workers occurred in 1994, when Marshman and Hewson [2] published what amounts to an update of Hewson's original 1990 paper [77] and cites data up to the end of the 1992-93 reporting period.

In 1996, in response to a request from the RCWA, Hewson [79], presented an analysis of doses to MSI workers in the reporting periods from 1993-4 to 1995-96, using the template established by MED in the second publication [78]. Disconcertingly, given that sales of monazite from the WA MSI ceased in May 1994 [80], the mean CED at one of the reporting entities in 1995-96 was reported as 11.5 mSv, and the maximum CED[4] is estimated as 32.1 mSv.

The practice of publication in peer-reviewed journals discontinued after 1994, and the opportunity for reporting entities to benchmark their performance also ceased, until 2005 when Marshman [81] wrote to individual mining operations comparing their dose distribution against other de-identified reporting entities. This practice was repeated the following year [82] but ceased thereafter.

On several occasions through the 2000's the SME responded to RCWA requests for updates to the historical record of doses to workers in reporting entities [83, 84]. The analyses were subject to review by the RCWA, which, on several occasions sought clarification of the supplied data. In January 2009 the SME provided the RCWA with information pertaining to doses for the 2006-07 reporting period [85, 86][5]. The Departmental record of correspondence between the SME and RCWA in relation to mine worker doses appears to end at this juncture [83], until Ralph [87] forwarded a copy of the research by Ralph, Chaplyn and Cattani [1] to the RCWA in 2020.

In 2008, one of the co-authors (NT) was commissioned by the the International Atomic Energy Agency (IAEA) to "compile, from available exposure records ... data from the MSI for 1995 to the present ... and a specified rare earths production facility ... for incorporation into the draft Safety Report on Radiation Protection and Management of NORM residues in the Production of Rare Earths from Thorium- Containing Minerals" [88]. Tsurikov (personal communication, September 23, 2020) confirmed that in order to complete the assignment, he had been able to obtain a copy of the MIDAS and Boswell databases and exposure summaries from each of the operational reporting entities, and where possible, from those operations that had ceased.

In compiling the information on behalf of the IAEA, Tsurikov observed "in many cases the Boswell database that was used by the [reporting entities] at the time was not providing accurate data and the detailed results from each MSI site have been used to re-calculate the radiation exposures of workers – using dose coefficients for the inhalation of radioactive dust that were applicable at the time of the report" (N. Tsurikov, personal communication, September 23, 2020).

Tsurikov summarised the workforce demographics and EDs for the period from 1994-95 to 2007-08, in two reports to the IAEA [89, 90] extracts of which were published as Tables 29 and 113 of IAEA Safety Reports Series No. 68 [91]. Itis noted that although Tsurikov conducted a site- by-site analysis, the WA MSI data cited in IAEA Safety Reports Series No. 68 [91] is aggregated, and although useful for assessing temporal trends across the entire industry, the richness of the individual reporting entity data is absent.

Notwithstanding Tsurikov's 2008 reports [89, 90] which assessed trends across the MSI, the research by Ralph, Chaplyn and Cattani [1], which was based on the MED 1992 template [78], was the first peer-reviewed analysis that allowed reporting entities to benchmark their worker doses since the article by Hewson and Marshman in 1993 [62]. Therefore, there is a gap of over a quarter of a century in the peer-reviewed body of knowledge of radiation doses to WA mine workers.

A coarse review of 148 papers (D. Crouch, personal communication February 24, 2021) published in the Journal of the Australian Radiation Protection Society [92] found 15 papers related to radiological issues in the Australian mining industry. Five of the 15 papers were directly related to uranium mining, with only one paper related to pre-commencement assessment of

4 - Estimated by adding the maximum internal dose to the maximum external dose.

5 - The correspondence cited as reference 214 is replete with errors, including the applicable reporting period being misquoted. The RCWA sought clarification of the supplied data, however, it is not apparent whether the errors were resolved.

a potential operation in WA [93]. In the 19 year period, the authors could locate only one paper written by a WA-based author [94], demonstrating a certain amount of apathy by the WA mining radiation protection community.

Perhaps the gap in the body of knowledge of mining-related doses is not an idiosyncrasy limited to WA? The absence of peer-reviewed worker dose data has been reflected elsewhere, with Sinclair stating "... for [US] nuclear reactor workers the declines in collective dose continue steadily up to the present time [1997]. Unfortunately, no recent general review of occupational radiation exposure in the United states seems to exist" [95]. Sinclair further reflects "This is an unfortunate lapse in the evaluation of recent radiation protection experience that I hope will not remain long unremedied" [95].

In alignment with Sinclair's sentiments, the results of this research address the gap in the body of knowledge in relation to radiation doses received by WA mine workers as a result of their exposure to NORs.

3 METHODOLOGY DEPLOYED IN THIS RESEARCH

3.1 Retrieval of annual reports

As was outlined in Section 2.5, two separate methods coexist for reporting entities to submit their annual reports of worker radiation doses, via hard copy (delivered either by hand or PDF version via email) or via the SRS software application. It was also highlighted that the management of the submissions by the Department's technical specialists has varied overtime which has led, in some circumstances, to identifying the storage location of historicalannual radiation reports problematic. As a result, some of the historical reports could not be located, and therefore there are gaps in the historical record.

The authors enlisted the assistance of the senior Departmental records management officer who interrogated the numerous record-keeping systems and located all of the available annual reports, whether in hard copy or electronic format, dating back to 1992. The records are largely complete from the 2000-2001 reporting period to 2018-19, allowing 166 annual reports to be located for this period, 39 of which had been stored electronically [96].

3.2 De-identified referencing of reporting entities

The information in Hewson and Marshman's 1993 article [62] 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 [81, 82]. A search of the Department records [76] located the keys to the two allocation processes, enabling the original seven mining operations used in the 1992 and 1993 publications [62, 78] to be aligned with that used in subsequent reporting periods[6] .

As was outlined in Section 2.5, a new mining operation must submit a PMP to the SME, and if it meets the criteria for reporting entities, must have an RMP approved prior to commencing operations. Records have been maintained by the Department of the dates on which RMPs have been approved [73, 74], and a numerical reference allocated in sequential order by the date of receipt of the RMP.

Twenty-eight reporting entities have been provided with a discrete numerical identifier.

3.3 Extraction of data from annual reports

All of the annual reports included dose assessments in which the worker was de-identified by replacing their name with their ' employeenumber' (either a payroll identifier manually entered by the reporting entity, or a reference number automatically generated by the MIDAS or Boswell software). A small number of the annual reports included individual worker names, which were not required for the purpose of this

6 - The reporting entity located in Jurien ceased operating in 1977, prior to the alpha-coding system being implemented. This reporting entity has been allocated the numerical code "0".

assessment. The Department's records management officers redacted the worker names from the reports, and forwarded the de-identified reports to the corresponding author.

Because of the lack of issues identified with the MIDAS software, each annual report for the MIDAS-era was interrogated for the dose-related data, from the consolidated information as it appeared in the report. Random audits of the consolidated data were conducted by analysing the individually reported data and correlating the results with the consolidated data. Audits were conducted on five of the 34 reports recovered by the Department's records management officers that were submitted between 2000-01 and 2004- 05 [97].

As was discussed in Section 2.4, issues were encountered from the outset with the implementation of Boswell as typified by the discussion in a report in 2007-08 submitted by Site #7 "the calculated figure [for external γ] does not agree with the actual [external dose from γ] for the year" [67]. As a result of these errors, the authors chose to not use the Boswell consolidated reports. Fortunately, the majority of annual reports that were produced whilst Boswell was in use, included print outs from the suite of reports that were able to be produced via the Boswell software. One of those reports, Boswell #23, ' EDE by employee number' includes much of the raw data needed for this research. Therefore, unlike the process applied to the MIDAS- generated reports, statistics for the Boswell period of this research were generated by manually assessing the de-identified individual records of the 2715 DEs (plus other non-DEs included in evaluations of the doses at new operations) included in the 139 annual reports submitted between the 2005-06 and 2018-19 reporting periods [97].

Each of the annual reports was interrogated for demographic data including the number of workers on site; the number of DEs; and the maximum and mean number of hours worked per year. Data pertaining to the three main pathways of exposure were identified, and the number of samples collected; the maximum and mean concentration of LLα and RnP/TnP recorded; and the maximum and mean dose from each pathway extracted. The maximum and mean CED in each annual report were recorded [97].

Tsurikov provided the data from the 2009 research [89, 90] to the corresponding author (N. Tsurikov, personal communication February 22, 2019), and where original copies of annual radiation reports were unable to be located, or specific data (e.g. mean LLα concentration) was absent, the Tsurikov [91] data has been used.

3.4 Recording of extracted data

A standard recording template was developed as a spreadsheet within Microsoft Excel (2016). Data from the annual reports for the 2018-19 reporting period was extracted and inserted into the spreadsheet, following the numeric site coding system for each reporting entity established as per Section 3.1.

Once the relevant data had been completely entered, the spreadsheet was duplicated and renamed, and the 2017-18 data was entered. This process was repeated until the 1993-94 information had been entered into the Microsoft Excel (2016) workbook.

In the absence of annual reports, the spreadsheets were completed by extraction of relevant data from the publications listed in Section 2.6, thereby completing the record back to the 1986 reporting year. Prior to 1986, data was extracted from the report of the Winn Inquiry and supplemented by, the Tsurikov [91] data.

Several additional spreadsheets were added to the Microsoft Excel (2016) workbook to enable statistical analysis and graphical representation of the collected data [97].

4 FACTORS AFFECTING REPORTED DOSES IN WA REPORTING ENTITIES

4.1 Number of reporting entities

The history of the mining industry in WA is replete with new entrants into the sector, project closures, mergers, acquisitions and consolidation driven largely by the cyclical nature of commodity prices and the exhaustion of economically extracted mineral resources from established deposits.

Reporting entities are a microcosm of the State's mining industry, and have exhibited a similar history to the rest of the mining industry. When Marshman and Hewson [2] published their research in 1993, they analysed data provided by seven reporting entities operating in the MSI. A further reporting entity was known to the Mines Inspectorate, but was excluded from the research, because of its specific focus on the MSI. At the turn of the new millennium only five of the eight reporting entities were still operating [97] and submitted annual reports for the 1999-2000 reporting period.

A decade later, one of the operations that had closed had recommenced operating, and a second was not mining, but was actively processing small volumes of mineral sands. Ten new operations had commenced in the decade, but six of these had subsequently closed by the time of the 2009-10 reporting period. An additional two sites had been identified as potential reporting entities and were being evaluated as to their status. A total of 21 reporting entities had either submitted, or were in the process of submitting RMP's, 11 of which were still operating and required to provide annual reports to the SME for the 2009-10 reporting period [97].

By the 2018-19 reporting period, the operation processing small volumes of mineral sands had closed. One of the reporting entities that closed in the previous decade recommenced, only to close again soon thereafter. A further operation had commenced, closed and recommenced. Three new reporting entities had commenced operating, with a further four mining operations being evaluated as to whether they should be considered as reporting entities. Three sites had been provided with partial exemptions, but the exemption conditions were subject to review as a result of the implication of ICRP-137 and ICRP-141 being applied to their operations.

The number of reporting entities that had operated, or were still operating in WA had increased to 28, 14 of which provided annual reports to the SME for the 2018-19 reporting period [97].

The boom-and-bust commodity cycle and the entrance / departure of reporting entities were factors that needed to be considered when evaluating trends in workforce exposures.

The number of reporting entities, by year, in the period from 1986 to 2018-19 is illustrated in Figure 1. Note that prior to 1986, the number of reporting entities was consistent, at 6.

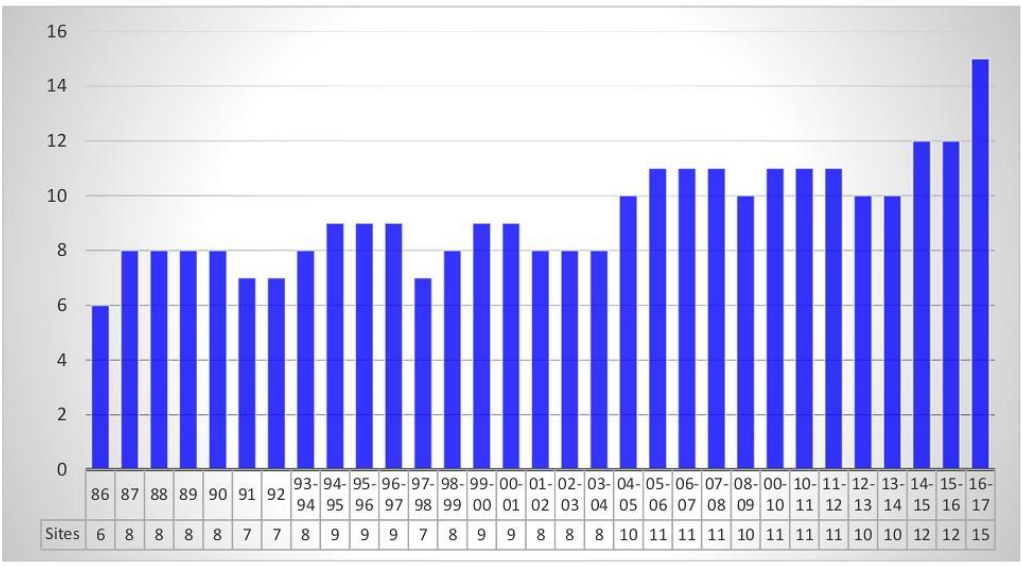


Figure 1: Number of Reporting Entities by Year, 1986-87 to 2018-19

4.2 Designated employees (DEs)

As was discussed by Ralph, Chaplyn and Cattani [1], the emphasis in the research published by Hewson [77], Mining Engineering Division [78], Hewson and Marshman [62] and Marshman and Hewson [165] was on analysing the CEDs received by DEs. In 1993, 212 workers (14.2% of the MSI workforce) were deemed as being DEs, due to their potential to receive CEDs greater than 5 mSv per annum (ie 10% of the annual limit of 50 mSv).

In 1995 the MSIR [46] was gazetted, bringing a derived annual dose limit of 20 mSv into effect. The Mines Inspectorate considered reducing the criteria for a DE to 2 mSv, thereby retaining the definition as 10% of the derived annual limit [98]. An analysis by Marshman [81] indicated that should the decrease be implemented, the number of DEs in the previous two reporting periods would increase from 135 to 220 (1993-94) and 110 to 156 (1994-95). The European Atomic Energy Community (Euratom) defined a similar categorization approach, where Category A workers are broadly equivalent to DEs in Australia. Euratom opted to use three-tenths of the annual limit as the reference point for Category A workers, equivalent to an annual effective dose of 6 mSv [99]. The Euratom position proved persuasive, and as a result the definition of a DE remained at 25% of the revised derived limit, equivalent to 5 mSv per annum.

Ralph, Chaplyn and Cattani [1] highlight that in the ensuing period, there has been confusion amongst reporting entities as to which cohort of their operations should be deemed as DEs, with some operations adhering to the "potential annual CED of 5 mSv" whilst others report any worker who participates in the radiation monitoring program is categorised as a DE.

The inconsistency in application of the definition of DE is problematic to this analysis.

4.3 Reporting of CED's less than 5 mSv

Ralph, Chaplyn and Cattani [1] reflected on the inconsistently applied definition of DE, stating "A difficulty occurs when endeavouring to compare the contemporary data to that published in 1992-93... [when] 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". The authors noted that "212 workers were deemed as DEs in 1993, and of these 157 received CEDs in excess of 5 mSv, and therefore had the source of their doses evaluated". Ipso facto the remaining 1339 workers (89.5% of the workforce) received CEDs less than 5 mSv, and their exposures were not fully evaluated.

Although they contemplated the impending reduction of the annual dose limit to 20 mSv, Marshman and Hewson [2] could not be aware of its significance a quarter of a century later. Ralph, Chaplyn and Cattani [1] point out "The maximum CED reported in 2018-19 of 4.4 mSv, ... is 22% of the derived annual limit of 20 mSv and warrants detailed evaluation, whereas in 1993 it would have attracted minimal, if any, attention, as it represented 8.8% of the annual limit".

The analysis performed by Tsurikov [89, 90] replicated that of MED [78] and did not produce in-depth analysis of CEDs less than 5 mSv. Therefore, although the derived annual limit of 20 mSv was implemented in 1995, an assessment of the doses below 5 mSv could not be constructed until the 2000-2001 reporting period at which time the Department's records are "largely complete".

The analysis in this research provides an amalgamated report of doses less than 5 mSv in the period leading up to and including the 1999- 2000 reporting period, and a more detailed analysis thereafter.

4.4 Dose coefficients and dose conversion factors

Because the radiation dose arising from intakes of dust containing NORs cannot be measured directly, 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.

As was outlined in Part I of this research [3], the models, which apply DCs to determine the dose from the intake of inhaled dusts containing LLα to CED, measured in mSv, have evolved since the first simple model was introduced by ICRP in 1959 [100]. With each iteration of ICRP's models, changes (if any) to DCs for members of the ^{232}Th and ^{238}U decay series willimpact on the dose conversion factors (DCFs) [7] for inhaled dusts containing NORs.

In Part I of this research [3], it was outlined that a seven-fold reduction in the DACs for inhaled dusts occurred between 1983 and 1986 asa result of revisions of DCs. Following publication of revised DC's published in ICRP 68 [101]; a revised model of the human respiratory tract in ICRP 66 [102]; and a systemic model for thorium in ICRP 69 [103], in the mid-1990's, DCFs applicable to WA's reporting entities decreased by a factor of 2.9 times from 0.028 mSvBq^{-1} [104] to 0.0097 mSvBq^{-1} [104, 105]. All other things being equal, doses arising from the inhalation of LLα should have decreased accordingly.

In 2009 following a revision to the NORM-5 Guideline, the SME wrote to reporting entities advising them of a relaxation of the DCF for dusts containing members of the ^{232}Th series in secular equilibrium. The DCF reduced from 0.0097 mSvBq^{-1} to 0.008 mSvBq^{-1} , and the doses arising from the inhalation of LLα should have decreased accordingly.

All of the annual reports assessed in this research were submitted prior to the release of ICRP-141 in December 2019. Accordingly, all CEDs reviewed in this research have been treated as they have been submitted to the SME by the reporting entities. However, it is noteworthy, that with the advent of the revised DCs published in ICRP-137 and ICRP-141 [106, 107], DCFs for ' typical' NOR-containing dusts in WA operations are forecast to double from those applied in previous reporting periods [20, 108].

5 RESULTS

5.1 The early years: 1977 to 1992 (calendar year reports)

A summary of the workforce demographics, analysis of dose estimates and a synopsis of the industry-wide monitoring programs for the calendar years from the earliest recorded assessment, made in 1977 until the Winn Committee of Inquiry in 1984 are presented in Tables 2 and 3.

The same information for the post-Winn Inquiry period, culminating in the last of the information published in a peer-reviewed journal for the 1992 reporting year is presented in Tables4 and 5.

The information reported in Tables 2, 3, 4 and 5 have been compiled from data reported in:

1. The Winn Inquiry [69];
2. Internal reports for the SME and IMRC by Hewson [27, 35, 36, 75, 76, 109];
3. Published articles by Hewson [77]; the Mining Engineering Division of the Department of Minerals and Energy WA [78]; Hewson, Kvasnicka and Johnston [18]; Hewson and Marshman [62]; and Marshman and Hewson [2];
4. Research by Tsurikov [89] published by the IAEA in IAEA 68 [91].

Some salient points in relation to the information provided in 2, 3, 4 and 5:

a) Up to 1989, summarised reports were provided to the SME and IMRC, based upona calendar year reporting period. Although this changed to the "radiation reporting year" in subsequent years, the reporting entities retained the calendar year as the bass for collecting and reporting their data, as illustrated in Table 29 of IAEA 68 [91];

b) The tin/tantalum operation, which was

7 - A DC applies to an individual radionuclide, whereas a DCF applies to a combination of radionuclides in secular equilibrium.

identified as having radiological characteristics, was not subject to reporting obligations. The 15 reports listed as ‘ not submitted’ all derive from this operation;

c) There are substantial discrepancies between the doses received from inhalation of LLα as hypothesised in Section 5.6 of the Report of the Winn Committee of Inquiry [69] and the doses retrieved by Tsurikov [89], and subsequently published in Table 29 of IAEA 68 [91]. Where a discrepancy occurs, in Table 2, and consequently in Table 3, the IAEA 68 data has been used;

d) As per [69] monitoring of external γ was not routinely conducted in the MSI until requested by the RCWA in 1978. Therefore, the mean external γ data reported in Table 2is absent for 1977, and must be treated with caution in 1978, and potentially 1979, due to low sample numbers;

e) The Department File 840/90 [76] contains hand-written notes that completes the record for external γ doses for the 1984 and 1985 reporting periods, as shown in Tables 2 and 4. The reports provided to the SME and IMRC constitute the official historical record, and have been used as the primary source in this research. This data largely correlates with that published in Table 29 of IAEA 68 [91], providing confidence in the data in Tables 2, 3, 4 and 5 from 1986 onwards;

f) In all of the reports provided to the SME and IMRC from 1986 onwards in Tables 2 and 4, only employees (including DEs) who worked greater than 500 hours in any working period were included in the reported analysis. This approach has the potential to decrease the actual number of workers in the industry whilst upwardly biasing the reported dose estimates;

g) An operation in the Jurien Bay district (numerically coded as “0”) closed during 1977. However, the number of reporting entities did not decrease the following year because an operation commenced in the Eneabba district during 1978.

5.2 The MIDAS years: 1993-94 to 2003-04

In 1993, reporting entities implemented the “radiation reporting year”, which required the reporting of the radiological characteristics and worker dose estimates from the 1st April each year to the 31st of March the following year.

A summary of the workforce demographics, analysis of dose estimates and a synopsis of the industry-wide monitoring programs extractedfrom 90 annual reports over the eleven radiation reporting years from 1993-94 to 2003-04 are presented in Tables 6, 7, 8 and 9. This period coincides with the advent of the initial approach to standardise dose calculation protocols via the computer-based Mines Dose Assessment System (MIDAS).

The information reported in Tables 6, 7, 8 and9 have been compiled from:

1. The Hewson report to RCWA [79] (which completes the record from 1993 to 1996);

2. Research by Tsurikov [89] published by the IAEA [91];

3. Files extracted from the Department’s records [96, 97, 110].

Some salient points in relation to the information provided in Tables 6, 7, 8 and 9:

a) Some reports did not contain all of the data required for this analysis. Where the relevant data was unable to be retrieved, data from Tsurikov [89, 111] or IAEA 68 [91] has been used.

b) The one report ‘ not submitted’ was from the tin/tantalum operation, which was identified as having radiological characteristics, but was not subject to reporting obligations.

c) A detailed analysis of CEDs less than 5 mSv was able to be conducted from 2000-01 onwards. As a result, the format of Table 8 changes from that in Table 6.

Table 2: Radiological Parameters and Doses to Mine Workers 1977 to 1984

Parameter	1977	1978	1979	1980	1981	1982	1983	1984
Number of Operations [1]	6 (5)	6 (5)	6 (5)	6 (5)	6 (5)	6 (5)	6 (5)	6 (5)
Workforce	Unknown				765 [3]	Unknown	Unknown	771 [4]
Designated Employees	Unknown				67 [3]	Unknown	314 [4]	223 [4]
Workers in Dose Range (mSv):								
0.0 to 1.0	Unknown							
1.01 to 5.0								
5.01 to 10.0								
10.01 to 15.0								
>15 (>50)								
Max. External γ (mSv)	Unknown						17.7 [4]	9.1 [4]
Mean External γ (mSv)	Unknown	6.8 [3]	6.3 [3]	3.5 [3]	3.4 [3]	4.4 [3]	3.5 [4]	3.0 [4]
Max. Internal Dose (mSv)	Unknown						66 [4]	92 [4]
Mean Internal Dose (mSv)	50.7 [2]	32.6 [2]	28.7 [2]	27.8 [2]	27.2 [2]	25.9 [2]	16 [4]	23 [4]
Collective Dose (man.mSv)	Unknown				2748 [4]	Unknown	5990 [4]	6298 [4]

[1] Number of reporting entities in parentheses.

[2] From Table 29 of IAEA-68 [91]. Note that this table cites CED, but does not include doses from external γ.

[3] From page 5.5 of the Report of the Winn Inquiry [69].

[4] From page 7 and 8 of Hewson [77], or Folio 11 of The Department File 840/90 [76], and includes an assumed 1 mSv per non-DE.

Table 3: Analysis of Radiological Parameters 1977 to 1984

Parameter	1977	1978	1979	1980	1981	1982	1983	1984
Workforce [1]	Unknown				765	Unknown	Unknown	771
Designated Employees [1]	Unknown				67	Unknown	314	223
DEs: Workforce (%)	Unknown				8.8%	Unknown	Unknown	28.9%
External γ Assessments	Not reported in this period							
Personal Dust Samples	Not reported in this period						244 [6]	278 [6]
Mean LLα (mBqm^{-3})	353 [2]	227 [2]	200 [2]	194 [2]	189 [2]	181 [2]	124 [2]	126 [2]
Mean CED per DE (mSv)	50.7 [1]	39.4 [3]	35.0 [3]	31.3 [3]	30.6 [3]	30.3 [3]	19.5 [3]	26.0 [3]
Collective Dose (man.mSv)	Unknown				2748 [4]	Unknown	5990 [1]	6298 [1]
Mean Worker CED (mSv)	Unknown				3.6 [5]	Unknown	Unknown	8.2 [5]

[1] From Table 2.
[2] From Table 113 of IAEA-68 [91].
[3] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 2.
[4] Calculated by multiplying the DE's by mean CED per DE. The original data was limited and therefore the reported result should be considered as a 'best estimate'.
[5] Calculated by dividing the Collective Dose by the number of workers.
[6] From Folio #30 of the Department File 840/90 [76].

Table 4: Radiological Parameters and Doses to Mine Workers 1985 to 1992

Parameter	1985	1986	1987	1988	1989	1990	1991	1992
Number of Operations [1]	6 (5)	6 (5)	6 (5)	6 (5)	8 (7)	8 (7)	8 (8)	8 (7)
Workforce	721 [2]	863 [3]	1113 [3]	1314 [3]	1746 [3]	1685 [3]	1609 [3,4]	1496 [3]
Designated Employees	270 [2]	266 [2,3]	287 [2,3]	301 [3]	331 [3]	287 [3]	217 [3,4]	212 [3]
Workers in Dose Range (mSv):								
0.0 to 1.0	Unknown	623 [3]	867 [3]	928 [3]	1136 [3]	1492 [3]	1475 [3,4]	1339 [3]
1.01 to 5.0								
5.01 to 10.0	Unknown	60 [3]	94 [3]	256 [3]	176 [3]	153 [3]	126 [3,4]	152 [3]
10.01 to 15.0								
>15 (>50)	Unknown	180 (26) [3]	152 (13) [3]	130 (1) [3]	121 (0) [3]	40 (0) [3]	8 (0) [3,4]	5 (0) [3]
Max. External γ (mSv)	8.7 [2]	8.8 [2,3]	10.4 [2,3]	8.3 [3]	6.3 [3]	5.0 [3]	5.2 [3,4]	4.9 [3]
Mean External γ (mSv)	2.8 [2]	2.4 [2,3]	1.7 [2,3]	2.1 [3]	2.0 [3]	1.4 [3]	1.1 [3,4]	1.5 [3]
Max. Internal Dose (mSv)	175 [2]	77 [3]	98 [3]	58 [3]	43 [3]	28 [3]	16.5 [3,4]	15.6 [3]
Mean Internal Dose (mSv)	28 [2]	22 [3]	18 [3]	15 [3]	13 [3]	7.2 [3]	4.3 [3,4]	6.3 [3]
Collective Dose (man.mSv)	8791 [2]	7097 [3]	6526 [3]	6114 [3]	5815 [3]	3898 [3]	2592 [3,4]	2984 [3]

[1] Number of reporting entities in parentheses.

[2] From pages 7 and 8 of Hewson [77], or Folio 11 of The Department File 840/90 [76].

[3] From Table 1 of Marshman and Hewson [2], and includes an assumed 1 mSv per non-DE.

[4] A tin processing operation was included as a reporting entity. Data has been extracted from Table 3 of Hewson, Kvasnicka and Johnston [18].

Table 5: Analysis of Radiological Parameters 1985 to 1992

Parameter	1985	1986	1987	1988	1989	1990	1991	1992
Workforce [1]	721	863	1113	1314	1432	1685	1609	1496
Designated Employees [1]	270	266	287	301	331	287	217	212
DEs: Workforce (%)	37.4%	30.8%	25.8%	22.9%	23.1%	17.0%	13.5%	14.2%
External γ Assessments	Not reported in this period							
Personal Dust Samples	508 [4]	631 [6]	1408 [6]	2011 [6]	2575 [6]	2072 [6]	1981 [6]	2032 [6]
Mean LLα (mBqm^{-3})	170 [5]	850 [6]	600 [6]	510 [6]	490 [6]	270 [6]	160 [6]	180 [6]
Mean CED per DE (mSv) [2]	30.8	24.4	19.7	17.1	15.0	8.6	5.4	7.8
Collective CED (man.mSv) [1]	8791	7097	6526	6114	5815	3898	2592	2984
Mean Worker CED (mSv) [3]	12.2	8.2	5.9	4.7	4.1	2.3	1.6	2.0

[1] From Table 4.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 4.

[3] Calculated by dividing the Collective Dose by the number of Workers.

[4] From Folio #30 of The Department File 840/90 [76].

[5] From Table 113 of IAEA-68 [91].

[6] From Tables 5 and 6 of Hewson [79].

d) As was highlighted in Section 4.2, and discussed at length by Ralph, Chaplyn and Cattani [1] an inconsistency arises in this period in the application of the definition of a Designated Employee. It is apparent that any worker who participated in a monitoring programme was categorised as a DE. From Table 8 onwards, the DE data has been retitled to "Monitored Workers", and all workers who worked greater than 200 hours in the reporting period are included in the analysis.

5.3 The Boswell years: 2004-05 to 2012-13

In 2004 the ageing MIDAS system was replaced with a new, bespoke computer-based dose reporting and recording software application called Boswell, written and maintained by the Mines Inspectorate. As was highlighted in Section 2.4, reports submitted by reporting entities in the nine-year period from when Boswell was firstimplemented in 2004-5 to when the Mines Inspectorate withdrew support in 2012-13 were beset with issues, notably with some of the reporting functions.

All of the 91 annual reports expected to be submitted by reporting entities over the nine-year period were retrieved by the Department's records management team, or were resubmitted upon request by the reporting entities. Each report was thoroughly assessed, by interrogating the input data and manually re-calculating relevant demographic and statistical information.

A summary of the workforce demographics, analysis of dose estimates and a précis of the industry-wide monitoring programs for the four reporting years from 2004-05 to 2007-08 are presented in Tables 10 and 11. This period was selected as it coincides with the last four years of the data retrieval project reported by Tsurikov [89, 111] and therefore the two data sets can be compared. Where a discrepancy was found, the Tsurikov data has been used to populate the Tables.

The same information for the post-Tsurikov analysis period, from 2008-09 to 2012-13 is presented in Tables 12 and 13.

5.4 The post-Boswell years: 2013-14 to 2018-19

A summary of the workforce demographics, analysis of dose estimates and a synopsis of the industry-wide monitoring programs for the six radiation reporting years from 2013-14 to 2018-19 are presented in Tables 14 and 15.

The analysis of annual reports for this period followed that of the Boswell years: each report had to be carefully analysed, using the input data and recalculating the relevant demographic and statistical parameters. The original data needed to prepare two reports, deriving from the same operation (#7), for the periods 2013-14 and 2014- 15 had been misplaced by the reporting entity, and reports could not be prepared. As a result, 68 annual reports were assessed during this stage of the analysis.

Importantly, and in line with an increased focus on the contribution of radon and thoron to CED:

- In 2013-14 reporting entity #15 commenced monitoring for RnP and TnP exposures. A maximum contribution of 1.2 mSv and a mean of 0.2 mSv were reported;
- In 2014-15, entities #3 and #9 commenced reporting CEDs from RnP and TnP. All three reporting entities reported doses from RnP and TnP in 2015-16;
- In 2016-17, reporting entities #6 and #18 commenced reporting CEDs from RnP and TnP, bringing the total to five operations. The reporting was repeated in 2017-18.
- In 2018-19, reporting entities #7 and #8 commenced reporting CEDs from RnP and TnP, bringing the total to seven operations, equivalent to 50% of the reporting entities, making assessments for the contribution of RnP and TnP to CED.

The contributions from RnP and TnP for those sites that have conducted monitoring have been included in the information reported for internal dose assessment in Tables 14 and 15.

Table 6: Radiological Parameters and Doses to Mine Workers 1993-94 to 1999-2000

Parameter	1993-94	1994-95	1995-96	1996-97 [3]	1997-98 [3]	1998-99 [3]	1999-2000 [3]
Number of Operations [1]	7 (6)	7 (7)	8 (8)	9 (9)	9 (9)	9 (9)	7 (7)
Workforce	1504 [2]	1667 [2,4]	1373 [2,4]	1213	1100	927	662
Designated Employees	217 [2]	190 [2,4]	195 [2,4]	218	157	190	101
Workers in Dose Range (mSv):							
0.0 to 1.0	1292 [3]	1282 [3,4]	1008 [3,4]	877	752	592	448
1.01 to 5.0	184 [3]	327 [3,4]	314 [3,4]	309	317	273	163
5.01 to 10.0	27 [3]	47 [3,4]	43 [3,4]	26	30	62	18
10.01 to 15.0	1 [3]	3 [3,4]	2 [3,4]	1	1	0	0
>15	0 [2,3]	8 [3,4]	6 [3,4]	0	0	0	0
Max. External Dose (mSv)	3.5 [2]	4.5 [2]	4.9 [2]	5.0	5.0	5.0	3.5
Mean External Dose (mSv)	1.3 [2]	1.0 [2]	0.7 [2]	1.0	0.8	0.8	0.6
Max. Internal Dose (mSv)	17.0 [2]	18.0 [2]	27.2 [2]	7.5	8.4	5.1	4.1
Mean Internal Dose (mSv)	5.2 [2]	4.8 [2]	6.0 [2]	1.3	1.4	1.4	1.2
Collective Dose (man.mSv)	2876 [2]	3177 [2]	2878 [2]	2862 [5]	2571 [5]	2102 [5]	1528 [5]

[1] Number of reports received from the reporting entities in parentheses.
[2] From Table 2 of Hewson [79], and includes an assumed 1 mSv per non-DE.
[3] Data is from Tsurikov [89] and analysis of annual reports submitted by the reporting entities, unless otherwise indicated.
[4] Includes contribution from the tin operation, extracted from Folios 98-101 of The Department File 840/90 [76] or DME File 2176/99 [112].
[5] From Tsurikov [89]. Includes all workers, whereas in the period prior to 1996-97, only doses to Designated Employees were reported.

Table 7: Analysis of Radiological Parameters 1993-94 to 1999-2000

Parameter	1993-94	1994-95	1995-96	1996-97 [4]	1997-98 [4]	1998-99 [4]	1999-2000 [4]
Workforce [1]	1504	1667	1373	1213	1100	927	662
Designated Employees [1]	217	190	195	218	157	190	101
DEs: Workforce (%)	14.4%	11.4%	14.2%	18.0%	14.3%	20.5%	15.3%
External γ Assessments	1501 [4]	1716 [4]	1769 [4]	1599	1883	1653	1269
Personal Dust Samples	1871 [5]	2045 [4]	1958 [4]	2292	2520	2328	1806
Mean LLα ($mBqm^{-3}$)	170 [5]	133 [4]	99 [5]	143	127	123	126
Mean CED per DE (mSv) [2]	6.5	5.8	6.7	2.3	2.2	2.2	1.8
Collective CED (man.mSv) [1]	2876	3177	2878	2862	2571	2102	1528
Mean Worker CED (mSv) [3]	1.9	1.9	2.1	2.4	2.3	2.3	2.3

[1] From Table 6.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 6.

[3] Calculated by dividing the Collective Dose by the number of Workers.

[4] From Tsurikov [89] and analysis of annual reports submitted by the reporting entities, including the tin operation.

[5] From Tables 5 and 6 of Hewson [79].

Table 8: Radiological Parameters and Doses to Mine Workers 2000-01 to 2003-04

Parameter	2000-01 [2]	2001-02 [2]	2002-03 [2]	2003-04 [2]
Number of Operations [1]	8 (8)	9 (9)	9 (9)	8 (8)
Workforce	1006	898	764	672
Monitored Workers	398	298	399	387
Workers in Dose Range (mSv):				
0.0 to 1.0	830	707	542	492
1.01 to 2.0	60	69	95	42
2.01 to < 3.0	51	46	48	58
3.01 to 4.0	14	41	25	31
4.01 to 5.0	16	17	9	15
5.01 to 10.0	35	18	31	33
>10.01	0	0	14	1
Max. External Dose (mSv)	3.5	2.3	2.1	2.9
Mean External Dose (mSv)	0.5	0.4	0.4	0.5
Max. Internal Dose (mSv)	7.4	4.7	14.3	8.4
Mean Internal Dose (mSv)	1.4	1.0	1.5	1.4
Collective Dose (man.mSv)	1694 [3]	1468 [3]	2602 [3]	2087 [3]

[1] Number of reports received from the reporting entities in parentheses.

[2] From Tsurikov [89] and analysis of annual reports submitted by the reporting entities, unless otherwise indicated.

[3] From Tsurikov [89].

Table 9: Analysis of Radiological Parameters 2000-01 to 2003-04

Parameter	2000-01 [2]	2001-02 [2]	2002-03 [2]	2003-04 [2]
Workforce [1]	1006	898	764	672
Monitored Workers [1]	398	298	399	387
Monitored Workers (%)	39.6%	33.2%	52.2%	57.6%
External γ Assessments	976	810	1302	1263
Personal Dust Samples	1444	1317	1683	1595
Mean LLα ($mBqm^{-3}$)	136	132	103	90
Mean CED per MW (mSv) [3]	1.9	1.4	1.9	3.6
Collective CED (man.mSv) [1]	1694	1468	2602	2087
Mean Worker CED (mSv) [4]	1.7	1.6	3.4	3.1

[1] From Table 8.

[2] From Tsurikov [89] and analysis of annual reports submitted by the reporting entities.

[3] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 8.

[4] Calculated by dividing the Collective Dose by the number of Workers.

Table 10: Radiological Parameters and Doses to Mine Workers 2004-05 to 2007-08

Parameter	2004-05 [2]	2005-06 [2]	2006-07 [2]	2007-08 [2]
Number of Operations [1]	8 (8)	8 (7)	10 (10)	11 (11)
Workforce	713	635	740	1217
Monitored Workers	323	378	348	301
Workers in Dose Range (mSv):				
0.0 to 1.0	532	476	535	960
1.01 to 2.0	65	90	71	112
2.01 to < 3.0	60	41	23	61
3.01 to 4.0	44	14	36	55
4.01 to 5.0	7	7	37	20
5.01 to 10.0	5	7	35	9
>10.01	0	0	3	0
Max. External Dose (mSv)	3.2	3.2	3.5	8.0
Mean External Dose (mSv)	0.5	0.6	0.4	0.6
Max. Internal Dose (mSv)	4.4	4.7	9.1	4.8
Mean Internal Dose (mSv)	1.1	1.0	0.9 [4]	1.2 [4]
Collective Dose (man.mSv)	1452 [3]	1206 [3]	1906 [3]	2511 [3]

[1] Number of reports received from the reporting entities in parentheses.

[2] From Tsurikov [89] and analysis of annual reports submitted by the reporting entities, unless otherwise indicated.

[3] From Tsurikov [89].

Table 11: Analysis of Radiological Parameters 2004-05 to 2007-08

Parameter	2004-05	2005-06	2006-07	2007-08
Workforce [1]	713	635	740	1217
Monitored Workers (MW)	323	378	348	301
Monitored Workers (%)	45.3%	59.5%	47.0%	24.7%
External γ Assessments	1126	1294	1464	1038
Personal Dust Samples	2018	1927	1456	1181
Mean LLα ($mBqm^{-3}$)	76	91	64	80
Mean CED per MW (mSv) [2]	1.6	1.6	1.3 [4]	1.8 [4]
Collective CED (man.mSv) [1]	1452	1206	1906	2511
Mean Worker CED (mSv) [3]	2.0	1.9	2.6	2.1

[1] From Table 10.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 10.

[3] Calculated by dividing the Collective Dose by the number of Workers.

[4] Includes contribution from RnP / TnP.

Table 12: Radiological Parameters and Doses to Mine Workers 2008-09 to 2012-13

Parameter	2008-09	2009-10	2010-11	2011-12	2012-13
Number of Operations [1]	11 (11)	11 (11)	10 (10)	11 (11)	11 (11)
Workforce	628	556	552	664	662
Monitored Workers	331	248	240	216	171
Workers in Dose Range (mSv):					
0.0 to 1.0	424	431	415	564	529
1.01 to 2.0	95	62	91	65	113
2.01 to < 3.0	75	38	37	27	9
3.01 to 4.0	21	18	8	5	1
4.01 to 5.0	7	3	1	3	0
5.01 to 10.0	5	3	0	0	0
>10.01	1	1	0	0	0
Max. External Dose (mSv)	3.9	4.0	2.0	2.2	1.5
Mean External Dose (mSv)	0.4	0.3	0.2	0.2	0.3
Max. Internal Dose (mSv)	9.3	9.3	2.8	3.9	2.4
Mean Internal Dose (mSv)	0.7 [2]	0.4	0.7	0.8 [2]	0.5
Collective Dose (man.mSv)	784	556	452	480	533

[1] Number of reports received from the reporting entities in parentheses.
[2] Includes contribution from RnP / TnP.

Table 13: Analysis of Radiological Parameters 2008-09 to 2012-13

Parameter	2008-09	2009-10	2010-11	2011-12	2012-13
Workforce [1]	628	556	552	664	662
Monitored Workers [1]	331	248	240	216	171
Monitored Workers (%)	52.7%	44.6%	43.5%	32.5%	25.8%
External γ Assessments	864	682	731	987	697
Personal Dust Samples	975	668	519	709	414
Mean LLα (mBqm^{-3})	66	82	97	76	63
Mean CED per MW (mSv) [2]	1.1 [4]	1.0	0.9	1.0 [4]	0.8
Collective CED (man.mSv) [1]	784	556	452	480	533
Mean Worker CED (mSv) [3]	1.2	1.0	0.8	0.7	0.8

[1] From Table 12.
[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 12.
[3] Calculated by dividing the Collective Dose by the number of Workers.
[4] Includes contribution from RnP / TnP.

Table 14: Radiological Parameters and Doses to Mine Workers 2013-14 to 2018-2019

Parameter	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
Number of Operations [1]	11 (10)	10 (9)	10 (10)	12 (12)	12 (12)	15 (15)
Workforce	446	462	434	545	593	1524
Monitored Workers	143	116	82	102	78	248
Workers in Dose Range (mSv):						
0.0 to 1.0	342	395	359	404	487	1362
1.01 to 2.0	92	53	49	136	82	118
2.01 to 3.0	11	12	24	5	14	29
3.01 to 4.0	1	2	2	0	0	3
4.01 to 5.0	0	0	0	0	0	2
5.01 to 10.0	0	0	0	0	0	0
>10.01	0	0	0	0	0	0
Max. External Dose (mSv)	2.4	1.9	2.2	1.6	2.5	1.5
Mean External Dose (mSv)	0.2	0.2	0.3	0.3	0.4	0.3
Max. Internal Dose (mSv)	1.2	1.3	2.5	1.7	2.1	3.7 [2]
Mean Internal Dose (mSv)	0.7 [2]	0.4 [2]	0.7 [2]	0.5 [2]	0.5 [2]	0.7 [2]
Collective Dose (man.mSv)	222	240	359	363	418	659

[1] Number of reports received from the reporting entities in parentheses.

[2] Includes contribution from RnP / TnP.

Table 15: Analysis of Radiological Parameters 2013-14 to 2018-2019

Parameter	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
Workforce [1]	446	462	434	545	593	1524
Monitored Workers [1]	143	116	82	102	78	248
Monitored Workers (%)	32.1%	25.1%	18.9%	18.7%	13.2%	16.3%
External γ Assessments	404	467	720	902	884	976
Personal Dust Samples	480	448	678	510	444	706
Mean LLα ($mBqm^{-3}$)	51	29	45	67	40	28
Mean CED per DE (mSv) [2]	0.9 [4]	0.6 [4]	0.8 [4]	0.8 [4]	0.9 [4]	1.0 [4]
Collective CED (man.mSv) [1]	222	240	359	363	418	659
Mean Worker CED (mSv) [3]	0.5	0.5	0.8	0.7	0.7	0.4

[1] From Table 14.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 14.

[3] Calculated by dividing the Collective Dose by the number of Workers.

[4] Includes contribution from RnP / TnP.

5.5 A summary of radiological data: 1977 to 2018-19

A summary of the workforce demographics, analysis of dose estimates for the 42-year period from 1977 to 2018-19 is presented in Table 16. The notes in Sections 4.1, 4.2, 4.3 and 4.4 and the footnotes to Tables 2 to 15 are germane to Table 16.

Table 16: Analysis of Workforce Demographics and Doses 1977 to 2018-19

Parameter	1977 to 2018-19
Reporting Entities (Site.years)	355
Reports Assessed [1]	335
Reporting Frequency (%)	94.4%
Sum of workforce by year [2]	***34240***
Designated Employees / Monitored Workers [3]	8960
Monitored Workers (%)	26.2%
Mean Hours Worked per Year [2]	1686
Maximum CED (mSv) [4]	163.4
Mean CED (mSv)	11.0
Collective CED (man.mSv)	108850
Mean Worker CED (mSv y^{-1}) [5]	3.2
Workers receiving between:	
0 and 1.0 mSv	10811
1.01 and 2.0 mSv	1566
2.01 and 3.0 mSv	668
3.01 and 4.0 mSv	321
4.01 and 5.0 mSv	144
Workers receiving less than 5.01 mSv [6]	***29898***
Workers receiving between 5.01 and 10 mSv	1340
Workers receiving greater than 10.01 mSv [7]	745
Workers with a Distributed Dose Estimate [8]	***31983***

[1] Assessed = summarised by other authors, or directly interpreted in this research.

[2] Workforce data for the 6 years from 1977 to 1980 and 1982 to 1983 were not available.

[3] Data for the 5 years from 1977 to 1980 and 1982 were not available.

[4] Calculated by summing the maximum external gamma and LLα doses for the 1987 reporting year.

[5] Calculated by dividing the Collective CED by the total number of worker years.

[6] Includes 16388 workers reported in the years from 1986 to 1999-00 where the detailed analysis ofdoses less than 5 mSv were not able to be assessed.

[7] Of the 745 workers, 132 received doses greater than 50 mSv, in the period prior to 1989-90.

[8] Mean doses were estimated for 2257 workers employed in 1981, 1984 and 1985, however the distributions of these doses were not reported.

A summary of the industry-wide monitoring programs for the 42-year period from 1977 to 2018-19 is presented in Table 17. The table also includes an analysis of the contribution of each exposure pathway to collective dose, and compares the contributions in the period from 1977 to 2018-19 to the period where monitoring from RnP commenced in 2006-07 until 2018-19.

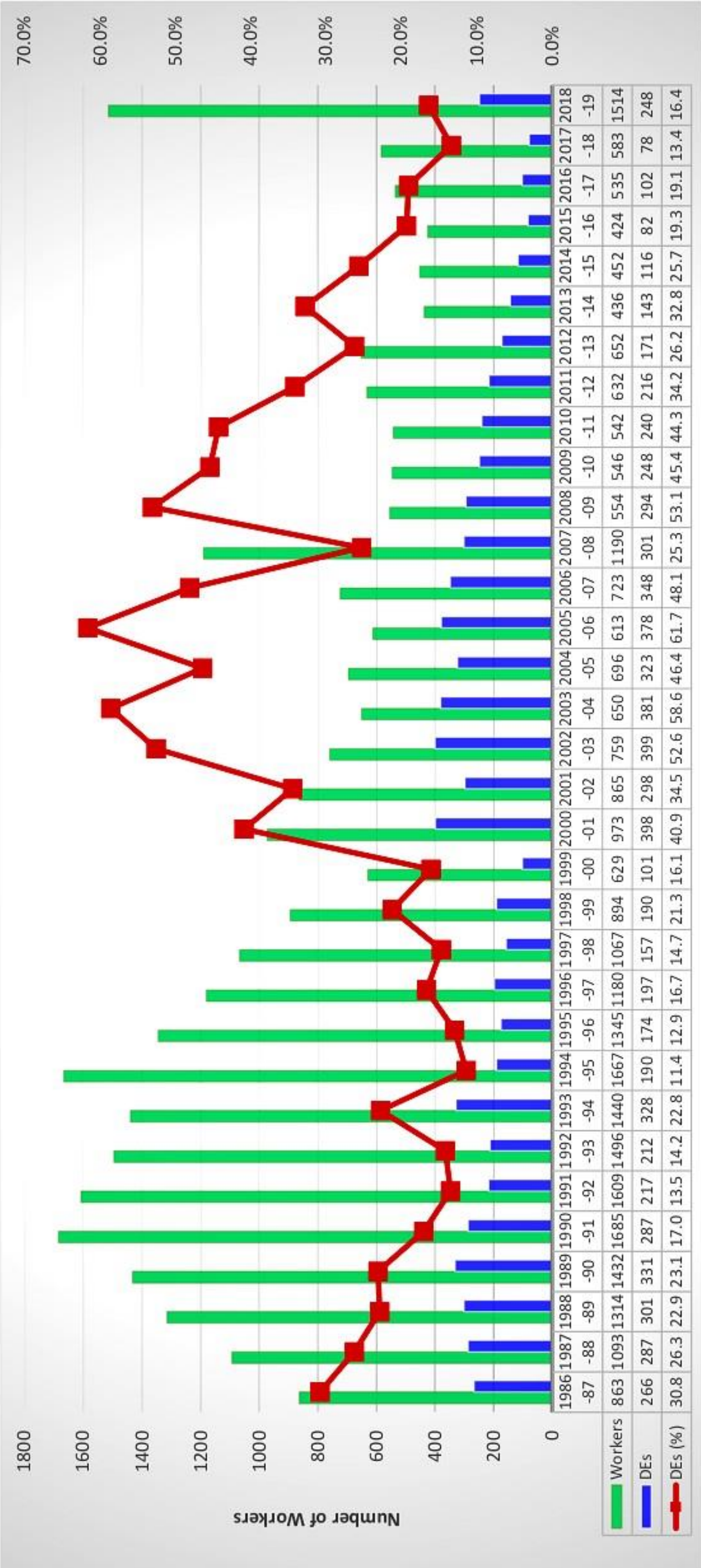
The notes in Sections 4.1, 4.2, 4.3 and 4.4 and the footnotes to Tables 2 to 15 are germane to Table 17.

The key demographic and workforce monitoring data are represented in Figures 2, 3, 4, and 5.

Table 17: Analysis of Radiological Parameters 1977 to 2018-19

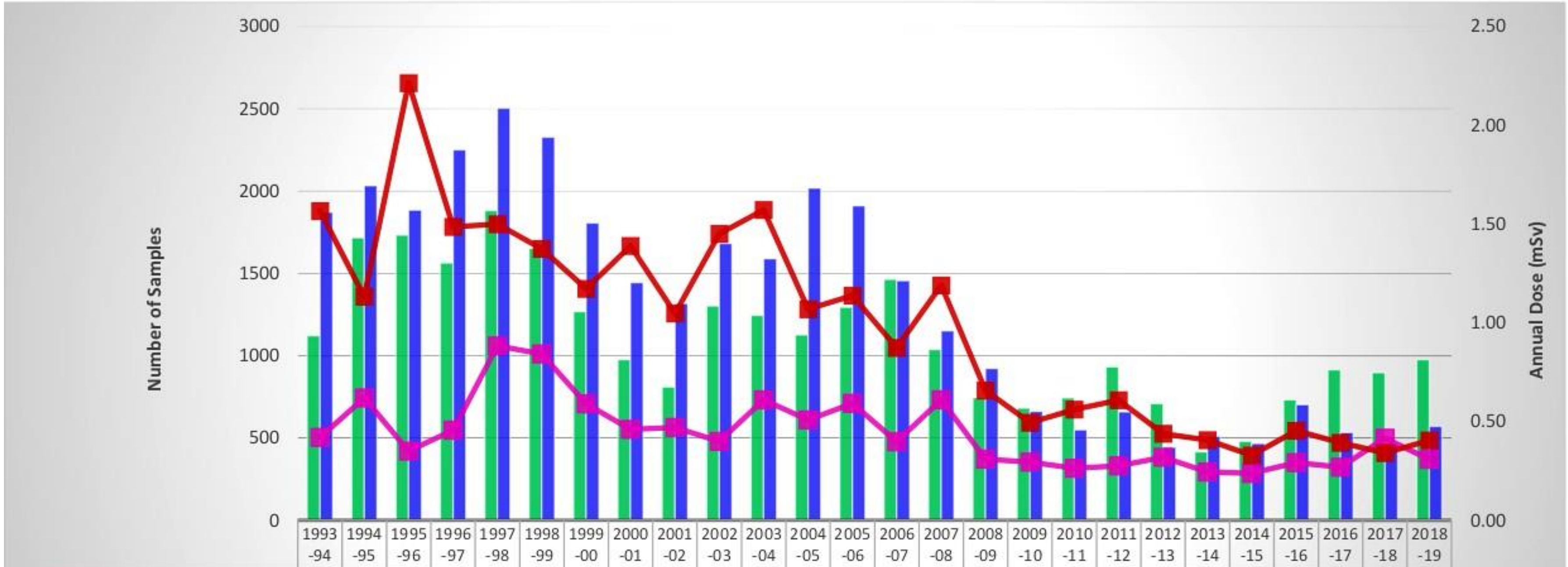
Parameter	1977 to 2018-19	
Sum of workforce by year	34240	
External γ Assessments	28910	
Maximum External γ (mSv)	17.7	
Mean External γ (mSv)	1.4	
Collective Dose from External γ (mSv) [1]	21515	
Personal Dust Samples	47720	
Maximum LLα Concentration ($mBqm^{-3}$)	4782	
Mean LLα ($mBqm^{-3}$)	170	
Maximum Dose from LLα (mSv)	153	
Mean Dose from LLα (mSv)	9.4	
Collective Dose from LLα (mSv) [1]	87061	
Maximum Dose from RnP (mSv) [2]	1.3	
Mean Dose from RnP (mSv) [2]	0.1	
Collective Dose from RnP (mSv) [2]	274	
Contribution to Collective Dose		
Parameter	**1977 to 2018-19**	**2006-07 to 2018-19**
Collective Dose (mSv)	108850	9433
External γ (%)	19.8	38.8
LLα (%)	80.0	58.3
RnP (%)	0.3	2.9

[1] Collective Dose for 1977 to 1980 and 1982 could not be calculated due to absent workforce data.
[2] Calculated from the first reports of RnP measurements, made in 2006-07 onwards.



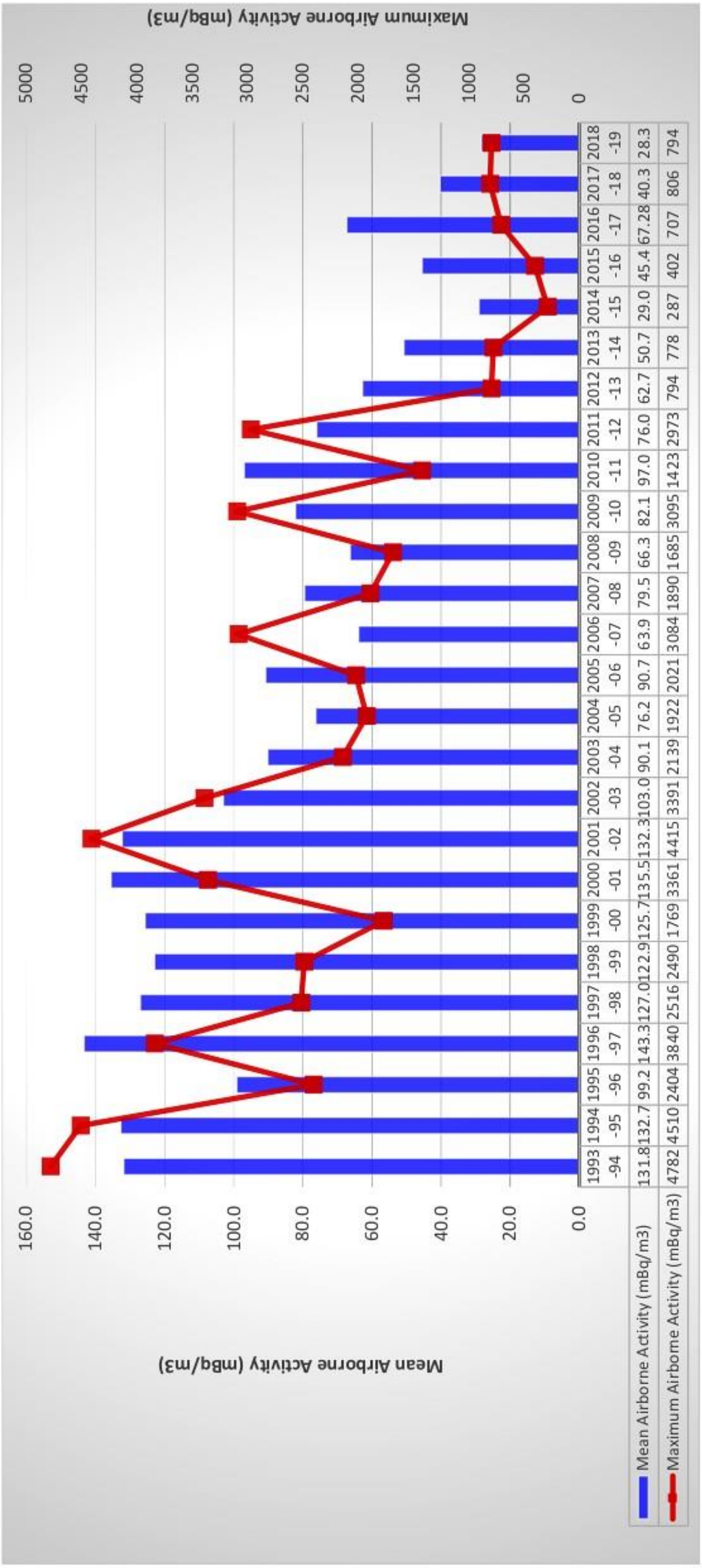
Year	Workers	DEs	DEs (%)
1986-87	863	266	30.8
1987-88	1093	287	26.3
1988-89	1314	301	22.9
1989-90	1432	331	23.1
1990-91	1685	287	17.0
1991-92	1609	217	13.5
1992-93	1496	212	14.2
1993-94	1440	328	22.8
1994-95	1667	190	11.4
1995-96	1345	174	12.9
1996-97	1180	197	16.7
1997-98	1067	157	14.7
1998-99	894	190	21.3
1999-00	629	101	16.1
2000-01	973	398	40.9
2001-02	865	298	34.5
2002-03	759	399	52.6
2003-04	650	381	58.6
2004-05	696	323	46.4
2005-06	613	378	61.7
2006-07	723	348	48.1
2007-08	1190	301	25.3
2008-09	554	294	53.1
2009-10	546	248	45.4
2010-11	542	240	44.3
2011-12	632	216	34.2
2012-13	652	171	26.2
2013-14	436	143	32.8
2014-15	452	116	25.7
2015-16	424	82	19.3
2016-17	535	102	19.1
2017-18	583	78	13.4
2018-19	1514	248	16.4

Figure 2. Workforce and DEs / Monitored Workers, 1986-87 to 2018-19



	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00	2000-01	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
Personal Gamma Monitors	1122	1716	1733	1563	1883	1653	1269	976	810	1302	1246	1126	1294	1464	1038	745	682	743	932	709	416	479	732	914	896	976
Personal Dust Samples	1871	2033	1884	2252	2504	2328	1806	1444	1317	1683	1589	2018	1911	1456	1151	923	662	549	658	444	510	466	702	534	468	570
Mean External Dose	0.42	0.62	0.35	0.46	0.88	0.84	0.59	0.46	0.47	0.40	0.61	0.51	0.59	0.40	0.61	0.31	0.29	0.26	0.28	0.32	0.24	0.24	0.29	0.27	0.42	0.31
Mean Internal Dose	1.57	1.13	2.21	1.49	1.50	1.38	1.17	1.39	1.05	1.45	1.57	1.07	1.14	0.87	1.19	0.66	0.49	0.56	0.61	0.44	0.41	0.33	0.45	0.39	0.34	0.40

Figure 3. Monitoring Profile and Contribution to CED, 1993-94 to 2018-19



	Mean Airborne Activity (mBq/m3)	Maximum Airborne Activity (mBq/m3)
1993 -94	131.8	4782
1994 -95	132.7	4510
1995 -96	99.2	2404
1996 -97	143.3	3840
1997 -98	127.0	2516
1998 -99	122.9	2490
1999 -00	125.7	1769
2000 -01	135.5	3361
2001 -02	132.3	4415
2002 -03	103.0	3391
2003 -04	90.1	2139
2004 -05	76.2	1922
2005 -06	90.7	2021
2006 -07	63.9	3084
2007 -08	79.5	1890
2008 -09	66.3	1685
2009 -10	82.1	3095
2010 -11	97.0	1423
2011 -12	76.0	2973
2012 -13	62.7	794
2013 -14	50.7	778
2014 -15	29.0	287
2015 -16	45.4	402
2016 -17	67.28	707
2017 -18	40.3	806
2018 -19	28.3	794

Figure 4. Maximum and Mean Airborne Activity

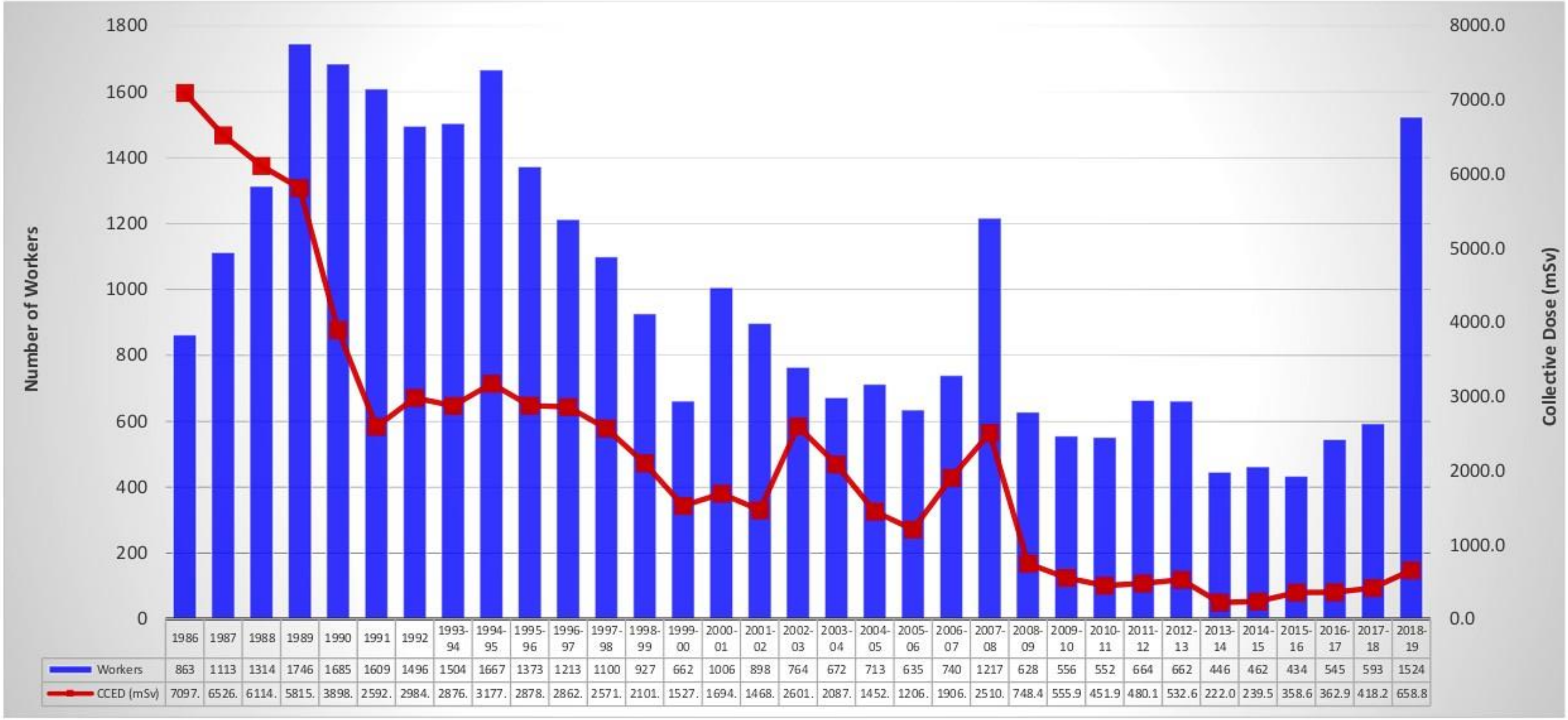


Figure 5. Size of Workforce and Collective Dose (mSv)

6 DISCUSSION

This research has demonstrated that by amalgamating: the early reports cited by the Winn Committee of Enquiry; official govermment agency records; the data reported in IAEA 68; and records held by reporting entities, the exposures of WA mining workers to radiation from NORMs can be effectively traced for the 42-years betweeen the earliest recorded assessment in 1977 and the time of writing.

6.1 Reporting entities

Despite changes in the physical location of, and the Government agency within which, the Mines Inspectorate resided, the historical record of the exposures to radiation of the WA mining workforce remain, remarakably intact. As is demonstrated by the information presented in Tables 2 through 15, other than the early years, in which the mining sector outside of the MSI was not required to report to the Mines Inspectorate, the WA mining industry has largely complied with the requirement to provide an annual report of worker radiation exposures.

Although the authors report in Table 16 that the reporting frequency is 94.4%, the majority of reports classified as ' missing' arise from Reporting Entity #8, which was not subject to reporting obligations until the mid-1990s. Acknowledging this regulatory setting, only two of the anticipated 220 annual reports expected to be received after Hewsons' [79] summary of the 1995 annual report data have not been able to be retrieved: a notable level of compliance with the statutory expectations, and a testament to the record keeping by the Department and mining industry.

Over the course of the period from 1977 to 2018-19, 28 separate mining operations were deemed as ' reporting entities', as defined inSection 2.1. As was indicated in Section 4.1, the commencement and subsequent closure of mining operations considered by the Mines Inspectorateto be reporting entities has added complexity to this analysis. Eight of the 28 reporting entities included in this analysis have ceased operating; three are in hiatus, awaiting improved marketconditions before recommencing; two have recently commenced and are yet to submit annual worker dose reports; and one has received a full exemption from the MSIR.

An additional complexity arises from those reporting entities which have been subsequently provided a level of exemption from compliance with the MSIR by the SME. Whilst one operation (#12) has receved a complete exemption, others (#9, #11, #13 and #27) have been granted partial exemptions, and all are required to submit reports of worker dose estimates on a regular, but not an annual, basis. Reporting entity #9 is required to submit a report on a biennial basis; #11 every five years; #13 biennially or every five years, contingent upon the grade of the ore being processed; and #27 biennially, but of only a small cohort of workers. In order to standardise the treatment of the data, the authors have assumed that the size of the workforce and the workplace exposure conditions (and therefore worker doses) remain consistent in the years for which a reportwas not required to be submitted. By way of example, reporting entity #9 submitted a report in 2017-18, and the data in that report has been replicated, by the authors for 2018-19 reporting period.

6.2 Workforce monitoring

Noting that data for the years between 1977 and 1980, and 1982-83 are not available, over a quarter of the workforce potentially exposed to NORMs have been involved in a monitoring programme in the 42-years covered by this research. Whilst this is in itself a notable level of performance, the significant decrease between 2007-08 to 2017-18, as illustrated in Figure 2, demonstrates that over the last decade, monitored workers declined from a peak of 53.1% of the workforce to 13.4% in 2017-18.

Tsurikov (personal communication, 20/11/2020) suggests that the decline in personal monitoring may be attributable to the publication of RPS 9 [113] in 2005, which infers that non-designated employees do not have to be monitored. This position is somewhat counter- intuitive in that workers with exposure profiles that might lead to doses of several milliSieverts would require regular monitoring to ensure they remain below the 5 mSv DE criteria. A contradictory position may apply to workers receiving less than a few mSv, but nonetheless, periodic checks of exposures should be made, to ensure maintenace of the *status quo*.

The data for 2018-19 indicates a reversal of the declining trend, however it must be highlighted that this data is upwardly biassed by the entrance of three new operations which conducted aggressive monitoring capaigns in order to support their case for exemption from compliance with the MSIR.

The decline in monitoring of the workforce is supported by the data presented in Figure 3, which illustrates the actual number of assessements conducted for external γ and LLα, in the period post production of monazite which ceased in May 1994 [80]:

- Personal external γ assessments peaked in 1997-98 at 1,883 but has steadiliy declined since that time to the point where 976 assessments were made in 2018-19, a decline of 48.2%;

- Personal LLα assessments also peaked in 1997-98 at 2,504 dust samples. In 2018-19 570 dust samples were collected, representing a decline of 77.2%.

An important finding of this research is, given the findings of the research by Ralph, Tsurikov and Cattani [20], and the advent of increased DCF's applicable to reporting entities, the declining trend in workers participating in a monitoring programme needs to be arrested.

6.3 Workforce monitoring for external γ

NORM Guideline 3.2 "Operational Monitoring Requirements" [114] promotes, where possible, the use of individual monitors for exposure to γ radiation, but also allows for assessments to be conducted based on measuring γ dose-rates in a work area and applying time and motion studies to determine occupancy rates. Doses are determined by the sum of the times spent in each work area multiplied by the applicable dose-rate [114].

Hewson [77] 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".

Ralph, Tsurikov and Cattani advise [20] "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".

The number of personal monitoring devices allocated to workers was not reported until 1993-94. As is shown in Table 17, over the period from 1993-94 to 2018-19, 28,910 personal γ radiation assessments were made, at an average of 1,111 per year. Over this period, the maximum Effective Dose from external γ was 17.7 mSv, reported in 1983, whilst the mean Effective Dose was 1.4 mSv.

As can be seen from Figure 3, in the period from 1993-94 to 2008-09, the number of personal γ assessments conducted was considerably less than, or approximately equal to, the number of personal dust samples collected. However, a reversal of that trend occurred in 2009-10, and has continued (the one exception being 2013-14) until 2018-19. As is demonstrated in Table 17, the dose from external γ radiation accounts for 19.7% of the collective dose to workers, and therefore doesnot warrant being the primary focus of the reporting entities' monitoring programme (despite the contribution nearly doubling to 38.7% in the period from 2006-07).

6.4 Workforce monitoring for internal dose

Although internal dose estimates are made in accordance with accepted procedures such as the NORM Guidelines, and those published by the

IAEA and ICRP, nonetheless, they are based upon assumptions about the physical properties of the inhaled dust and the behaviour of radionuclides in the body after inhalation. As counselled by Marshman and Hewson [2] "the estimates are made using conservative assumptions, to limit the likelihood of understating dose. Accordingly, such estimates should be interpreted and usedwith caution" and are subject to "a considerable degree of uncertainty". Similar caution should be exercised, when interpreting the results presented in this research, especially the estimates of internal doses from dust containing LLα and from exposure to TnP and RnP.

The current version of the NORM Guidelines and those cited by Hewson [77] are consistent in that they 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 six to seven days) to allow for the decay of TnP and RnP, the collected dust samples are subject to gross alpha analysis [115].

Internal dose estimates from LLα arecalculated using the gross alpha analysis results in conjunction with the characteristics of the dust, and a worker breathing rate of 20 litres per minute, equivalent to 1.2 cubic metres per hour.

Secular equilibrium of NORs in the low-solubility inhaled dusts is assumed, based upon research summarised by Hartley and Hewson [40]. A default Activity Median Aerodynamic Diameter (AMAD) value of five microns was used as the basis of the calculation for most of the submitted reports, although in the early 1990's the SME approved the use of a 10 um AMAD by two reporting entities based upon the results of 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 [77]. Workers were 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 results of the LLα analysis for the collected dust samples were taken as being representative of all of the workers in the SEG, and the mean concentration of all of the dust samples analysed for LLα, (in Bqm -3) over the reporting period for each SEG was calculated.

The intake of LLα for each DE who worked greater than 500 hours from 1986 to 1996 and greater than 200 hours from 1997 to 2018-19 was calculated from:

1. Intake (Bq) = $Time_{SEG1}$ x mean activity $concentration_{SEG1}$ + $Time_{SEG2}$ x mean activity $concentration_{SEG2}$ + $Time_{SEG3}$ x mean activity $concentration_{SEG3}$ ...

The resulting dose is calculated by:

2. Dose (mSv) = Intake (Bq) x DCF ($mSvBq^{-1}$)

As was discussed in Section 4.4, the DCF for LLα and the DC for RnP / TnP have changed over time, in response to the findings of international research and dosimetric modelling.

The measurements of RnP and TnP in 1988 by Ralph [26], as summarised in Table 1, were collected by manual techniques. Contemporay measurements are conducted via integrating electronic instruments, and are much less labour- intensive and can provide near-instantaneous concentration results. In a similar fashion to the method used to calculate doses from LLα, doses from RnP and TnP are calculated by time and motion studies to determine occupancy factors and the mean RnP / TnP concentration is used to calculate intake. A DC is then applied to calculate dose. The findings from the Ralph research were not applied to the dose estimates of the workforce,as they were not confirmed, or acknowleged in, submitted annual reports. Doses from RnP / TnP only began to be reported in 2006-07, with more reporting entities attributing doses from thispathway over the succeeding years. The authors contend that the increase in DC for RnP / TnP that occurred in 2018 [116-118] will require a greater focus from reporting entities on evaluating the doses arising from this source of exposure.

Internal CEDs are calculated by summing thedose from LLα with that from RnP / TnP. Over the period from 1993-94, when maximum LLα concentrations were able to derived, the maximum reported LLα concentration was 4,782 $mBqm^{-3}$, reported in 1993-94, and the mean was 170 $mBqm^{-3}$. The maximum Effective Dose from LLα was estimated as 153 mSv, reported in 1987, whilst the mean Effective Dose (in the period from 1986 to 2018-19) is 9.4 mSv. The mean Effective Dose over the entire period of this analysis is heavily influenced by the internal doses reported in the mid-to-late 1980's.

As can be interpeted from Figure 3, in 1997- 98, after the introduction of the 20 mSv dervived annual limit, and three years after monazite producton ceased, the mean internal dose from LLα was 1.5 mSv, whereas it had declined to 0.4 mSv in 2018-19. Some of the decrease can be explained by the reduction of the DCF, from 0.0097 $mSvBq^{-1}$ to 0.008 $mSvBq^{-1}$ introduced in 2009. However, if all things had remained equal, only approximately 18% of the mean dose reduction can be attributed to the decreased DCF.

In an endeavour to provide an explanation ofthe decline in internal dose, the maximum and mean airbone concentrations of LLα are shown in Figure 4. There is a general downward trend in both the maximum and mean LLα concentrationsfrom 1993-94 to 2018-19, but the decrease really only commenced after 2001-02. Post 2001-02, the mean LLα concentration decreased for several years, and then progressively increased, as seen in the periods from 2008-9 to 2010-11 and 2014-15 to 2016-17.

In [20], Tsurikov hypothesised that "Typically the newer reporting entities have airborne dust concentrations much less than those that were encountered in the MSI in the 1990s". Ralph, Cattani and Tsurikov [20] support this proposition by stating "Only 234 workers were employed in the MSI in 2018-19, with the vast majority (1,240,or 84%) of mine workers employed by reportingentities that were processing the lower activity concentration ores and minerals. This is, in all likelihood, the major contributing factor to the overall reduction of CEDs in the WA mining sector".

However, and significantly, there have been no material changes in the manner in which minerals are treated in the MSI that provide a definitive explanation for the observed decrease in the five reporting entities that were operating in the 1990's and are currently in operation. This finding requires further investigation.

Although the maximum LLα concentration in 2018-19 has decreased by 82% from that in 2001-02, it is highlighted that:

- Three peak concentrations of ~3,000 $mBqm^{-3}$ occurred in the 17-year period to 2018-19;
- An otherwise unexplained step-decrease occurred in 2012-13 resulting in the maximum LLα concentration reducing from 2,973 $mBqm^{-3}$ the year before, to 794 $mBqm^{-3}$;
- After a very low maxima in 2014-15, the maximum LLα concentration has steadily increased, and has seemingly plateaued at ~800 $mBqm^{-3}$.

The three maxima that are approximately 3,000 $mBqm^{-3}$ serve as a reminder that NORMs are present in the mineral suite, and indicate the potential for highly elevated LLα concentrations to be encountered, and therefore excessive doses may occur. Similar to the commentary on mean LLα concentrations, a definitive explanation for the step-decrease in 2012-13 is not readily apparent, and is worthy of further investigation.

Finally, in relation to the analysis of LLα concentration, it is important to highlight the reduction in DACs that will apply from the 2019-20 reporting year. As was discussed in the first paper, the DAC for a 5µm, ^{232}Th dust in secular equilibrium will be 500 $mBqm^{-3}$, and as shown in Figure 4, the increasing trend of maximum results witnessed in the period from 2014-15 to 2018-19 has plateaued at approximately 800 $mBqm^{-3}$, which appears to be the norm in the post 2011-12 period. This value is 60% higher than the DAC, and indicates that doses considerably exceeding the derived annual limit are possible.

As was shown in Table 17, a total of 47,720 personal dust samples were collected since the number of samples were first reported, in 1983 until 2018-19, an average of 1,325 per year. However, it is important to highlight that in no single reporting year since 2006-07 has the number of samples exceeded the average, reaching a nadir in 2012-13 where only 414 samples were collected across the industry.

Another way of assessing the efficacy of the industry's LLα monitoring programme is the number of samples collected per worker per year. Commencing from 1985 when the focus on LLα in dust sampling began in earnest, an average of 1.5 samples per worker per year has been collected, peaking at 3.0 in 2005-06. The minimum of 0.5 samples per worker occurred in 2018-19, and it is worthy to note that in the period from 2008-09, in only one year (2015-16) was the average exceeded (recording 1.6 samples per worker per year).

In Section 6.3 the authors discussed the trendof personal γ assessments vis a vis personal dust samples, and noted that in the post 2009-10 period, the number of gamma assessments exceeded those for LLα. Given the contribution of LLα to the worker collective dose, the authors argue that this is indicative of a misallocation of attention to monitoring that requires addressing across reporting entities.

Further, the authors contend that 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.

6.5 Designated employees and dose distribution

An estimated 34,240 worker-years are included in this analysis. This value is not a count of individuals, as many workers would have been employed for more than one year, but is indicativeof the number of workers for which either personal or SEG dose assessments have been made. Noting that workforce numbers were not available for 1977 to 1980 and 1982-83, an average of 951 workers per year were included in the dose assessment process over the 36 years for which workforce data is available.

As was discussed in Section 4.2, it has become apparent over the passage of time that a non-standardised approach has evolved in the application of the definiton of Designated Employee. As reported in the notes to Table 8, the divergence required the authors to re-label the category of workers who participated in their operation's monitoring programme as ' Monitored Workers'. It should also be noted that whereas the information provided in Tables 9, 10, 11 and 12 is based upon DEs who worked greater than 500 hours per year, the informaton for Monitored Workers applies a minimum 200 working hours per year criteria.

Applying the above criteria, 8,960 workers by year, equivalent to 26.2% of the total workers by year were categorised as either DEs or Monitored Workers. Data was not obtainable for the four years from 1977 to 1980, and 1982, and therefore over the 37 years that data was available, an average of 242 workers per year particicipated in a monitoring programme, as either a DE or a Monitored Worker.

As shown in Table 16, the mean CED over the 42-year period from 1977 to 2018-19 was 11.0 mSv, calculated by adding the mean contribution from external γ; LLα; and RnP / TnP. The mean is biased by the exceptionally high mean doses reported in the period from 1977 to 1989, and is upwardly influenced by the absence of workforce data for some years (the mean dose is included in calculations, but the workforce is unaccounted for). The authors suggest an alternate method fordetermining the mean of the entire working population, in Section 6.6.

As was discussed in Section 4.3, from 2000-01 the researchers were able to access the suite of annual reports submitted by reporting entities, enabling a detailed analysis of the distribution of workers receiving doses less than five mSv. Prior to 2000-01 doses less than five mSv were considered as having little significance, and were amalgamated into a single cohort.

In order to accommodate as much of the available information as possible, the analysis in this research provides an amalgamated report of doses less than five mSv in the period leading upto and including the 1999-2000 reporting period, and a more detailed analysis of the distribution of the less than five mSv doses thereafter.

The workforce data for the period from 1977to 1985 is largely absent, and where it has been sourced, (1981, 1984 and 1985) the distribution of doses was not able to be determined. Mean doses were estimated for 2,257 workers employed in 1981, 1984 and 1985, however because their distributions were not reported, the data was excluded, and the analysis of the aggregated less than five mSv data was conducted between 1986 and 1999-00.

The distribution of doses for the workforce (where data was available) is provided in Table 16. As can be seen from Table 16, the doses of 31,983 workers were able to be stratified, with 10,811 (33.8%) workers assessed as receiving doses of less than one mSv per year. A further 2,699 workers received doses between 1.01 and 5.0 mSv per year. When combined with the 16,388 workers who were categorised as receiving less than five mSv between 1986 and 1999-00, the total number of workers who received less than five mSv was 29,898, or 93.5% of the distributed dose estimates.

A total of 2,085 workers (6.5%) received CEDs greater than five mSv in the period from 1986 to 2018-19, and of these, 745 (2.3%) received CED's greater than 10 mSv, and ofthese, 132 (0.4%) received CEDs greater than 50 mSv.

The maximum reported CED was 163.4 mSv, reported in 1987. In the 1990's the maximum reported CED was 32 mSv in 1994-95; in the 2000's the maximum reported CED was 15.7 mSv in 2002-03; and in the 2010's the maximum reported CED was 4.4 mSv in 2010-11, 2011-12 and 2018-19. The downward trend of maximum CED's is noteworthy, and an important finding of this research.

Whereas the last worker to receive a CED of greater than 50 mSv was recorded in 1988, when monazite production was occurring, the most recent exceedance over 10 mSv was reported in 2009-10, some 15 years after monazite production had ceased, confirming the author's assertion that the potential for excessive doses exists because of the omnipresent NORMs in the suite of minerals being processed.

6.6 Collective Dose

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" [46]. Regulation 16.15 of the MSIR requires "the manager of a mine must ensure ... the collective effective dose of radiationto employees generally is reduced to levels that are as low as practicable" [46].

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 [119].

Nonetheless, an analysis of collective dose receeived by the workforce provides the opportunity to assess the success (or otherwise) of intervention methods implemented in order to reduce radiation doses to the mining industry workforce as a whole, and to derive trends over time.

The collective dose for each reporting entity is estimated by adding the mean EDs from external γ, LLα and RnP/TnP to determine the mean CED, which is then multiplied by the workforce for each reporting entity. The sum of the collective doses from each reporting entity provides the Collective Dose per Year, as given in Tables 2 to 17.

A slightly different methodology to estimate the collective dose was deployed in Table 17. In order to derive the contribution from each exposure pathway the Collective Dose per Year from the respective exposure pathways are added. The authors acknowledge that this approach loses some of the detail apparent in the year-by-year analysis, but contend that it was the most efficient method to derive an exposure pathway contribution analysis.

As can be seen in Table 17, over the period covered by the research, Collective Dose is dominated by the contribution from LLα (80% of Collective Dose), whilst external γ contributes 19.7% of Collective Dose, and the contribution from RnP/TnP is negligible. However, as shown in the comparison data drawn from 2006-07 (the time at which RnP/TnP commenced), when doses have reduced significantly from those in the 1980's and 1990's, the contribution from LLα has decreased to 58.4%, external γ has increased to 38.7% of Collective Dose, and the contribution from RnP/TnP has increased 10-fold to three percent, with a maximum contribution of 1.3 mSv (which accounted for 30% of CED at the operation where the 1.3 mSv was calculated).

Figure 5 compares the Collective Dose to thesize of the workforce since 1986-87. Figure 5 starkly illustrates the decline in Collective Dose since the report of the Winn Committee of Enquiry. After declining in the late 1980's, to 1991, the peak Collectve Dose of 3,177 mSv occurred in 1994-95, approximately 80% of which derived from internal exposure. From the time of cessation of monazite production in 1994, the general trend has been for Collective Dose to steadily decrease over time with intermittent periods of increases. A sudden increase occurred in the 2002-03 reporting period, due to one reporting entity processing stockpiles of tailings materials produced in the early 1990's that exhibited elevated concentrations of monazite. The most recent reversal of the downward trend occurred in the periods from 2005-06 to 2007-08; and 2015-16 to 2018-19; both of which correspond to an increase in the size of the workforce.

Because workforce data is not available for the period from 1977 to 1980 and 1982, Collective Dose for these five years cannot be calculated. However, over the remaining 37 years, the Collective Dose to the workforce of the reporting entities was 108,850 mSv (108.85 Sv).

Dividing the Collective Dose by the Sum of the Workforce by year (34,240) provides an estimate of the mean CED per worker, over the period of this analysis, which as shown in Table 16 is 3.2 mSv.

The decreasing trend in Collective Dose, as illustrated in Figure 5 is noteworthy, and can be inferred as the reporting entities demonstration of compliance with the intent of MSIR Regulation 16.15.

However, the cautions mentioned in earlier Sections of this Discussion, in relation to the declining workforce participation in monitoring programmes; the precedence of monitoring for external γ over LLα; and the emerging importance of monitoring for RnP / TnP serve as caveats to the positive trend identifed in the Collective Dose analysis.

6.7 An Eye to the Future

All of the annual reports assessed in this research were submitted prior to the release of ICRP-141 in December 2019. All CEDs reviewed in this research have been treated as they were presented to the SME by the reporting entities.

It is noteworthy that with the advent of the revised DCs published in ICRP-137 and ICRP-141 [106, 107] DCFs for ' typical' NOR- containing dusts in WA operations are forecast to double from those applied in previous reporting periods [20, 108].

In 2018-19, 33 workers received CED's greater than two mSv, and it is suspected that a portion of these workers will exceed five mSv in the 2019-20 reporting period, as the revised DCFsare included in dose calculations.

Should this occur this will be the first time since 2009-10 that the mining industry will have workers deemed as Designated Employees.

7 CONCLUSIONS

34,240 assessments of worker exposures to the radiation from NORMs, over the period from 1977 to 2018-19 have been analysed. 8960 workers actively participated in personal monitoring programmes.

The maximum CED reported in the 42-year period was 163.4 mSv, more than eight times the contemporary derived annual dose limit. The mean CED over the period of analysis, heavily influenced by large doses experienced in the 1970's, 80's and 90's is 10.9 mSv, whereas an alternative method of determining the average dose to the average worker returned a more conservative value of 3.2 mSv.

93.5% of all workers in the 42-year period received CEDs of less than five mSv per year. The most recent reported exceedance over 10 mSv (10.3 mSv) was reported in 2009-10, some 15 years after the cessation of monazite production, indicating the potential for elevated CEDs to occur despite the absence of the mineral with the highest content of NORs.

Exceedances over 50 mSv were frequently reported in the 1970's and 1980's, however, the last reported exceedance occurred in 1988. The last reported CED that exceeded the contemporary derived annual dose limit of 20 mSv occurred in 1995-96.

The trend in Collective Dose presents a very positive picture of the management of worker exposures to NORMs, however, as the WA mining industry has become accustomed to lower CEDs, monitoring of potentially exposed workers has decreased, as indicated by the number of personal dust samples collected across the industry, which has declined steeply over the past two decades. Given the advent of increased DCF's that will apply in the 2019-20 reporting period, a renewed focus on representative personal dust sampling must be implemented in order that the impact ofthe revised DCFs on the mining industry can be appropriately evaluated.

The final word on this research belongs to those who contributed to the Winn Inquiry, the catalyst for the improvements witnessed in the past 42 years: " ... 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" [69].

The Winn Commissioners were not to be aware of the challenges that revisions to the ICRP inhalation models or dose coefficients would bring, however, their message is as salient today as when it was first issued in 1984.

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9 DECLARATION OF INTEREST

The corresponding author, Mr. Ralph, is an employee of the Western Australian Department of Mines, Industry Regulation and Safety. Mr. Ralph was the author of Ralph [26]; one of the co- authors of Ralph, Chaplyn and Cattani [1]; Ralph, Tsurikov and Cattani [20]; Ralph, Hinckley and Cattani [120]; Hewson, Tippet [121]; [29], Hewson and Ralph [122]; and a contributor to Chamber of Minerals and Energy of Western Australia [12]; and Mason, Carter [34].

Mr. Tsurikov is the author of Tsurikov [71, 89, 90, 111]; a co-author of Ralph, Tsurikov andCattani [20]; and a contributing author to IAEA 68 [91].

Dr. Cattani is one of the co-authors of Ralph, Chaplyn and Cattani [1]; Ralph, Tsurikov and Cattani [20]; and Ralph, Hinckley and Cattani [120].

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