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Towards establishing a fit-for-purpose regulatory framework for radiation protection in Western Australia's mining industry: Evaluating mine worker exposures to naturally occurring radionuclides

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THESIS TITLE PAGE

TOWARDS ESTABLISHING A FIT-FOR-PURPOSE REGULATORY FRAMEWORK FOR RADIATION PROTECTION IN WESTERN AUSTRALIA'S MINING INDUSTRY: EVALUATING MINE WORKER EXPOSURES TO NATURALLY OCCURRING RADIONUCLIDES

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for the award of
Doctor of Philosophy (Integrated) J42

School of Medical and Health Sciences
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DECLARATION:

I certify that this Thesis does not, to the best of my knowledge and belief:

i. Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education.

ii. Contain any material previously published or written by another person except where due reference is made in the text of this Thesis.

iii. Contain any defamatory material.

[redacted]

Martin Ian Ralph

21st December 2022

DEDICATION

To my father, Stuart Robert George Ralph,

a “miner’s miner”.

Thank you for accidentally starting my career-long journey, and for the counsel you continue to provide on matters related to the noble pursuit of improving the health and safety of mine workers.

To my colleague, fellow researcher, and dear friend, the late Garry George Claxton*,* PhD.

Your advocacy for, and contribution to, a better understanding of what is needed to improve worker health and safety survives as your legacy (Claxton, 2017).

ABSTRACT:

Mining in the state of Western Australia (WA) formally commenced in the 1840s, and over the ensuing 180 years has evolved to be the epicentre of the Australian mining industry and a significant contributor to the national economy. The lithology of WA is replete with mineralisation that hosts uranium and “critical minerals” required for the global renewable energy sector. The state’s first uranium mine is under development, and high levels of activity are occurring in the state’s nascent critical minerals sector, with 168 WA-based companies pursuing rare earths-bearing minerals, 51 of which are actively drilling on their tenements.

WA’s mineral deposits typically contain levels of the naturally occurring radionuclides (NORs) thorium-232 and uranium-238 that are elevated above the global crustal average. Workers are exposed to NORs during the mining and mineral extraction processes, and radiation doses that exceed applicable exposure standards may eventuate.

The central issue addressed by this research is “*what is the potential for radiation exposures from NORs to the significantly increased workforce, and is the regulatory framework fit-for-purpose to ensure radiation doses are kept as low as reasonably achievable?*”

The research traces the history of worker radiation doses from 1977 to 2020, finding the maximum dose was 163.4mSv, more than eight times the current derived annual dose limit. Whilst 93.5% of all workers received doses of less than 5.0mSv per year, the potential for elevated doses is ever-present as witnessed by 10.3mSv reported in 2009-10.

The increase in activity coincides with a revision of the dose coefficients (DCs) associated with the intake of radionuclides. The research evaluates the revised DCs and forecasts doses from inhalation of radioactive dusts will nearly double, and lead to workers receiving doses exceeding 5mSv for the first time since 2009-10.

The research raises issues with the evaluation of worker doses and recommends personal dust sampling be prioritised.

The revised DCs reinforce the need for effective long-term management of NOR-contaminated wastes arising from mineral processing activities. The research investigated a technique for the removal and capture of NOR-contaminated scale from a piece of disused mining equipment, reporting capture efficiencies of greater than 90%. The technique has the potential to significantly reduce the environmental footprint of NOR-contaminated wastes and to minimise doses to workers involved in the removal process.

The research finds that the current regulatory framework is fit-for-purpose. However, inter-agency relationships require strengthening, and the capacity of the regulator to effectively regulate the current and future number of mining operations is questioned. The mining industry is similarly vulnerable to capability and capacity constraints – but has failed to respond to issues in relation to competent radiation safety officers first raised by the Winn Inquiry in 1984. Disconcertingly, monitoring of worker exposures to NORs reached a nadir in the final years covered by this Thesis, raising questions as to the veracity of worker doses reported to the regulatory agency.

Academic papers for publication have been developed and are drawn upon in each Chapter. Six papers have been published in peer-reviewed journals, and a seventh is undergoing the editorial process.

ACKNOWLEDGEMENT OF ACADEMIC ASSISTANCE:

Principal Supervisor: Dr Marcus Cattani

Supervisor: Dr David Leith

Supervisor: Associate Professor Steven Hinckley, PhD

ACKNOWLEDGEMENTS

The metaphor that comes to mind when I reflect on the pursuit of my PhD journey is that it will provide the exclamation mark to my forty something year career in radiation protection. The successful completion of my accidental journey (as outlined in Appendix 4) has depended on the help and support of many people, who have been instrumental in inspiring, motivating and keeping me focussed upon my research objectives.

Enormous personal thanks and acknowledgment go to my principal supervisor, Dr Marcus Cattani for his unwavering support of my research, and for his assistance in navigating the intricacies of life as a researcher. I would also like to acknowledge my supervisors Dr Stephen Hinckley and Dr David Leith, and Professor Jacques Oosthuizen, who illuminated a pathway to funding assistance, at a time when I was floundering on how to progress my research activities.

Special mentions must also be made to those who contributed to the practical aspects of the research as detailed in Chapter Nine. My gratitude is expressed to Ms Leanne Downey whose untiring efforts resulted in gaining access to much-needed laboratory facilities; Mr Courtney Ackland and Mr Russell Browne from Iluka Resources who arranged the logistics for the site visit to conduct the field studies; and Professor Pere Basque-Marre for overseeing the radiometric analyses and providing advice on how to interpret the results.

It would be remiss of me to not state just how grateful I am to the Minerals Research Institute of Western Australia (MRIWA) and the MRIWA team for their support of research into the state's mining industry. I was fortunate enough to secure a MRIWA scholarship (MRIWA Project M10454), and my whole-hearted thanks go in particular to Ms Nicole Rooke and Dr Geoffrey Batt for welcoming me into the "MRIWA family".

I am also indebted to those who contributed to my published papers as co-authors, specifically Mr Andrew Chaplyn, the Western Australian State mining engineer; Mr Nick Tsurikov of Calytrix Consulting Pty Ltd; Mr Craig Rothleitner from ARI Water Solutions; and Ms Madeleine Williams-Hoffman. A special thank you is reserved for my graphical artist Tse Yin Chang who helped me compile some of the more complex illustrations included in the Thesis. There were a handful of others who assisted in the preparation of the papers for publication, and I have opted to retain the mentions of my gratitude to them in the specific chapters in this Thesis.

The PhD process can promote a certain level of selfishness, which can have a knock-on effect, to those around us, especially for the mature-age researcher. I am aware that I could have been a better husband, father, and son during these past handful years. To my wife Michelle, my sons Jarryd and Callum, and my parents, Stuart, and Gil, thank you from the bottom of my heart for your love, support, and patience as I regaled you with what must have often been the boring minutiae of my research. To Michelle in particular words cannot begin to express my appreciation for your assistance in preparations for the papers presented as Chapters Five, Six, Seven and Eight; your capacity to look the other way while I turned our home into an archive of documents and a museum of radiation detection instrumentation; and your support while urging me to strive to be my best.

This research is supported by an Australian Government Research Training Program (RTP) Scholarship.

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TABLE 1: ABBREVIATIONS, ACRONYMS AND DEFINITIONS

ABSORBED DOSE, D	The fundamental dosimetric quantity defined as the mean energy imparted by ionising radiation to a mass of matter in a known volume. The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy).
ACTIVITY (A)	The quantity of a radionuclide, defined as the number of spontaneous nuclear transformations per second. The SI unit for activity is termed the becquerel (Bq) which is equal to one atomic disintegration per second (dps).
ACUTE EXPOSURE	Exposure received within a short period of time. Normally used to refer to exposures of sufficiently short duration that resulting doses can be treated as instantaneous. The effects of acute exposure often result in deterministic effects.
ALARA	As Low as Reasonably Achievable (economic and societal factors being considered). ALARA is a fundamental concept of the International Commission on Radiological Protection System of Radiological Protection.
ALPHA (α) PARTICLE	Composite particles consisting of two protons and two neutrons tightly bound together. They are emitted from the nucleus of some radionuclides during a form of radioactive decay, called alpha-decay. An alpha-particle is identical to the nucleus of a normal helium atom.
ACTIVITY MEDIAN AERODYNAMIC DIAMETER (AMAD)	A measure of the median size of the radioactive particles in airborne dust. AMAD is a critical variable in determining the DCF, which in turn is used to calculate doses from inhalation.
BETA (β) PARTICLE	Beta particles (β) are high energy, high speed electrons (β-) or positrons (β+) that are emitted from the nucleus by some radionuclides during radioactive decay. Beta emissions normally occur in nuclei that have too many neutrons to achieve stability.
CHRONIC EXPOSURE	Exposures that occur over an extended period of time, normally years, and at low exposure rates. Chronic exposures are associated with stochastic effects.
COLLECTIVE DOSE	The sum of all Effective Doses across a population, whether that be workers or members of the public. The unit of collective dose is man millisieverts man-mSv.

DERIVED AIR CONCENTRATION (DAC)	The maximum activity concentration of airborne dust that a worker can be exposed for a 2000 hour working year, breathing at a rate of 1.2 Bqm^{-3} and meet the annual derived dose limit.
DESIGNATED WORKER (DW) FORMERLY DESIGNATED EMPLOYEE	An employee whose exposure to radiation whilst at work exceeds a regulatory imposed dose constraint, nominally 10% of the applicable worker dose limit. Designated workers require personalised assessment of their radiation exposures.
DETERMINISTIC EFFECT	A radiation induced health effect for which generally a threshold dose exists, above which the severity of the effect is greater for a higher dose.
DETRIMENT	Detriment is an ICRP concept. It reflects the total harm to health experienced by an exposed group and its descendants as a result of the group's exposure to a radiation source. Detriment is a multidimensional concept, including stochastic risks, probability of fatal and non-fatal cancer; heritable effects; and length of life lost if harm occurs.
THE DIRECTORY (NDRP 2ND EDITION, 2021)	The National Directory for Radiation Protection (2nd Edition, 2021) published by ARPANSA. It supersedes the 1st Edition of the Directory and subsequent revisions, published as Radiation Protection Series (RPS) No. 6.
DOSE	A measure of the energy deposited by radiation in a target. May refer to absorbed dose, committed dose, effective dose, equivalent dose, or organ dose, as indicated by the context.
DOSE COEFFICIENT (DC)	In this text, DC is applied to intake via the inhalation pathway, and is defined as per the ICRP, as a synonym for dose per unit intake of a radionuclide.
DOSE CONSTRAINT	A restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source. If exceeded it should trigger an internal investigation into its cause, and remedial steps to required. Note a constraint can never be higher than a dose limit.
DOSE CONVERSION FACTOR (DCF)	A term used to define the dose per unit intake from a mixture of radionuclides. The WA NORM-V Guideline illustrates the process for calculating DCFs from dusts by applying the dose coefficients for individual radionuclides within the ^{238}U, $^{235}U$and ^{232}Th decay chains.

DOSE LIMIT	The value of the effective dose or the equivalent dose to individuals in exposure situations that is not to be exceeded. A dose limit will, in most circumstances be higher than a dose constraint.
EFFECTIVE DOSE (ED)	Effective dose is a measure of dose designed to reflect the amount of radiation detriment likely to result from the dose. Values of effective dose from exposure for any type(s) of radiation and any mode(s) of exposure can be compared directly. The SI unit for effective dose is joule per kilogram (J/kg), termed the sievert (Sv).
ENVIRONMENTAL IMPACT ASSESSMENT (EIA)	A requirement of the (WA) EPA that environmentally significant development proposals consider the potential environmental impacts and how these impacts are to be managed.
EQUILIBRIUM FACTOR (F)	The ratio of the RnP to the radon gas concentration, or TnP to thoron gas concentration. F can range from 0 to 1.0.
EQUIVALENT DOSE (ED)	Equivalent dose is a measure of the absorbed dose delivered by a type of radiation to a tissue or organ designed to reflect the amount of harm caused. The SI unit for equivalent dose is joule per kilogram (J/kg), termed the sievert (Sv).
EXEMPTION	The determination by a regulatory authority that a source or practice need not be subject to some or all aspects of regulatory control on the basis that exposures are sufficiently low, or the optimum level of protection has been achieved.
EXISTING EXPOSURE SITUATION	A situation of exposure that already exists when a decision on the need for control needs to be taken. Existing exposure situations include exposure to natural background radiation that is amenable to control; and exposure due to residual radioactive material that derives from past practices that were never subject to regulatory control. According to the ICRP, all exposures to NORM should be treated as Existing Exposure Situations.
EXPOSURE	The state or condition of being subject to radiation. External exposure is exposure to radiation from a source outside the body. Internal exposure is exposure to radiation from a source within the body.

GAMMA () RAYS	A gamma ray is a packet of electromagnetic energy (photon) emitted by the nucleus of some radionuclides following radioactive decay. Gamma photons are the most energetic photons in the electromagnetic spectrum.
IONISING RADIATION	Radiation capable of producing ion pairs in biological material. In this research, it relates to α particles, β particles and γ rays emitted from NORM. When these radiations pass through the tissues of the body, they have sufficient energy to damage DNA.
ISOTOPE	Isotopes are atoms that have the same number of protons and electrons but different numbers of neutrons and therefore have different physical and chemical properties. If an isotope is radioactive, it is referenced as a radionuclide in this text. At first mention in this text a radionuclide will be spelt out with its full chemical name and mass number (e.g., uranium-238) and thereafter follows the convention of identifying the radionuclide by its mass number and chemical symbol (e.g., ^{238}U).
JUSTIFICATION	A radiation protection principle. The process of determining whether a proposed protective or remedial action is likely, overall, to be beneficial; that is whether the expected benefits to individuals and to society form introducing or continuing the protective measure outweigh the cost of such action and any harm or damage caused.
LIMITATION	A radiation protection principle. The requirement that radiation doses and risks must not exceed a value regarded as unacceptable.
LINEAR NON-THRESHOLD (LNT) HYPOTHESIS	The assumption that the long term, biological damage caused by ionising radiation is directly proportional to the radiation dose. LNT assumes ionising radiation is always harmful with no safety threshold and that the sum of several small exposures has the same effect as one large exposure. The LNT model is part of a precautionary approach to ensure radiation protection and is linked to ALARA.
MEMBER OF THE PUBLIC	Any individual who receives an exposure that is neither occupational nor medical.
MICRON (μM)	One millionth of a metre. A unit commonly used to define the particle size of airborne dusts (refer to AMAD).
MSI	Mineral Sands Industry

MSIA	Mines Safety and Inspection Act 1994.
MSIR	Mines Safety and Inspection Regulations 1995.
NATURALLY OCCURRING RADIOACTIVE MATERIAL (NORM)	Radioactive material containing no significant amounts of radionuclides other than the naturally occurring (primordial) radionuclides ^{40}K, ^{87}Rb and the members of the ^{238}U, ^{235}U and ^{232}Th decay series. Materials in which the activity concentrations of the naturally occurring radionuclides have been changed by some processes are included.
NATURALLY OCCURRING RADIONUCLIDES (NORs)	Radionuclides that occur naturally on Earth in significant quantities. The term is most often used to refer to the primordial radionuclides ^{40}K, ^{87}Rb and the members of the ^{238}U, ^{235}U and ^{232}Th decay series.
OCCUPATIONAL EXPOSURE	Exposure of workers incurred in the course of their work.
OPTICALLY STIMULATED LUMINESCENCE (OSL)	A method for measuring personal dose from γ radiation. When optically simulated the material in the detector emits a light signal proportional to the dose of radiation that has been incident on the device.
OPTIMISATION	A radiation protection principle. The process of determining what level of protection and safety would result in the magnitude of individual doses, the number of individuals (workers and members of the public) subject to exposure and the likelihood of exposure being ALARA.
PRSM	Potentially Radioactive Scrap Metal
PUBLIC EXPOSURE	Exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure and the normal local natural background radiation.
RADIATION	For the purposes of this research, the term “radiation” refers only to ionising radiation, which is radiation capable of producing ion pairs in biological material(s).
RADIATION PROTECTION	The protection of people from harmful effects of exposure to ionising radiation, and the means for achieving this.
RADIATION RISKS	Detrimental health effects of exposure to radiation (including the likelihood of such effects occurring), and any other safety related risks (including those to the environment) that might arise as a direct consequence of: (a) exposure to radiation

	(b) the presence of radioactive material (including radioactive waste).
RADIATION SAFETY OFFICER (RSO)	An individual technically competent in radiation protection matters who is designated by the mine operator to oversee the application of the requirements of the applicable legislation. Under mine safety legislation, a radiation safety officer for naturally occurring radioactive materials must meet specific criteria and be approved by the RRAM.
RADON (RN)	An inert, gaseous, radioactive decay product of ^{238}U, ^{235}U, and ^{232}Th. - The ^{238}U series produces the isotope ^{222}Rn (radon). - The ^{235}U series, produces the isotope ^{219}Rn, commonly referenced as actinon. - The ^{232}Th series produces the isotope ^{220}Rn, commonly referenced as thoron (abbreviated as Tn).
RADON-222 PROGENY (RNP)	The decay products of ^{222}Rn (radon), comprising the short-lived decay products from ^{218}Po through ^{214}Po. Radon progeny were historically referenced as “radon daughters”.
RADON-220 PROGENY (TNP)	The decay products of ^{220}Rn (thoron), comprising the short-lived decay products from ^{216}Po through ^{208}Tl. Thoron progeny were historically referenced as “thoron daughters”.
RISK BASED APPROACH	An approach where the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control.
RMP	Radiation Management Plan
RSA	Radiation Safety Act 1975
RSGR	Radiation Safety (General) Regulations 1983
RWMP	Radioactive Waste Management Plan
SI	System Internationale
SIMILAR EXPOSURE GROUP (SEG)	A grouping of workers based upon their work profile, in which the jobs they perform lead to exposures to workplace contaminants (including radiation) that are common across the group. The exposures, and resultant doses can be estimated by sampling of representative workers within the group.

SOMATIC EFFECT	A radiation induced health effect that occurs in the exposed person.
SPECIFIC ACTIVITY (SA)	Measures the radioactivity of a unit weight or unit volume of substance. The units are becquerels per gram or becquerels per litre. The Specific Activity of a radionuclide is inversely proportional to its atomic weight and its half-life. Note – not to be mistaken for Activity Concentration.
STOCHASTIC EFFECT	A radiation induced health effect such as solid cancers or leukaemia, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose. Stochastic effects may be somatic effects or hereditary effects, and generally occur without a threshold level of dose.
THERMO-LUMINESCENT DOSIMETRY **(TLD)**	A method for measuring personal dose from γ radiation. When thermally simulated the material in the detector emits a light signal proportional to the dose of radiation that has been incident on the device.
THORON (TN)	Radon-220. See Radon.
WA	Western Australia
WHS ACT **(WHSA)**	The WA Work Health and Safety Act 2020. Proclaimed on the 10th of November 2020 and came into effect on the 31st of March 2022, replacing the MSIA.
WHS (MINES) REGULATIONS **(WHSR(MINES))**	The WA Work Health and Safety (Mines) Regulations 2022. Came into effect in WA on the 31st of March 2022, replacing the MSIR.
WORKING LEVEL (WL)	The historical unit for the activity concentration of radon or thoron progeny.
WORKING LEVEL MONTH (WLM)	The cumulative exposure from breathing an atmosphere at a concentration of one Working Level for a working month of 170 hours.

TABLE 2: INSTITUTIONAL ACRONYMS

ANSTO	AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
ARPANSA	AUSTRALIAN RADIATION PROTECTION AND NUCLEAR SAFETY AGENCY
CIM	Chief Inspector of Mines Replaced the SME when the WHSR(Mines) came into effect in WA on the on the 31st of March 2022.
CMEWA	The Chamber of Minerals and Energy WA
THE DEPARTMENT	The WA Government agency Department charged with oversight of safety in the mining industry. It has undergone numerous name changes in the period covered by this research and was previously referred to as Department of Mines and Energy (DME) WA; Department of Mines and Petroleum (DMP) WA; or Department of Mines (DoM) WA. Is now named DMIRS.
DMIRS	Department of Mines, Industry Regulation and Safety (WA).
ECU	Edith Cowan University
EPA	Environmental Protection Authority of WA
IAEA	International Atomic Energy Agency
ICRP	International Commission for Radiological Protection
IMRC	Interim Mines Radiation Committee ~1982-1990 (replaced by MRSB)
MI (THE INSPECTORATE)	Mines Inspectorate Is part of the Department. Administered the MSIA and MSIR under the direction of the SME and administers the WHSA and WHSR(Mines) under the direction of the RRAM.
MRSB	Mines Radiation Safety Board ~1990 to 1996
NHMRC	National Health and Medical Research Council
THE REGULATOR	The WorkSafe Commissioner The regulatory authority specified in the WHSA and has regulatory oversight of the WHSR(Mines).
RCWA	Radiological Council of WA The regulatory authority specified in the RSA and designated as the peak radiation protection body in WA.

RHB	Radiation Health Branch of the Health Department of WA. Provides technical and secretariat support to the RCWA. Recently became the Radiation Health Unit.
RRAM	Relevant Regulatory Authority: Mining A term used in this document to define the regulator in tandem with the CIM
SME	State mining engineer The regulatory authority responsible for the administration of the MSIA and MSIR. Replaced in the WHSR (Mines) by the CIM.
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WAHD	WA Health Department
WHO	World Health Organisation

STRUCTURE OF THIS THESIS:

The genesis of this research arose from the changes introduced to the models for evaluating worker radiation doses when the International Commission for Radiological Protection published the first volume of the Occupational Intake of Radionuclides (ICRP, 2015).

Coincidentally, the international treaty on climate change enshrined in the Paris Agreement (UNFCCC, 2015) established the platform for a material increase in global demand for uranium, and what are collectively referenced as “critical minerals” used in the manufacture of technology to support reductions in greenhouse gas emissions. Western Australia’s lithology is replete with deposits of these resources, and therefore the state is well-placed to become a major supplier to meet the increase in global demand. However, Western Australia’s lithology typically contain levels of NORs that are elevated above the global crustal average: workers may be exposed to NORs during the mining and mineral extraction processes, and if not effectively managed, the wastes from processing activities may present a radiological hazard to the community and environment.

The core purpose of this research was to investigate and document the sources, and magnitude of the radiation doses to Western Australian mine workers arising from exposure to NORs, in order to answer the research question:

“what is the potential for radiation exposures from NORs to the significantly increased workforce, and is the regulatory framework fit-for-purpose to ensure radiation doses are kept as low as reasonably achievable?”

This coherent body of research is presented in eleven chapters:

CHAPTER ONE: AN OVERVIEW OF THE WESTERN AUSTRALIAN MINING INDUSTRY, THE OCCURRENCE OF NORS AND THE RISKS OF EXPOSURE TO IONISING RADIATION.

Chapter One provides an overview of the Western Australian mining industry and the risks of exposure to NORs. Three principal mining regions are identified, which provide the foundation for the assessment of worker radiation doses in subsequent Chapters.

CHAPTERS TWO, THREE AND FOUR: LITERATURE REVIEW:

The literature review covers three connected but differing subject areas. Chapter Two reviews the global approach to regulation of exposures to ionising radiation, and the influence on Australian and Western Australian regulatory frameworks; Chapter Three chronicles radiation doses incurred as a result of exposure to NORs in mining jurisdictions outside of Western Australia; and Chapter Four analyses the potential for radiation exposures to Western Australian mine workers as a result of their being employed in the three principal mining regions identified in Chapter One.

CHAPTER FIVE: CHRONICLE OF RADIATION EXPOSURES OF WESTERN AUSTRALIAN MINE WORKERS 1977 TO 2019-20

This Chapter addresses a lacuna in the body of knowledge of radiation exposures of Western Australian mine workers by drawing upon the 166 annual occupational radiation reports submitted by Reporting Entities (REs). The precis of the historical record is supplemented by: estimates made during the Winn Committee of Inquiry; research by the Department; reports made by the Australian Radiation Laboratories; and records retrieved from archives held by the Radiological Council of Western Australia.

The sources and magnitude of radiation exposures to mine workers in Western Australian have been compiled for the 42 reporting periods from 1977 to 2019-20.

CHAPTER SIX: EVALUATING THE IMPACTS OF REVISED DOSE COEFFICIENTS FOR THE INHALATION OF RADON AND RADON PROGENY IN UNDERGROUND NON-URANIUM MINES

This Chapter evaluates the potential radiation doses to the state’s underground mining workforce as a result of the revised dose coefficients for introduced by the International Commission for Radiological Protection in Volume 3 of the Occupational Intake of Radionuclides (ICRP-137) in December 2017.

The majority of radiation dose to underground workers derives from exposure to radon and radon progeny. Because the dose coefficients from this exposure pathway had increased significantly from previous models, it was postulated that the changes may result in elevated radiation doses in the state’s underground mines.

Using data derived from research conducted into the state’s underground mining workforce by the Department in 1994, the radiation exposure profile of the contemporary underground workforce was reassessed by application of the revised dose coefficients.

CHAPTER SEVEN: EVALUATING THE IMPACTS OF REVISED DOSE COEFFICIENTS FOR THE INHALATION OF NOR-CONTAINING DUSTS

Following the publication of Volume 4 of the Occupational Intake of Radionuclides (ICRP-141) in December 2019 the revision of dose coefficients for all members of the ^{238}U and ^{232}Th decay chains was completed, allowing a revision of the dose conversion factors for inhalation of insoluble mineral dusts.

As discussed in Chapter Five, inhalation of long-lived alpha particle emitters in dusts is the major exposure pathway to workers in the mineral sands, tantalum, and rare earths sectors of WA's mining industry. Increases to the dose conversion factors had the potential to significantly influence the dose estimates to workers. This Chapter explores the possible impacts and provides an estimate of the potential increase in worker dose as a result of exposure to "typical" dusts encountered in the mineral sands industry.

This research led to a revision of the Departments Dose Assessment guideline, NORM-V.

CHAPTER EIGHT: IMPACTS OF REVISED DOSE CONVERSION FACTORS (DCFS): COMPARISON OF 2018-19 AND 2019-20 ANNUAL RADIATION REPORTS

Chapter Eight applies the techniques deployed in Chapters Five and Seven and compares the worker radiation doses as submitted by Reporting Entities (REs) in their annual occupational radiation reports for 2019-20 against those reported in 2018-19.

The 2019-20 reporting period was the first in which the revised dose conversion factors (DCFs) as determined in Chapter 7, and featured in the Department's guideline NORM-V, were applied to calculate doses from inhalation of long-lived alpha particle emitters in mineral dusts.

The comparison between the year preceding, and the year immediately after implementation of the revised dose conversion factors allowed for an evaluation of the impacts of the revisions, and validation of the conceptual increase in dose as outlined in Chapter Seven.

CHAPTER NINE: AN INVESTIGATION INTO CONTROLLING THE RISK TO WORKERS AND THE ENVIRONMENT FROM POTENTIALLY RADIOACTIVELY CONTAMINATED MINING PLANT AND EQUIPMENT

This Chapter pursues the emerging issue for the WA mining industry arising from the need to safely handle and dispose of radioactively contaminated plant and equipment, identified in Chapter Four.

The volume of the contaminated plant and equipment across the WA mining sector is difficult to estimate, however one disused mineral processing facility reports “several hundred thousand tonnes, spread over an area of several square kilometres”. The environmental footprint of this volume of material is significant and presents a high potential for worker exposures to a variety of radioactive contaminants.

The research reported in this Chapter investigates a potential method to significantly reduce the environmental footprint and commensurate worker risks of exposure by applying high-pressure water cleaning to remove the radioactive contaminants and capturing them in a high-filtration-efficiency geotextile.

The results of the field-based research were profound and present a disruptive approach to minimising the risks to workers, the community and the environment that warrants further investigation.

CHAPTER TEN: A PROPOSED MODEL FOR HARMONISING THE APPROACH TO REGULATING RADIATION EXPOSURES IN THE WESTERN AUSTRALIAN MINING INDUSTRY

Chapter Ten presents a precis of current issues in the WA radiation regulatory framework. The Chapter draws upon the recommendations made by a parliamentary inquiry into a similar regulatory impasse in another Australian mining province, to develop a revised regulatory model and makes recommendations on how the current shortcomings may be addressed.

CHAPTER ELEVEN: CONCLUSIONS

Chapter Eleven provides the conclusion to the research and reviews the findings against the aims and objectives.

The research presented in the eleven Chapters relate to seven papers authored by the researcher, details of which are provided in Appendix 1, entitled “Research Outputs”.

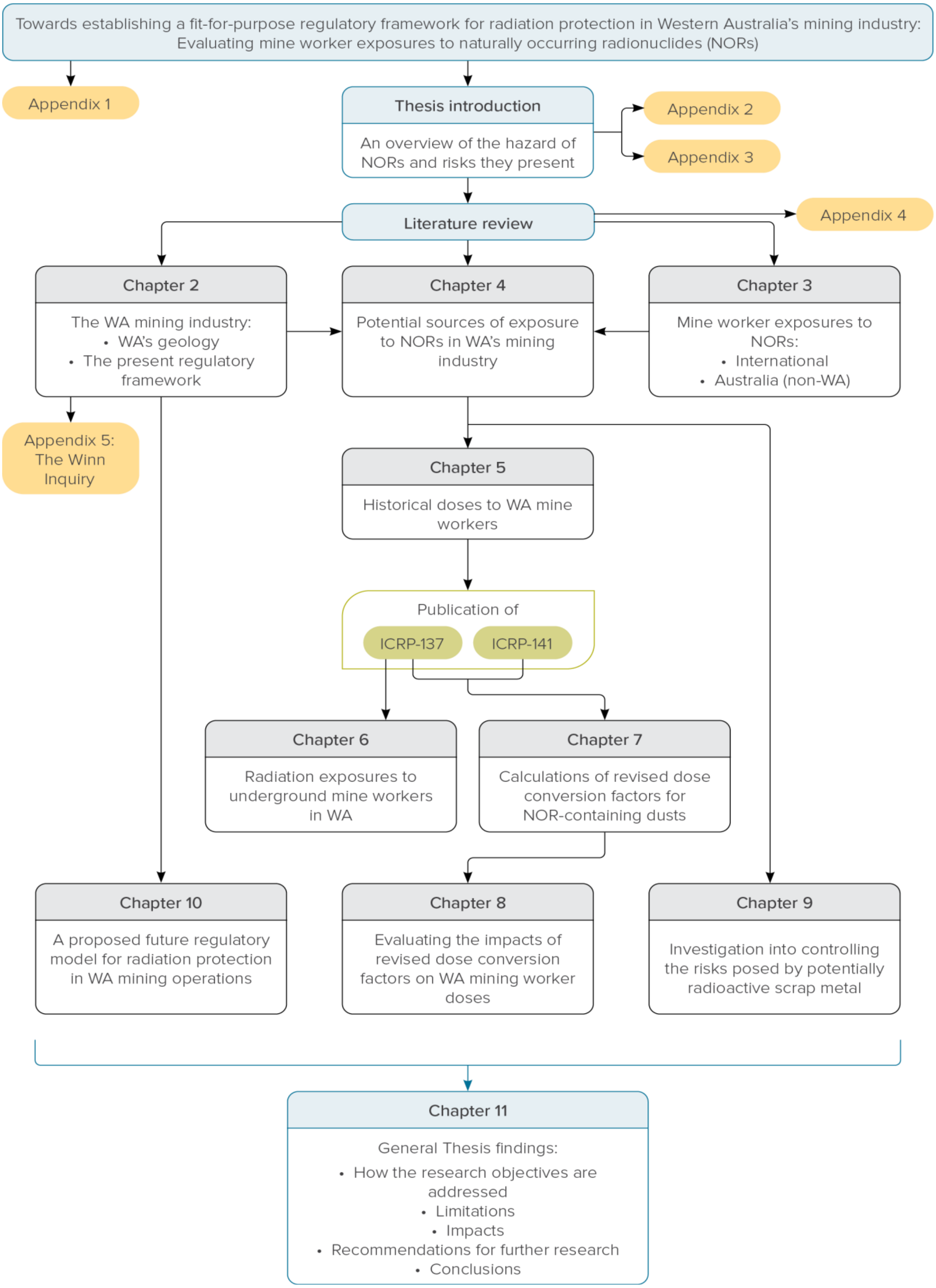

FIGURE 1: STRUCTURE OF THIS THESIS

INFLUENCES ON THE RESEARCH

The research was influenced by a number of factors emanating from a changing international, national, and domestic legislative landscape; and a period of geopolitical instability that threatened global supply chains of critical minerals, which in turn promoted a dramatic increase in the number of mining operations in WA that are likely to encounter NORMs. These challenges occurred at a time when the international models for evaluating the radiation risks to workers were being re-evaluated.

A chronological summary of the influencing factors is provided in detail as Appendix Four.

The international, national and WA-based-developments and their influence upon the production of minerals, and the regulatory environment are illustrated in Figure 2.

- Significant catalysts for change are coloured in green; the influences of the catalysts are coloured in blue; the 'products' of the influences are coloured in yellow; the outputs of the developments are coloured in grey; and the outcomes are coloured in red.

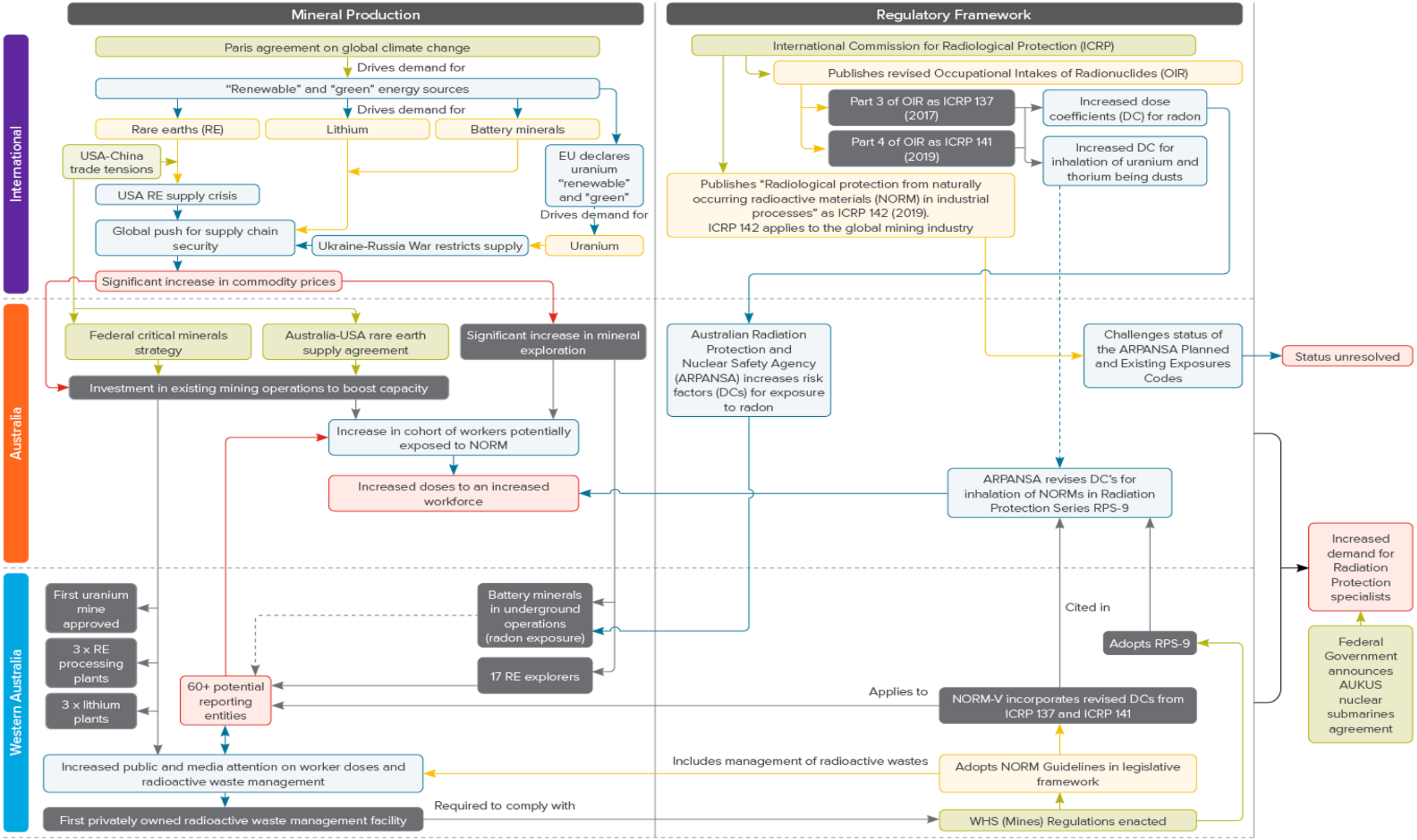

FIGURE 2: DEVELOPMENTS THAT INFLUENCED THIS THESIS

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CHAPTER ONE: AN OVERVIEW OF THE WESTERN AUSTRALIAN MINING INDUSTRY, THE OCCURRENCE OF NORS AND THE RISKS OF EXPOSURE TO IONISING RADIATION

Western Australia (WA) is the epicentre of Australian mining and a major player in the international mining industry. It hosts a huge number of high-grade resources and some of the largest mines in the country. New mineral exploration is constantly underway in WA with a new spotlight on lithium and vanadium to meet with the growing demand of green energy alternatives and new battery technologies.

WA is ranked by the Fraser Institute as the top region in the world for mining investment.

Australasian Institute of Mining and Metallurgy: Mining in Western Australia

(AusIMM, 2022).

This Chapter introduces the lithology of Western Australia and provides an overview of the main commodities produced by the WA mining industry in order to estimate the mining workforce potentially exposed to NORs. Three principal mining regions are identified, which provide the foundation for the assessment of worker radiation doses in subsequent Chapters. The Chapter also serves to introduce the occurrence of naturally occurring radionuclides (NORs), and the pathways by which mine workers may be exposed. Finally, the basis for the contemporary dose-health risk model, which is germane to this research, is discussed and concludes that although the risks such as those experienced by mine workers from NORs are subject to uncertainty, they are nonetheless, quantifiable.

1.1 THE WESTERN AUSTRALIAN MINING INDUSTRY: OVERVIEW

Mining in Western Australia (WA) commenced with the extraction of lead from the "Northampton Block" in the 1840s, and expanded over the ensuing years to the point that in 1912 the *Western Australian Yearbook* reported that "*just about every known mineral had been found in the State*" (EC, 1979). Since that time the mining industry has been a significant component of the state's economy, contributing approximately $170 billion in 2020-21, equivalent to 47% of the Gross State Product (JTSI, 2022).

According to the Western Australian Department of Mines, Industry Regulation and Safety (the Department, DMIRS), in 2018-19, 21,348 mineral tenements were applied, covering 47,189,000 hectares, equivalent to approximately 19% of the mainland area of Western Australia (DMIRS, 2019a). Of the tenements, 5,862 are active mining leases (DMIRS, 2019a) which host 557 actively producing mining operations (DMIRS, 2020a).

1.2 THE WESTERN AUSTRALIAN MINING INDUSTRY: COMMODITIES AND DEMOGRAPHICS

Western Australia is one of the world's top contributors to the global commodity market, and according to the 2021 major commodities resources data, is the leading producer of iron ore, garnet and lithium; and ranks amongst the top five countries for the production of alumina (#2), cobalt (#3), gold (#3), nickel (#5), rare earths (#4), salt (#5) and zircon (#2) and in the top ten producers of ilmenite, manganese and rutile (DMIRS, 2022a).

Radiation doses were first systematically addressed in Western Australia in the 1986-1987 reporting period (Hewson, 1989b), and therefore 1987 serves as the base from which to evaluate the state's mining industry demographics.

The size of the Western Australian mining workforce between 1987 and 2021 is illustrated as Figure 2.

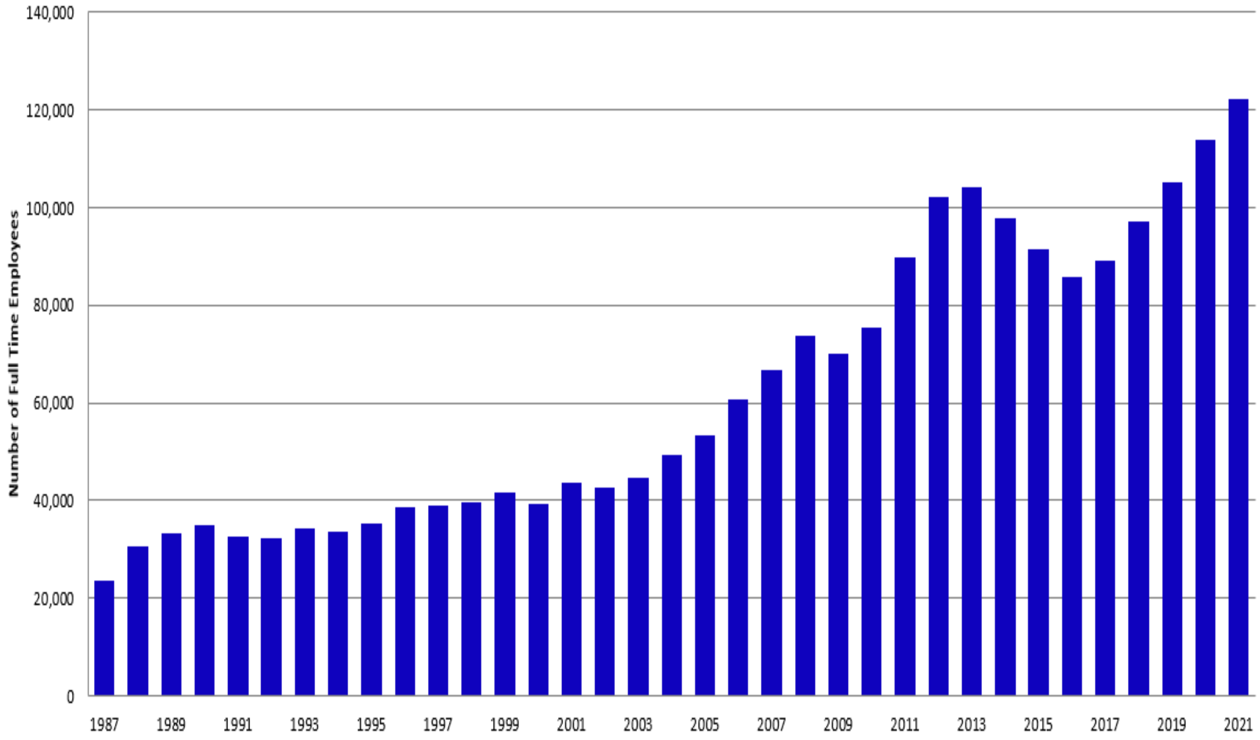

FIGURE 3. SIZE OF THE WA MINING WORKFORCE 1987 TO 2021

As shown in Figure 3, the Western Australian mining workforce has expanded considerably over the past three decades. The workforce peaked at 104,000 workers in 2013, and after a decline over the subsequent three years, growth resumed, with the contemporary workforce at an historical peak level.

Table 3 compares compare the distribution of the Western Australian mining workforce by commodity in 1987 to the contemporary mining industry, using data from DMIRS (2022a).

As shown in Table 3, in the 2020-21 financial year, the Western Australian mining industry employed 120,248 full time equivalent (FTE) workers. These roles are filled by 151,347 individuals (DMIRS, 2022a) [1].

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[1] Preliminary information indicates the growth continued in 2021-22, with an estimated 123,132 full time equivalent workers employed, filled by 156,238 individuals (DMIRS, 2022b).

TABLE 3: WA MINING WORKFORCE BY COMMODITY MINED - COMPARISON OF 1987 TO 2020-21

Commodity	1987 Workforce		2020-21 [2] Workforce	
	FTEs	%	FTEs	%
Alumina / Bauxite [1]	4,022	17.2	6,810	5.7
Base metals [1]	160	0.7	1,887	1.6
Coal [1]	1,163	5.0	642	0.5
Construction Materials	Not reported		703	0.6
Diamonds	128	0.5	97	0.1
Gold	3,368	14.4	29,413	24.5
Iron ore	9,920	42.4	61,172	50.9
Mineral sands [1]	628	2.7	1,917	1.6
Nickel [1]	2,911	12.4	7,812	6.5
Salt	401	1.7	645	0.5
Lithium [1]	Not reported		1,957	1.6
Others	720	3.1	2,950 [3]	2.5
Exploration	Not reported		4,243	3.5
FTE Workers	**23,421**		**120,248**	

[1] Identified by IAEA (2006); ICRP (2019b); RHSAC (2005) to encounter NORs. Refer to the discussion in Section 1.7

[2] Reporting by financial year commenced in 2001-02. Prior to this period, reporting was by calendar year.

[3] Includes 240 FTE roles in the rare earth's sector, filled by 313 workers.

1.3 GEOLOGICAL FEATURES OF WESTERN AUSTRALIA AND THE STATE'S MINING INDUSTRY

The Geological Survey of Western Australia (GSWA) has identified the major geological features of the state as illustrated in Figure 4 (DMIRS, 2020c).

There are three major geological features that are of significance to this research:

1. the "***Great Plateau***" which is comprised of several distinct geological formations illustrated in Figure 3, including the Yilgarn and Pilbara Cratons and the Hamersley, Gascoyne, Fortescue, and Ashburton Basins. These formations occupy the inland west of the State, lying approximately between 20° and 34° south and 116° and 124° west.
2. the Darling Scarp colloquially known as the "***Darling Ranges***" a low escarpment that lies to the east of the state capital Perth, and runs north to south, abutting the Swan Coastal Plain – a narrow formation that at its widest is 40 kilometres from the coast.

   The Darling Ranges are an expression of the Darling Fault, which runs approximately 1000 kilometres from Shark Bay, located in the Southern Carnarvon Basin, to the southern coast, at Albany in the southern Yilgarn Craton-Nornalup Zone- Eucla Basin region; and
3. a series of formations described in the Western Australian Atlas of Human Endeavour (EC, 1979, pp. 10-11) as "***Tidal Flats***", which run along the coast of the state, notably the Eucla Basin, Nornalup and Buranup Zones, Leeuwin Inlier, Perth Basin, Northampton Inlier and Southern Carnarvon Basin.

Each of the three geological features have differing radiological profiles that have a bearing upon potential radiation exposures to mine workers and members of the community.

As illustrated in Figure 5 (DMIRS, 2020e), many of the major mineral deposits in Western Australia are found in these three geological formations.

As can be interpreted from Figure 5, mineral deposits have been identified outside of the three major formations, however despite their prospectivity (for example, potential mineral sands deposits have been identified in the Tidal Flats of the Canning Basin in the north-west of Western Australia (Sheffield Resources Ltd, 2021) and rare earth prospectivity has been identified in the King Leopold sandstone formations in the Pilbara Basin (IAEA, 2019a, p. 99)), they constitute a minor proportion of the state's current operating mining projects.

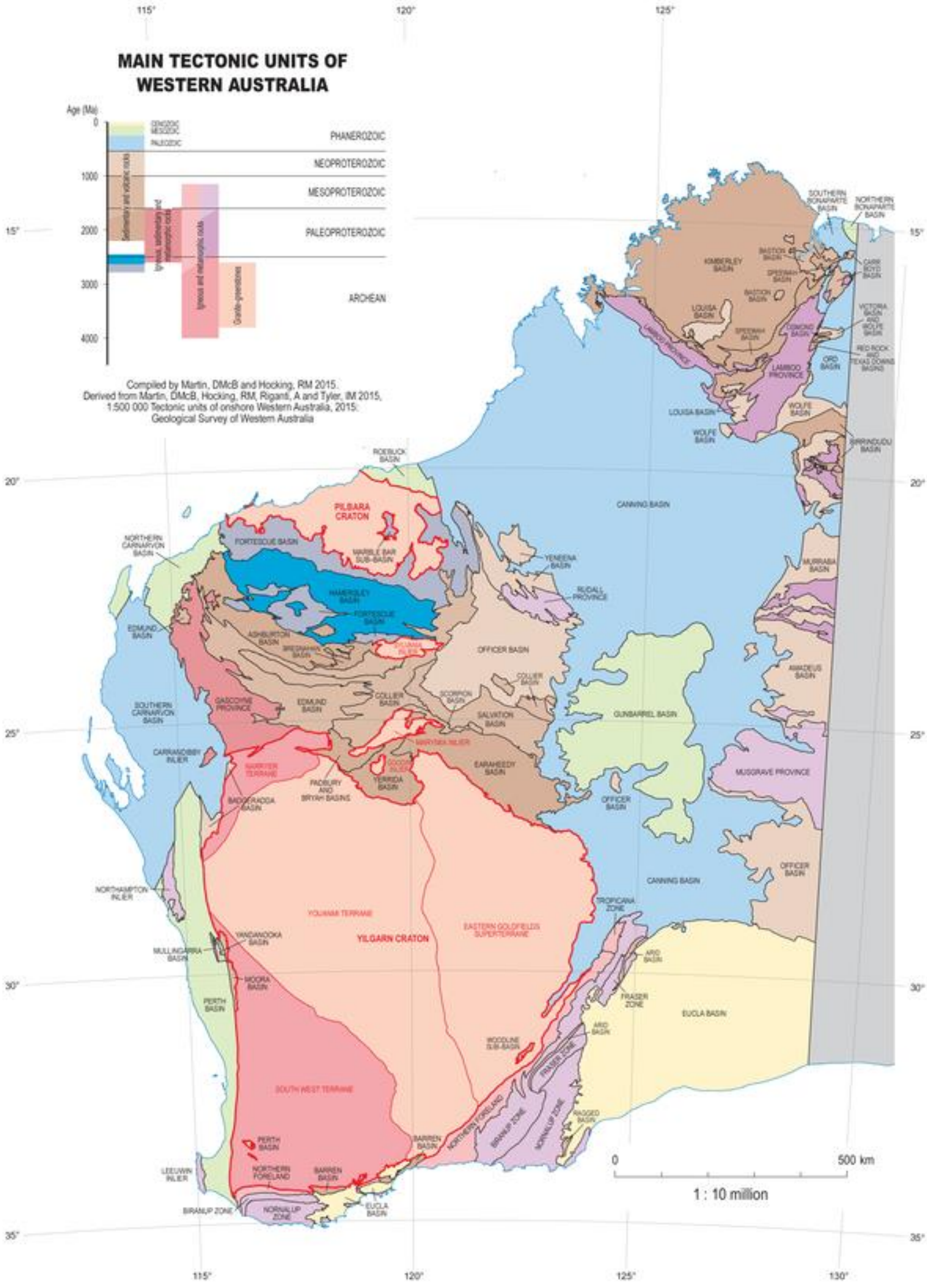

FIGURE 4. GEOLOGY OF WESTERN AUSTRALIA (DMIRS, 2020C)

FIGURE 5. LOCATION OF MAJOR MINING RESOURCE PROJECTS IN WA (DMIRS, 2020E)

1.4 URANIUM LITHOLOGY IN WESTERN AUSTRALIA

According to Eisenbud and Gesell (1997, p. 134) "In most places on earth [^{238}U] varies only within narrow limits, but in some localities there are wide deviations from normal levels because of abnormally high soil concentration of radioactive minerals". If amenable to mining, the areas of abnormally high concentration represent potential commercially exploitable deposits.

The lithology of mainland Western Australia hosts in excess of 60 known potentially commercially sustainable uranium deposits (GWA, 2013a, pp. 6-7), totalling a known resource of 250,000 tonnes of triuranium octoxide (U_3O_8) (GWA, 2017), supporting the statement "[in Australia] the state with the largest prospect for future uranium development is WA" (NERA, 2017, p. 9). Despite the significant potential, and several attempts to develop a domestic uranium production industry (detailed in Chapter Five) Western Australia has, at time of writing, not established a producing uranium mine. [2]

A moratorium that has been intermittently applied to the nascent uranium industry over the past four decades was lifted in November 2008 (Clarke, 2008). The incumbent government has "honour[ed] the four uranium projects which received State Ministerial approval under the previous Government", but "Does not support uranium mining in Western Australia and will not approve any new uranium proposals" (GWA, 2017).

- None of the four approved operations have commenced mining, and as a result uranium is a notable absentee from the commodities listed in Table 3.

Ralph, Hinckley and Cattani (2020b) and Ralph, Tsurikov and Cattani (2020c) highlight that many of the uranium deposits in Western Australia lie within the Great Plateau, along a line that runs from Exmouth on the north-west coast and south-east to Kalgoorlie-Boulder in the Eastern Goldfields district.

- As can be interpreted from Figure 5, the identified uranium deposits are congruent with many of the state's existing mining operations.

It is postulated that the congruence may indicate that mines in the Great Plateau will exhibit elevated concentrations of uranium in the rocks that host the minerals being mined, and by extension, workers in mining operations in the Great Plateau have the potential to receive elevated radiation doses.

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[2] However, and as discussed in Chapter 5, the Mulga Rock Project is scheduled to deliver its first uranium product in 2025 (ABC News, 2021).

1.5 THE THORIUM-232 (^{232}TH) AND URANIUM-238 (^{238}U) RADIOACTIVE DECAY SERIES

The primordial NORs thorium-232 (^{232}Th) and uranium-238 (^{238}U) [3] are widely distributed in the environment and are present to some extent in all rocks and soils (Australian Radiation Protection and Nuclear Safety Agency (ARPANSA, 2020b), the International Atomic Energy Agency (IAEA, 2003, 2006), the International Commission for Radiological Protection (ICRP, 2019b) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000)).

Thorium-232 and ^{238}U are the parent isotopes of decay series in which the product of their radioactive decay is another radioactive isotope, with the sequence continuing through 10 and 14 steps respectively until a stable isotope of lead (Pb) is produced. During the radioactive decay process ionising radiations in the form of alpha (α) particles, beta (β) particles, and gamma (γ) rays are emitted.

The decay series of ^{232}Th and ^{238}U, the half-lives of the principal members of each decay series, and the emissions from their radioactive decay are illustrated in Appendices 2 and 3.

From the information presented in Appendices 2 and 3 it can be seen that the ^{232}Th and ^{238}U decay series share several characteristics (CMEWA, 1994, pp. 2-10, 11):

i. both parent isotopes have extremely long half-lives.
ii. the decay series include alpha-emitting radionuclides with half-lives in excess of 100 days.
iii. they contain an isotope of the gaseous element, radon (Rn), ^{220}Rn (colloquially called thoron) and ^{222}Rn (radon) respectively.
iv. the series of isotopes that follow the radioactive decay of the Rn isotope contains isotopes of very short half-lives (called thoron progeny (TnP) and radon progeny (RnP) respectively; and
v. both terminate with a stable isotope of lead (^{208}Pb and ^{206}Pb respectively).

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[3] 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. The contribution is accounted for when assessing the internal dose due to inhalation of NOR-containing dusts, as outlined in Chapter Seven.

1.5.1 Secular equilibrium

The parent radionuclides ^{232}Th and ^{238}U have much longer half-lives than the other members of their radioactive decay series. If the decay series remains undisturbed, a condition called secular equilibrium occurs in which the activity of the progeny radionuclides equals that of the parent. Note that the condition only applies to the activity and is not reflective of the number of atoms, or the mass, of each radionuclide present. By way of example, if the ^{232}Th series is in secular equilibrium, ^{232}Th will constitute almost the entire mass, but will contribute only one-tenth of the activity, as there are 10 members of the decay series, ^{232}Th being one of them (CMEWA, 1994, pp. 2-17).

Secular equilibrium is an important concept in assessing the radiation dose to mine workers and members of the community, as it allows for the dose calculation models to be simplified – if the activity of the parent radionuclide or one of the members of the decay series is known, and secular equilibrium has been preserved, the activity of all other members of the relevant decay series are also known.

The presence of the isotope of the noble gas radon in both decay series is an important influence on secular equilibrium. If thoron and/or radon has the opportunity to escape from the material in which its parent isotope of radium (Ra), ^{224}Ra in the ^{232}Th series or ^{226}Ra in the ^{238}U series exists, secular equilibrium will be broken by the extent to which the gas can escape. The contribution doses to underground workers arising from exposure to thoron, radon and their progeny are explored in later Chapters in this Thesis.

A further challenge to secular equilibrium occurs if the ore containing ^{232}Th and ^{238}U is subject to chemical or thermal treatment. As well as its radiological properties, each radionuclide in the decay series will exhibit the physical and chemical properties as determined by its atomic number [4]. For example:

- elemental thorium is highly insoluble. Therefore, the two isotopes of thorium (^{232}Th and ^{228}Th) present in the ^{232}Th decay series, and ^{230}Th from the ^{238}U decay, series are insoluble.
- elemental radium is soluble in water. Therefore, the isotopes ^{228}Ra and ^{224}Ra from the ^{232}Th series, and ^{226}Ra from the ^{238}U series, are soluble and can be mobilised under appropriate conditions.

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[4] The atomic number is the number of protons in the nucleus.

- the boiling point of polonium (Po) is 962°C. If ore containing NORs is subject to heating, for instance in a kiln or furnace, and the temperature exceeds the boiling point, the isotopes ^{216}Po and ^{212}Po from the ^{232}Th series, and ^{218}Po, ^{214}Po and ^{214}Po from the ^{238}U series, are likely to be volatised and mobilised from the material being processed.

In instances where isotopes are mobilised, secular equilibrium is disturbed or "broken", and the assumption of equal activities of parent and progeny is no longer valid. However, if the mobilised radioisotope is subsequently undisturbed, it may become the parent of a new (but shorter) decay series. If the "new parent" has a long half-life when compared to its progeny, secular equilibrium between the "mobilised new parent" and its progeny may occur.

- For example, if ^{226}Ra is mobilised and separates from its parent ^{238}U, the 1620-year half-life of ^{226}Ra allows it to establish secular equilibrium with its much shorter half-life (3.8 days) progeny ^{222}Rn and its decay products.

In summary, it is important to understand the chemical and thermal properties of the parent radionuclide and its progeny as well as their radiological properties.

1.6 SOURCES OF EXPOSURE TO NORS FROM MINING OPERATIONS

The IAEA states "All minerals and raw materials contain radionuclides of natural terrestrial origin … The activity concentrations of these radionuclides in normal rocks and soil are variable, but generally low. However, certain minerals, including some that are commercially exploited contain uranium and/or thorium series radionuclides at significantly elevated activity concentrations … Any mining operation … involving a mineral or raw material has the potential to increase the effective dose received by individuals" (IAEA, 2006, p. 1).

According to ARPANSA (2008, 2011a); IAEA (2006, 2018a); Koperski (1993b); Sonter and Hondros (1989) the most significant pathways of exposure for mine workers arising from exposure to the ^{232}Th and/or ^{238}U decay series are:

- External irradiation from exposure to gamma radiation (γ) emitted by most members of each decay series.
- Inhalation of dusts which contains long-lived alpha (LLα) emitting isotopes; and

- Inhalation of the radioisotopes of thoron (^{220}Rn) and radon (^{222}Rn); and the products of their decay, all of which have short half-lives, and are referenced as thoron progeny (TnP); or radon progeny (RnP).

The sum of the contributions from each of the three significant pathways is used to calculate the committed effective dose (annual dose), measured in millisieverts (mSv), which is compared against legislatively imposed limits.

In addition to the three significant pathways, ARPANSA states "… any operation in which material is extracted from the earth and processed can potentially concentrate NORM in product, by-product or waste (residue) streams … has potential to lead to exposures to both workers and members of the public …" (ARPANSA, 2008, p. 4).

As was discussed in Section 1.5.1, the extraction and processing of minerals can lead to the dispersal of radionuclides and secular equilibrium being broken. This may result in an uneven distribution of activity concentrations in different parts of the processing cycle; plant and equipment; or in waste streams ICRP (2019b). Highly elevated activity concentrations of specific radionuclides may occur as a result of the dispersal, and present levels of risk of exposure not otherwise encountered in mining activities where secular equilibrium is not disturbed.

The potential for secular equilibrium to be broken and consequent dispersal of radionuclides must be identified in order for the risk of exposures to workers and the community and contamination of the environment to be minimised. Once the potential has been recognised, specialised monitoring techniques, for instance gamma or alpha spectrometry are required to determine the presence and concentration of the dispersed radionuclides. The use of gamma spectrometry to identify and quantify dispersed radionuclides in contaminated mining equipment is explored in Chapter Nine of this Thesis.

1.7 MONITORING OF THE THREE PRINCIPAL EXPOSURE PATHWAYS

Other than localised heating effects at very high rates of exposure, ionising radiation cannot be detected by any of the five human senses. Therefore, detection of ionising radiation is reliant upon sophisticated instrumentation which must be suitable for the type and energy of the emissions; be regularly calibrated to ensure it provides results that are accurate and reproducible; and are used according to the techniques applicable to the instrumentation.

1.7.1 Monitoring of external γ radiation and measurement of external dose

Monitoring of external γ radiation is relatively straightforward, and can follow one (or both) of two techniques:

- Area monitoring, where hand-held instruments with an energy range that can detect the γ emissions from the ^{232}Th and ^{238}U decay series (as per Appendices 2 and 3) are used to measure the γ levels and provide a direct reading in either μGyh^{-1} or μSvh^{-1}, depending upon the method used to calibrate the instrument. Worker doses are calculated from time and motion studies, based upon doserate in an area multiplied by time spent in that area.
- Personal monitoring, where an individual worker is allocated a passive device either a thermo-luminescent dosimeter (TLD) or optically stimulated luminescence (OSL) “badge” which is worn at the worker’s waist level during all working hours. The device is worn for a period of between one and three months, at the end of which it is returned to the service provider for analysis. The analytical laboratory will return a report on the workers individua dose in mSv.

Where possible the use of individual monitors for exposure to γ radiation, but allowances are made for time and motion studies where exposure rates are low (GWA, 2010a, pp. 6-7).

On occasion, where exposure rates are anticipated to be elevated, personal electronic dosimeters (PEDs) may be used to directly measure a worker’s daily dose. This methodology is being deployed in increasing frequency over the past two years, as monazite production has recommenced.

1.7.2 Monitoring of LLα in dusts and measurement of dose $_{LL\alpha}$

Monitoring for LLα in dusts is complex, and the calculation of internal dose from the inhalation of LLα (dose $_{LL\alpha}$) in those dusts is reliant upon complex dosimetric models.

The airborne dust is collected on filter papers housed in sampling devices, that perform in accordance with International Standards Organisation inhalability criteria. The sampling devices are worn in the workers breathing zone for a minimum of a four-hour sampling period, and up to 12 hours in duration. 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 in an alpha spectrometer that is set to a mode that does not apply energy discrimination (i.e. it counts all incident alpha particles, regardless of their energy)(GWA, 2010c).

The result from the gross alpha analysis provides an activity value in Bq. This value is divided by the volume of air drawn through the sampling device worn by the worker to provide an activity concentration of the LLα in the collected dust in Bqm^{-3}.

Internal dose estimates are calculated using the activity concentration of the LLα multiplied by an assumed worker breathing rate of 2,400 m^3 per annum [5] to estimate an annual intake of LLα in Bq.

At this juncture the characteristics of the dust (discussed at length in Chapters Seven and Eight) are used to determine the dose conversion factor (DCF) for the inhaled dust. The DCF provides a value for dose per unit intake, measured in mSvBq^{-1}. When multiplied by the estimate of annual intake, an annual internal dose from LLα (dose $_{LL\alpha}$), in mSv, is derived.

In a similar fashion to monitoring of external γ, personal monitoring of the potentially most exposed individual workers is preferred, however, as discussed in Chapters Seven and Eight, has not been widely deployed in Western Australian mining operations that encounter NORs. Instead, an approach that uses Similar Exposure Groups (SEGs) [6] is commonly utilised. Workers are assigned to one (or more) of the SEGs, dependent upon their work activities, and the dust samples collected for any member of the SEG are assumed to represent all members of the SEG. The time each worker spends in each SEG are recorded for dose calculation purposes, and their annual dose is calculated as the sum of the dose received by each SEG.

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

1.7.3 Monitoring of Tn, TnP, Rn and RnP and measurement of internal dose $_{(TnP\ \&\ RnP)}$

The measurement of the gaseous Tn and Rn is relatively straightforward (George, 2008), whilst the measurement of TnP and RnP is, by comparison, complex.

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[5] Derived from a breathing rate of 20 litres per minute, equivalent to 1.2 cubic metres per hour for a 2,000-hour working year.

[6] SEGs are defined on the basis of commonality between the location within a processing plant, or job type, or exposure characteristics. Eight SEGs were defined for application across the WA mineral sands industry (Hewson, 1990b, p. 7). These SEGs are largely still in application.

Until the revision of dose coefficients for Tn, Rn, TnP and RnP published in ICRP-137 (ICRP, 2017), the contribution to worker dose from this exposure pathway was thought to be minimal. However, as discussed in Chapters Five, Six, Seven and Eight, that view has changed in the years since ICRP-137 was published, and campaigns for monitoring worker exposure have commenced in many mining operations.

In a similar fashion to external γ, monitoring of the concentrations of Tn and Rn can be conducted via either passive or electronic devices. Passive devices, usually deploying a track-etch technology where α-particles leave trails on a reactive film, are left in situ for a period of up to three months and forwarded to a laboratory for analysis. Electronic instruments draw air through a chamber and via complex algorithms can calculate the Tn and/or Rn concentration and provide via direct reading. Both techniques provide a concentration result in Bqm^{-3}. Worker occupancy times are multiplied by the assumed breathing rate of 2,400 m^3 per annum (refer to Footnote 5) and the concentration to estimate an annual intake in Bq. The dose coefficient for Tn or Rn is provided in $mSvBq^{-1}$. When multiplied by the estimate of annual intake, an annual internal dose in mSv, is derived.

However, Tn and/or Rn exposure contributes minimal dose from this pathway. The contribution from TnP and RnP is much higher (ARPANSA, 2011a, p. 37), and therefore the measurement of the concentration of TnP and RnP is important. However, the monitoring techniques (which are described in detail in CMEWA (1994)) require a skilled practitioner to be deployed effectively and other than some minimal sampling campaigns by Ralph and Hewson (1988) and Browne (2016) have not been routinely practised in the Western Australian mining industry.

It is prudent to state that monitoring for exposures from this pathway is in its infancy, and whilst monitoring for Tn and Rn is a first step, nonetheless, reliance solely upon Tn and/or Rn concentrations as an indicator of worker dose is inherently error-prone and increases the uncertainty in dose estimates significantly. DMIRS (2021b) discourages the practise, stating “Therefore, while it is a relatively straightforward technique, monitoring for radon or thoron gas in isolation is usually not suitable for dose estimation”.

The investigation of the contribution to worker dose from TnP and RnP is an opportunity for future research.

1.8 THE WESTERN AUSTRALIAN MINING INDUSTRY: POTENTIAL FOR ENCOUNTERS WITH NORS

The Australian Radiation Health and Safety Advisory Council (RHSAC), the IAEA and the ICRP have identified a range of ores and minerals in which NORs are encountered (IAEA, 2006; ICRP, 2019b; RHSAC, 2005), many of which are mined and processed within Western Australia.

- The suite of potentially NOR-including commodities includes mineral sands, coal, phosphate ores, sandblasting materials, and the production of bauxite, titanium dioxide pigment, copper, zinc, lead, tin, tantalum, and the refining of zircon.
- The commodities identified by the RHSAC, IAEA and ICRP to contain NORs that are currently mined and processed in Western Australia are ascribed the footnote [1] in Table 3.
- As highlighted in footnote [3] to Table 3, rare earths also contain NORs. The industry is nascent in Western Australia, and does not, as yet, have a workforce of the size that warrants a category of its own in DMIRS (2022a).

As can be seen from Figure 2 and Table 3, the workforce has increased significantly since 1987, and the cohort of workers potentially exposed to NORs has increased accordingly. By way of context, and excluding underground gold miners, but including the estimated 313 workers in the rare earths sector (see notes to Table 3), approximately 23,800 mine workers are potentially exposed to NORs – equivalent to the size of the entire Western Australian mining workforce in 1987.

- Gold mining is not listed by the RHSAC, IAEA and ICRP as an activity likely to encounter NORs. However, this should not discount the potential for underground gold miners working in mining operations in the Great Plateau to receive radiation doses, primarily through inhalation of Rn and RnP.
- Radiation exposures to underground workers in the Great Plateau are evaluated in Section 4.1.

The influence of the state's lithology on the potential for mine worker exposures to NORs is discussed in detail in Chapter Four. As a precursor to Chapter Four, it is highlighted that recently, Western Australia has begun to exploit its significant reserves of "battery minerals" including lithium, cobalt, graphite, manganese, vanadium (GWA, 2019b; JTSI, 2019) and rare earths (Lynas Corporation Ltd, 2020). Exploration for, and development of, critical minerals is occurring in all three of the major geological features identified in Section 1.3:

- At time-of-writing, 168 Western Australian-based companies listed on the Australian Stock Exchange cite rare earths in the portfolio of minerals contained within their prospects.
- 51 of the listed companies are actively drilling on their tenements DMIRS (2022b).
- Further, production of Western Australia's most radioactive mineral, monazite (a rich source of rare earth elements) has re-commenced for the first time since the mid-1990s (Iluka Resources Limited, 2020).

These developments, and the emergence of interest in the state's uranium resources add to the portfolio of minerals that are likely to encounter NORs and will expand the size of the workforce potentially exposed to radiation in the course of their work.

The vast Western Australian resources sector hosts many operations that involve altering the physicochemical properties of the lithology in which the resource occurs and generate significant volumes of potentially NOR-contaminated discharges, residues and plant and equipment, that require appropriate management. As was outlined in Sections 1.5 and 1.6, the radionuclides dispersed by chemical or thermal treatment of ores present additional sources of exposure to workers and the community and contamination of the environment.

1.9 RADIATION EXPOSURE RISK AND THE ALARA PRINCIPLE

Willhelm Röntgen discovered X-rays in November 1895, and a few months later, harmful effects arising from exposure had been reported, such as X-ray dermatitis in the USA, and radiation damage to the hands and fingers of pioneering experimenters in the United Kingdom and Germany (Clarke & Vanlentin, 2008, p. 77).

The effects of acute exposures (those that occur over minutes or hours) at high dose rates are exceptionally well understood and manifest themselves as somatic effects. However, and despite the passage of 125 years since Röntgen's discovery, the effects of chronic exposures, sustained over periods measured in years, such as those faced by workers in the mining industry are less well defined.

According to Steinhausler (1993, p. 38) "the mining and extraction industries have been associated with the highest individual occupational exposures to radioisotopes" and "health effects range from relatively weak associations to statistically significant excesses for a variety of symptoms such as respiratory diseases or cancer of the bone, lung or pancreas". The association between health effects and exposure to radiation is a motivator for ensuring that all doses should be reduced to as low as reasonably achievable (ALARA).

Chronic exposure to radiation continues to be the subject of debate within the radiation protection community, however, it is (largely) agreed that low doses involve stochastic risks, in that the likelihood of a negative health effect (such as cancer) increases with increasing exposure of an exposed cohort (but not necessarily seen at the individual level).

Modelling of dose-response relationships consider amongst many variables: the route of exposure; the physical and chemical properties of the source of exposure; and the organs in the body which have been exposed. Models for evaluating the risk of exposure to ionising radiation are subject to intense scrutiny, and, as briefly discussed in Chapter Two, evolve over time. The findings of authoritative international bodies such as the ICRP, IAEA and the World Health Organisation (WHO) are integrated into the domestic legislative statutes of participating nations, and form part of the regulatory standards of that nation.

The prevailing methodology for assessing the risk associated with radiation exposure is called the Linear Non-Threshold (LNT) hypothesis, which draws upon data derived from acute exposures such as Japanese atomic bomb survivors, where the deterministic health effects from estimated exposures are well known, and postulates that a linear relationship extends from this data to the origin, as illustrated in Figure 6.

The risks of an adverse health outcome for persons exposed to ionising radiation have been studied for over a century and are able to be quantified with some certainty. As can be seen from Figure 6 a range of models of risk to health from chronic exposure to ionising radiation are postulated. Models (a) and (b) suggest a quadratic response but are in opposition to each other; Model (c) describes a threshold, below which no risk occurs (noting that several other industrial agents exhibit a similar dose-effect relationship); and Model (d) illustrate a hormesis effect, which suggests that low doses of ionising radiation have a positive effect on health. At this juncture the conservative, extrapolated LNT hypothesis is favoured by the international radiation protection community (RHSAC, 2017). However, an outcome of the LNT hypothesis is the idiom that "*every dose of radiation carries some level of risk*".

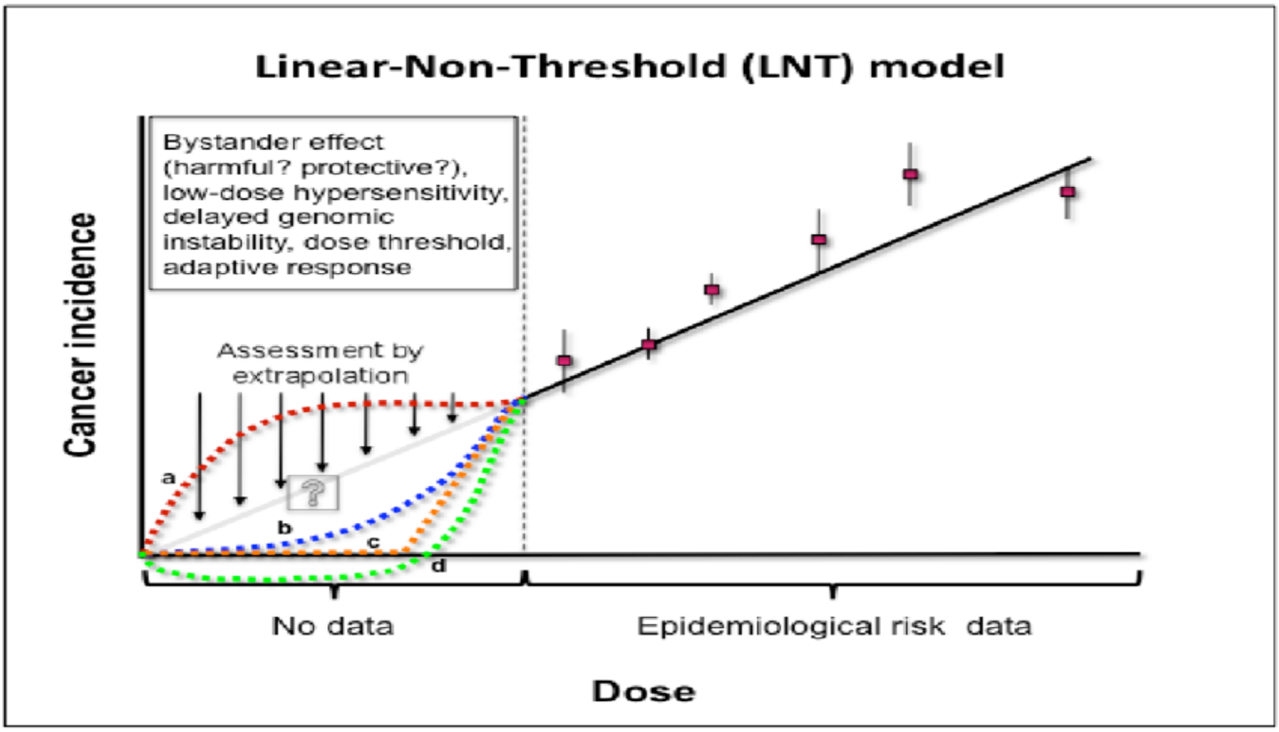

FIGURE 6: THE LINEAR NON-THRESHOLD (LNT) HYPOTHESIS (MANCUSO ET AL., 2012)

Clarke (2004, p. 309) endeavours to articulate a radiation dose-risk framework for chronic exposures , stating "… individual doses of the order of 100mSv, the risk … cannot be justified, except in extraordinary circumstances" and in relation to doses likely to be received by workers "in the intermediate region, doses between a fraction of a millisievert and a few tens of millisieverts are legitimate matters for significant concern, calling for regulatory action".

According to Hopkins (2005) the United Kingdom's Health and Safety Executive (HSE) has embraced a three-tier approach to risk, in which quantifiable risks are categorised as either intolerable; tolerable; or acceptable.

Hopkins cites an offshore industry example of an individual risk criteria, in which risks:

- greater than 1 in 1,000 are intolerable and require risk reduction measures to be applied.
- between 1 in 1,000 and 1 in 100,000 are considered tolerable if risk reduction is impracticable or costs are grossly disproportionate to the benefits derived; and
- less than 1 in 100,000 are acceptable.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) states “the risk factor averaged over all ages and cancer types is about 1 in 10,000 per millisievert” [arising from acute exposures] and “there is evidence that a dose accumulated over a long period carries less risk than the same dose received over a short period … while not well quantified, a reduction of the high-dose risk factor by a factor of two has been adopted internationally, so that for radiation protection purposes the risk of radiation-induced fatal cancer is taken to be about 1 in 20,000 per millisievert of dose for the population as a whole” (ARPANSA, 2018b).

As is explored in Chapter 3 of this dissertation, the annual derived dose limit for workers is 20mSv. Following the ARPANSA (2018b) fatal cancer risk of 1 in 20,000, an annual dose of 20mSv equates to a 1 in 1000 risk of a worker developing a negative health effect from their radiation exposure.

According to the HSE model cited above from Hopkins (2005), the level of risk at the annual derived dose limit is on the cusp of intolerability. Self-evidently doses to workers need to be kept below the derived dose limit and should be reduced to ALARA.

Having established the size of the mining workforce potentially exposed to NORs; the sources of exposure; and the risk framework; the Thesis now addresses the regulatory framework which establishes the level of risk tolerance of exposures, by establishing dose limits and controls required to limit exposure, and the mechanisms by which doses are calculated.

CHAPTER TWO: LITERATURE REVIEW PART I - THE WESTERN AUSTRALIAN RADIATION PROTECTION LEGISLATIVE FRAMEWORK

2.14. The government shall ensure that adequate arrangements are in place for the protection of people and the environment, both now and in the future, against harmful effects of ionizing radiation, without unduly limiting the operation of facilities or the conduct of activities that give rise to radiation risks. This shall include arrangements for the protection of people of present and future generations and populations remote from present facilities and activities.

2.17. The government shall ensure that the regulatory body has the legal authority, competence, and resources necessary to fulfil its statutory functions and responsibilities.

IAEA General Safety Requirements Part 3

(IAEA, 2014, pp. 20-21).

The legislative framework for radiation protection in the mining industry establishes the tolerable levels of exposure to workers and the community by establishing dose limits, and the controls required to be implemented to ensure the levels are not exceeded. The methodology for calculating doses is integral to ensuring compliance with the legislatively imposed tolerance level.

Radioactive minerals have been extracted in Australia for over 100 years (Sonter, 2014), and because of the extended periods covered by this research, the changes that have occurred to the regulatory framework, including the limits of exposure, and the dose calculation methodologies in the intervening period need to be considered.

The Mines Safety and Inspection Act 1994 (MSIA) and Regulations 1995 (MSIR) (GWA, 1994, 1995) were the governing legislation for protection of mine workers from the risk of exposure to NORM throughout most of the period covered by this research. However, during final production of this Thesis, the Western Australian Work Health and Safety Act (WHSA) and Work Health and Safety (Mines) Regulations (WHSR(Mines)) (GWA, 2020, 2022d) were proclaimed [7] (Parliament of Western Australia, 2020). Accordingly, where required, this Chapter, reflects the changes in the legislative framework.

2.1 HISTORY OF THE DEVELOPMENT OF THE RADIATION PROTECTION LEGISLATIVE FRAMEWORK

Uranium ores have been mined in Australia since 1910, for extraction of radium, used mainly for cancer therapy. The first Australian “uranium rush” commenced in the 1940s, continuing into the early 1960s, to supply uranium for the United Kingdom and United States weapons programs. Consequently, the Australian uranium mines were seen as of having great strategic significance, and were held under tight government [agency] control (Sonter, 2014). According to Sonter (2014) “The fact that government bodies held operator or owner roles meant there was no independent oversight of radiation safety or environmental issues … The Chief Inspectors of Mines expressed concern that secrecy provisions meant they could not gain access to the defence-contract governed mines…”.

In 1947 the Geological Survey of Western Australia investigated the beaches and rivers of the state searching for monazite in mineral sands deposits as part of a national program to define Australia’s potential radioactive mineral resources SWDA (1990, Ch1-5). As a result, it is judicious to suggest that the radiological characteristics of Western Australian mineral sands deposits were known prior to the

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[7] The legislation came into effect on 31st March 2022.

state's first mineral sands operation at Cheyne Bay in 1949, and for the subsequent 35 years until the advent of the Winn Inquiry (refer to Section 2.1.3 and Appendix 5).

It is prudent to contend that throughout the 1950s and 1960s the legislative framework, in the respect of uranium mining, and by extension all NORs, was largely absent, or was subject to confidentiality provisions due to national security concerns. The Department appears to confirm this contention by stating that "The WA Health Department's (WAHD) Radioactive Substances Act 1954, although not framed to specifically include mining and processing of uranium ores, was nevertheless applied to the licensing of uranium mining in this State. Worker and public protection conditions were attached to the licenses" (DME, 1997).

From commencement of the Cheyne Bay operations in 1949-50, the Western Australian mineral sands industry (MSI) fell within the regulatory remit of the RSA (and its preceding legislation), enforced by the Radiological Council of Western Australia (RCWA) via the (various) Radiation Health Section(s) of the Health Department of Western Australia.

According to Hewson, Kvasnicka and Johnston (1992) "The [MSI] in WA commenced in the late 1950s and since this time has been subject to some form of regulatory control". However, it was not until July 1966 that an operation in the MSI in the south west of Western Australia was informed by the RCWA (1983) that "the monazite had a thorium oxide content [and] was radioactive". Hewson (1990b) adds "Government in WA has been aware of the need for some level of radiation protection surveillance in the MSI since the mid-1960s … The increase in monazite production in the mid-1970s heralded significantly greater Government surveillance … from the late 1970s formal radiation monitoring requirements were imposed on the industry through the application of general radiation safety regulations administered by the WAHD".

This regulatory framework was an extension of that applied to uranium mining under the Radioactive Substance Act 1954 and replaced by the RSGR when they were assented to in August 1983.

2.1.1 Early Codes of Practice

Prior to the introduction of the specific regulations in the MSIR in 1995, radiation protection in the mining of radioactive ores was regulated via Codes of Practice. The earliest specific mining code was the Commonwealth Code of Practice in the Mining and Milling of Radioactive Ores (DOHA, 1975). This code failed to receive support of the Western Australian MSI because it targeted uranium mining (SWDA, 1990; Watson & Taylor, 1984). According to Sonter (2014) "The 1975 Code was actually quite a good document but with the glaring omission that it required control over internal organ doses *but gave no way of calculating them*".

The 1975 Code was superseded in 1980 by the Commonwealth Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (DOHA, 1980), formulated under the provisions of the Environmental Protection (Nuclear Codes) Act 1978, and designed to apply to all sites where radioactive ores were involved. Watson and Taylor (1984) highlighted the shortcomings of the revised Code in respect of its application to the MSI, with the South West Development Authority (SWDA) bluntly reporting "The [MSI] did not wish to be regulated by this Code as it felt that association with the uranium industry would put the mineral sands companies in bad light" (SWDA, 1990, pp. Ch3-13).

Subsequently, the WAHD and the MSI produced separate revisions of the 1980 Code. The MSI Code was published in 1981 as the Code of Practice on Radiation Protection in the Mining and Concentrating of Monazite Ore (1981). However, the narrow focus on monazite was unacceptable to the WAHD (SWDA, 1990, pp. Ch3-13), and as a result the MSI Code was not recognized by the regulatory authorities.

The differences in regulatory philosophy were such that an intervention was required, which saw a tripartite approach to the development of the 1982 Code of Practice on Radiation Protection in the Mining and Processing of Mineral Sands (DoM, 1982; Watson & Taylor, 1984). This Code was colloquially referenced as the Mineral Sands Code.

In January 1983, the Mineral Sands Code was adopted under the Mines Regulation Act 1946 (DME, 1997), the fore-runner to the MSIA. The Mineral Sands Code was also included in the RSGR.

2.1.2 A regulatory impasse

Through the 1970s, monazite production expanded significantly and despite the potential for elevated worker exposures, it "became apparent, however, that the RSA did not have suitable powers to enable proper control of radiation on mine sites as it had been designed principally to control medical uses of radiation" (Hartley & Hewson, 1990). Winn, Mathews and Tough (1984) observed that whilst some companies adhered to the regulatory authority's advice, added "Others have in the past shown some diffidence towards complying".

The lack of appropriate legislative authority is evident in the submission made by the RCWA to the Winn Inquiry (RCWA, 1983). The RCWA reports that the site advised of radiological issues in 1966 was inspected on numerous occasions through the 1970s, with officers representing the RCWA noting that “doses in the office area would exceed the ICRP limits for the general public” and “a monazite bagger could receive between 20 and 100 milliRem/week [8] from external γ. The RCWA commented further “Altogether the operations of this plant have been relatively unsatisfactory over the years … The company has been relatively slow in responding to requests from Council to clean up their procedures … Indeed [according to site management] … no radiation protection measures were thought necessary” (RCWA, 1983).

- It is apparent that sections of the MSI were, through their unwillingness to comply with directions from the RCWA, challenging the legislative powers inferred by the RSA.

Hartley and Hewson (1990) reflected “From the late 1970s the MSI has excited considerable controversy … through increased community concern about environmental issues. Those involving radiation have attracted particular media attention, which in turn has generated anxiety amongst both workers and the broader community” and “... public perceptions about the community radiation hazard arising from MSI operations[s] have tended to escalate. The intense public scrutiny has at times complicated the functioning of the regulatory authority [RA]”.

In 1982, the Cabinet of the Government of Western Australia agreed to form the Interim Mines Radiation Committee (IMRC) to oversee the implementation of actions to overcome the regulatory impasse (RCWA, 1983).

However, the issues and community concerns persisted, leading to the following statement attributed by Winn et al. (1984) to the Western Australian Minister for Health: “Following widespread concern about the levels of ionising radiation in the MSI, the Western Australian government established a Committee of Inquiry (the Winn Inquiry) in mid-1983 to report and make recommendations on:

(a) The adequacy of, and compliance with, codes of practice and legislation regulating radiation in the mining, processing and transport of heavy mineral sands and the disposal of tailings “.

It is evident that the intention of the Western Australian government in commissioning the Winn inquiry was to resolve the seeming legislative impasse.

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[8] Equivalent to 10 to 50mSv per year.

2.1.3 The Winn Inquiry

The Winn Inquiry (Winn et al., 1984, Ch 6.3-6.4) agreed that the existing regulatory structures were inadequate up until the adoption of the Mineral Sands Code (DME, 1997) in 1983, stating “the RCWA and its predecessor the Radiological Advisory Council … have for many years found themselves in a position of administering radiation protection standards in the MSI without any clear legal standards”.

Whilst Winn et al. (1984) stated “The committee has found no major breaches of legislation, regulations or codes of practice”, the committee contended that the performance of the MSI could be improved, pointedly stating “the Commissioners believe the goal of bringing radiation levels As Low as Reasonably Achievable, i.e., the ALARA principle; needs to be pursued with more vigour”.

Two of the more poignant comments to this research made by in the report of the Winn Inquiry (Winn et al., 1984) were in relation to:

- a shortage of appropriately qualified and experienced Radiation Safety Officers (RSOs) would detract from the MSI’s ambitions to effectively manage the exposure of its workers and the public. Trenchantly, the Commissioners stated “a further cause of concern has been the inadequacy of training facilities for companies’ [RSOs]”; and
- proposed changes to the dose coefficients for members of the ^{232}Th and ^{238}U decay series. Prophetically the Commissioners stated that they “see a difficulty for the MSI in the future as it attempts to comply with the proposed new maximum limits for the radioactivity of dust”.

The Winn Inquiry made sweeping recommendations, the majority of which were implemented [9], leading to significant changes in the regulatory governance of worker radiation exposures in the MSI, and over time, other mining operations that encountered NORs.

As reported by Hartley and Hewson (1990), 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 (GWA, 1987).

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[9] The only recommendation not implemented was the commissioning of a detailed epidemiological study of long-term exposed MSI workers.

- relocation of regulatory responsibility for radiation protection in Western Australian mines from the RCWA to the State mining engineer (SME) [10]; and
- commissioning of a specialized Radiation Secretariat within the Mines Inspectorate (later renamed the Radiation Safety Section, RSS).

The Winn Inquiry signified an exigency for the manner in which worker exposures to NORs were managed by the MSI and regulated by government agencies.

- Because of its significance to this research, the findings and ramifications of the Winn Inquiry are detailed in Appendix 5.

2.1.4 Legislative framework post-Winn Inquiry

The changes in regulatory governance, most significantly the relocation of regulatory responsibility for radiation protection in Western Australian mines from the RCWA to the SME, laid the foundation for a period in which Western Australia's oversight of radiation protection in the mining industry was recognised to be performing at world's best practice (Fitch, 1988; Koperski, 1993c).

An updated Commonwealth Code of Practice on Radiation Protection in the Mining and Processing of Radioactive Ores (CoA, 1987) (the Radiation Protection Code) was produced in 1987, and was adopted under the Mines Regulation Act Regulations 1976, in January 1989 (DME, 1997), replacing the Mineral Sands Code. Simultaneously, the Commonwealth Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores 1982 (the Waste Management Code), also formulated under the provisions of the Environmental Protection (Nuclear Codes) Act 1978, was incorporated in the Mines Regulation Act Regulations 1976 (Hewson et al., 1992).

The Radiation Protection Code was based upon ICRP-30 (ICRP, 1979), which introduced SI units and confirmed the ICRP position supporting the Linear, No-Threshold (LNT) hypothesis (discussed in Chapter One). Hewson et al. (1992) indicate that the introduction of the Radiation Protection Code "triggered profound changes in radiation protection practices … by virtue of its adoption of the dose additivity principle and internal dosimetry methods of ICRP-30". Previously, each of the three pathways were treated as separate exposures, and the combinative effects were not considered.

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[10] The State mining engineer was the regulatory authority appointed to enforce the MSIA and MSIR. Under the provisions of the WHSR(Mines) this role lies with the regulator (refer to Section 2.6).

Both the Radiation Protection Code and the Waste Management Code were subsequently incorporated into the RSGR. This initiative introduced a nationally consistent legislative framework for radiation protection in mining until the proclamation of the MSIA and MSIR, in November 1994 and December 1995 respectively (GWA, 2021). The radiation protection regulations introduced into the MSIR [11] were largely based upon the Radiation Protection Code and Waste Management Code, and incorporated internationally and nationally accepted practises, including those recommended in ICRP-60 (DME, 1997).

Despite some minor amendments in 1996, 1998 and 2009 (GWA, 1995) the Western Australian mining-industry-specific legislative requirements applied, largely unchanged, from December 1995 until proclamation of the WHSR(Mines) on the 31st March 2022 (as discussed at the beginning of this Chapter). The impacts of the WHSR(Mines) legislation are briefly discussed in subsequent Sections in this Chapter.

2.2 HISTORY OF THE BASIS FOR WORKER DOSE ESTIMATES AND REGULATORY LIMITS

In 1964, the National Health and Medical Research Council (NHMRC) published the first Radiation Protection Standards, based upon the 1964 recommendations of the ICRP in Publication 6. Upon the release of ICRP-Publication 9 in 1966 (which introduced the concept of acceptable risk of radiation exposure), the NHMRC produced the “revised protection standards for individuals exposed to ionizing radiation” in 1967, an amendment to which was produced in 1977 (Dessent, 2017).

The ICRP also approved Publication 26 in 1977, introducing the “as low as reasonably achievable” (ALARA) principle, and removed quarterly dose limits, replacing them with an annual limit. ICRP-26 also introduced the three principles of radiation protection: justification; optimization and the application of dose limitation (Clarke & Vanlentin, 2008). Subsequently, the NHMRC produced the first in the Radiation Health Series (RHS) of publications “RHS 1: recommended radiation protection standards for individuals exposed to ionizing radiation” in 1980 (Dessent, 2017).

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[11] Included as Part 16, Divisions 1 and 2

2.2.1 Dose calculation methodology: 1980s

Prior to 1986, internal dose calculations were based upon ICRP-2 (ICRP, 1964) which was superseded by the Publication 30 series, and Publications 54, 68 and 78 (ICRP, 1980a, 1988, 1994c, 1997), released progressively between 1980 and 1988.

SWDA (1990) reports that at this time the MSI was able to meet the 50mSv annual dose limit imposed by the Mineral Sands Code by "adjustment of work practices". Despite these assurances the methodology for calculating worker doses as per the Mineral Sands Code was based upon an incorrect interpretation of the ICRP-2 recommendations for inhalation of dusts containing the ^{232}Th decay series. Reinterpretation of the ICRP-2 recommendations resulted in a two-fold decrease in the maximum allowable intake of dusts containing the ^{232}Th decay series (Hewson, 1990b; SWDA, 1990).

According to Hartley and Hewson (1990) "After much deliberation and investigation the Interim Mines Radiation Committee (IMRC) recommended the application of the ICRP Publication 30 annual limits of intake which were significantly more restrictive than previous inhalation limits for thorium". Based upon ICRP-26 (ICRP, 1977) and its companion document ICRP-30 (ICRP, 1979), the maximum allowable intake reduced by a further factor of 3.5, resulting in "companies which had been in compliance with the previous dose limits now find themselves assessing doses which were in excess of the 50mSv limit" (SWDA, 1990).

Hewson et al. (1992) advised that a degree of uniformity of radiation safety practice evolved through the adoption by states and territories of the recommended standards, codes of practice and other advice as published by the NHMRC, which "… are based on ICRP Publication 26".

Hewson (1990b) illustrates the impacts on the MSI as a result of the new models and revisions of previous assumptions:

- prior to 1985 the derived air concentration (DAC) of LLα in airborne dusts, based on ICRP-2 was 5.2 Bqm^{-3}.
- in 1985 the data in ICRP-2 was re-interpreted, and the DAC decreased to 2.7 Bqm^{-3}; and
- the introduction of ICRP-26 and ICRP-30 saw the DAC reduced to 0.8 Bqm^{-3} in mid-1986.

Hartley and Hewson (1990) summarise the impact of the revisions as “There had been an effective seven-fold reduction in the derived limit for thorium ore dust from 1983 to 1986 as a result of the adoption of the new data”. [12]

2.2.2 1990: Significant decrease in annual dose limit

After an extensive review of the health effects of exposure to radiation by atomic weapons survivors and other acutely exposed populations, the ICRP revised the radiation risk assessment methodology published in ICRP-26 and released new recommendations in Publication 60 (ICRP, 1990) in 1990.

The impacts of ICRP-60 included the reduction of the annual derived limit for effective dose (ED) from 50mSv to 20mSv (ICRP, 1990).

ICRP-60 also introduced revised the dose coefficients (DCs) for the members of the ^{238}U and ^{232}Th decay series, the effects of which were to marginally increase the DAC for of LLα in airborne dusts (Hartley, 1992).

In 1991 the NHMRC published Radiation Health Series 33 implementing the recommendations made in ICRP-60, and decreasing the derived annual limit to 20mSv (Dessent, 2017).

The national ‘Mining and Milling Code’ (CoA, 1987) applied, and guidance was provided in IAEA Safety Guide No. 95 (IAEA, 1989), in the intervening five years until the ICRP-60 recommendations were implemented in Western Australian mining legislation in 1995 (GWA, 1995).

From the time of proclamation of the MSIA and MSIR in the mid-1990s, the assessment of worker internal doses were performed in accordance with the NORM Guidelines (DMIRS, 2020g) which reference the ICRP Publication 30 series, using the guidance provided in Publications 54 and 78, and applying the DCs listed in ICRP-30 (ICRP, 1980a, 1988, 1994c, 1997).

2.2.3 1990s: Revision of risk factors in relation to exposure to isotopes of radon

During the early 1990s, research was being performed on the hazards of radon exposure, and improving the model of the human respiratory tract. ARPS (1993) and Clarke (1993) forewarned of

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[12] Note that as a result of the changes in dose coefficients as introduced in Sections 2.2.5 and 2.2.9, and discussed in detail in Chapter Seven, the DAC decreased further. The changes in DAC over time are illustrated in Figure 9.

impending changes to ICRP modelling for Rn and RnP exposure that were documented in ICRP-65 (Protection against Radon) and ICRP-66 (Respiratory Tract Model) in 1994 (ICRP, 1994a, 1994b).

In relation to the global mining industry, Clarke (1993) counselled that "Annual doses from radon may be … remarkably variable. ICRP concentrates on radon in mines. In Publication 60 [ICRP] recommends that miners be regarded as occupationally exposed, not only in uranium mines, but in many other underground mines. [ICRP] commits itself to review the occupational limit".

The changes in the risks of exposure to Rn and RnP by mine workers were the catalyst for research by Hewson, Tippet, O'Connor, Ralph, and Evans (1991) and Hewson and Ralph (1994), which are re-evaluated in Chapter Four of this Thesis.

2.2.4 Consolidation of the national regulatory framework

In 1999, the Australian Radiation Laboratory, which had been the authorising body governing radiation across Australia since 1973, (ARPANSA, 2021a) was merged with the Nuclear Safety Bureau to form a single over-arching regulatory authority to govern radiation and nuclear safety, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

The term NORM formally entered the radiation protection lexicon in 1999, when it was used in paragraph 6 of ICRP Publication 82: "Protection of the public in situations of prolonged radiation exposure"(ICRP, 1999, p. 15).

Through the 2000s and early 2010s ARPANSA assumed responsibility for the administration of the former Radiation Health Series of documents previously published by the NHMRC, as well as the codes developed under the Environment Protection (Nuclear Codes) Act 1978 (Dessent, 2017). The publications were progressively reviewed and republished as part of the Radiation Protection Series (RPS), commencing in March 2002 when the joint NHMRC and NOHSC Publication No. 39 in the Radiation Health Series was retitled as RPS No. 1 to reflect the discontinuation of the Radiation Health Series of publications (ARPANSA, 2016). RPS-1 was produced as a joint publication between NOHSC and ARPANSA.

In 2014 RPS-1 was superseded by the ARPANSA publication Radiation Protection Series F-1: "Fundamentals for protection against ionising radiation" (ARPANSA, 2014a). ARPANSA (2020a) describes RPS-F-1 as "the top tier document in the Australian national framework to manage risks from ionising radiation as laid out in the Radiation Protection Series".

In 2016 ARPANSA published the RPS-C-1: “Code for radiation protection in planned exposure situations”, based upon the IAEA “Radiation protection and safety of radiation sources: International basic safety standards general safety requirements Part 3, GSR Part 3” (ARPANSA, 2016) colloquially known as the Basic Safety Standards (BSS), which in turn drew upon the ICRP’s recommendations made in ICRP-103 (refer to Section 2.2.5).

The scope of RPS-C-1 is of importance to the Western Australian mining industry, as it clearly articulates that the Code is applicable to occupational exposures from “the mining and processing of raw materials that involve exposure due to radioactive material”.

- As a result, doses to workers arising from exposure to NORMs in the mining industry in Australia are deemed as Planned Exposures, and RPS-C-1 constitutes the relevant guidance.

2.2.5 ICRP developments that influence contemporary dose assessment methodologies

In 2007 the “Recommendations of the International Commission on Radiological Protection”, ICRP Publication 103 (ICRP, 2007) were published. The recommendations in ICRP-103 took a consistent approach for all types of radiation exposure situations, with the central consideration being the optimisation of radiation protection.

Research on the hazards of exposure to radon and refinement of the models for assessing internal exposures continued through the 2000s and early 2010s. Following an extensive period of consultation and advice of impending changes (ICRP, 2009), a comprehensive review of the links between radon exposure and lung cancer was published as ICRP-115 (ICRP, 2010) and was followed by ICRP-126 (ICRP, 2014) which provided guidance on protection against radon.

In 2015, ICRP commenced publication of the Occupational Intake of Radionuclides (OIR) and indicated that the series of five parts would replace the Publication 30 series and Publications 54, 68 and 78 (ARPANSA, 2018a).

Part 1 of the OIR, published as ICRP Publication 130 (ICRP, 2015) provides an introduction to the methodology used in the revision of revised DCs for occupational intakes of radionuclides by inhalation and ingestion. The models used include the Human Alimentary Tract Model (ICRP, 2006); a revision of the Human Respiratory Tract Model; and revised models for the systemic distribution of radionuclides absorbed to blood.

OIR Part 2, issued as ICRP-134 (ICRP, 2016) provided the first set of revised DCs for radioisotopes of elements of lower atomic number, not relevant to the assessment of doses arising from NORMs containing the ^{238}U or ^{232}Th decay series (Ralph et al., 2020c).

ICRP-137 was published as Part 3 (ICRP, 2017) and ICRP-141 as Part 4 (ICRP, 2019a) of the OIR in 2017 and 2018 respectively.

As reported by ARPANSA (2018c) and Ralph et al. (2020b) the changes in DCs were significant, and (dependent upon the exposure scenario) could lead to doses from Rn and RnP increasing by factors of between two and four times that determined by previous DC conventions. Paquet et al. (2017) highlighted the nearly order of magnitude increase in the DC for ^{232}Th, while Hondros and Secen-Hondros (2019) brought attention to the fact that "there are more significant changes in other inhalation factors" that would impact on the mining and milling industry, adding "In some cases the inhalation dose factors have increased by a factor of 10".

- The consequent publication of the Western Australian NORM-V Guideline is discussed in Section 2.9.

A summary of the major legislative amendments and changes to the methodology for estimating worker doses is illustrated in Figure 7. The establishment of significant mining operations are also included in Figure 7.

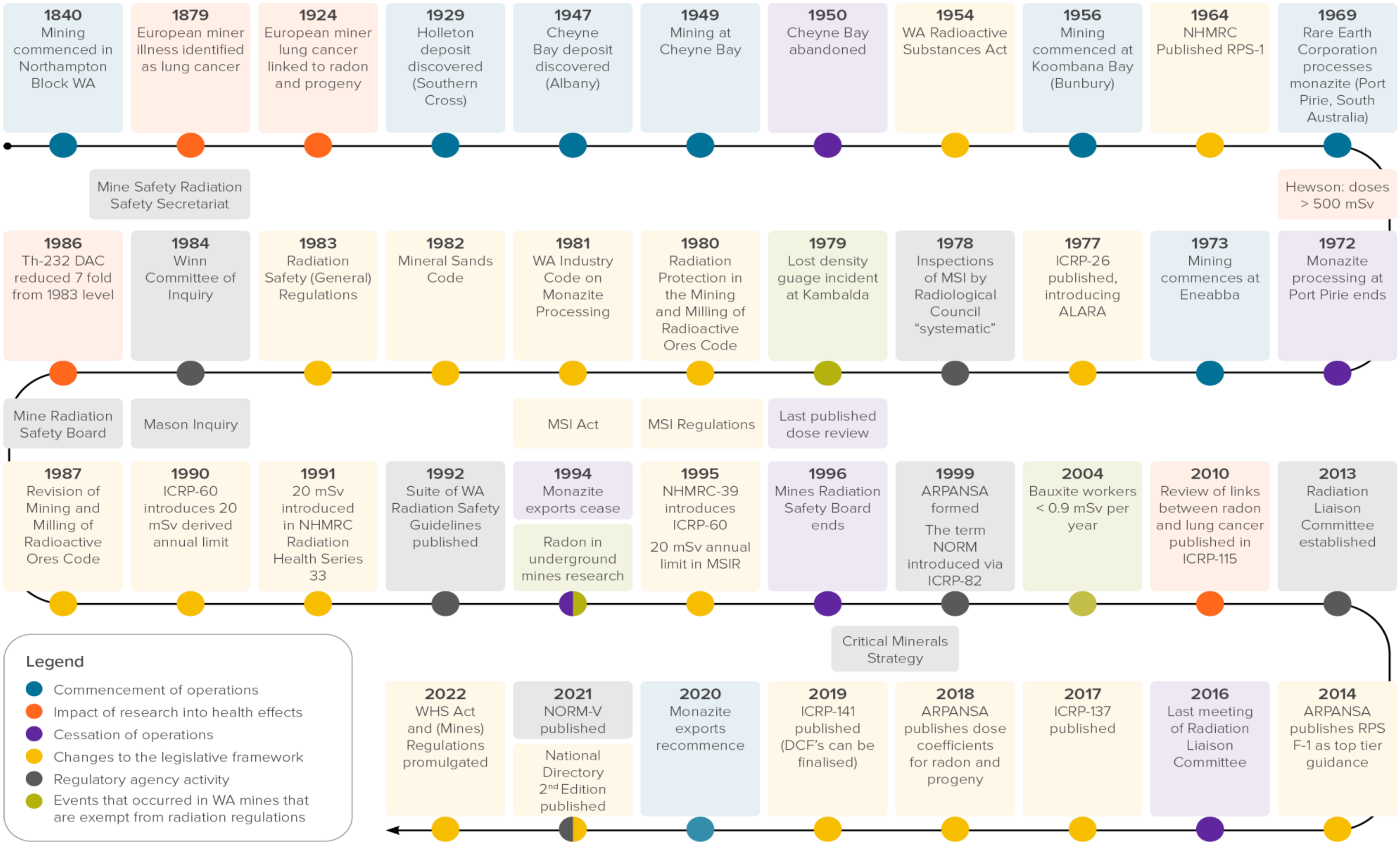

FIGURE 7: TIMELINE OF SIGNIFICANT EVENTS IN RADIATION PROTECTION IN WA MINING OPERATIONS

2.3 AN OVERVIEW OF THE NATIONAL LEGISLATIVE FRAMEWORK

In Australia, regulation of workplace radiation protection is the responsibility of the individual States and Territories (RHC, 2018a), with the promotion of national uniformity an identified function of the Chief Executive Officer of ARPANSA, supported by the Radiation Health and Safety Advisory Council (RHSAC) and the Radiation Health Committee (RHC) (ARPANSA, 2022d).

- Membership of the RHSAC, and RHC, includes technical representatives from each state and territory (ARPANSA, 2021a).

"The RHC advises the Chief Executive Officer of ARPANSA and the RHSAC on matters relating to radiation protection, including formulating draft national policies, codes and standards for the promotion of uniform national standards of radiation protection for consideration by the Commonwealth, states and territories" (ARPANSA, 2022d).

- Although the RHC includes representatives from each of the nine jurisdictions in Australia, none specifically regulate the mining sector.

The promulgation of policies, codes and standards by ARPANSA are intended to achieve national uniformity, with an agreed framework established in the National Directory for Radiation Protection (NDRP) (ARPANSA, 2017b) which was revised during the period of this research to NDRP (2nd edition, 2021) (ARPANSA, 2021c).

However, as highlighted by RHC (2018a, p. 4) "the lack of national uniformity in radiation protection legislation adversely impacts on the effectiveness and efficiency of the administration of radiation protection among jurisdictions". The pursuit of national uniformity has failed to meet its objectives as accentuated in a review by the IAEA (2018b, p. 18) which found "many issues of uniformity remain unaddressed". The Western Australian mining industry is a specific example of where national uniformity of radiation protection legislation has not been formally achieved. In part this is due to the way the NDRP was established – its first iteration, published in August 2004, specified that it did not apply to the mining industry.

Therefore, in practice, regulation is best described as complex interactions between federal and state regulatory agencies, which are influenced by "the international obligations and expectations expressed by bodies such as the IAEA, ICRP and WHO" (D. Smith, personal communication September 24th, 2019).

2.3.1 An Australian-ICRP regulatory impasse of notable consequence

Whilst the impacts of ICRP-137 and ICRP-141 were being evaluated, ICRP released Publication 142: "Radiological protection from naturally occurring radioactive materials (NORM) in industrial processes" (ICRP, 2019b).

The release of ICRP-142 was not without controversy, a point reinforced by Lecomte (2020). 24 submissions are listed on the ICRP-142 comments web page, five of which were made by Australian institutions (ICRP, 2019d). The five submissions are consistent in their criticisms of the draft of ICRP-142, most notably in relation to the exclusion of exposure to Rn and RnP; and the treatment of exposures to NORMs as an Existing Exposure (as opposed to a Planned Exposure, as outlined in Section 2.2.4).

- A revelatory submission was made by ARPANSA (ICRP, 2019e) which states "… there are significant flaws in this document as it stands and if published without change would potentially lead to confusion among regulators and industries" and "if this new definition [of mining operations being construed as Existing Exposures] is published it would be in conflict with ARPANSA's recently published guidance in Australia for Radiation Protection in Existing Exposure Situations, RPS-G-2 and IAEA GSR Part 3".

Note that RPS-G-2 (ARPANSA, 2017a) is the companion document to RPS-C-1 (ARPANSA, 2020a), which, as outlined above constitutes important guidance for the managing occupational exposures to radiation in the Australian mining industry.

- Note that if RPS-G-2 is amended to reflect the ICRP-142 philosophy, RPS-C-1 would also require revision.

The ICRP response to the feedback on which exposure scenario is appropriate for mining has been to adhere to definitions that were found in paragraphs 284 and 288 of ICRP-103 (ICRP, 2020b), advising that "… existing exposure situations … do not require urgent action because the types, forms and concentrations of radionuclides realistically do not have prospect to cause deterministic effects over a short period of time" (ICRP, 2019d). Lecomte (2020) reinforces the ICRP position by pointing out that "ICRP Publication 103 (2007) indicates that NORM is a well-known example of existing exposure positions. This opinion is repeated in Publication 142".

At time of writing, the status of ICRP-142 in the Australian domain remains unresolved, with ARPANSA in a seemingly invidious position of adopting the ICRP-142 philosophy and revising RPS-C-1 and RPS-G-2 or bypassing the ICRP-142 position and maintaining the *status quo* in Australian mining, in the knowledge that it does not align with international practices.

However, the importance of achieving an expedited resolution for the Western Australian mining industry cannot be understated: Paragraph 19 of ICRP-142 states that “the recommendations in the present publication for radiological protection in industries involving NORM supersede all previous related recommendations in *Publications 103, 104, 124* and *126*” which underpin the current approaches to regulating radiation protection in the mining industry.

The researcher has raised this issue with ARPANSA and is aware that an ARPANSA working group has been formed to respond to the matter (C. Lawrence, personal communication July 29th, 2022).

At time of writing, the researcher is unaware of any progress being made to resolve the seeming impasse. The researcher contends that whilst this impasse remains, the contemporary radiation protection regulatory framework in Western Australia must be considered deficient.

2.4 THE RELATIONSHIP BETWEEN INTERNATIONAL BODIES AND THE NATIONAL LEGISLATIVE FRAMEWORK

The deliberations of bodies such as the IAEA, ICRP, UNSCEAR and WHO are considered by the RHC, and if they are compelling are integrated into ARPANSA policies, codes, and standards. Under the auspice of national uniformity, states and territories should adopt the ARPANSA guidance into their regulatory standards, as illustrated in Figure 8.

However, this is not a unilateral obligation: the RHC is faced with many challenges, and if specific issues in radiation protection affect a jurisdiction it is incumbent upon that jurisdiction to react or bring the issue to the attention of the RHC.

- In turn this requires state and territory regulatory agencies to be constantly scanning the research published by IAEA, ICRP, UNSCEAR and WHO, and others, to ensure that their regulatory framework reflects contemporary international deliberations.

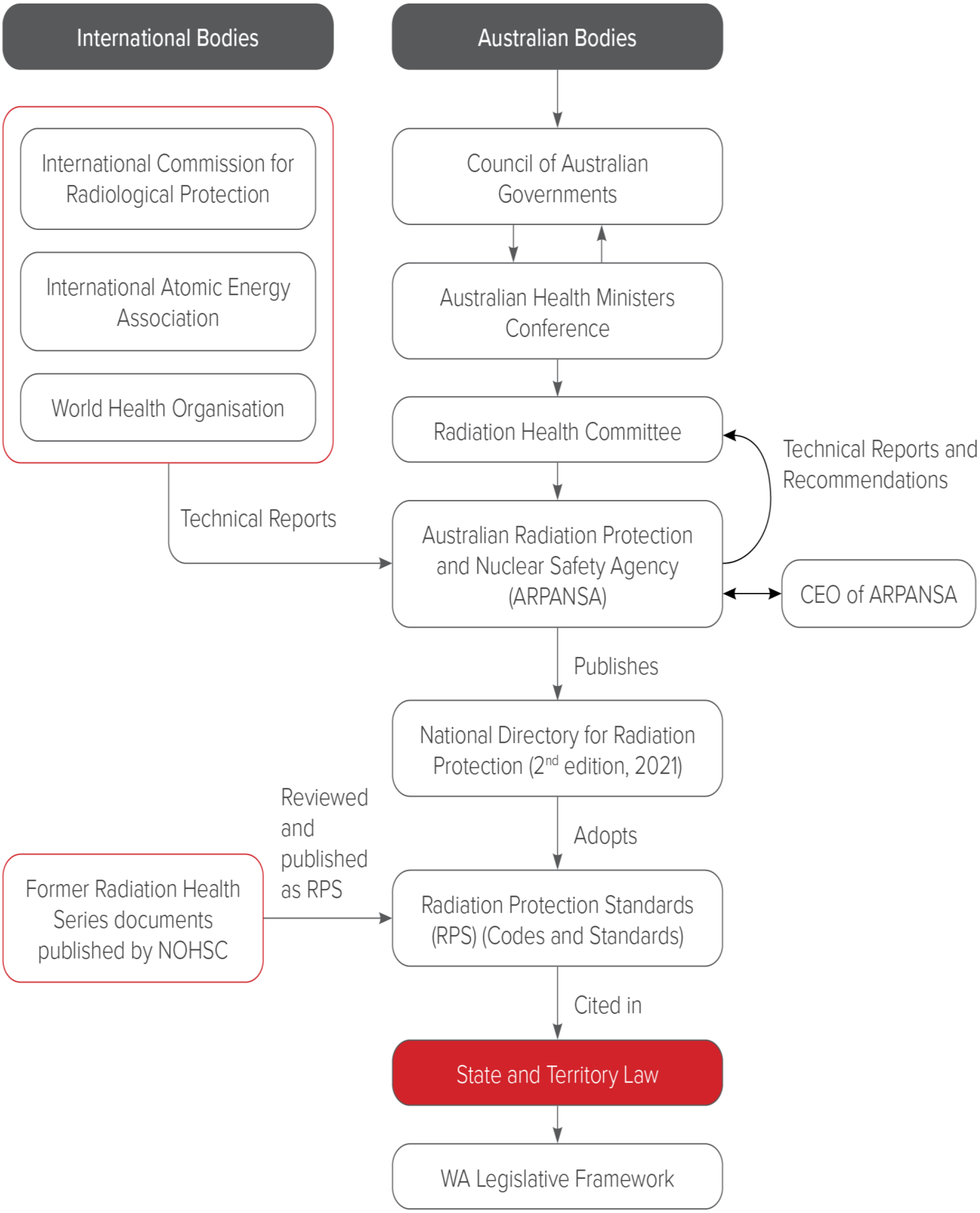

FIGURE 8: INFLUENCE OF INTERNATIONAL AUTHORITATIVE BODIES ON WA'S REGULATORY FRAMEWORK

Issues with the jurisdictional-based regulation approach have been reported, for example:

- According to RHC (2018a) “there is no national picture of radiation practices across Australia [including] no national register of radiation sources or of those assessed to be competent to use those sources [or] places in which radiation practices are authorised to be conducted”.
- IAEA (2018b) benchmarked Australia’s performance against international best practice, finding “relevant safety standards have not been implemented consistently by all Australian jurisdictions and harmonisation and uniformity within the Australian legal and regulatory framework has not been achieved at the necessary level” (Furness, 2019a)

The issues for Western Australia are perhaps best typified by the Scope of the international best practice review by the IAEA (2018b, p. 11) mentioned above:

- “It … covers all facilities and activities regulated in Australia, with the exception of the uranium mining industry and the management of waste containing naturally occurring radioactive material (NORM)”.

In Western Australia, these are two of the most contentious issues facing radiation protection in the state’s mining industry, but were precluded from the international best practice review...

2.5 INTERACTIONS BETWEEN REGULATORY AGENCIES IN WESTERN AUSTRALIA

Since the proclamation of the MSIA in 1994, the dual regulatory approach has been problematic for the mining industry (DME, 1994). The RCWA and RRAM collaborate in order to minimise the regulatory burden on REs, and avoid, where possible, the duplication of effort by the regulatory agencies. By way of example, in the late 2010s the RCWA made compliance with RPS-9 mandatory for REs as a condition of their registration, and subsequently RPS was included in the WHSR(Mines).

Regulatory oversight is more complex if the mining operation is deemed by the Environmental Protection Authority (EPA) (GWA, 2022a) to be a “significant development proposal” requiring an environmental impact assessment (EIA) (GWA, 2022b). The EPA require that an Environmental Impact Assessment (EIA) shall consider the environmental factor of “Human Health” which includes “the design, operation, ongoing management and monitoring of proposals minimise emission of radiation to the environment” and “that exposure to radiation meets regulatory dose limits set for radiation and then is further managed to as low as reasonably achievable” (GWA, 2016).

Despite the reduction of the replication of regulatory compliance as a result of the proclamation of the WHSR(Mines), regulatory oversight by multiple agencies persists.

In an attempt to streamline the sharing of information between the agencies a Memorandum of Understanding between the SME and RCWA was formalised in 2013, establishing the Radiation Liaison Committee (RLC), with the EPA an invited member (Department of Industry and Resources, 2013). After its initial meeting the RLC made some early progress, but failed to achieve consensus on several critical issues, and lost momentum. Subsequently, and despite some recent endeavours to reinvigorate it, the RLC has remained dormant since its last meeting in early 2016 (Department of Industry and Resources, 2013).

Without a functioning formalised consultative forum, the success (or otherwise) of the multiple regulatory agency approach is largely dependent upon the will of the individuals within those regulatory agencies, due to what Hewson described in 1990 as “A complex regulatory surveillance structure … and detailed inter-relationships … between the various regulatory agencies” (Hewson, 1990b). This is particularly significant given the RRAM is not represented on the RHC and relies upon the RCWA (which is a member of the RLC) for information on national strategies that may impact upon Western Australia’s mining sector.

The theoretical inter-relationships between RCWA and RRAM (and other agencies) are illustrated in Figure 9.

It is contended that the current circumstance in which the interaction between government agencies is reliant upon personal relationships, is a retrograde step from that described in Hewson’s (1990) commentary, and requires addressing in order to meet the expectations of the IAEA General Safety Requirements Part 3 (IAEA, 2014, pp. 20-21) listed on the title page of this Chapter.

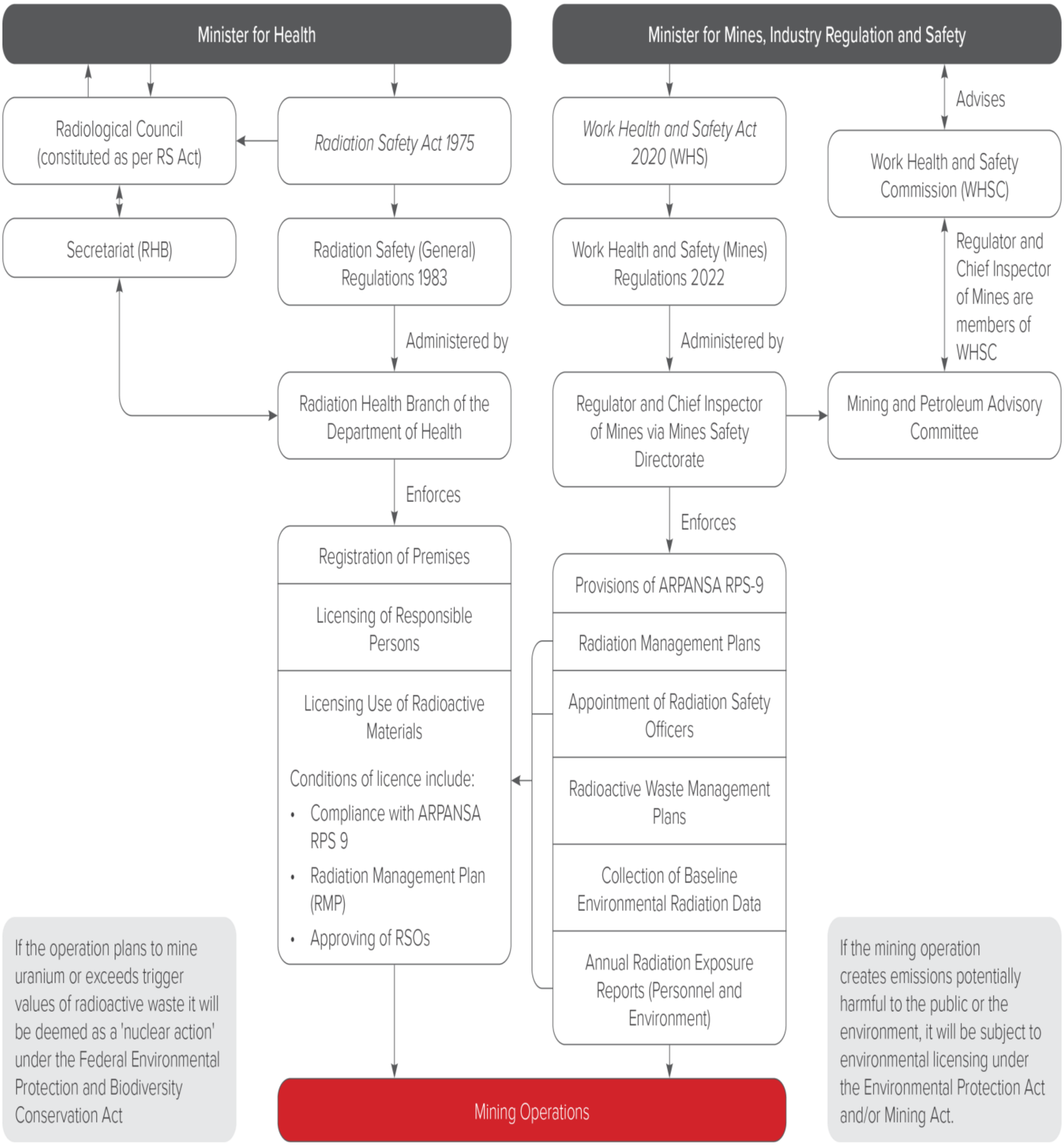

FIGURE 9: THEORETICAL RELATIONSHIP BETWEEN RCWA, RRAM AND OTHER GOVERNMENT AGENCIES

2.6 HISTORY OF CONSULTATION WITH WORKER REPRESENTATIVES

Hewson (1990b) and Hartley and Hewson (1990) summarised the roles of two committees, specifically established to provide tripartite oversight of radiation exposures in the State's mining industry:

(1) the Interim Mines Radiation Committee (IMRC); which was subsequently replaced by

(2) the tripartite Mines Radiation Safety Board (MRSB).

The membership of both the IMRC and MRSB included representation from the RCWA.

In response to questions raised in the Parliament of Western Australia, Hewson (1996b) responded "The operation of the [MRS] Board was characterised by acrimony and a lack of consensus on most issues. Under these circumstances the Department had no hesitation in repealing the [legislative] provisions relating to the establishment of the [MRS] Board when the opportunity arose to establish a broader Mines Occupational Health and Safety Advisory Board [MOHSAB]".

- A specialist sub-committee dealing with radiation-related matters was recommended to be established under the MOHSAB structure to replace the MRSB.

The dissolution of the MRSB in 1996 marked the end of the formal oversight of radiation matters in mining by an independent authority.

- There is no evidence in the historical record that the sub-committee of MOHSAB, recommended to replace the MRSB, was ever formally constituted.

It is apparent that the SME and RCWA endeavoured to formalise a relationship as early as 2002 (DME, 1994), however as discussed in Section 2.8, the relationship was not formalised until January 2013 and the resultant RLC has remained dormant since early 2016 (Department of Industry and Resources, 2013).

It is prudent to highlight that formal worker consultation on matters pertaining to radiation protection in Western Australia's mining sector ceased with the dissolution of the MRSB, over a quarter of a century ago.

2.7 THE CONTEMPORARY WA REGULATORY FRAMEWORK: TOWARDS NATIONAL UNIFORMITY

In Western Australia, the management of radioactive materials is primarily governed by the Radiation Safety Act 1975 (RSA) and Radiation Safety (General) Regulations 1983 (RSGR) (GWA, 1983, 2021). The RSA requires mining operations that use, store or transport radioactive substances (including NORMs) to be 'registered', and that persons responsible for the use, storage, or transportation to be 'licensed'. Registrations and licenses are approved by the RCWA, which is defined in the RSA as the peak body for radiation protection in the state.

However, and as detailed in Section 2.1, since 1987, regulation of radiation protection activities in mining operations that encounter NORMs is also governed by mine safety legislation, formerly the MSIR,[13] but as a result of the recent changes, is now the WHSR(Mines).

- The obligations of mining operations that were required to comply with the MSIR and referred to as "reporting entities" (REs) have continued under the WHSR(Mines).

Several important steps towards national uniformity have been achieved via the implementation of the WHSR(Mines) legislation. Part 10.2, Division3, Subdivision 3B, (GWA, 2022d, pp. 421-434)entitled Radiation in Mines incorporates the major provisions of the radiation protection regulations in the MSIR, but also adopts the ARPANSA publication Radiation Protection Series No. 9: Code of Practice and Safety Guide: Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (ARPANSA, 2005), referenced as RPS-9.

The adoption of RPS-9 provides a platform for national uniformity by establishing:

a) Annual dose limits for exposed workers, viz:

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

To ensure compliance with the 100mSv in 5-year limit, a derived annual limit of 20mSv is applied. Maintaining worker annual doses below the derived limit is the primary method deployed by REs to demonstrate compliance with RPS-9, and therefore the WHSR(Mines).

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[13] Specifically, Part 10.2, Division 3, Subdivision 3B – Radiation in mines

b) Annual dose limits for members of the public, viz:

- Effective Dose (ED) in a single year: 1 millisievert (mSv); and

c) The definition of radioactive material as any substance that has an activity concentration >1 Bqg^{-1}[14].

d) The content for Radiation Management Plans (RMPs) and Radioactive Waste Management Plans (RWMPs); and

e) The requirement for demonstrated access to appropriate professional expertise in radiation protection

In order to align with RCWA licenses conditions and national uniformity provisions, as a result of the introduction of the WHSR(Mines) REs have an additional obligation to comply with the provisions of RPS-9.

2.7.1 Legislative obligations on reporting entities

In accordance with IAEA and ARPANSA recommendations (ARPANSA, 2020a; IAEA, 2006, pp. 7-11), the WHSR(Mines) adopt a graded approach to regulation of exposures to NORM.

Mining operations that can demonstrate that radiation doses to their workforce are less than 1mSv per year may apply for exemptions from the radiation in mines provisions of the WHSR(Mines) [15]. *Ipso facto* a mining operation in which workers receive doses greater than 1mSv per year, are required to comply with Part 10.2, Division 3, Subdivision 3B of the WHSR(Mines) and are categorised as REs.

The WHSR(Mines) impose stringent requirements upon REs, including the appointment of duly qualified and experienced RSOs; development of radiation management plans (RMPs) and radioactive waste management plans (RWMPs) to be approved by the RRAM; and the submission of annual reports of worker doses to the RRAM for review and comparison against dose limits, reference levels and other statutory requirements.

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[14] Equivalent to 80ppm ^{238}U; 240ppm ^{232}Th; or a combination of the ratios that exceeds 1 Bqg^{-1}.

[15] The MSIR also stipulated a reference level of radon for exemption. However, at time of writing the Reference Level has not been formally agreed and has not (as yet) been included in the WHSR(Mines).

Regulation 641S of the WHSR(Mines) requires REs to classify their workers as either "designated" (DW) or "non-designated". A DW is a "worker who works, or may work, under conditions so that the effective dose of radiation the worker receives may exceed 5 millisievert per year"(GWA, 2022d, p. 429). DWs "are then monitored more intensively (including, where appropriate, personal monitoring), and their doses are assessed individually"(ARPANSA, 2005, p. 28).

2.8 THE REGULATOR AND THE MINES INSPECTORATE

The Western Australian WorkSafe Commissioner is the statutory authority appointed as the 'regulator' under the WHSA and WHSR(Mines) (GWA, 2020, p. 8).

The regulator is assisted in discharging their duties by the Chief Inspector Mines (CIM) a statutory appointment also made under the WHSA (GWA, 2020, p. 4). To avoid confusion in the use of terminology, future reference to the tandem roles of the regulator and CIM will be referenced as the Relevant Regulatory Authority: Mining (RRAM) [16]. The RRAM replaces the role of the State mining engineer (SME) appointed under the MSIA and MSIR.

The RRAM is supported in regulating the mining industry by a team of Inspectors, appointed under the WHSA, and collectively referenced in this Thesis as the "Mines Inspectorate". The Mines Inspectorate forms part of the government agency charged with oversight of mine safety, which has undergone numerous name changes in the period covered by this research. For the purposes of this Thesis, the government agency is referenced as "the Department".

2.9 THE ROLE OF THE DEPARTMENT'S NORM GUIDELINES IN THE LEGISLATIVE FRAMEWORK

As is elaborated in Appendix 5, in July 1983 the Western Australian Minister for Health commissioned a Committee of Inquiry (the Winn Inquiry) into the management of radiation in the state's MSI.

A tangible outcome was the Department's publication of a series of ten [17] Guidelines, to assist REs to implement a system of radiation protection at their mining operation (Hewson, 1989b). Over time the "NORM Guidelines" have been edited and condensed and have become a critical component in the Western Australian radiation protection legislative framework (DMIRS, 2020g).

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[16] The term "relevant regulatory authority" is used in RPS-9 (ARPANSA, 2005), and is adopted in this Thesis.

[17] There were 14 Guidelines in the 2010 series.

Importantly, the NORM Guidelines have become the mechanism by which international best practice, as advocated by the ICRP and IAEA have been integrated into the Western Australian legislative framework for radiation protection in mining operations.

2.9.1 NORM Guidelines: Dose coefficients, dose conversion factors, and derived air concentrations

As was outlined in Section 2.4, it is incumbent upon state jurisdictions to bring specific issues to the attention of the RHC, or to react accordingly, as exemplified in 2015 when ICRP commenced the publication of the ICRP Occupational Intake of Radionuclides (OIR), and indicated that the series of five parts would replace the Publication 30 series and Publications 54, 68 and 78 (ARPANSA, 2018a).

- As this series of publications were applied in Western Australia to calculate doses to mine workers arising from inhalation of NOR-containing dusts, the review was of significance to the state.

In 2017 the ICRP published Part 3 of the OIR as ICRP-137 (ICRP, 2017), and although endorsing the ICRP revised DCs for Rn and RnP (ARPANSA, 2018c; ICRP, 2018), ARPANSA advised regulators that DCs for the inhalation of dusts containing members of the ^{232}Th and $^{238+235}$U decay series could not be completed until such time as Part 4 of the OIR (ICRP-141) was published (ARPANSA, 2018a).

ICRP-141 (ICRP, 2019a) became available in December 2019. The revision of the DCs for all of the members of the ^{232}Th and $^{238+235}$U decay chains was therefore complete, allowing Ralph et al. (2020c) to evaluate the potential impacts of the revisions on the Western Australian mining workforce.

Following the publication of Ralph et al. (2020c), the NORM Guideline NORM-V Dose Assessment (DMIRS, 2021b) was published in 2021. ARPANSA adopted the revised dose conversion factors published in Ralph et al. (2020c) in July 2022 (ARPANSA, 2022c; ECU, 2022).

As was highlighted in Section 2.2.1, prior to 1985 the DAC for LLα in airborne dusts, was 5.2 Bqm^{-3}, and the introduction of ICRP-26 and ICRP-30 saw a seven-fold reduction in the DAC to 0.8 Bqm^{-3} in mid-1986 (Hartley & Hewson, 1990).

The revised dose coefficients as published in ICRP-137 and ICRP-141 have resulted in a further decrease of the DAC for LLα in airborne dusts. The revised DAC of 0.5 Bqm^{-3} is a reduction of 37.5% from that which had applied in mid-1986 and is one-tenth of that which applied prior to 1985.

The changes in DAC for LLα in airborne dusts since the mid-1980s are illustrated in Figure 10.

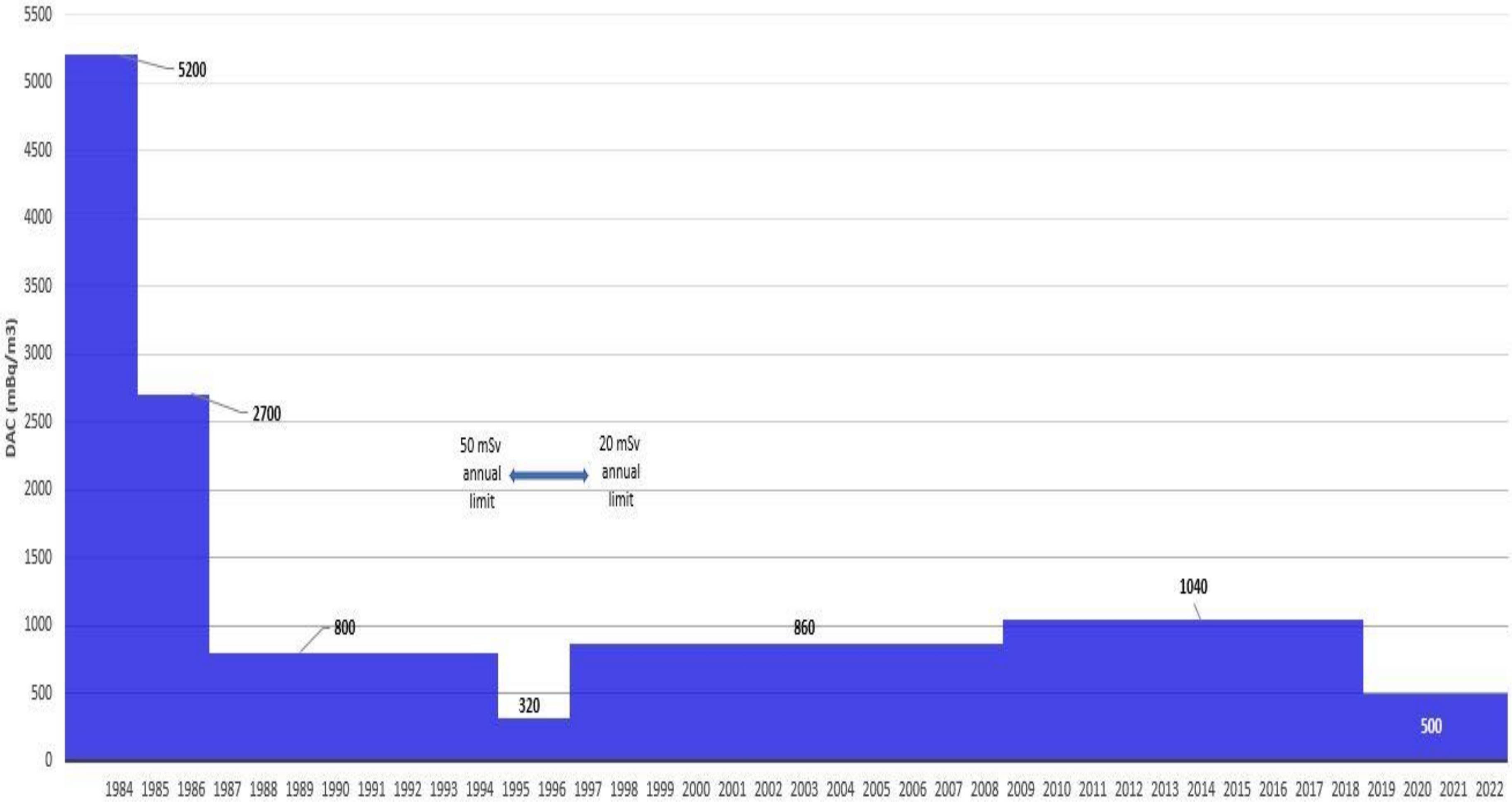

FIGURE 10: CHANGES IN DERIVED AIR CONCENTRATION (DAC) LIMIT (MBQM^{-3})

- Note that the DAC of 0.32 Bqm^{-3} in 1994 and 1995 is hypothetical and based upon the reduction of the annual derived dose limit from 50mSv to 20mSv.
- No records for the implementation of this DAC in Western Australia could be located in this research, and the DAC increased immediately after the implementation of the revised DCs for the ^{232}Th and ^{238}U decay series introduced in ICRP-60.

The significant reductions in DAC for LLα in airborne dusts serves to reinforce why the ALARA principle is applied exposures to NORs in the mining industry.

2.9.2 NORM Guidelines: Standardised annual reporting format

As was discussed in Section 2.7.1, operations meeting the RE criteria must provide annual reports of estimates of radiation doses received by the workforce to the RRAM. According to Hewson (1989b) the requirement for REs to submit annual reports of worker radiation doses was implemented in 1984. Since 1986 when the SME became the RA for REs, the Department has been responsible for the keeping of records associated with the radiation exposure of mine workers [18].

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 RE.

As technology improved, the records management officers 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)" (Veluppillai, 2020b). 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-2010s, submissions have been made via email, or the bespoke Mines Inspectorate computer-based record and communication information management system, the Safety Regulation System (SRS) (DMIRS, 2020f). Whilst the transition to SRS was occurring, an ad-hoc process developed

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[18] Under the WHSR(Mines) legislation this obligation now resides with the RRAM. In the event that a RE ceases operation, copies of personal dose records will also be retained by the RCWA.

whereby some technical specialists opted to forward electronic copies of the annual reports to the records management officers for retention in Records Manager (2005).

A standardised format was introduced in 1988, with guidance on the contents of the reports provided in NORM Guideline #8 entitled “Reporting Requirements” (Hartley & Hewson, 1990). 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 (GWA, 2010e).

The information provided in annual reports to the SME have been presented in a (mostly) standardised format since 1988, with the exception that in 1992 it was agreed to change the reporting period from a calendar year to a “radiation reporting year” which runs from 1st April each year to 31st March in the following year. The first radiation reporting year was 1993-1994.

The historical record of worker dose assessments is remarkably intact and bears testament to the record-keeping system implemented by the RA. Further, the consistency in reporting format contributed significantly to this research, allowing an assessment of the historical record of exposure scenarios and to identify trends in worker doses as reported in Chapter Five, and enabling the assessment of the impact of the revised DCs, as reported in Chapters Seven and Eight.

This Chapter provides an overview of the complexity of the Western Australian regulatory framework, and highlights that under the current arrangements, the mining regulator must react to national strategies for radiation protection from NORs in mining rather than influence them.

The next Chapter of this Thesis investigates the radiation exposures to mine workers in order to establish a case for the regulator to be represented on national decision-making bodies.

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CHAPTER THREE: LITERATURE REVIEW PART II – MINE WORKER EXPOSURES TO NORS

By far the largest category of workers exposed to ionising radiation are those employed in the extractive and processing industries. … mining and mineral processing may lead to exposures in workplaces where there is often no perception, let alone appreciation, among workers of the various relevant radiation protection problems.

United Nations Scientific Committee on the Effects of Atomic Radiation

(UNSCEAR, 2010).

The global mining industry is extensive, and the potential for mine workers to be exposed to NORs associated with the commodities identified in Chapter One, at levels that exceed tolerable risk, as defined by the statutory limits discussed in Chapter Two, is largely dependent upon the radiation protection frameworks implemented in the country in which the mining operations occur.

This Chapter provides a synthesis of the literature of radiation exposures to mine workers in international jurisdictions, and in the mainland states of Australia, outside of Western Australia. The Chapter establishes benchmarks for exposures to mine workers against which the potential exposures to Western Australian mine workers, evaluated in Chapter Four, can be compared.

3.1 MINE WORKER RADIATION EXPOSURES TO NORS

As stated in the title page of this Chapter, mine workers constitute the largest category of workers exposed to ionising radiation. UNSCEAR (2010, p. 284) adds that mining and mineral processing “may lead to exposures in workplaces where there is often no perception, let alone appreciation, among workers of the various relevant radiation protection problems. This situation exists despite knowledge of mine worker exposures to NORs being evaluated for over a half-a-century, as evidenced by:

- the hazards associated with the mining and processing of NORs being the subject of international forums since 1965 (IAEA, 1976);
- the publication of the first edition of the IAEA document “Radiation Protection in the Mining and Milling of Radioactive Ores” (IAEA, 1983) in 1968; and
- a technical manual on identification of hazards and exposure controls published in 1976 (IAEA, 1976).

The ICRP states “in the majority of [mining] workplaces, both the average and the maximum assessed doses received by workers are below a few mSv per year, but higher doses – in some cases, as high as a few tens of mSv – may occur in specific workplaces, and approximately 100mSv year^{-1} in a very few underground mines (ICRP, 2019b, p. 20).

UNSCEAR (2010) and van der Steen et al. (2004) advise that data on workforce numbers and exposure profiles is problematic to obtain, but estimates that the global mining workforce amounts to 11.5 million workers, comprising:

- 6.9 million workers in the coal industry, with an average annual effective dose of 2.4mSv; and

- 4.6 million workers in non-coal mines with an annual effective dose of 3.0mSv.

UNSCEAR (2010) summarises the exposure status of the global mining workforce in 2008 as having "increased significantly since the UNSCEAR report in 2000 … The estimated average effective dose is 2.9mSv and the estimated collective effective dose is 37,260 man-Sv, which is about seven times higher than the previous estimate".

3.2 FACTORS AFFECTING MINE WORKER RADIATION EXPOSURES

Radiation exposure to mine workers depend upon a number of factors including the:

- Lithology.
- Type of mine (whether it is underground or on the surface).
- Radionuclides involved, and their activity concentration.
- Physical and chemical characteristics of the processing activity; and
- Working conditions (with a particular emphasis on ventilation).

The activity concentration of NORs in the orebody, products or tailings streams can be a useful indicator of potential worker exposures. The IAEA (2011, Appendix VIII), cite an extensive list of NOR-containing sources of exposure in the global mining industry illustrating the influence of lithology on potential exposures:

- IAEA (2011, Table 99) cites typical values of the activity concentration of NORs in Heavy Mineral Concentrate (HMC) [19] for several countries indicating that HMC ranges up to 3.8 Bqg^{-1} in Australia; 7.3 Bqg^{-1} in Bangladesh; 9.7 Bqg^{-1} in Brazil; and 14.7 Bqg^{-1} in Vietnam. All things being equal, the radiation exposure risk to Vietnamese workers is nearly four times that of mine workers in Australia, by virtue of the increased activity concentration.
- IAEA (2016) report that the tantalite concentrate produced in Ethiopia has an activity concentration of up to 89 Bqg^{-1}. In Finland the activity concentrations of a niobium-rare earths

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[19] HMC is the feedstock for the mineral sands industry. It is derived by separating the gangue, comprising the lighter, mostly silicate minerals from the ore via wet gravity techniques.

deposit contained up to 15 Bqg^{-1}; two gold-cobalt mines report up to 4.3 Bqg^{-1}; and a gold deposit nearly 1,000 times that of the gold-cobalt mines, reporting up to 4,000 Bqg^{-1}.

The importance of the physical and chemical aspects of the processing operations are highlighted by Kim, Wu, Birky, and Bolch (2006) who reported a maximum annual dose of 2.24mSv to phosphate workers in Florida. The authors emphasize the "Values of the inhalation effective dose vary by a factor of between 7 and 22 depending on the absorption types of the radionuclides ...", which are affected by the processing activities.

Notwithstanding the important contribution from the lithology of an orebody and the physical and chemical processes applied to extract the mineral(s), Harris (2019) summarises the challenge for managing doses from NORs as:

- "It is often not a question of specific activity (sic) [20] but rather of site-specific factors: often the most exposure comes from the lowest level of radioactivity … It is a question of how workers get the exposure ...".

3.3 RADIATION DOSES RECEIVED BY SURFACE MINE WORKERS IN OPERATIONS OUTSIDE OF AUSTRALIA

UNSCEAR (2010) reports that average annual doses in: surface copper mines in Poland are about 1.5mSv; in a surface gold mine in Ghana were 0.26mSv; workers in the Brazilian extractive and processing industries receive an average of slightly greater than 1mSv per year; and 98 percent of surface workers in South African non-gold operations receive annual doses of less than 5mSv, with the highest doses being recorded in copper mines.

Iwaoka et al. (2017) reported annual worker doses in a Japanese monazite processing plant as being 0.62mSv. Udompornwirat (1993) estimated doses to workers in amang [21] plants in Malaysia, Indonesia and Thailand to be between 18mSv and 19mSv; whilst Omar, Sulaiman, Hassan, and Wood (2007) reported worker annual doses in 16 amang plants in Malaysia ranged from 1.7mSv to 10.9mSv, with a mean of 4.1mSv. These findings compare favourably to those of Ademola (2008) who found annual doses to the gonads of workers in a Nigerian tin mining area to be 92.4mSv.

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[20] The term activity concentration should have been used.

[21] Amang is a general descriptor used in Southeast Asia for the tailings from the tin processing industry.

Mollah and Rahman (1993) estimated annual doses in a Bangladeshi mineral processing plant to average 6.9mSv; and the IAEA (2011) report annual doses in dry mineral separation plants in India ranged from 1.1mSv to 10mSv and average annual doses in a similar plant in Vietnam were 6mSv.

Hartley (2001) reports that a study conducted by Boothe (1980) from the use of zircon in the United States implied annual doses arising from external exposure were of the order of 3.4mSv per annum, with contributions from Rn and RnP and LLα not being assessed. Hartley (2001) also cites a 1985 study by the Italian National Group for Studying Radiological Implications in the Use of Zircon, and reports that the annual dose was approximately 5mSv, largely arising from LLα in fumes generated by the smelting process. These values are higher than those reported by Iwaoka, Tabe, Suzuki, and Yonehara (2013) who determined that the maximum annual dose in Japanese zirconium refractory plants was 0.43mSv.

The final report of the European Commission's Strategies and Methods for Optimisation of Protection against Internal Exposures of Workers from Industrial Natural Sources (SMOPIE) project attempted to categorise the exposure profile of European workers exposed to NORMs, as summarised in Table 4 (van der Steen et al., 2004).

TABLE 4: EXPOSURE PROFILE OF EUROPEAN WORKERS EXPOSED TO NORM (FROM SMOPIE PROJECT)

Range of Potential Annual Dose from Inhalation (mSv)	Type of NORM Industry
Greater than 20	Some workers in rare earths processing
From 6 to 20	Some workers in zircon milling
Below 6	All other NORM Industries

The data presented in this Section illustrates that although exposures in surface mining and mineral extraction processes can be effectively controlled to limit worker annual doses to less than 2mSv, potential doses can exceed, and in the case of the Nigerian tin mining workers, significantly exceed, statutory limits if exposures are not effectively controlled.

3.4 RADIATION DOSES RECEIVED BY UNDERGROUND MINE WORKERS IN OPERATIONS OUTSIDE OF AUSTRALIA

The ICRP (1986, p. 2) states “The radiation environment in mines is complex and variable. Miners are exposed to airborne radon [Rn], short-lived radon decay products [RnP], long-lived radionuclides [LLα] in ore dust and to external gamma [γ] and beta radiations.” and “In … non-uranium mines (such as coal or metalliferous mines) … the main problem is the inhalation of ^{222}Rn and its decay products”.

The health effects of Rn and RnP have been investigated for nearly a century. High mortality rates among central European underground miners in the 17th century were identified as lung cancers in 1879; and attributed to exposure to Rn and RnP in 1924 (ARL, 1981; George, 2008; WHO, 2009).

The ICRP (2010) conducted a meta-analysis of epidemiological studies conducted on the risk of lung cancer associated with exposure Rn and RnP in underground mines, and demonstrated significant associations between cumulative radon exposure and lung cancer mortality at low levels of cumulative exposure. Laurier (2019) and Laurier, Marsh, Rage, and Tomasek (2020) confirmed the ICRP Publication 115 findings, concluding there is “strong evidence for an association between radon and lung cancer risk, even at low levels of exposure”.

Importantly for non-uranium underground mines, Sahu, Panigrahi and Mishra (2016, p. 9) state that “ore grade does not necessarily bear a unique relation to [Rn diffusion] rate”, and therefore the concentration of NOR in the host rock does not necessarily correlate with the concentration of Rn and RnP in the mine atmosphere. The IAEA (2018a, p. 99) concur, stating “The highest concentrations of Rn tend to occur in underground workplaces … in some underground mines, including some in which the [NOR] concentrations are not significantly elevated, high concentrations of Rn arise from the entry of Rn via groundwater”.

Excursions over the regulatory exemption levels have been reported in underground non-uranium mines in international jurisdictions. By way of example, an investigation by Schmitz and Fritsche (1992) into radon in underground workplaces in Western Germany found 40% had radon concentrations in excess of 1,000 Bqm^{-3} (10mSv for 2,000 hours per year exposure) and 10% of mines exceeded 5,000 Bqm^{-3} (50mSv for 2,000 hours per year exposure).

UNSCEAR (2010) reports the average annual effective dose (ED) to workers in underground operations in Canada and Germany range from 1.07 to 4.13mSv; in South African gold mines the average ED was 7.0mSv; in Turkish coal mines the average ED to 12,510 workers was 4.9mSv; and in an Irish lead / zinc mine EDs ranged from 1 to 6mSv. The maximum ED received by Polish workers in coal mines (in 1997) was 3.5mSv, whereas the maximum ED in four metal mines was 9.6mSv with an average of 2.5mSv. The ED to workers in 80 coal mines in China averaged 2.4mSv, with a maximum in excess of 10mSv. Workers in six coal mines in Pakistan received EDs from Rn between 2.1mSv and 7.0mSv; and in a cautionary note for the global phosphate industry, a study on Egyptian phosphate mines found EDs ranging from 12.2mSv to 136.9mSv, with an average of 70.2mSv, well in excess of the current annual derived dose limit.

Other researchers report annual EDs of 1.83mSv in a Ghanaian gold mine (Darko, Tetteh & Akaho, 2005); 8.3mSv in an Iranian manganese mine (Ghiassi-Nerad, Beitollahi, Fathabadi, & Nasiree, 2002); 5.53mSv in metal mines in China (Liu & Pan, 2011); and up to 21mSv (from Rn alone) in six underground mines in Brazil, with a mean of 9mSv (Santos et al., 2014).

In the United States, the cohort of workers that receive the highest occupational exposures is the 10,000 “underground miners” who receive, on average, 8.4mSv per annum [22] (Sinclair, 2000, pp. 475-476); and Hewson et al. (1991) cite a maximum annual dose estimate of 240mSv in an underground copper mine in Poland.

Liu and Pan (2011, p. 349) report that approximately 10 million mine workers were occupationally exposed to NORM in China in 1996-2000, averaging 2.1mSv per year; and provide a case study of an iron and rare earth mine in Inner Mongolia, in which the annual dose to ore mining workers was estimated to be 3.38mSv.

- It is highlighted that all of the studies cited above pre-date the increased risk factors for Rn and RnP as published in ICRP-137 (ICRP, 2017) and endorsed by ARPANSA (2018c).

Therefore, it is probable that many of the annual doses reported in this Section could be understated, with some approaching or exceeding the 20mSv derived annual limit.

In the case of the Egyptian phosphate miners reported by UNSCEAR (2010) the mean dose could exceed 150mSv, and as per Chapter One, requires the implementation of institutional controls to reduce the intolerable level of risk.

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[22] The 2nd highest exposed cohort is the 91,000 workers in the nuclear fuel cycle who receive, on average 6.0mSv ~ 70% of the miner cohort dose.

3.5 RADIATION EXPOSURES TO AUSTRALIAN SURFACE MINE WORKERS IN JURISDICTIONS OUTSIDE OF WA

Thus far this Chapter has established that although mean doses to mine workers in international jurisdictions can be maintained below annual dose limits, exposures to NORs in mining operations can lead to excessive doses. The following Sections assess the potential in jurisdictions within Australia, but outside of Western Australia.

In response to an approach by the International Labour Organisation and IAEA to “convene a meeting of experts to prepare a Code of Practice for Radiological Protection in Mining and Milling of Radioactive Ores” Holmes and Stewart (1965) conducted surveys of six mining and processing plants in New South Wales (NSW) and Queensland. Measurements were made of external γ dose-rates; contamination of surfaces by α-emitting radionuclides; and airborne dust containing LLα. Although estimates of worker doses were not made the following comments are pertinent:

- “The dose-rate becomes significant in the secondary concentration plants”. The results … illustrate dose rates of up to 8.0 millirem per hour in the secondary concentration plant (equivalent to 80 µSvh^{-1}) and 15 millirem per hour around monazite stockpiles (equivalent to 150 µSvh^{-1}); and
- “In nearly every case, the concentrations of airborne radioactive dust exceeded the maximum permissible value for continuous exposure”. The results provided by Holmes and Stewart (1965, Table 3) demonstrate that the maximum permissible concentration of thorium (sic) was consistently exceeded by a factor of approximately six times.

Similar evaluations of four different operational mining and processing operations were reported in by Morris (1973), who revealed that airborne LLα levels were approximately 7,400 mBqm^{-3} (about an order of magnitude higher than the contemporary DAC – refer to Figure 10) and surface contamination levels at one plant exceeded the maximum permissible concentration by up to 3.7 times. In a similar fashion to Holmes and Stewart (1965), Morris did not attempt to estimate worker annual doses.

Mason, Cooper, Solomon, and Wilks (1984) conducted radiological assessments of two mineral separation plants in Australia in 1984, investigating for the first time the physical characterisation of airborne dusts. The authors’ preliminary findings indicated very low levels of thoron; no LLα concentrations in excess of the Western Australian DAC of 1,100 mBqm^{-3}; and external doses “typically kept below 25mSv per year for the most exposed workers, with about 75% of the monitored workforce receiving less than the public limit of 5mSv per year (sic)”.

Carter and Coundouris (1993) evaluated the potential for worker doses in the studies by Holmes and Stewart (1965) and Morris (1973) and reported that data collected in 1965 indicated annual doses were “likely to have exceeded 100mSv”, and the 1973 data indicated annual doses were of the order of 70mSv. Carter and Coundouris (1993) concluded that “radiation protection in the NSW mineral sands industry is not a minor issue; it is likely that some workers are receiving doses in excess of the 20mSv annual limit”.

A summary of the radiological impact of the Queensland MSI by Alexander, Stewart and Wallace (1993) included a rudimentary assessment of worker doses. The authors highlight that dose monitoring began in 1983, but it was not until 1987 that the combined contribution of external and internal doses was considered. Doses were “below 15mSv”, however, the authors caution “deficiencies … have led to various administrative and engineering controls being introduced to reduce the levels of radiation doses to employees well below 20mSv”.

Mason, Cooper, Solomon, and Wilks (1988) reported on radiological assessments on beach sand-mining operations on the west coast and east coast of Australia, conducted by the Australian Radiation Laboratories. They report:

- Radon concentrations up to 200 Bqm^{-3} and thoron concentrations up to 1,200 Bqm^{-3} were measured in latter stages of the secondary concentration plant.
- Thoron concentrations up to 5,000 Bqm^{-3} were measured near a bulk monazite stockpile.
- Most employees received less than 5mSv per year from external radiation, but some may have received up to 20mSv in a year.
- Activity Median Aerodynamic Diameters (AMADs) of airborne dusts ranged from 2 microns (µm) to 12 µm, with an average of 6 µm being seemingly appropriate for the purposes of dose calculation.
- The DAC for monazite dust is approximately 0.9 alpha disintegrations per second per cubic metre ($\alpha_{dps}m^{-3}$), with many of the measured concentrations exceeding this value; and
- There appears to be a significant difference in mean alpha activity between operations on the west coast (mean ~ 1 $\alpha_{dps}m^{-3}$) and the east coast (mean ~ 0.1 $\alpha_{dps}m^{-3}$).

Mason et al. (1988) conclude their findings by stating “Inhalation of radioactivity in dust during mineral sands processing is clearly a very significant exposure pathway”.

Hartley (2001) conducted research into worker exposures in five zircon milling plants in Australia (including Western Australia) indicating a theoretical worst-case ED of 5.5mSv, comprising 3.3mSv from inhalation of LLα and 2.2mSv from external γ. Measurements indicated annual doses, based on normal work practices, ranging from 0.66mSv to 1.03mSv. Despite the low measured doses, Hartley (2001) cautions “the bagging of zircon flour represented a significant source of exposure to dust”.

In 2015 ARPANSA published Technical Report Series No. 165 (ARPANSA, 2014b), which provided an overview of the Australian MSI (including Western Australia) and reported that in early 2013 regions outside of Western Australian hosted seven operations, comprising two in South Australia; one in Victoria; one in NSW; two in Queensland and one in Tasmania. An analysis of workers doses from external γ for the years 2004, 2008 and 2012, derived from Personal Radiation Monitoring Service (PRMS) is included in ARPANSA (2014b, Appendix E).

- The maximum doses for all three years were recorded by the worker category dry plant operator and ranged from 6.4mSv in 2004 to 9.5mSv in 2008.
- The mean doses in the dry plant operator category ranged from 0.4mSv (166 workers) in 2012 to 1.0mSv (114 workers) in 2004.
- Paradoxically, the highest mean dose in 2004 was recorded by the category wet plant operator, a category which in most circumstances receives low EDs due to the absence of dusts containing LLα.

3.6 RADIATION EXPOSURES TO AUSTRALIAN UNDERGROUND MINE WORKERS IN JURISDICTIONS OUTSIDE OF WA

The ICRP (1986, p. 3) observes that “… the individual doses may be similar in non-uranium mines to those in uranium mines … the collective dose in mining occupations other than uranium mining is likely to be greater because of the larger number of people employed” and “Radiation protection in non-uranium mines should be given more consideration than it has in the past“.

Robinson (1992) reported that 15 of 68 measurements of RnP in underground non-uranium mines in the Northern Territory exceeded a derived action level of 40mWL, equivalent to an ED of 4.8mSv [23].

3.6.1 Australian experience in underground uranium mining and processing

According to Sonter (2014), underground mining of uranium commenced at Radium Hill in South Australia in 1910 and ceased in 1914-15. After a hiatus, the Radium Hill operations were reopened, producing about 850 tonnes of U_3O_8 between 1954 and 1961.

- Sonter (2014) pointedly states "there was not much monitoring done …" and describes working conditions that were sub-standard by contemporary requirements.

Woodward, Roder, McMichael, Crouch, and Mylvaganam (1991) conducted a retrospective study of 2,574 workers that worked at Radium Hill between 1952 and 1987 and found that the underground workers had an increased relative risk of lung cancer mortality five times that of the surface workers, reflecting "at the time, these findings were a stark reminder of the risks of underground uranium mining, especially due to the risks of exposure to Rn and RnP".

Sonter and Hondros (1989) modelled the potential doses to workers in Australia's only underground uranium mine, and forecast a median annual dose of 4.8mSv with 10% of the workforce receiving greater than 12mSv. Fry (1992) confirmed the Sonter and Hondros (1989) models, reporting:

- a maximum of 13.7mSv.
- a mean of 7.0mSv; with
- approximately equal contributions from γ, Rn and RnP and LLα.

Findings by Fitch (1993) on EDs to underground workers in 1991-92 aligned with Fry (1992), reporting a mean of 6.1mSv, and a maximum of 12.8mSv, however the proportion of contributions differed from those reported by Fry (1992), with 45% of the dose being delivered by RnP; 40% from external γ; and 15% from LLα.

BHP (2018), operator of the country's only underground uranium mine reported that the maximum ED to underground mine production drilling workers was 4.9mSv. The mean ED for this worker category

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[23] Using a DC of 10mSv per WLM

was 3.8mSv, with approximately half the mean dose being due to external γ exposure and a similar contribution from Rn and RnP, with LLα contributing ~5%. The report:

- indicates that of 2,066 underground workers, 451 (21.8%) received EDs of less than 1mSv; and
- estimates the mean exposure to the underground mine production drilling category as a result of application of the changes to DCs introduced with ICRP-137 and ICRP-141 (as per Sections 2.2 and 2.9 and detailed in Chapter Seven) would . increase by 53%. From 3.8mSv to 5.8mSv.

The BHP (2018) estimates support the hypotheses of Hondros and Secen-Hondros (2019) and Ralph et al. (2020c) in relation to the potential significance of the changed DCs on calculated worker doses, as is outlined in Chapter Seven.

3.7 AUSTRALIAN EXPERIENCES IN SURFACE MINING AND PROCESSING OF CRITICAL MINERALS AND URANIUM

The Winn Inquiry (Winn et al., 1984) cites the experience of the Rare Earth Corporation of Australia which processed monazite in Port Pirie, South Australia from 1969 to 1972. Doses to workers are not reported, but it is of historical significance that Australia has prior experience in this emerging industry sector. It is also noteworthy that Hewson (1993) considered potential exposures, concluding “annual doses in excess of 15mSv may be received” from external γ, and “internal doses to monazite plant workers may be substantial, with doses perhaps an order of magnitude or more greater than the existing exposure standard of 50mSvy^{-1} (sic)”.

It is evident from Hewson’s analysis that very high doses can be encountered in such facilities, and because of the era in which the South Australian facilities operated, it is prudent to contend that worker doses would have exceeded (potentially, significantly) the current 20mSv annual derived dose limit.

Fry (1992) reported that maximum EDs to workers in an open pit uranium mine in the Northern Territory were 7.9mSv, with a mean of 5.9mSv. Eighty five percent (5.0mSv) of the mean dose was attributed to LLα.

Fitch (1993) provided a summary of radiation doses to workers in Australia’s two operating uranium mines:

- Workers in the open pit mine reported EDs of 5.7mSv, whilst mill operators at the same operation received mean EDs of 6.0mSv. Fitch (1993) states “Maximum doses were less than twice these [mean] values”.

- Workers in the metallurgical plant [on the surface] associated with the underground mine received a mean ED of 2.4mSv, with a maximum of 18.1mSv. Fitch (1993) states “approximately 85% [of the ED] is due to the inhalation of radioactive dust”.

According to BHP (2018) the maximum ED to workers in the surface operations of a uranium mine was 4.4mSv, received by the smelter shutdown worker category. This category of workers received a mean ED of 3.6mSv, approximately 90% of which was contributed by LLα. The report indicates that of the 1601 surface operation workers, 757 (47.3%) received EDs of less than 1mSv.

The Australian experience suggests elevated worker doses can occur in the emerging critical minerals and uranium mining sectors and serves as a salient indicator to Western Australia of the radiological risks associated with mining and processing these commodities.

The information presented in this Chapter illustrates that while the majority of mine workers receive annual radiation doses of the order of several mSv or less, the potential exists for elevated, and in some cases, excessive, radiation doses as a result of their exposure to NORs, whether they be in products, intermediate process streams or tailings.

Importantly, for surface operations, elevated doses tend to be related to the radionuclides present and their activity concentration, which as illustrated in Section 3.3 can vary significantly by lithology or mineralogy.

The research has determined that annual doses in underground non-uranium mines can be similar to underground uranium mines. The analysis of the international experience in underground mines serves to highlight annual doses well in excess of the 20mSv annual derived limit can occur, and that the activity concentration of the NORs present in the lithology are often not the pre-determining factor.

The research in Europe by van der Steen et al. (2004), summarised in Table 4, which demonstrated that workers in the zircon industry can receive doses that approach, whilst their counterparts in the rare earth sector can exceed, the derived annual limit, is particularly salient as Western Australia embraces the Future Battery Strategy (GWA, 2019b) and contributes to the Australian Critical Minerals Strategy (Mining dot Com, 2019).

The next Chapter of this Thesis investigates the potential for radiation exposures to mine workers in Western Australia and benchmarks the exposures against the findings reported in this Chapter.

CHAPTER FOUR: LITERATURE REVIEW PART III – THE INFLUENCE OF WESTERN AUSTRALIA'S GEOLOGICAL FORMATIONS ON POTENTIAL EXPOSURES TO NORMS

The reason that granites have higher concentrations of uranium and thorium is because these elements are incompatible within magmas … and easily replaced by other elements. So as magma cools, uranium and thorium are some of the last elements to be incorporated into crystals, so the melt component of the magma becomes progressively enriched in uranium, thorium, and other incompatible elements.

Uranium is highly soluble so it can be easily dissolved, transported, and precipitated within ground waters by subtle changes in conditions ... a factor in the wide variety of geological conditions in which uranium mineralisation can occur.

Thorium-rich minerals are commonly found in igneous and metamorphic rocks. Apart from heavy mineral sand deposits, thorium can be present in other geological settings such as alkaline igneous intrusions and complexes, including carbonatites, and in veins and dykes. In these deposits, thorium is usually associated with other commodities such as rare earths, zirconium, niobium, tantalum, and other elements.

Uranium and thorium

Geoscience Australia (2022)

As was outlined in Section 1.3, the GSWA has identified three major geological features of the Western Australian mainland that are of significance to this research, viz: the "*Great Plateau*"; the "*Tidal Flats*"; and the "*Darling Ranges*".

This Chapter discusses the potential for, and research into, radiation exposures in these geological formations.

4.1 POTENTIAL FOR RADIATION EXPOSURES IN MINING OPERATIONS IN THE GREAT PLATEAU

Other than the information analysed for Reporting Entity #15 and reported in Chapters Five and Eight, there is limited data on the abundance of, and radiation doses arising from, minerals containing ^{232}Th in the Great Plateau. However the IAEA (2019a, p. 97) summarises the thorium grades of two rare earths deposits located in the Terraine formations of the Yilgarn Craton, as ranging from 388 parts per million (ppm) to 5,230ppm [24]. Whilst both deposits have high rare earth oxide content, their lithologies are very different, with one being a "carbonatite complex" with a maximum of 626ppm thorium [25], whilst the second deposit is an "ironstone" that contains 1,062ppm [26] to 5,230ppm.

The examples above serve to highlight the importance of the lithology of the mineral deposit being processed. Based upon a general principle that the risk of exposure to radiation is positively associated with the concentration of NORs in the lithology, the second deposit presents an (almost) order of magnitude elevated level of risk of exposure when compared to the first deposit, by virtue of its higher thorium content.

Notwithstanding the paucity of data in relation to exposures to the ^{232}Th decay series, as discussed in Section 1.4, the majority of Western Australia's 57 underground mining operations lie within the Great Plateau and are congruent with many of the state's identified uranium deposits. As a result, it is feasible that these mines will exhibit elevated concentrations of uranium in the lithology that hosts the minerals being mined, and by extension, workers in those mining operations have the potential to receive elevated radiation doses.

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[24] 1.6 to 21.8 Bqg^{-1}

[25] 2.6 Bqg^{-1}

[26] 4.4 Bqg^{-1}

Accordingly, this Section of the literature review concentrates on underground mines in the Great Plateau geological formation. The research reported in the previous Chapter by the ICRP (2010), Laurier (2019) and Laurier et al. (2020) that found “strong evidence for an association between radon and lung cancer risk, even at low levels of exposure” are persuasive, and therefore the focus is on evaluating worker exposures to Rn and RnP in the underground mines.

4.1.1 RADIOLOGICAL PROPERTIES OF ^{222}RN AND RNP

The ICRP (1986, p. 2) states “In … non-uranium mines (such as coal or metalliferous mines) … the main problem is the inhalation of ^{222}Rn and its decay products”.

The level of risk to humans from exposure to Rn and RnP is determined by:

a) Their concentration.

- The SI unit of measurement of Rn concentration in air is becquerels per cubic metre (Bqm^{-3}).
- RnP concentration is measured in joules per cubic metre (Jm-3).

b) The length of time exposed.

- Rn exposure is measured in the SI unit becquerel-hours per cubic metre (Bqhm-3).
- RnP exposure is measured in joule-hours per cubic metre (Jhm-3).

c) The ratio of Rn to RnP in air, a variable known as the *Equilibrium Factor* (F) (ARPANSA, 2011a, 2017a; Solomon et al., 2018).

- F is defined as the ratio of equilibrium equivalent concentration of radon (EECRn) to the concentration of Rn in the air, where EECRn is the concentration of Rn, that in equilibrium with RnP, would correspond to the same value of potential alpha energy concentration that is actually present (ARPANSA, 2011a, p. 37; ICRP, 1986).

  At equilibrium, 1.8 x 10^8 Bqhm^{-3} (EECRn) is equivalent to 1 Jhm^{-3} RnP.

  Theoretically, F can vary from 0 representing complete disequilibrium, to full equilibrium, where F=1 (WHO, 2009). Rarely, if ever, will conditions of full equilibrium, or full disequilibrium exist (ARPANSA, 2011a, p. 37; ICRP, 2017, p. 449), and as a result, F will lie between the two extremes.

The quantity of Rn and RnP in the air, and therefore F, is influenced by the rate of dilution ventilation (ICRP, 2011; Robinson, 1992). Concentrations of RnP can increase rapidly with increasing residence time of the air (ICRP, 1986), and theoretically, equilibrium (F=1) will be achieved between Rn and RnP if air is undisturbed for approximately 30 minutes (CMEWA, 1994, p. 6.16).

Sahu, Panigrahi and Mishra (2014) and Hewson et al. (1991) cite studies that confirm Fs are inversely related to fresh air ventilation rates, with high Fs related to low ventilation rates.

Because high Fs imply potentially higher doses from RnP than from low Fs, it is important that either Rn is prevented from diffusing into the working atmosphere (a process called radon exhalation), or the air containing Rn in a workplace is exchanged frequently enough to prevent the build-up of RnP.

4.1.2 MEASUREMENT OF ^{222}RN AND RNP

As introduced in Section 1.7, the measurement of Rn is relatively straightforward (George, 2008), whilst the measurement of RnP is, by comparison, complex. If Rn is the only factor assessed, in the absence of measured Fs, an assumption is made that F lies between 0.4 and 0.5 (George, 2008; Robinson, 1992; Solomon et al., 2018; Solomon, Langroo, Lyons, & James, 1996).

However, in air in which Rn and RnP are in equilibrium, the RnP deliver 99% of the dose to the lung (ARPANSA, 2011a, p. 37), and therefore the measurement of the concentration of RnP is important. ARPANSA (2011a) advises ”… measurement of Rn serves as a surrogate for assessment of the RnP, which works well when equilibrium conditions [F] are known and stable.” and “An underground mine is a good example of a location where [F] can be highly variable and dependent upon the ventilation. For this reason the dose assessment at minesites is based on measurement of PAEC [RnP] rather than the use of radon measurements.” Kusnetz (1956, p. 1) goes further, and states “use of the Rn concentration as the only index of hazard to an individual is poor practice”.

What can be stated with certainty is that radiation doses to the human respiratory system are delivered by the inhalation of RnP, and the degree of equilibrium (F) between Rn and RnP is important to the estimation of doses. Reliance upon Rn concentrations in the absence of a determination of F increases the uncertainty in dose estimates significantly, and is discouraged, with the Mines Inspectorate advising “Therefore, while it is a relatively straightforward technique, monitoring for radon or thoron gas in isolation is usually not suitable for dose estimation. Where it is used, it must be accompanied by an assumption as to the F that has been applied.” (DMIRS, 2021b)

4.1.3 EXPOSURE TO ^{222}RN AND RNP IN UNDERGROUND MINES IN WA

The earliest reported study into radiation exposures of underground mine workers in Western Australia was conducted in 1973 by the Australian Radiation Laboratory and the Western Australian State X-Ray Laboratory. The findings were presented to the Western Australian Commissioner for Public Health by the researchers Leith and Hartley as a "Report on a survey of radioactivity in air of underground non-uranium mines and uranium and thorium mills in Western Australia from 19 November to 5 December 1973" (Armstrong, McNulty, Levitt, Williams, & Hobbs, 1979, p. 205), but were not published in peer-reviewed literature [27].

Hewson and Ralph (1994) cited the findings of the Leith and Hartley research, however data pertaining to the sampling methodologies utilised; uranium content of the host rock; ventilation rates in the mines; and derived Fs were not able to be sourced.

It is known however that Leith and Hartley conducted sampling in nine mines reporting concentrations of Rn ranging from 74 to 660 Bqm^{-3} and RnP ranging from 40 to 930 nJm^{-3} (Hewson & Ralph, 1994, p. 360). The maximum values were recorded in return airways, which are not normally a workplace, and occupancy times by workers would be less than the 2,000 hours assumed for dose calculation.

As discussed in further detail in Chapter Six, the contemporary DC for RnP for mines is 3.14mSv per $mJhm^{-3}$ (ICRP, 2019c) and applying this DC to the range of RnP concentrations reported by Leith and Hartley (40 to 930 nJm^{-3}) equates to an annual dose range of 0.25 to 5.8mSv [28]. The research confirmed the presence of Rn and RnP in the underground mines, but, as the doses from areas that were not return airways were less than ten percent of the 50mSv annual dose limit applicable at the time, the researchers concluded that the hazard due to the inhalation of Rn and RnP in gold and nickel mines in Western Australia was "*likely to be negligible*" (Hewson & Ralph, 1994, p. 360).

The significance of the earliest reported study cannot be understated. Armstrong et al. (1979), Peters, Reid, Fritschi, Musk, and de Klerk (2013) and Sodhi-Berry et al. (2017) have investigated an elevated incidence of cancers (notably lung cancer) in the underground mining workforce in Western Australia. Despite the original Leith and Hartley report being unable to be located, the listed authors all cite their research, and on the basis of Leith and Hartley's findings, and despite the caution issued by ICRP (2010),

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[27] Despite several exhaustive searches, the Hartley and Leith (1973) report could not be located.

[28] Assuming an exposure period of 2,000 hours, and a worker breathing rate of 1.2 m^3h^{-1}.

linking exposure to Rn and lung cancer (as discussed in Chapter 4), dismiss exposure to Rn and RnP as a possible contributing factor to the observed increased cancer incidence.

The ICRP (1986, p. 3) stated "… individual doses may be similar in non-uranium mines to those in uranium mines" and "Radiation protection in non-uranium mines should be given more consideration than it has in the past". The statements generated a heightened level of interest in evaluating the potential for radiation exposures in underground mines, and as a result, two research projects into the Western Australian underground sector were undertaken.

- Hewson et al. (1991), conducted a preliminary study of Rn in underground mines in Western Australia, the purposes of which was to survey a number of existing mines, and to develop a computer model for the prediction of Rn levels in specified underground mining environments; and
- Hewson and Ralph (1994) conducted an intensive survey of evaluating Rn concentrations and ϒ flux levels in 26 mines, and RnP and F determinations in nine of the 26 mines.

Hewson and Ralph (1994) found that the average annual dose across the 26 mines, employing 2,173 workers was 1.4 ± 1.0mSv, ranging from 0.4mSv in a nickel mine to 4.2mSv in a coal mine. Rn and RnP contributed approximately 70% of the doses to workers. Hewson and Ralph (1994) concluded "On the basis of this preliminary investigation it was concluded that no regulatory controls are specifically required to limit radiation exposures in Western Australian underground mines".

Research by Hewson et al. (1992) included a broad assessment of 118 workers (23 of which were DEs) in a tin/tantalum mining and processing operation located in the South West Terraine formation associated with the Yilgarn Craton. The average annual dose was 4.5mSv, with a maximum of 8.2mSv. After the development of an underground mine and addition of rare earths to the suite of minerals being processed, Auld (2005) conducted three Rn surveys in the underground operations, reporting a mean concentration of 103 Bqm^{-3}. Concentrations ranged from 9 Bqm^{-3} in a fresh airway to 358 Bqm^{-3} in working area of the underground mine, with an estimated maximum worker annual dose of 0.7mSv.

Significantly, and as discussed in Section 2.2.5, the studies cited above predate the present ICRP position on radon as outlined in (ICRP, 2014, 2018), and with the exception of Auld (2005) predate the implementation of ICRP-60 (ICRP, 1990) in Western Australia. Therefore, the conclusions were based upon the maximum dose estimates being less than 10% of the applicable annual dose limit of 50mSv, as opposed to the contemporary derived limit of 20mSv.

Between July and November 2018, the Mines Inspectorate conducted a small survey of Rn concentrations in a well-ventilated underground mine as part of an undergraduate research project (McMahon & Ralph, 2019). Rn concentrations ranged from 30 to 109 Bqm^{-3} with a mean of 54 Bqm^{-3}. In order to evaluate the contribution of lithology and ventilation upon Rn concentration, rock chip samples and airflow measurements were collected at the locations in which the Rn was monitored. At time of writing, this information was being evaluated, however, the project demonstrated that Rn was present at levels that exceed the ambient concentration of 16 Bqm^{-3} for the area (ARPANSA, 2011b, ref: Mukinbudin) in an underground mine considered by the Mines Inspectorate to be “well-ventilated” (N. McMahon, personal communication March 13th, 2018).

Solomon (2019) applied the revised Rn and RnP DCs to dose estimates made in 1994 to workers in Australian tourist caves. The impact of the revised DCs was significant, and potentially has a bearing on this research. The 1994 data indicated that no worker would exceed an annual dose of 10mSv, whilst the revision indicates that 15% of workers would exceed 10mSv and 6% would exceed the 20mSv derived annual limit. Solomon (2019, p. 298) concluded “the updated radon progeny estimates are a significant radiation protection issue for the affected individuals and their employers”.

As is discussed in detail in Chapter Six, Ralph et al. (2020c) revisited the Hewson and Ralph (1994) data and applied the DCs for Rn and RnP published in ICRP-137 (ICRP, 2017), reporting that EDs in 12 of the 23 still-operating underground mines, employing an estimated 5,400 workers, would exceed the 1mSv regulatory threshold.

Similarly, it is contended that doses estimated by Auld (2005) will increase significantly [29]. Assuming the ARPANSA (2018c) prediction of doses from Rn and RnP increasing by factors of between two and four times that determined by previous DC conventions the maximum annual dose (ignoring contributions from external γ and LLα) would lie between 1.4mSv and 3.2mSv, levels at which compliance with the WHSR(Mines) would be required.

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[29] However, the raw data is not available, and therefore only best estimates can be made.

4.2 POTENTIAL FOR RADIATION EXPOSURES IN MINING OPERATIONS IN THE DARLING RANGES

The potential for radiation exposures arising from the presence of ^{232}Th in the rocks and soils of the Darling Scarp were extensively researched in the 1980s and 1990s. A significant finding was reported by Alach, Breheny, Broun, and Toussaint (1996) who found the specific activity (sic) [30] of soils in the Darling Scarp were ten times the global average.

Thompson (1995) found the major contributor to doses received by Perth residents was gamma rays, however Efendi and Jennings (1994) (using electronic detectors) found that ^{220}Rn and ^{222}Rn were the major contributors to the estimated 3.5mSv annual dose received by residents in the Perth Metropolitan Area; and Toussaint (2005) found that annual doses to residents living on the Darling Scarp were 4.6mSv, nearly 2.5 times the dose to residents living on the Swan Coastal Plain.

Erosion of the rocks and soils of the Darling Ranges contributed to the formation of mineral deposits to the east of the escarpment, and to the west, along ancient coastlines, referenced in this research as the *Tidal Flats*. The weathering process towards the west, aided by wind and wave action developed mineral sands deposits, and similar weathering processes to the east of the escarpment led to the formation of tin/lanthanum/lithium and rare earths mineralization in areas distant from the Darling Ranges, and also led to commercially sustainable bauxite deposits within the Darling Ranges.

Greenbushes located 250 km south of Perth is recognised as the longest continuously operating mining area in Western Australia. Mining of tin commenced in 1888; production of tantalum commenced in the 1940s; and lithium operations were established in 1983. The Greenbushes region has also been identified as hosting the minerals ilmenite, zircon, and monazite (mindat.org, 2021a). Two mining operations in the region are REs, and analysis of their worker exposure data is included in Chapters Five and Eight. However, in order to preserve their anonymity, the RE reference numbers are not cited here.

Although bauxite mining in the Darling Ranges commenced in the early 1960s, the potential for NORs to be encountered in bauxite/alumina operations was not investigated until 1982 (O'Connor, 2004). Alumina is produced via the Bayer process from bauxite (Habashi, 2016), and as a result the NORs in the bauxite, derived from the soils and rocks of the Darling Ranges, are concentrated.

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[30] The term was in common, but errant, use at the time. The term activity concentration should have been used.

The NORs do not concentrate in the final alumina product, but rather, report to the tailings (residue) streams which are referenced as “red sand” and “red mud”.

- Concentrations of NORs in the “red sand” are approximately 10% higher than that in the bauxite feedstock and are in the range of the 1 Bqg^{-1} regulatory activity concentration threshold.
- The NOR concentration in “red mud” is increased by 100% of the bauxite feedstock, and consistently exceeds the 1 Bqg^{-1} threshold (O'Connor, 2004).

Upton (1995) and Terry (1997) reported the results of four monitoring campaigns conducted from September 1995 to November 1996 to determine the concentrations of Tn and Rn in bauxite processing residue storage areas.

- Rn ranged from 11 Bqm^{-3} to 222 Bqm^{-3} with a mean concentration of 56 Bqm^{-3}.
- Tn ranged from 11 Bqm^{-3} to 229 Bqm^{-3}, with a mean concentration of 78 Bqm^{-3}.

Terry (1997) notes that “The mean radon concentration at the residue storage areas is approximately three times the mean radon concentration of 16 Bqm^{-3} in Western Australian homes” but adds “the exposure of … [the] workforce to radon and thoron cannot be regarded as … adventitious...”.

Despite the elevated activity concentrations of “red sand” and “red mud”, estimates of worker exposures are such that the 1mSv threshold criteria is not exceeded (O'Connor, 2004; O'Connor, Donoghue, Manning, & Chesson, 2013; Terry, 1997).

O'Connor (2004) reported that annual doses to operators ranged from 0.28mSv to 0.9mSv, with an estimate for all workers being 0.5mSv. O'Connor et al. (2013) reported that a “typical … refinery employee has a combined background and incremental exposure of about 0.8mSv per year, obtained over [a working year of] 1920 hours”.

Significantly, all of the above-listed research was conducted prior to the adoption of the revised DCs published in ICRP-137 (ICRP, 2017), and ICRP-141 (ICRP, 2019a) into the NORM-V Guideline (DMIRS, 2021b), as discussed in Section 2.9.

- In all likelihood the doses reported by O'Connor et al. (2013) are under-estimated, and will exceed the 1mSv threshold for regulatory compliance, once the revised DCs are applied.

Although doses to workers reported to date are below the regulatory threshold, the red sand and red mud residues present potential environmental legacy issues due to their radiological properties.

Sutar, Mishra, Sahoo, Chakraverty, and Maherana (2014) state the “enormous quantity (sic) of red mud is generated worldwide every year posing a very serious and alarming environmental problem” and long-term management of the solid waste residues from the Bayer process “remains a worldwide issue”. Several attempts to introduce “red mud” into industrial processes have occurred in Western Australia over the recent past and have proved to be controversial due to its radiological properties. The Red Mud Project (2014) cites the use of bricks made from bauxite residue being used to build homes in the South-west of Western Australia in the 1980s and advises “…the Health Department rejected the building after tests registered radioactivity readings which bordered on the maximum acceptable radiation exposure levels”.

A number of authors report that “red mud” has beneficial properties as a soil amendment when applied to highly porous, leached soils like those typically found in Western Australia (Department of Water, 2015; Grant, 2014; Harris & Howard, 2010; Summers, Guise & Smirk, 1992). However, Summers, O'Connor and Fox (1993) caution that “the 1mSv limit … for the general public is reached … at an amendment rate of 1500 tonnes per hectare of bauxite reside”.

According to Ryle (2002) the Western Australian Agricultural Department conducted a series of field trials on farming properties in the South-west of Western Australia in the early 1990s. Despite the Agriculture Department claiming the trials to be successful in “prevent[ing] algal blooms in the Peel-Harvey estuary by reducing run-off”, subsequent tests found elevated concentrations of heavy metals in farm animals, which led to media attention, resulting in headlines such as “Red mud a dirty disappointment” (Bell, 2014); “The great red mud experiment that went radioactive” (Ryle, 2002); and “Residents fear radioactivity” (Adolph, 2004).

- The trials concluded in 1996, and to the best of the researcher’s knowledge, no further large-scale trials of “red mud” as a soil amendment have occurred, and the disposal of the solid waste residues from the Bayer process remains largely unresolved.

4.3 POTENTIAL FOR RADIATION EXPOSURES IN MINING OPERATIONS IN THE TIDAL FLATS

Semeniuk (2019) describes Tidal Flats as “low-gradient, tidally inundated, coastal surfaces” and cites Jackson’s definition as Tidal Flats being “extensive, nearly horizontal, marshy, or barren tracts of land alternately covered and uncovered by the tide and consisting of unconsolidated sediment”.

The commodities of significance to this research in the Tidal Flats of Western Australia are the deposits of garnet and heavy mineral sands, [31] formed by the erosion of inland rocks and soils, “washed as grains by streams and rivers to the coast where natural gravity separation, currents, wave actions and wind concentrate them where topography and water movement dictate” (SWDA, 1990).

One of the most significant deposits of garnet in the world occurs at Port Gregory, approximately 520 kilometres north of Perth (Geoscience Australia, 2021). The deposit is associated with minor concentrations of mineral sands products, resulting in an elevated activity concentration in the ore that approaches the 1 Bqg^{-1} criteria, and in a zircon by-product that is circa 5 Bqg^{-1}. Estimates of worker exposures were such that EDs did not exceed 1mSv per year (Gundry, 2008), and the operations were granted a conditional exemption from the MSIR, on the proviso that estimates of worker doses were submitted to the SME every two years. With the advent of the WHSR(Mines), the conditional exemption was discontinued, and full compliance is required.

- Note that garnet in Bangladesh has been reported to have an activity concentration of 11.9 Bqg^{-1} (IAEA, 2011), an order of magnitude greater than the 1 Bqg^{-1} radioactive material criteria, indicating the need for ongoing surveillance of potential worker exposures in the Western Australian operations.

The major valuable heavy mineral sands in the deposits in the Tidal Flats of Western Australia are:

- ilmenite, leucoxene, and rutile (which are all sources of titanium).
- zircon (a source of zirconium); and
- monazite and xenotime (which are sources of rare earths).

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[31] Heavy mineral sands is a term used to describe those MSI minerals which have a specific gravity greater than 2.96

In 1947 high grade concentrations of heavy mineral sands were discovered in Cheyne Bay, situated about 390km southeast of Perth. The deposit was mined in 1949, but production ceased in 1950 (SWDA, 1990; Winn et al., 1984).

Mining of deposits of beach sands for titanium and zircon minerals in the southern region of the Swan Coastal Plain began in Koombana Bay, 170 kilometres south of Perth in 1956, whereas deposits in the Northern Swan Coastal Plain were first mined in 1973, initially at Eneabba, 270 kilometres north of Perth (SWDA, 1990).

Winn et al. (1984) stated "In 1982 Australia produced ilmenite, natural rutile, zircon and monazite totalling 1.8 million tonnes, of which WA's share was 1.4 million tonnes … WA had over 20% of the world's production". A decade later Marshman and Hewson (1994, p. 60) reported that "A significant proportion of the world's production of mineral sands occurs in Australia. The majority of Australia's production of mineral sands occurs on the Swan Coastal Plain region of WA".

As shown by the activity concentrations listed in Table 5, NORs are present to some degree in the suite of heavy mineral sands produced by the Western Australian MSI (after Koperski (1993b) and IAEA (2011)).

As can be seen from the activity concentration data presented in Table 5, all of the mineral sand products, with the exception of the ore as mined and HMC, exceed the 1 Bqg^{-1} criteria and are therefore deemed as radioactive. It is also evident that two minerals, monazite and xenotime present the highest source of radiation hazard in the MSI due to their elevated NOR content.

Sales of monazite from the Western Australian MSI ceased in May 1994 (Hewson & Upton, 1996).

However, the NORMs monazite and xenotime are still present, to some degree, in the ore and accompany the other minerals, through the various processing circuits, thereby making the risk of exposure to NORs omnipresent. Furthermore, as the other minerals become concentrated, monazite and xenotime report to tailings streams, with most operations producing tailings with enhanced activity concentration levels, often in excess of 15 Bqg^{-1} (DMIRS, 2019c).

TABLE 5: TYPICAL ^{232}TH AND ^{238}U CONCENTRATIONS BY MASS AND ACTIVITY IN MSI PRODUCTS

Mineral	Typical ^{232}Th Content [1]		Typical ^{238}U Content [1] [2]		Typical Maximum Activity Concentration (Bqg^{-1}) [3]
	Weight (ppm)	Activity Concentration (Bqg^{-1})	Weight (ppm)	Activity Concentration (Bqg^{-1})	
Ore as Mined	5-15	0.02 - 0.06	~3	~0.04	0.1
HMC	80-110	0.3 – 0.4	<10	<0.1	0.5
Rutile	>50-350	<0.2 – 1.4	<10-20	<0.1 – 0.6 [4]	2.0 [4]
Ilmenite	50-500	0.2 – 2.0	<10-30	<0.1 – 0.4	2.4
Leucoxene	80-700	0.3 – 2.8	20 - 50	0.2 – 0.5	3.3
Zircon	150-250	0.6 – 1.2 [4]	150-300	1.8 – 4.0 [4]	5.2 [4]
Xenotime	15,000	60	4,000	50	110
Monazite	50,000 - 70,000	200 - 280	1,000 - 3,000	12 - 37	320

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

[2] The contribution by ^{235}U is negligible and has been omitted from the Table.

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

[4] The activity concentration has been updated to reflect Appendix VIII of IAEA (2011), however the weight concentration (ppm) is as reported in Koperski (1993b)

4.4 A POTENTIAL STATE-WIDE ISSUE: MANAGEMENT OF RADIOACTIVELY CONTAMINATED MINING PLANT AND EQUIPMENT

The ICRP (2019b) processing of minerals can lead to the dispersal of radionuclides or to their physicochemical properties being changed, resulting in an uneven distribution of activity concentrations in different parts of the processing cycle or in waste streams. As was discussed in Chapter One, secular equilibrium may be broken and the individual radionuclides dispersed according to their physical and chemical properties, where they may present risks to workers, the community, or the environment.

The dispersed radionuclides may be deposited in various stages of a mineral processing circuit and accumulate in relatively high activity concentration sludge or corrosion scales in pipes or process vessels. An important consideration in this research is provided by the IAEA (2021, p. 11) which states "… pipes, valves, process vessels, pumps and machinery … contaminated by NORM residues … can be a concern during the operation and particularly during the decommissioning of relevant facilities … These residues are often associated with scrap metals which also require appropriate management".

Hereinafter, this research adopts terminology introduced by Dehmel, McNaulty and Johnson (1992), and uses potentially radioactive scrap metal (PRSM) as the generic descriptor for "pipes, valves, process vessels, pumps and machinery etc contaminated by NORM [32]residues in the mining industry".

Turner (2006) claims that since 1983 more than 80 confirmed accidents involving melting of PRSM have occurred, costing millions of dollars to remediate and leading to a decline in consumer confidence. Duftschmid (1999) reported that as of June 1997, a database established by the US Nuclear Regulatory Commission contained over 2,300 reports of radioactive materials in recycled metal scrap, and that the majority (62%) of the reports concerned NORMs. A decade later, Johnson (2006) contended that the perceived risks associated with recycling of previously contaminated metals results in decisions *not* to recycle.

The magnitude of the challenge presented by PRSM was assessed by Dehmel et al. (1992) cited in Report No. 141 of the US National Council on Radiation Protection and Measurements (NCRP, 2002), who estimated that of the nine million metric tons of PRSM, one-third arises from industrial activities that encounter NORMs.

It is difficult to estimate the volume of PRSM in the Western Australian resources sector, however, one decommissioned plant contains several tens of thousand tonnes of PRSM spread over a surface area of several square kilometres (R. Browne, personal communication, September 24th, 2019).

The Ohio State University (2022) cites a cost for disposal of NOR-contaminated waste of USD40 per pound, equivalent to AUD130,000 per tonne. On that basis disposal of the PRSM at the decommissioned plant will exceed AUD2 billion. As there are 79 additional processing plants operating

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[32] Note the inter-changeability of NORM and NORs in this Section. The sludge and corrosion scales are NORMs containing NORs. In turn, PRSM is a NORM due to the presence of the NOR-contaminated sludge and corrosion scales.

in Western Australia (GWA, 2022c), it is prudent to consider that there is a very high potential to encounter large volumes of PRSM, and their disposal will incur significant, if not prohibitive, costs.

4.4.1 DISTINCTION BETWEEN NORM WASTE AND RESIDUES

ARPANSA (2008, p. 29) states that "Processing of NORM materials gives rise to products, wastes and residues".

- The IAEA (2019b, p. 186) defines radioactive *waste* as "material for which no further use is foreseen … ".
- The IAEA (2021, p. 1) define NORM *residue* as "material that remains from a process and comprises or is contaminated by NORM", and ARPANSA (2008, p. 29) expands on this definition and states "*Residues* are those materials that have the potential for utilisation".

Based on these definitions, the researcher considers that the disused items of contaminated plant and equipment are residues, whilst the scales and sludges that adhere to the surfaces of the plant and equipment are wastes.

The distinction between *waste* and *residue* is important to this research because, if the removal and capture of NORM-contaminants is successful, the NOR-contaminated plant and equipment destined to be managed as *waste* could be considered as a *residue*, with a possible future use and attendant commercial value.

4.4.2 BACKGROUND: OCCURRENCE OF CORROSION SCALE

The issue of corrosion in steel pipes and structures leading to residues and scales is well known and extensively researched. Corrosion scales are solid deposits of inorganic salts formed on the internal surfaces of infrastructure as a result of the oxidation of metallic iron (Koppel et al., 2022; Sarin, Snoeyink, Bebee, Kriven, & Clement, 2001). Water quality parameters such as pH, alkalinity, hardness and temperature can influence the formation of corrosion scales in iron/steel structures, and as a result, corrosion scales have features unique to the processes that generated them (Li, Liu & Chen, 2018; Sarin et al., 2001; Sarin, Snoeyink, Little, & Kriven, 2004).

However, the radiological characteristics of corrosion scale have been less-well investigated, with the paucity of peer-reviewed publications noted by Krieger (2005), and more recently MacIntosh et al. (2022) noted that research into the environmental impacts of abandoned structures has only emerged in the last five years, and very little is known about the long-term fate and impacts of the NORM contaminants.

4.4.3 NORs IN CORROSION SCALES

Field, Fisher, Valentine, and Kross (1995, p. 568) suggest that “Iron oxides, which ordinarily occur in water treatment plants and distribution systems … may bind radium. In addition, radium can adsorb and/or coprecipitate to various substances including iron and manganese oxides” and Sarin et al. (2001) state that amongst other properties “corrosion scales can adversely affect water quality … by adsorption and accumulation of substances such as arsenic and radium…”. Valentine and Stearns (1994) and Field et al. (1995) investigated the occurrence of radon-222 (^{222}Rn) in drinking water in several cities in the United States of America, and concluded that the presence of significant increases in waterborne ^{222}Rn were linked to deposits of corrosion scale that contained radium-226 (^{226}Ra) in the water distribution system, with the most significant factor in determining the impact of the radium-bearing scale being the amount of time during which a volume of water is in contact with the corrosion scale.

NORs are ubiquitous in oil and gas reservoirs around the world and may form contamination products including scales and sludges in subsea infrastructure (Ali, Zhao, Li, & Maglas, 2019; Botezatu & Grecea, 2004; Hamilton et al., 2004; Koppel et al., 2022; Krieger, 2005; Misdaq, Chaouqi, Ouguidi, Touti, & Mortassim, 2015; Schmidt, 2000). Schmidt (2000) provides a detailed explanation as to how the chemical properties influence the mobilisation of the progeny radionuclides. Radium-228 (^{228}Ra) and ^{226}Ra can co-precipitate in sulphates and carbonates, and lead-210 (^{210}Pb) can follow other lead mineralisation in tailings streams including scale and residues.

Changes in pressure and temperature can lead to the precipitation of radium-rich sulphates as scales, on the inner walls of production equipment, or in sludge. Scales typically have the highest radioactivity of any NOR-contaminated product in the oil and gas industry (Botezatu & Grecea, 2004). Activity concentrations of ^{226}Ra in scale are “difficult to predict” but have reported as varying from 100 to 15,000,000 Bqkg^{-1} in scale and from 5 to 800,000 Bqkg^{-1} in sludge (ICRP, 2019b, p. 58). If the equipment is aged, significant amounts of the progeny of radium may develop, with ICRP (2019b, p. 58) reporting activity concentrations of ^{210}Pb up to 75,000 Bqkg^{-1} have been found in scale, and up to 1,300,000 Bqkg^{-1} in sludge.

- The cited activity concentrations exceed the radioactive material criteria by several orders of magnitude and can present significant risks if not effectively managed.

Valentine and Stearns (1994) provide the conclusion to this discussion: “It is quite logical then to expect that radium would concentrate in a variety of environments within treatment plants and distribution systems”. This point is expanded upon by Hamilton et al. (2004) “… the occurrence of pipe scale is widespread, inevitable at some point in the water cycle, expensive to prevent, and costly to remove”.

4.4.4 NORS IN CORROSION SCALES IN THE MINING INDUSTRY

As reported by Basson and Selzer (1975), the formation of radioactive scale arising from mining operations has been known since at least 1975, when the authors discovered radioactive residues in a South African municipal dump and traced their origin to a sulphuric acid plant that utilised iron pyrites from gold/uranium mines.

In a similar fashion to occurrences in the oil and gas sector the extent, and sequence of, chemical, physical, and thermal forces which act on the ore as it passes through the recovery process will have a bearing on the movement of radioactive materials. By way of example, Wendel (1998, p. 92) illustrates that, as opposed to the low ρH environments that support radium mobilisation, “in high ρH circuits, the radionuclides are substantially insoluble, and no enhanced activity scales are found”.

The research that is available in relation to the mining sector tends to focus on radium mobilisation, and illustrates how variable the mobilisation can be: radium may interact with process components such as rubber linings and stainless steels (Wendel, 1998, p. 92); radium sulphate scale was found inside the gas purification and cooling sections of the plant (Basson & Selzer, 1975); and in mining circuits that neutralise low ρH solutions using lime, radionuclides may precipitate and cause enhanced scale formation in, and immediately after, the neutralisation process (Wendel, 1998).

Cook et al. (2018) evaluates the opportunity for the build-up of ^{210}Pb and ^{210}Po as a result of the disturbance of secular equilibrium in the chemical or thermal processing of NOR-containing minerals. The following quotations have particular relevance to the research reported in Chapter Nine:

i. “Anomalous concentrations of ^{210}Pb and ^{210}Po are associated with exploitation of mineral sands for production of zircon and zirconia, titanium dioxide and rare earth elements. The minerals within such sands all host trace to minor amounts of uranium and thorium and all are highly refractory.”

> ii. The manufacture of zirconia … involves production of highly-enriched radionuclide waste as well as volatilisation of ^{210}Pb and ^{210}Po. Titanium oxide pigment production from rutile also results in a radionuclide-enriched solid waste residue.
>
> iii. … there are relatively few published studies detailing ^{210}Pb and ^{210}Po geochemistry in mineral sands … This could, however, be an area in which ^{210}Pb and ^{210}Po release is set to increase since demand for these commodities, especially rare earth elements is booming, and new mineral sands operations are being established around the globe.
>
> Cook et al. (2018, p. 10)

It is evident that some of the processing circuits on a mining operation are more likely than others to demonstrate elevated concentrations of NORs. These include areas where low ρH is used such as leaching circuits, and/or high temperature is applied such as roasting and smelting. However, it may not be readily apparent which items of plant and equipment might become contaminated.

4.4.5 NOR-CONTAMINATED CORROSION SCALES IN THE WESTERN AUSTRALIAN MINING SECTOR

Chapters Five, Six, Seven and Eight of this Thesis evaluated doses to workers exposed to NORM in the Western Australian mining industry in operations that process minerals by utilising their physical properties such as specific gravity, magnetism, and electrical conductivity.

However, the potential for worker exposures, and the long-term management of residues and wastes arising from “wet chemical extraction processes” [33] and “thermal processes for the extraction, processing and combustion of minerals” in Western Australian mining operations have been less extensively researched.

A substantial contribution was made by Hewson (1993) who identified the radiological aspects of downstream processing of mineral sands products, noting that a potential source of NOR-contamination arises from the chemical and thermal treatment of the mineral ilmenite to produce the more valuable commodity “synthetic rutile” via the Becher process (Kothari, 1974). Although the subsequent radiological issues associated with this process are largely bypassed, Hewson (1993, p. 8). does flag the need to “undertake confirmatory monitoring for ^{210}Po when mineral sands are subject to high temperature processes” such as those that are encountered in the Becher process.

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[33] These terms are used in IAEA (2006).

ANSTO Minerals (2017, 2018) conducted analyses of corrosion scales from a Western Australian mineral sands "polishing" plant [34] and reported that secular equilibrium had been disturbed, with the radium radionuclides and their progeny, present in much higher concentrations (of the order of two orders of magnitude) than their respective parent radionuclides, concluding that the "the majority of radium in the scale is due to volatilization/condensation … because of the high temperatures used in the process".

NOR-contamination issues are not limited to the mineral sands industry, as evidenced by a report in late 2019 that PRSM recovered from an underground nickel mining operation in the north-eastern-goldfields region of Western Australia [35] had triggered radiation detectors at a scrap metal yard (L. Dahlskog, personal communication, February 7th, 2020). This indicates that further investigation into the source of, and potential for contamination at, mining operations in the region is required.

The late-2019 contamination incident proved the catalyst for the investigation conducted as part of this research, which is reported in Chapter Nine.

Having identified the international and non-Western Australian experiences of radiation exposures to mine workers in earlier Chapters, this Chapter highlighted the occurrence of NOR-containing mineralogy across the three main geological formations in Western Australia in order to establish the potential for exposure to NORs of the state's mine workers.

The lithology of the mineral deposit is an important factor in determining potential exposures, and it is concluded that the occurrence of NORs is widespread across the state, and therefore the potential for worker exposures is correspondingly high.

Whilst there is established sources of data to evaluate potential exposures in the Tidal Flats, there is a paucity of data for the Great Plateau and Darling Scarp (with the exception of data from the two REs mentioned in Section 4.2), and the research that does exist pre-dates the release of the revised dose

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[34] A polishing plant utilizes sulphuric acid to reduce contaminants on the surface of zircon grains.

[35] Historically, the gold and nickel mines in this region have not been associated with NORMs.

coefficients in the Occupational Intake of Radionuclides ICRP (2017, 2019a). It is this finding that is the catalyst for the research reported in Chapters Six, Seven and Eight.

Finally, Section 4.4 identifies an emergingly significant radiological issue that is present across all three geographical regions where mineral processing via chemical or thermal treatment occurs. As exemplified by the PRSM derived from an underground nickel mine, low concentrations of NORs in mineral feedstock can become concentrated in the right conditions leading to PRSM. This is not an isolated issue, and one that requires consideration in order to minimise risks of exposure to workers, the community, and the environment. Chapter Nine presents research into a potential method for minimising the risks presented by dispersed radionuclides in corrosion scale in disused mining equipment.

The potential for radiation exposures to mine workers in Western Australia has been established. At this juncture the research delves into the various sources of historical records to address the lacuna in body of knowledge of worker doses.

RESEARCH AIMS AND OBJECTIVES

The Western Australian mining industry is undergoing a metamorphosis, driven by the global demand for minerals used in the manufacture of technology to support reductions in greenhouse gas emissions. This has resulted in a significant increase in the number of mining operations; the size of the cohort of mine workers exposed to NORs; and the volume of plant and equipment potentially contaminated by NORs. The increases are forecast to continue over the mid-term future and are accompanied by commensurate increases in exposure to radiation to workers, the Western Australian community, and the environment.

The core purpose of this research was to investigate and document the sources, and magnitude of the radiation doses to Western Australian mine workers arising from exposure to NORs, in order to answer the research question:

"what is the potential for radiation exposures from NORs to the significantly increased workforce, and is the regulatory framework fit-for-purpose to ensure radiation doses are kept as low as reasonably achievable?"

Specifically, the research objectives were to:

i. Address the gap in the knowledge of radiation doses from NORs to the Western Australian mining industry workforce.

ii. Evaluate the risks to past workers, by comparing the historical dose records against current exposure standards.

iii. Evaluate the risks to present workers by analysing current data, evaluating the resultant exposure against applicable exposure standards, and applying internationally accepted dose-risk criteria.

iv. Provide recommendations to effectively manage potential radiation doses from NORs to future workers.

The research was designed to provide a series of outcomes. It has informed the mining sector and regulators about the reported and potential radiation exposures of workers through seven papers the researcher has published.

- details of the research papers are provided in Appendix 3, entitled "Research Outputs".

Further, the research has provided recommendations to effectively manage potential radiation doses from NORs to future mine workers. Thirdly, it has yielded a methodology to integrate Western Australia's approach to radiation management in the state's mining industry with that of the Federal government, to assist the state government and other stakeholders manage exposures from mining operations to below health-based limits.

A summary of the alignment between the Research Objectives, published papers and Chapters in this Thesis is provided in Table 6.

TABLE 6: ALIGNMENT OF RESEARCH OBJECTIVES WITH PUBLISHED PAPERS AND CHAPTERS IN THE THESIS

Research Objective	Chapter Reference(s)	Published Paper(s)
i. Address the gap in the knowledge of radiation doses from NORs to the Western Australian mining industry workforce.	Chapter Five Chapter Six Chapter Eight	Paper #1: Published in Radiation Protection Dosimetry Volume 191, Issue 3, September 2020 Paper # 3: Published in Journal of Radiological Protection, Volume 40, Number 4, 23 November 2020
ii. Evaluate the risks to past workers, by comparing the historical dose records against current exposure standards	Chapter Five Chapter Six Chapter Eight	Paper # 4: Published in Radiation Protection in Australia, Volume 38, Number 1, 24 April 2021 Paper # 5: Published in Radiation Protection in Australia, Volume 38, Number 2, 21 September 2021
iii. Evaluate the risks to present workers by analysing current data, evaluating the resultant exposure against applicable exposure standards, and applying internationally accepted dose-risk criteria.	Chapter Six Chapter Seven Chapter Eight	Paper #2: Published in Journal of Radiological Protection, Volume 40, Number 4, 20 November 2020 Paper # 6: Published in Journal of Radiological Protection, Volume 42, Number 1, 12 January 2022

Research Objective	Chapter Reference(s)	Published Paper(s)
iv. Provide recommendations to effectively manage potential radiation doses from NORs to future workers.	Chapter Nine Chapter Ten	Paper #7: Submitted to Science of the Total Environment, 26 September 2022. Under Editorial Review: Reference STOTEN-D-22-24063

CHAPTER FIVE: CHRONICLE OF RADIATION EXPOSURES OF WA MINE WORKERS 1977 TO 2019-20

Managing risks [is] an act of the imagination. And the human imagination is a poor tool for judging risk. People are really good at responding to the crisis that just happened, as they naturally imagine that whatever just happened is most likely to happen again.

They are less good at imagining a crisis before it happens – and taking action to prevent it.

What was most easily imagined was not what was most probable ... It is the less detectable, systemic risks.

Another way of putting this is: the risk we should most fear is not the risk we easily imagine. It is the risk we don't.

Michael Lewis in "The Fifth Risk"

(Lewis, 2018).

The objective of this Chapter is to address the gap in the knowledge of radiation doses from NORs to the Western Australian mining industry workforce.

The history of Western Australian mine workers being exposed to radiation from NORMs dates back almost a century when mining of the mineral xenotime to extract radium for the treatment of cancer occurred at Holleton in the Yilgarn Shire in 1929 (mindat.org, 2021b; Mudd, 2005). However, radiation exposures of workers only began to be considered in the 1970s, with formal reporting to the RRAM commencing in the mid-1980s.

This Chapter endeavours to complete the lacuna in the historical record of reported mine worker exposures to radiation from NOR(M)s. The Chapter commences with a discussion on the methodology applied to source the information; the significant role played by computerised dose calculation applications; and the limitations of the methodology. Subsequent Sections provide:

- An overview of radiation exposures received by workers employed in the state's trials of producing uranium; and
- The workforce demographics, and sources and magnitude of radiation exposures to Western Australian mine workers in the 42 reporting periods from 1977 to 2019-20.

5.1 METHODOLOGY: COMPILATION OF DOSE HISTORIES

As was outlined in Section 2.9, REs 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 (DMIRS, 2020f; Veluppillai, 2020b), and a numerical reference allocated in sequential order by the date of receipt of the RMP. At the end of the 2018-19 reporting period, 30 REs had been allocated a numerical identifier, which had increased to 41 REs at time of compilation of this Thesis. [36].

- The allocation of a numerical identifier unique to an RE allowed the RE-by-RE analysis reported in Chapter Eight.

Each RE is required to submit an annual report of estimates of radiation doses to their workforce. The Department has been responsible for the keeping of records associated with the radiation exposure of mine workers since 1986. The researcher enlisted the assistance of the senior Departmental records

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[36] A RE located in the district of Jurien ceased operating in 1977, prior to the alpha-coding system being implemented. This RE has been allocated the numerical code "0" and is counted among the 41 REs.

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 from 1992.

- 166 annual reports were located, 39 of which had been stored electronically (Ralph, 2020a).

Tsurikov (N. Tsurikov, personal communication February 22nd, 2019) provided the data from research (Tsurikov, 2009a, 2009b) that was published in IAEA (2011) to the researcher, 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 (2009a) data was used.

Workers employed by an RE are allocated a personal numerical identifier, which is cited in the submitted annual reports, preserving the workers anonymity. However, despite this information not being required in this research, a small number of the annual reports also included the names of individual workers. The Department's records management officers redacted the worker names from the reports and forwarded the de-identified reports to the researcher for analysis.

5.1.1 Records of dose estimates from 1983 to 1992-93

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 (DoM, 1990; Hewson, 1988a, 1989b; Hewson & Ralph, 1987).

- The first report was published in 1990 by Hewson (1990b) who summarised the exposure status of the MSI workforce between 1983 and 1988.
- The second publication was released as a technical report by the Mining Engineering Division of the Department (MED, 1992). This report established a reporting template that was followed in the third report by Hewson and Marshman (1993) and replicated by Ralph, Chaplyn and Cattani (2020a).
- The final peer-reviewed publication of doses to MSI workers occurred when Marshman and Hewson (1994) published what amounts to an update of the original paper by Hewson (1990b) and cites data up to the end of the 1992-93 reporting period.

The publication by Marshman and Hewson (1994) established a template for reporting and analysing worker doses, which has been adopted and adapted slightly, by analysing annual doses of less than 5mSv, for this research in Sections 5.6 to 5.9.

The three publications were used to complete the historical record from the time of the Winn Inquiry in 1983 to 1992-93 where the Departmental records of annual reports commence.

5.1.2 Records of dose estimates from 1977 to 1982

Winn et al. (1984) reported that systematic inspections of the MSI commenced in 1978, and using this time as a reference point, constructed a timeline of worker doses up until 1982.

- The analysis of worker exposures, and the corresponding dose assessments as conducted by Winn et al. (1984) are discussed in detail in Appendix 5.

The research by Tsurikov (2009a) allowed the record of worker dose estimates to be extended back to 1977.

The data from Winn et al. (1984) supplemented by the research by Tsurikov (2009a) has been used as the basis of compiling the exposure histories from 1977 to 1982 when the peer-reviewed publications listed in Section 5.1.1 commenced.

5.2 METHODOLOGY: COMPUTER-BASED DOSE CALCULATION, RECORDING AND REPORTING SYSTEMS

Increased regulatory scrutiny from 1986 onwards eventually led to the standardised reporting format discussed in Section 2.9.2. As a result of the concerns expressed by Winn et al. (1984) in relation to the competence of industry-based RSOs, in 1988 the Department opted to develop an electronic database for the recording of monitoring data and the calculation of worker doses (Hewson, 1989b; Marshman & Hewson, 1994).

As is discussed in detail in Appendix 5, the database, known as the Mines Dose Assessment System (MIDAS). was implemented in 1992 by all operating REs. Following the implementation of MIDAS Marshman and Hewson (1994) highlighted that “The acceptance of MIDAS by industry has … [enabled] reporting by companies [to be] in a uniform format which expedites the analysis of annual reports”.

As well as the annual reports submitted by the REs, copies of their electronic data as stored in the MIDAS database are also held by the Department.

In this research each annual report submitted in the era between 2000-01 and 2004-05 in which MIDAS was deployed was interrogated for the dose-related data, from the consolidated information as it appeared in the report. Random audits of the consolidated data in five of the 34 reports were conducted by analysing the data stored in MIDAS and juxtaposing the two data sets (Ralph, 2020b). All five random audits confirmed the veracity of the reported data.

5.2.1 The Boswell data recording, dose calculation, and reporting system

In September 2004 a software application called Boswell, which utilised the Microsoft Access (2000) platform was implemented across the MSI to replace the ageing MIDAS. The REs in operation at the time were required to develop their 2004-05 annual reports by using Boswell (Knee, 2004).

As is discussed in Appendix 5, the transition to Boswell was problematic, and as a result of the system's inherent errors, a number of the annual reports submitted during the time Boswell was utilised by REs, were flawed and/or incomplete.

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.

5.2.2 The post-Boswell era

In May 2014 the Mines Inspectorate opted to withdraw support for Boswell (DMIRS, 2019d), and therefore the 2013-14 reporting period was the last in which a standard (albeit flawed) reporting format was used by all REs. Despite the withdrawal of support, several REs continued to use Boswell, in the knowledge that many of the reporting functions are flawed, complicating the extraction of data for this research .

In this research, all reports subsequent to the 2013-14 reporting period have been manually assessed, using the copies of the annual reports stored in SRS.

5.3 EXTRACTION AND RECORDING OF DATA FROM ANNUAL REPORTS

Each of the annual reports was interrogated for demographic data including the number of workers on site; the number of DWs; and the maximum and mean number of hours worked per year. Data pertaining to the three main pathways of exposure were identified (where available), 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 dose in each annual report were also recorded (Ralph, 2020b).

Data from the period in which MIDAS was used was able to be extracted directly from the annual reports, as submitted by each RE. However, all data for the Boswell and post-Boswell periods had to be derived by searching each report and manually calculating the relevant input. The de-identified dose records of 2,715 monitored workers; and the data from the three sources of exposure drawn from the

139 annual reports submitted between the 2005-06 and 2018-19 reporting periods were manually evaluated (Ralph, 2020b).

A standard recording template was developed as a spreadsheet within Microsoft Excel (2016). Commencing with the annual reports for the 2018-19 reporting period, data was extracted for each RE, and inserted into the spreadsheet, following the numeric site coding system discussed in Section 5.1. 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 1986-87 information had been entered into the Microsoft Excel (2016) workbook.

Several additional spreadsheets were added to the Microsoft Excel (2016) workbook to enable statistical analysis and graphical representation of the collected data (Ralph, 2020b).

5.4 ISSUES AFFECTING METHODOLOGY

Collection and analysis of the worker dose records from the various published sources and the 166 annual reports submitted by the REs was complicated by several factors which are discussed in this Section.

5.4.1 Issues affecting methodology: Number of REs

The history of the mining industry in Western Australia 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.

REs are a microcosm of, and have exhibited a similar history to, the rest of the Western Australian mining industry. By way of example Marshman and Hewson (1994) analysed data provided by seven REs. A further RE, the tin / tantalum (and now a rare earths) mining and processing operation located in the Darling Ranges (one of those mentioned in Section 4.2) was known to the Mines Inspectorate, but because the research focused only on the MSI, the data from this site was excluded. At the turn of the new millennium only five of the eight REs were still operating (Ralph, 2020b) and submitted annual reports for the 1999-2000 reporting period.

A decade later, in the 2010-11 reporting period, 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. 21 REs had been allocated a numeric identifier, eleven of which were required to provide annual reports to the SME for the 2009-10 reporting period (Ralph, 2020b).

By the 2018-19 reporting period the number of REs allocated a numeric identifier had increased to 34, 15 of which were required to provide annual reports to the SME (Ralph, 2020b).

The number of REs, by year, in the period from 1986 to 2019-20 is illustrated in Figure 11.

- Note that prior to 1986, the number of REs was consistent, at 6
- The 2019-20 data is included as a prelude to the results provided in Chapter Eight [37].

5.4.2 Issues affecting methodology: DWs (DEs)

The research published by Hewson (1990b); MED (1992), Hewson and Marshman (1993) and Marshman and Hewson (1994) emphasis doses received by DWs [38]. In 1993, 212 workers (14.2% of the MSI workforce) were deemed as being DWs, due to their potential to receive doses greater than 5mSv per annum.

Ralph et al. (2020a) highlight that in the ensuing period, there has been confusion amongst REs as to which cohort of their operations should be deemed as DWs, with some operations adhering to the "potential annual dose of 5mSv" whilst others report any worker who participates in the radiation monitoring program as a DW.

The inconsistency in interpretation of the definition of DW is problematic, and the impacts are evaluated in the Discussion Section of this Chapter.

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[37] The increasing trend continued with 19 REs reporting in 2020-21 and 23 in 2021-22.

[38] Referenced as Designated Employees (DEs) in the MSIR.

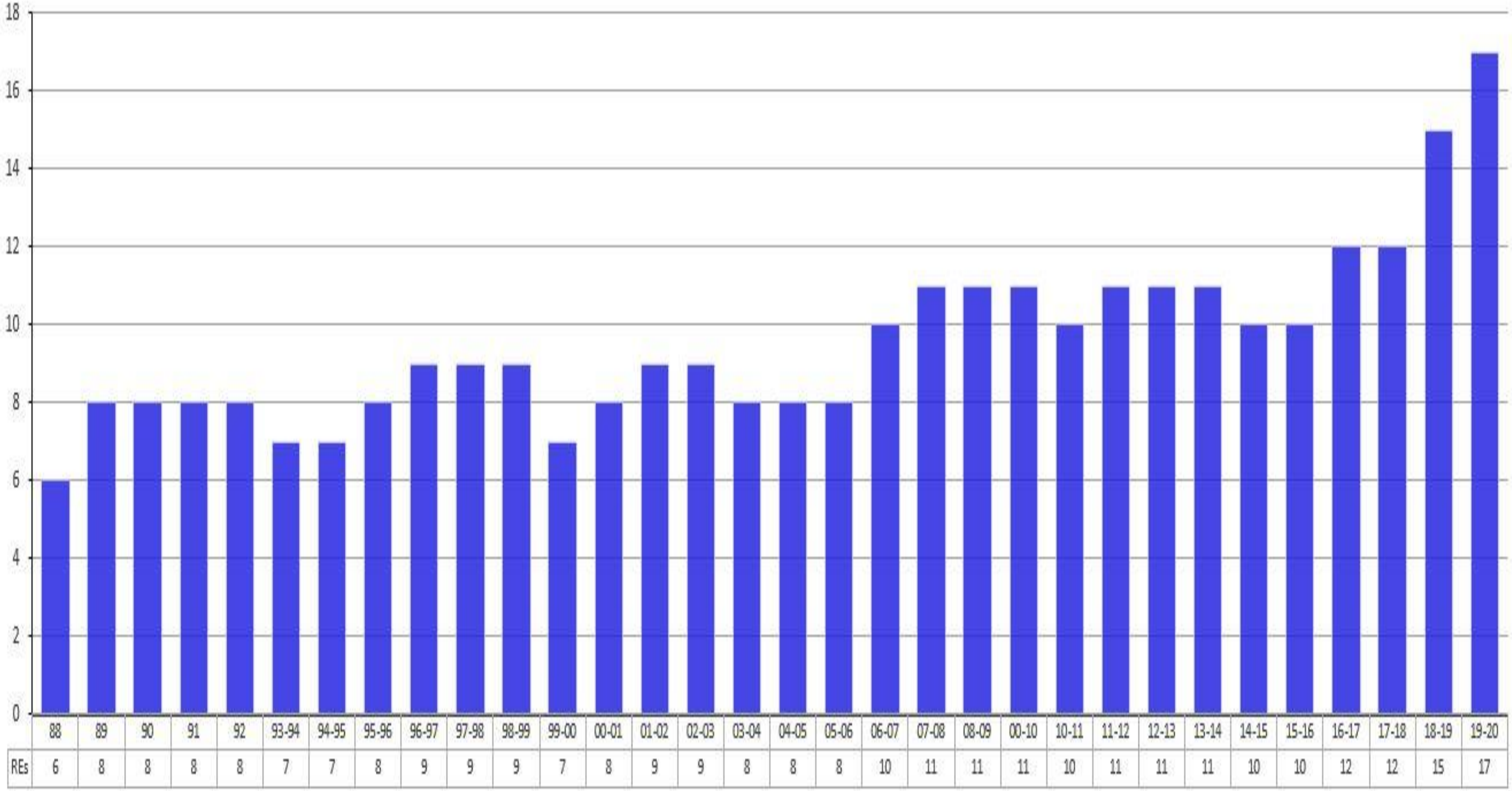

FIGURE 11: NUMBER OF REPORTING ENTITIES (REs) 1988 TO 2019-20

5.4.3 Issues affecting methodology: Reporting of annual doses less than 5mSv

Ralph et al. (2020a) noted “212 workers were deemed as DEs in 1993, and of these 157 received annual doses in excess of 5mSv, and therefore had the source of their doses evaluated”. *Ipso facto* the remaining 1,339 (89.5% of the workforce) received annual doses less than 5mSv, and their exposures were not fully evaluated.

The analysis performed by Tsurikov (2009a, 2009b) replicated that of MED (1992) and did not produce an in-depth analysis of annual doses less than 5mSv. Therefore, although the derived annual limit of 20mSv was implemented in 1995, an assessment of the doses below 5mSv could not be constructed until the 2000-2001 reporting period at which time the Department’s records are observed by the researcher as being “largely complete”.

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

5.4.4 Issues affecting methodology: DCs and DCFs

As was outlined in Section 2.2, the models, which apply DCs to determine the dose from the intake of inhaled dusts containing LLα, have evolved since the first simple model was introduced by ICRP in 1959 (Boecker, 1995). With each iteration of ICRP’s models, changes (if any) to DCs for members of the ^{232}Th and ^{238}U decay series will impact on the DCFs [39] for inhaled dusts containing NORs:

- A seven-fold reduction in the DACs for inhaled dusts occurred between 1983 and 1986 as a result of revisions of DCs.
- In the mid-1990s, DCFs applicable to Western Australia’s REs decreased by a factor of 2.9 times from $0.028mSvBq^{-1}$ to $0.0097mSvBq^{-1}$ (Hewson, 1998; Reilly & Gordon, 1997). All other things being equal, doses arising from the inhalation of LLα should have decreased accordingly.

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[39] A DC applies to an individual radionuclide, whereas a DCF applies to a combination of radionuclides in secular equilibrium.

- In 2009 the DCF reduced significantly from $0.0097mSvBq^{-1}$ to $0.008mSvBq^{-1}$, and all things being equal, the doses arising from the inhalation of LLα should have decreased accordingly. (Knee, 2009b) [40].

All of the annual reports assessed in this research were submitted prior to the release of ICRP-141 in December 2019. Accordingly, all doses reviewed in this Chapter are "*as they were submitted to the RRAM by the REs*".

5.5 WA MINE WORKER DOSES: MINING AND PROCESSING OF URANIUM

As was discussed in Section 1.4, despite plentiful identified deposits, Western Australia has not developed a producing uranium mine [41]. However, Western Australia has trialled uranium mining and processing in the past, with several projects advancing to a pilot production phase, the two most notable being:

1. Manyingee; located in the northern part of the Carnarvon Basin, where pumping testing conducted in 1984 confirmed that the deposit was suitable for solution mining. Subsequently an in-situ leaching test was carried out in 1985 for 5 months, producing about 470 kg of uranium concentrate before the tests were suspended (Bautin & Hallenstein, 1997). The uranium concentrate was reinjected into the wells, and the project was placed in care and maintenance.
2. Yeelirrie; which was discovered in 1972 and was mined in 1980 to supply approximately 13,000 tonnes of uranium ore (average grade of 2,200 ppm U_3O_8) for metallurgical testing at the attendant Kalgoorlie Research Plant (KRP) (Laidlaw, 2006). The KRP was commissioned in 1980 and operated until the test work was completed in 1983 (Crouch, 2003; SKM, 2005).

5.5.1 Radiation exposures at Yeelirrie

The Yeelirrie operations were subject to several research projects conducted by the Australian Radiation Laboratories (Department of Health, 2018a, 2018b, 2018c, 2018d). Leach, Solomon and Gan (1980), reported on field analyses conducted in mid-August 1980, whilst mining operations were being

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[40] No explanation was provided by the Mines Inspectorate as to how the revised DCF was determined. The impact of the significant decrease in DCF on worker doses was not investigated at the time but is worthy of further analysis.

[41] However, the Mulga Rock Project is scheduled to deliver its first uranium product in 2025 (ABC News, 2021).

conducted. Two significant observations were reported that indicated the potential for elevated worker doses:

i. A maximum Rn concentration of 4,900 Bqm^{-3}, almost five times the current regulatory exemption concentration was measured at 04:00 hours on an upper level of the mine pit.
ii. Levels of RnP measured at night were "2 to 3 orders of magnitude higher than those measured during the day". A maximum RnP concentration of 0.34 Working Levels was measured.
    - A worker exposed to this concentration for a working year would receive an internal dose of approximately 16mSv.

Workers were monitored for radiation exposure at the Yeelirrie mine site during 1980, and at the KRP from the time of start-up in August 1980 to shut down in 1981 (Department of Health, 2018c, 2018d). The operations pre-dated the implementation of additivity of exposure pathways, and as was the standard of the day, doses were divided into two categories:

a. "Whole Body" (External γ, measured by TLD badges); and
b. "Lung" estimated by area monitoring and occupancy times.

An annual limit of 5,000 milliRem (50mSv) applied to "Whole Body" doses and 15,000 milliRem (150mSv) to "Lung" doses (Department of Health, 2018c, 2018d).

A summary of worker doses was submitted to the RCWA by the RE (Department of Health, 2018c) [42]. Because a large portion of the workforce did not work at either of the two sites for longer than 12 months, the report normalised the worker doses to a period of 4 weeks, equivalent to 160 working hours. Estimates of the annual doses to workers, are provided in Table 7.

- In order to extrapolate the reported data to an annual dose, the data in Department of Health (2018c) has been multiplied by 12.5, equivalent to a 2,000 hour working year.

As can be seen from the data presented in Table 7, applying the additivity principle, the potential maximum dose (in contemporary terminology) is 15.6mSv whilst the mean is 3.3mSv.

Rehabilitation of the Yeelirrie mine site was completed between June and December 2004. 50 individuals were monitored for radiation exposure. The majority of workers received annual doses of

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[42] The report is a draft and is not formally signed by a representative of the mine operator. However, the data is the only analysis on the public record, and as such is considered indicative of actual exposures.

less than 0.2mSv (mean 0.04mSv) and the maximum annual dose was 0.33mSv by a truck driver who worked the highest number of hours (768).

The KRP was decommissioned between 1986 and 2003. Crouch (2003) found a maximum radon exhalation rate of 0.072 $Bqm^{-2}s^{-1}$, approximately double that of a nearby control site, but “well below the target value of 0.150 $Bqm^{-2}s^{-1}$ set by the [Mines Inspectorate]”. The assessment report concluded “there should be no need to impose restrictions on use of the site for general industrial purposes” but added “it is recommended conditions be put on the title prohibiting excavations to depths greater than 3m below the surface”.

The project proponents declare “ The report [into radiation parameters at the KRP] identifies that completion criteria to satisfy a return to pastoral land use have been met” (Bradshaw, 2004).

TABLE 7 WORKER DOSE ESTIMATES: YEELIRRIE AND KALGOORLIE RESEARCH PLANT (1980-81)

Location	Worker Category	No. of Workers	Whole Body Dose from External γ (mSv)			Lung Dose from LLα and RnP (mSv)		
			Minimum	Maximum	Mean	Minimum	Maximum	Mean
Yeelirrie	Mine workers	46	0.4	4.6 [1]	1.8	0.5	11 [1]	5.3
Yeelirrie	Support Staff	16	0.0	1.5	0.4	0.0	3.9	1.3
KRP	Workers employed for >12 months	35	0.3	0.8	0.5	1.1	2.8	1.4
KRP	Process operators who worked <12 months	75	0.0	1.8	0.5	1.0	6.9	1.8
KRP	Office Staff	6	0.3	0.4	0.3	0.9	1.0	1.0
Total		**178**	0.0	4.6	0.8	0.0	11	2.5

[1] The sum of these values provides the maximum estimated dose of 15.6mSv.

5.6 WA MINE WORKER DOSES : THE EARLY YEARS – 1977 TO 1992

A summary of the workforce demographics, analysis of dose estimates and a précis 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 8 and 9.

- The dose estimates reported by the Winn Inquiry are outlined in detail in Appendix 5.
- IAEA (2011) re-evaluated the worker dose data reported by the Winn Inquiry.

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 are presented in Tables 10 and 11.

5.6.1 Sources of data: 1977 to 1992

The information reported in Tables 8, 9, 10 and 11 have been compiled from data reported in:

- Winn et al. (1984);
- Internal reports for the SME and IMRC by Hewson DoM (1990); Hewson (1988a, 1989b, 1990a, 1991); Hewson and Ralph (1987);
- Published articles by Hewson (1990b); MED (1992); Hewson et al. (1992); Hewson and Marshman (1993); and Marshman and Hewson (1994);
- Research by Tsurikov (2009a) published in IAEA (2011).

5.6.2 Notes to 1977 to 1992 analysis

Salient points in relation to the information provided in Tables 8, 9, 10 and 11:

a) Up to 1989, summarised reports were provided to the SME and IMRC, based upon a calendar year reporting period. Although this changed to the “radiation reporting year” in subsequent years, the REs retained the calendar year as the bass for collecting and reporting their data, as illustrated in Table 29 of IAEA (2011).

b) The tin/tantalum operation, which was identified as having radiological characteristics, was not subject to reporting obligations. The 15 reports are 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 Winn et al. (1984) and the doses retrieved by Tsurikov (2009a), and subsequently published in Table 29 of IAEA (2011). Where a discrepancy occurs, in Table 8, and consequently in Table 9, the IAEA (2011) data has been used.

d) As per Winn et al. (1984) monitoring of external γ was not routinely conducted in the MSI until requested by the regulators in 1978. Therefore, the external γ data reported in Table 8 is 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 (DoM, 1990) contains hand-written notes that completes the record for external γ doses for the 1984 and 1985 reporting periods, as shown in Tables 8 and 10. 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 (2011), providing confidence in the data in Tables 8, 9, 10 and 11 from 1986 onwards.

f) In all of the reports provided to the SME and IMRC from 1986 onwards in Tables 8 and 10 only employees (including DWs) 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 closed during 1977. However, the number of REs did not decrease the following year because an operation commenced in the Eneabba district during 1978.

TABLE 8: RADIOLOGICAL PARAMETERS AND DOSES TO MINE WORKERS IN THE “EARLY YEARS” 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				2,748 [4]	Unknown	5,990 [4]	6,298 [4]

Notes to Table 8:

[1] Number of REs in parentheses.

[2] From Table 29 of IAEA (2011). Note that this table cites annual dose, but does not include doses from external γ.

[3] From page 5.5 of Winn et al. (1984).

[4] From page 7 and 8 of Hewson (1990b), or Folio 11 of The Department File 840/90 (DoM, 1990), and includes an assumed 1mSv per non-DE.

TABLE 9: ANALYSIS OF RADIOLOGICAL PARAMETERS IN THE "EARLY YEARS" 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 dose 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 dose (mSv)	Unknown				3.6 [5]	Unknown	Unknown	8.2 [5]

[1] From Table 8.

[2] From Table 113 of IAEA (2011).

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

[4] Calculated by multiplying the DEs by mean annual dose 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 (DoM, 1990).

TABLE 10: 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]	1,113 [3]	1,314 [3]	1,746 [3]	1,685 [3]	1,609 [3,4]	1,496 [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]	1,136 [3]	1,492 [3]	1,475 [3,4]	1,339 [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)	8,791 [2]	7,097 [3]	6,526 [3]	6,114 [3]	5,815 [3]	3,898 [3]	2,592 [3,4]	2,984 [3]

Notes to Table 10:

[1] Number of REs in parentheses.

[2] From pages 7 and 8 of Hewson (1990b), or Folio 11 of The Department File 840/90 (DoM, 1990).

[3] From Table 1 of Marshman and Hewson (1994), and includes an assumed 1mSv per non-DE.

[4] A tin processing operation was included as a reporting entity. Data has been extracted from Table 3 of Hewson et al. (1992).

TABLE 11: 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]	1,408 [6]	2,011 [6]	2,575 [6]	2,072 [6]	1,981 [6]	2,032 [6]
Mean LLα (mBqm^{-3})	170 [5]	850 [6]	600 [6]	510 [6]	490 [6]	270 [6]	160 [6]	180 [6]
Mean dose per DE (mSv) [2]	30.8	24.4	19.7	17.1	15.0	8.6	5.4	7.8
Collective dose (man.mSv)	8,791	7,097	6,526	6,114	5,815	3,898	2,592	2,984
Mean Worker dose (mSv)	12.2	8.2	5.9	4.7	4.1	2.3	1.6	2.0

[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] From Folio #30 of The Department File 840/90 (DoM, 1990).

[5] From Table 113 of IAEA (2011).

[6] From Tables 5 and 6 of Hewson (1996a).

5.7 WA MINE WORKER DOSES :THE MIDAS YEARS, 1993-94 TO 2003-04

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

A summary of the workforce demographics, analysis of dose estimates and a précis of the industry-wide monitoring programs extracted from 90 annual reports over the eleven radiation reporting years from 1993-94 to 2003-04 are presented in Tables 12, 13, 14 and 15. This period coincides with the advent of the initial approach to standardise dose calculation protocols via the computer-based Mines Dose Assessment System (MIDAS).

5.7.1 Sources of data: 1993-94 to 2003-04

The information reported in Tables 12, 13, 14 and 15 have been compiled from:

- The Hewson (1996a) report to RCWA (which completes the record from 1993 to 1996).
- Research by Tsurikov (2009a) published in IAEA (2011).
- Files extracted from the Department’s records (Ralph, 2020a, 2020b; Veluppillai, 2020a).
- A Microsoft Excel (2007) spreadsheet entitled “MSI Dose History”, that captured the original data reported in Tsurikov (2009a) (N. Tsurikov personal communication, September 23rd, 2020).

5.7.2 Notes to 1993-94 to 2003-04 analysis

Salient points in relation to the information provided in Tables 12, 13, 14 and 15:

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 (2009a), the MSI Dose History spreadsheet or IAEA (2011) 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 doses less than 5mSv was able to be conducted from 2000-01 onwards. The format of Table 15 changes from that in Table 13.

d) As was highlighted in Section 5.4.2, and discussed at length by Ralph et al. (2020a) an inconsistency arises in this period in the application of the definition of a Designated Worker (Employee). It is apparent that any worker who participated in the monitoring programme was categorised as a DW(E).

  - From Table 14 onwards, the DW(E) 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.

TABLE 12: 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	1,504 [2]	1,667 [2,4]	1,373 [2,4]	1,213	1,100	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	1,292 [3]	1,282 [3,4]	1,008 [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)	2,876 [2]	3,177 [2]	2,878 [2]	2,862 [5]	2,571 [5]	2,102 [5]	1,528 [5]

Notes to Table 12:

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

[2] From Table 2 of Hewson (1996a), and includes an assumed 1mSv per non-DE.

[3] Data is from Tsurikov (2009a) and analysis of annual reports submitted by the REs, unless otherwise indicated.

[4] Includes contribution from the tin operation, extracted from Folios 98-101 of The Department File 840/90 (DoM, 1990) or DME File 2176/99 (DME, 1999).

[5] From Tsurikov (2009a). Includes all workers, whereas in the period prior to 1996-97, only doses to DEs were reported.

TABLE 13: 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]	1,504	1,667	1,373	1,213	1,100	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	1,501 [4]	1,716 [4]	1,769 [4]	1,599	1,883	1,653	1,269
Personal Dust Samples	1,871 [5]	2,045 [4]	1,958 [4]	2,292	2,520	2,328	1,806
Mean LLα (mBqm^{-3})	170 [5]	133 [4]	99 [5]	143	127	123	126
Mean dose per DE (mSv) [2]	6.5	5.8	6.7	2.3	2.2	2.2	1.8
Collective dose (man.mSv) [1]	2,876	3,177	2,878	2,862	2,571	2,102	1,528
Mean Worker dose (mSv) [3]	1.9	1.9	2.1	2.4	2.3	2.3	2.3

[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] From Tsurikov (2009a) and analysis of annual reports submitted by the REs, including the tin operation.

[5] From Tables 5 and 6 of Hewson (1996a).

TABLE 14: 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	1,006	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)	1,694 [3]	1,468 [3]	2,602 [3]	2,087 [3]

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

[2] From Tsurikov (2009a) and analysis of annual reports submitted by the REs, unless otherwise indicated.

[3] From Tsurikov (2009a).

TABLE 15: ANALYSIS OF RADIOLOGICAL PARAMETERS 2000-01 TO 2003-04

Parameter	2000-01 [2]	2001-02 [2]	2002-03 [2]	2003-04 [2]
Workforce [1]	1,006	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	1,444	1,317	1,683	1,595
Mean LLα (mBqm^{-3})	136	132	103	90
Mean dose per MW (mSv) [3]	1.9	1.4	1.9	3.6
Collective dose (man.mSv) [1]	1,694	1,468	2,602	2,087
Mean Worker dose (mSv) [4]	1.7	1.6	3.4	3.1

[1] From Table 14.

[2] From Tsurikov (2009a) and analysis of annual reports submitted by the REs.

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

[4] Calculated by dividing the collective dose by the number of workers.

5.8 WA MINE WORKER DOSES :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. As was highlighted in Section 5.1, reports submitted by REs in the nine-year period from when Boswell was first implemented in 2004-5 to when the Mines Inspectorate withdrew support in 2012-13 were beset with issues, notably with some of the reporting functions.

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 16 and 17. This period was selected as it coincides with the last four years of the data retrieval project reported by Tsurikov (2009a) and the data in an Excel spreadsheet entitled "MSI Dose History from research by Tsurikov (N. Tsurikov, personal communication February 22nd, 2019), introduced in Section 5.1. Therefore, the two data sets can be compared. Where a discrepancy was found, the Tsurikov data or the data in the "MSI Dose History" spreadsheet 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 Table 18 and 19.

5.8.1 Sources of data: 2004-05 to 2012-13

All of the 91 annual reports expected to be submitted by REs over the nine-year period were retrieved by the Department's records management team or were resubmitted by the REs upon request.

Each report was thoroughly assessed, by interrogating the input data and re-calculating relevant demographic and statistical information.

TABLE 16: 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	1,217
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)	1,452 [3]	1,206 [3]	1,906 [3]	2,511 [3]

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

[2] From Tsurikov (2009a) and analysis of annual reports submitted by the REs.

[3] From Tsurikov (2009a). Includes all workers.

[4] Includes contribution from RnP / TnP.

TABLE 17: ANALYSIS OF RADIOLOGICAL PARAMETERS 2004-05 TO 2007-08

Parameter	2004-05	2005-06	2006-07	2007-08
Workforce [1]	713	635	740	1,217
Monitored Workers (MW)	323	378	348	301
Monitored Workers (%)	45.3%	59.5%	47.0%	24.7%
External γ Assessments	1,126	1,294	1,464	1,038
Personal Dust Samples	2,018	1,927	1,456	1,181
Mean LLα (mBqm^{-3})	76	91	64	80
Mean dose per MW (mSv) [2]	1.6	1.6	1.3 [4]	1.8 [4]
Collective dose (man.mSv) [1]	1,452	1,206	1,906	2,511
Mean Worker dose (mSv) [3]	2.0	1.9	2.6	2.1

[1] From Table 16.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 16.

[3] Calculated by dividing the collective dose by the number of workers.

[4] Includes contribution from RnP / TnP.

TABLE 18: 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 REs in parentheses.

[2] Includes contribution from RnP / TnP.

TABLE 19: 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 dose per MW (mSv) [2]	1.1 [4]	1.0	0.9	1.0 [4]	0.8
Collective dose (man.mSv) [1]	784	556	452	480	533
Mean Worker dose (mSv) [3]	1.2	1.0	0.8	0.7	0.8

[1] From Table 18.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 18.

[3] Calculated by dividing the collective dose by the number of workers.

[4] Includes contribution from RnP / TnP.

5.9 WA MINE WORKER DOSES :THE POST-BOSWELL YEARS – 2013-14 TO 2018-19

A summary of the workforce demographics, analysis of dose estimates and a precis of the industry-wide monitoring programs for the six radiation reporting years from 2013-14 to 2018-19 are presented in Tables 20 and 21.

5.9.1 Sources of data: 2013-14 to 2018-19

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.

- 68 annual reports were assessed during this stage of the analysis.
- Data from RE#7, for the two periods 2013-14 and 2014-15 had been misplaced by the RE, and reports could not be prepared.

5.9.2 Notes to 2013-14 to 2018-19 analysis

Importantly, and in line with an increased focus on the contribution of Tn and Rn (and their progeny) to worker dose:

a) In 2013-14, RE#15 commenced monitoring for RnP and TnP exposures. A maximum contribution of 1.2mSv and a mean of 0.2mSv were reported.

b) In 2014-15, REs#3 and #9 commenced reporting doses from RnP and TnP. All three REs reported doses from RnP and TnP in 2015-16.

c) REs#18 and#6 commenced reporting doses from RnP and TnP, bringing the total to five operations. The reporting was repeated in 2017-18.

d) In 2018-19, REs#7 and #8 commenced reporting doses from RnP and TnP, bringing the total to seven operations. 50% of the REs assessed the contribution of RnP and TnP to worker dose.

e) 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 20 and 21.

TABLE 20: 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

Parameter	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
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

Notes to Table 20:

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

[2] Includes contribution from RnP / TnP.

TABLE 21: 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 dose per DE (mSv) [2]	0.9 [4]	0.6 [4]	0.8 [4]	0.8 [4]	0.9 [4]	1.0 [4]
Collective dose (man.mSv) [1]	222	240	359	363	418	659
Mean Worker dose (mSv) [3]	0.5	0.5	0.8	0.7	0.7	0.4

[1] From Table 20.

[2] Extrapolated, by adding the Mean External γ and Mean Internal Dose from Table 20.

[3] Calculated by dividing the collective dose by the number of workers.

[4] Includes contribution from RnP / TnP.

5.10 WA MINE WORKER DOSES : SUMMARY OF DATA 1977 TO 2018-19

A summary of the workforce demographics and analysis of dose estimates for the 42-year period from 1977 to 2018-19 is presented in Table 22.

- The notes in Sections 5.6, 5.7, 5.8 and 5.9 and the footnotes to Table 8 to 21 are germane to Table 22.

TABLE 22: 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]	***34,240***
Designated Employees / Monitored Workers [3]	8,960
Monitored Workers (%)	26.2%
Mean Hours Worked per Year [2]	1,686
Maximum dose (mSv) [4]	163.4
Mean dose (mSv)	11.0
Collective dose (man.mSv)	108,850
Mean Worker dose (mSv y^{-1}) [5]	3.2
Workers receiving between:	
0 and 1.0mSv	10,811
1.01 and 2.0mSv	1,566
2.01 and 3.0mSv	668
3.01 and 4.0mSv	321
4.01 and 5.0mSv	144
Workers receiving less than 5.01mSv [6]	***29,898***

Parameter	1977 to 2018-19
Workers receiving between 5.01 and 10mSv	1,340
Workers receiving greater than 10.01mSv [7]	745
Workers with a Distributed Dose Estimate [8]	***31,983***

Notes to Table 22:

[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 dose by the total number of worker years.

[6] Includes 16,388 workers reported in the years from 1986 to 1999-00 where the detailed analysis of doses less than 5mSv were not able to be assessed.

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

[8] Mean doses were estimated for 2,257 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 23. 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.

Key demographic and radiological data are illustrated in Figures 12, 13, 14, 15 and 16:

- Figure 12: illustrates the number of Designated Workers (Employees) as a ratio of the workforce over the period from 1993-94 to 2018-19.
- Figure 13: compares monitoring for personal γ to personal dust samples, and the mean dose from internal and external exposures over the period from 1993-94 to 2018-19.
- Figure 14: illustrates the maximum and mean concentrations of LLα from 1993-94 to 2018-19.
- Figure 15: compares the number of personal γ to personal dust samples on a per worker basis, over the period from 1993-94 to 2018-19; and
- Figure 16: shows the size of workforce and collective dose from 1986 to 2018-19.

TABLE 23: ANALYSIS OF RADIOLOGICAL PARAMETERS 1977 TO 2018-19

Parameter	1977 to 2018-19
Sum of workforce by year	34,240
External γ Assessments	28,910
Maximum External γ (mSv)	17.7
Mean External γ (mSv)	1.4
Collective dose from External γ (mSv) [1]	21,515
Personal Dust Samples	47,720
Maximum LLα Concentration (mBqm^{-3})	4,782
Mean LLα (mBqm^{-3})	170
Maximum Dose from LLα (mSv)	153
Mean Dose from LLα (mSv)	9.4
Collective dose from LLα (mSv) [1]	87,061
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)	108,850	9,433
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.

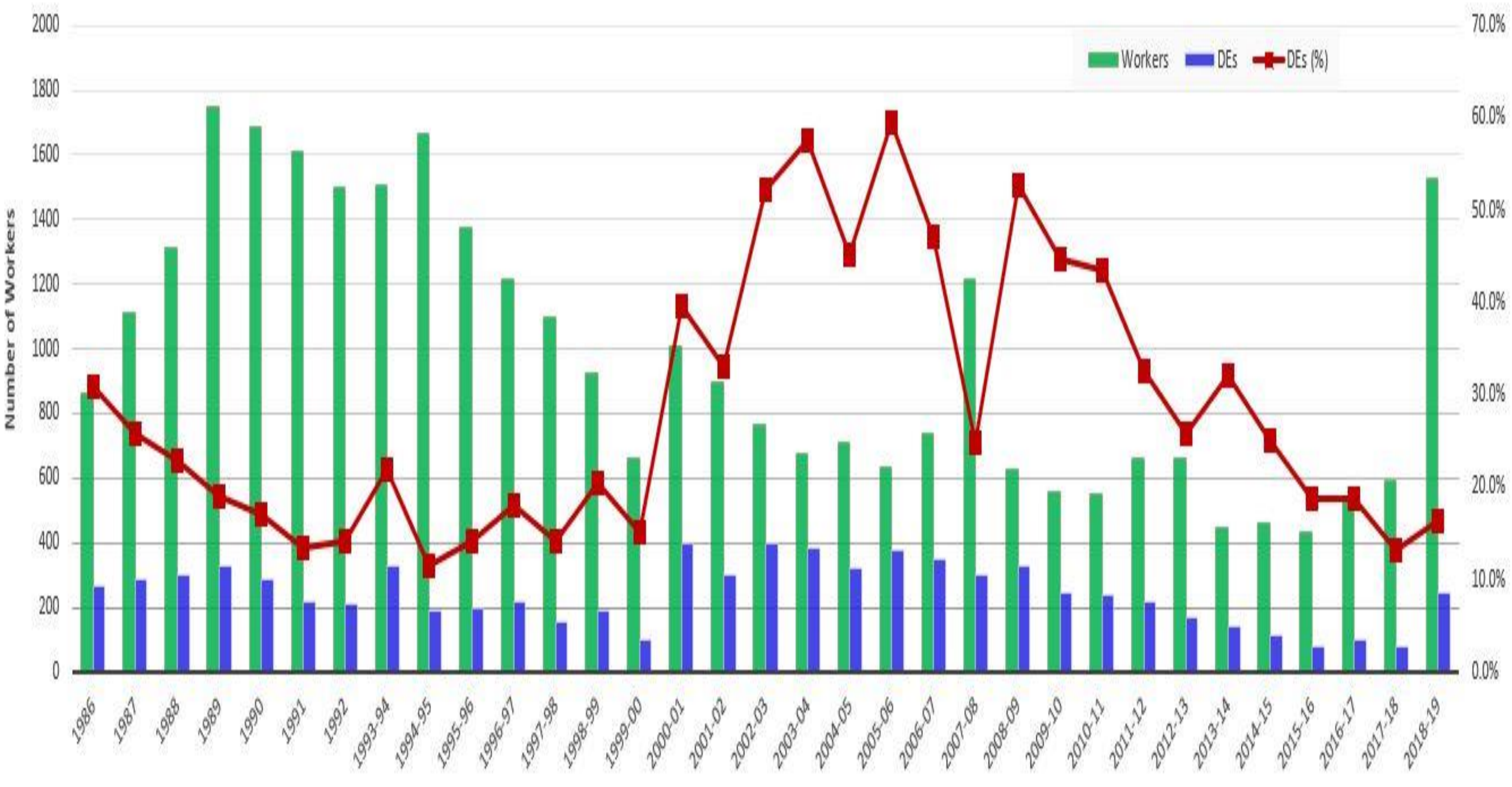

FIGURE 12. WORKFORCE AND DEs / MONITORED WORKERS, 1986-87 TO 2018-19

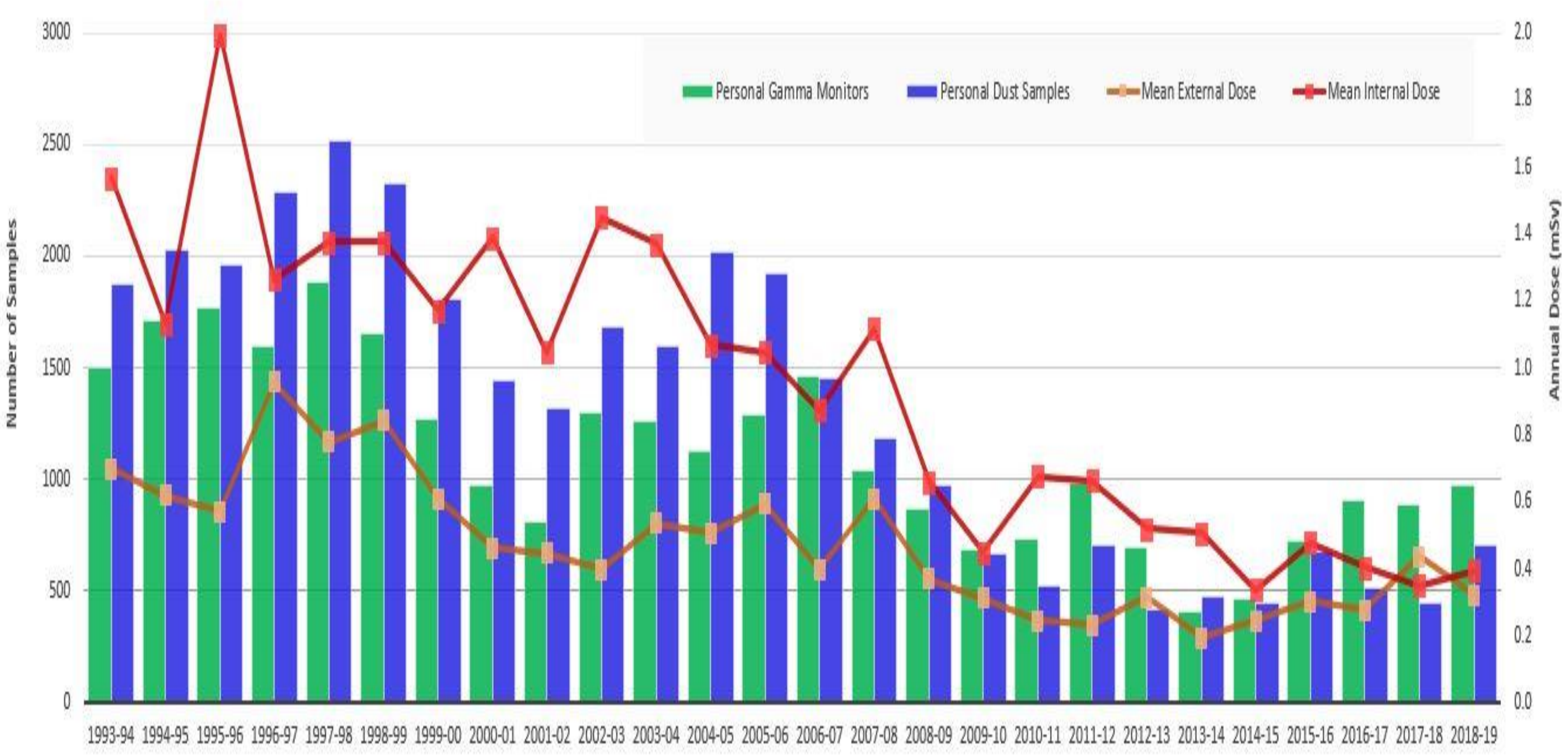

Figure 13. Monitoring profile and contribution to annual dose, 1993-94 to 2018-19

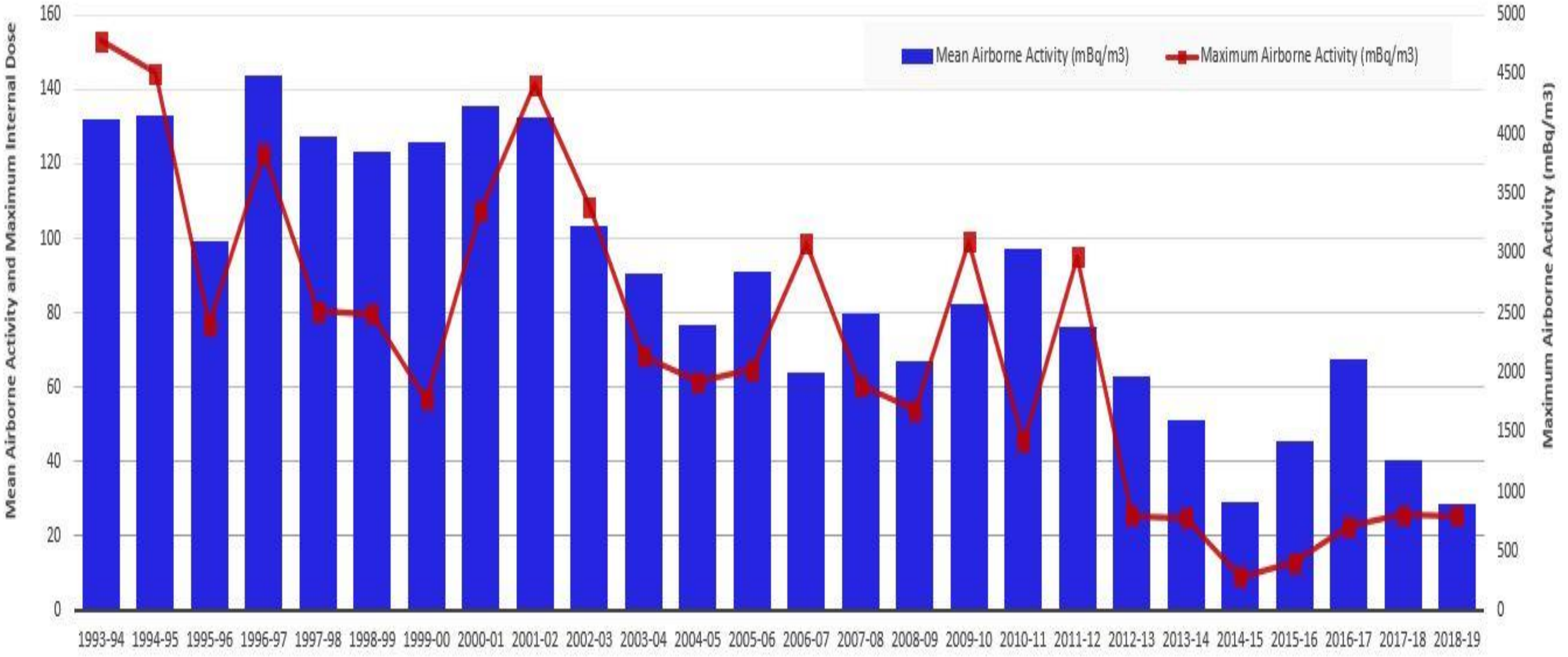

FIGURE 14. MAXIMUM AND MEAN AIRBORNE ACTIVITY

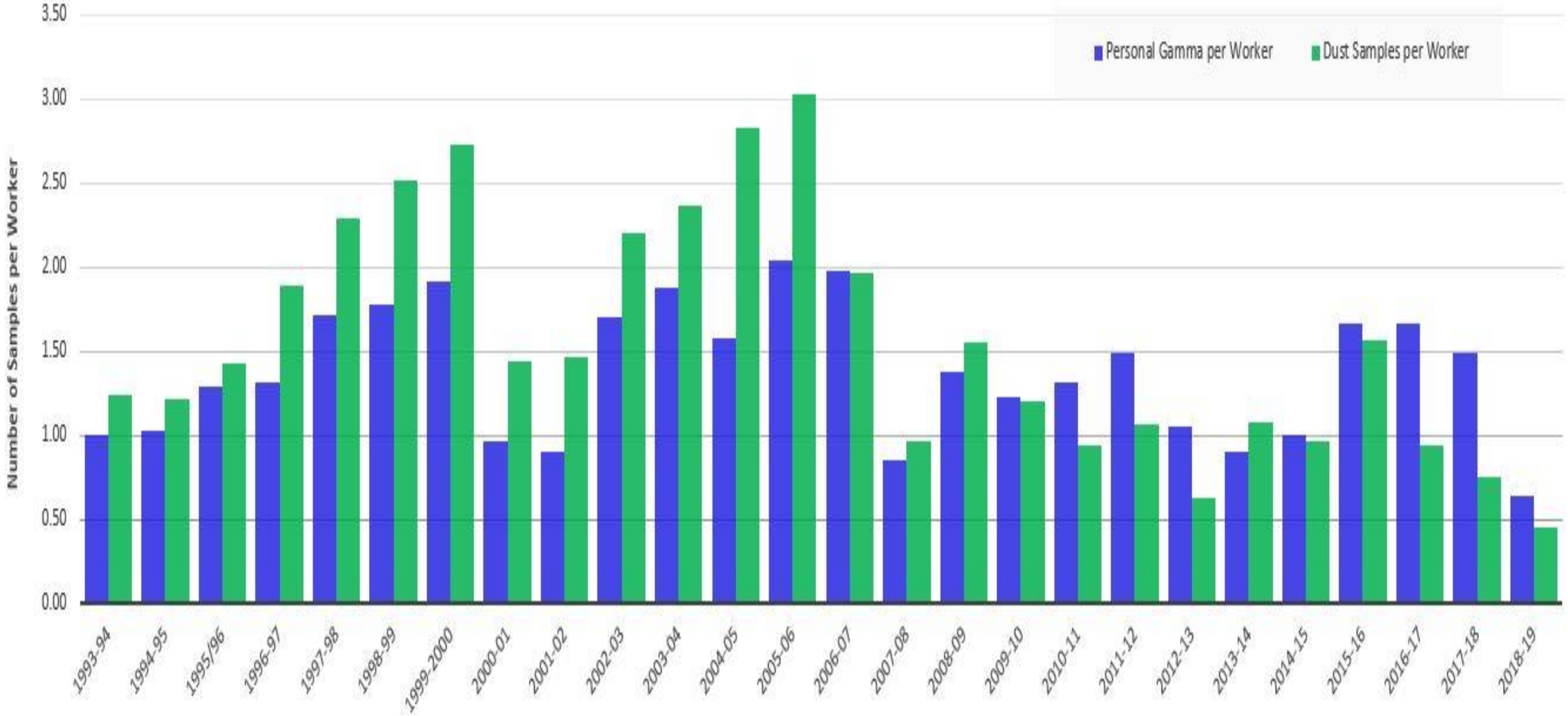

FIGURE 15: PERSONAL MONITORING: GAMMA V DUST SAMPLES

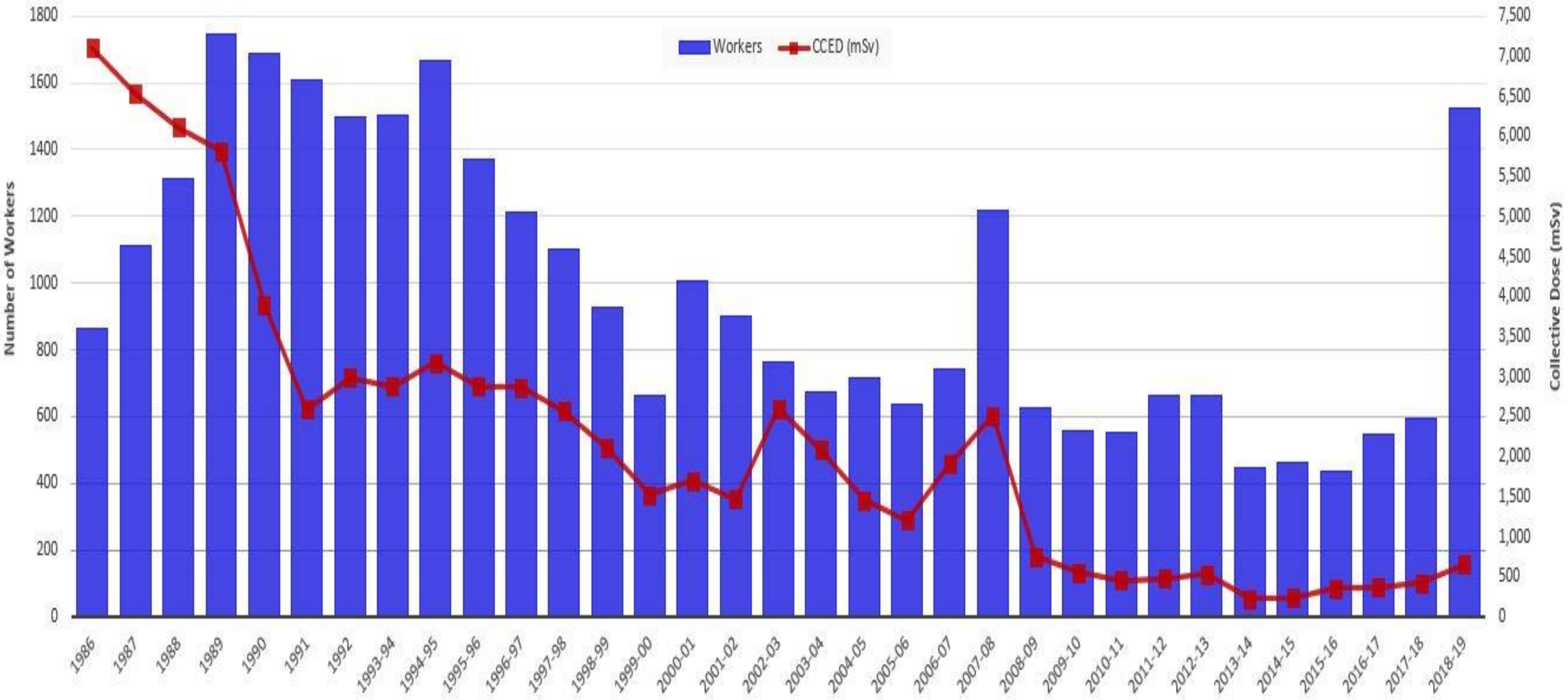

FIGURE 16. SIZE OF WORKFORCE AND COLLECTIVE DOSE (MSV)

5.11 DISCUSSION

This research has demonstrated that between the early reports cited by the Winn Committee of Enquiry; official govermment agency records; IAEA 68; and records held by REs, the exposures of Western Australian mining workers to radiation from NORMs can be effectively traced for the 42-years betweeen the commencement of systematic monitoring in 1977 and the time of implementation of the revised dose coefficients published in ICRP-137 and 141 (ICRP, 2017, 2019a).

Despite changes in the physical location of, and the Government agency within which, the Mines Inspectorate has resided, the historical record of exposures to radiation of the Western Australian mining workforce remain remarkably intact. As is demonstrated by the information presented in Table 8 to Table 21, other than the early years, in which the mining sector outside of the MSI was not required to report to the Mines Inspectorate, the Western Australian mining industry has largely complied with the requirement to provide an annual report of worker radiation exposures.

Although Table 22 indicated that the reporting frequency is 94.4%, the majority of reports classified as “missing” arise from RE#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’ (1996a) summary of the 1995 annual report data have not been able to be retrieved. The level of compliance with statutory expectations is a notable 99.1%, which is deserving of acknowledgement to the REs, and is testament to the record keeping by the Department.

5.11.1 Reporting entities

Over the course of the period from 1977 to 2018-19, 28 separate mining operations met the relevant criteria, and deemed as REs. As was outlined in Section 5.4, the commencement and subsequent closure of mining operations considered by the Mines Inspectrorate to be REs has added complexity to this analysis. By way of example, in the 2018-19 reporting period, eight of the 28 REs had ceased operating; three are in hiatus, awaiting improved market conditions before recommencing; and two have recently commenced and are yet to submit annual worker dose reports.

An additional complexity arises from those REs which had been provided a level of exemption from compliance with the legislation. 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:

- RE #9 is required to submit a report on a biennial basis;
- RE #11 is required to submit a report every five years;
- RE #13 is required to submit a report biennially or every five years, contingent upon the grade of the ore being processed; and
- RE #27 is required to submit a report biennially, but only on a limited cohort of workers in a nominated part of the operations.

In order to standardise the treatment of the data, where partial exemptions have been applied, an assumption has been made that the size of the workforce and the workplace exposure conditions (and therefore worker doses) remain consistent in the years for which a report was not required to be submitted.

- By way of example, reporting entity #9 submitted a report in 2017-18. The reporting obligation is on a biennial basis, and because the next report is due in 2019-20, the data in the 2017-18 report has been replicated for the 2018-19 reporting period in this research.

5.11.2 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 in workforce monitoring between 2007-08 to 2017-18, as illustrated in Figure 12, demonstrates that over the last decade, monitored workers declined from a peak of 53.1% of the workforce to 13.4%.

Tsurikov (personal communication, November 20th, 2020) suggests that the decline in personal monitoring may be attributable to the publication of RPS-9 (ARPANSA, 2005), which infers that non-designated employees do not have to be monitored. If this position is a ealistic explanation for the decline in montoring, it is based upon a false premise, as it mis-represents the wording, and the intent of RPS-9 (ARPANSA, 2005, p. 28) which states “Such designated employees are then monitored more intensively (including, where appropriate, personal monitoring), and their doses are assessed individually. Non-designated employees [workers] will then be monitored less intensively, and their doses assessed as an average of their relevant workgroup(s)”. Note that the requirement is that workgroups will be monitored, with the inference being that, as per the monitoring of other mining workplace contaminants, the number of samples collected is sufficient to be statistically representative of the entire workgroup. The Mines Inspectorate has issued guidance on the number and frequency of samples to be collected, for example (DMIRS, 2018, p. 18; GWA, 2010b, p. 5), however, the evidence of the declining sample frequency indicates that this guidance has been overlooked.

Further, the position articulated by some REs that sampling is not required for non-DWs 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 5mSv DW 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 maintenance of the *status quo*.

The data for 2018-19 indicates a reversal of the declining trend in workforce monitoring, however it must be highlighted that this data is upwardly biassed by the entrance of three new REs all of which conducted aggressive monitoring campaigns in order to support their case for exemption under the former legislation (viz, the MSIR).

The decline in monitoring of the workforce is supported by the data in Figure 13, 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 (Hewson & Upton, 1996):

- 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 that, given the findings of the research by Ralph, Tsurikov and Cattani Ralph et al. (2020c), and the advent of increased DCFs applicable to REs, the declining trend in workers participating in a monitoring programme across all DEs needs to be arrested.

5.11.3 Workforce monitoring of external γ

NORM Guideline 3.2 promotes, where possible the use of individual monitors for exposure to γ radiation, but also allows for assessments to be conducted based on 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 (GWA, 2010a, pp. 6-7).

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

Ralph et al. (2020c) advise “In 2018-19, REs 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 23, 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 dose from external γ was 17.7mSv, reported in 1983, whilst the mean dose was 1.4mSv.

As can be seen from Figure 13, 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 presented in Table 23, the dose from external γ radiation accounts for 19.8% of the collective dose to workers, and therefore does not warrant being the primary focus of monitoring programmes implemented by REs (despite the contribution nearly doubling to 38.8% in the period from 2006-07).

5.11.4 Workforce monitoring for internal dose

Although internal dose estimates are made in accordance with the NORM Guidelines, which are based upon procedures 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.

A protocol specific to Western Australian REs is that eight Similar Exposure Groups (SEGs) were defined for application across the MSI (Hewson, 1990b, p. 7), based upon location within a processing plant, job type and exposure characteristics. Workers are assigned to one (or more) of the SEGs, dependent upon their work activities, and their working periods in each SEG recorded for dose calculation purposes. In the absence of personal monitoring data, information for the SEG is used to calculate an indivdual workers’ dose estimate.

As counselled by Marshman and Hewson (1994, p. 61) “the estimates [of internal dose] are made using conservative assumptions, to limit the likelihood of understating dose. Accordingly, such estimates should be interpreted and used with caution”. Similar caution needs to 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.

5.11.4.1 *<u>Internal dose from LLα</u>*

The current version of the NORM Guidelines and those cited by Hewson (1990b, p. 6) 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 (GWA, 2010c).

Internal dose estimates from LLα are calculated 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 (1993).
- A default Activity Median Aerodynamic Diameter (AMAD) value of 5µm was used as the basis of the calculation for most of the submitted reports, although in the early 1990s the SME approved the use of a 10µm AMAD by two REs based upon the results of an extensive particle sizing campaign at their mining operations.

The results of the LLα analysis for the collected dust samples are 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 is 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 Equation 1:

- Intake (Bq) = $\text{Time}_{\text{SEG1}}$ x mean activity $\text{concentration}_{\text{SEG1}}$ + $\text{Time}_{\text{SEG2}}$ x mean activity $\text{concentration}_{\text{SEG2}}$ + $\text{Time}_{\text{SEG3}}$ x mean activity $\text{concentration}_{\text{SEG3}}$ …

EQUATION 1: INTAKE PROPORTIONED BY SEG

The resulting dose is calculated from Equation 2 :

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

EQUATION 2: CALCULATION OF DOSE (MSV)

The methodology for calculating DCF is outlined in Chapter Seven.

5.11.4.2 <u>Internal dose from RnP / Tnp</u>

An outcome of the report by Winn et al. (1984) was the measurement of RnP and TnP by Ralph and Hewson (1988), as summarised in Appendix 5. The estimated mean dose from the combination of exposure to TnP and RnP was 0.23mSv, and ranged from 0.04mSv to a maximum of 0.39mSv., noting that a potential maximum of 0.92mSv was reported. The research indicated that TnP and RnP were present in the MSI working environment, and could be meaningfully measured. Further, the Ralph and Hewson (1988) research indicated that the TnP and RnP exposure pathway should not be discounted from worker dose estimates.

The research by Ralph and Hewson (1988) involved samples that 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. Browne (2016) conducted research in a MSI dry separation plant using an electronic instrument, detecting very low levels of Rn, but reporting Tn concentrations that ranged from 153 to 1,003 Bqm^{-3}, with a mean of 396 Bqm^{-3}. Browne (2016, p. 25) concludes “Thoron gas measurements indicate elevated levels were present in the mineral sands plant … [the] thoron results … were significantly above the recommended action level of 300 Bqm^{-3}”.

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. However, as cautioned by Browne (2016, p. 34) “only if experienced hygienists or radiation safety personnel can provide a realistic and accurate assessment of SEG ocupancy will the positional monitoring program (i.e. time and motion approach) provide an accurate result”.

The findings from the Ralph and Hewson (1988) 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 REs attributing doses from this pathway over the succeeding years. The majority of TnP and RnP sampling conducted by REs has been by passive monitors, despite a caution from Browne (2016) “… the most effective and suitable method for estimating annual dose in a minerals sands plant is from positional monitoring using [an electronic] meter. The [passive device] was not robust enough for personal monitoring and turnaround time for results seriously reduces its ability to limit exosure …”.

The increase in DC for RnP / TnP that were announced by ARPANSA (2018a, 2018c) will require a greater focus from the industry on evaluating the doses arising from this source of exposure, and monitoring should not be performed by passive devices.

5.11.4.3 Estimation of internal dose

Internal doses are calculated by summing the dose from LLα with that from RnP / TnP.

Commencing in 1993-94, when maximum LLα concentrations were able to derived from the submitted reports, the maximum reported LLα concentration was 4,782 mBqm^{-3}, reported in 1993-94, and the mean was 170 mBqm^{-3}. The maximum dose from LLα was estimated as 153mSv, reported in 1987, whilst the mean dose (in the period from 1986 to 2018-19) is 9.4mSv. The mean dose is significantly influenced by the doses reported in the mid-to-late 1980s.

As can be interpeted from Figure 13, in 1997-98, after the introduction of the 20mSv dervived annual limit, and three years after monazite producton ceased, the mean internal dose from LLα was 1.5mSv, whereas it had declined to 0.4mSv in 2018-19. Some of the decrease can be explained by the reduction of the DCF, from 0.0097mSvBq^{-1} to 0.008mSvBq^{-1} introduced in 2009 (discussed in Section 5.4). However, if all things had remained equal, only approximately 18% of the mean dose reduction could be attributed to the decreased DCF.

In an endeavour to provide an explanation of the decline in internal dose, the maximum and mean airbone concentrations of LLα are shown in Figure 14. There is a general downward trend in both the maximum and mean LLα concentrations from 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 2008-09 to 2010-11 and 2014-15 to 2016-17.

Ralph et al. (2020c), hypothesised that “Typically the newer REs generate airborne dust concentrations much less than those that were encountered in the MSI in the 1990s” and 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 REs that were processing the lower activity concentration ores and minerals.

- This is, in all likelihood, the major contributing factor to the overall reduction of annual doses in the Western Australian mining sector”.

However, and significantly, there have been no material changes in the manner in which minerals are treated in the MSI that could provide a definitive explanation for the observed decrease in airborne activity in the five REs that were operating in the 1990s 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, Figure 14 illustrates:

- Three peak concentrations of ~3,000 mBqm^{-3} occurred in the 17-year period to 2018-19.
- An unexplained step-decrease occurred in 2012-13, resulting in the maximum LLα concentration reducing from 2,973 mBqm^{-3} in 2011-12, to 794 mBqm^{-3}; and
- 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, which may result in elevated doses. Similar to the commentary on mean LLα concentrations, a definitive explanation for the step-decrease in 2012-13 is not readily apparent from the interrogation of annual reports and is worthy of further investigation.

As illustrated in Figure 10, from 2019-20 the DAC for a 5µm, ^{232}Th dust in secular equilibrium is 500 mBqm^{-3}, and as shown in Figure 14, the maximum concentration of LLα appears to have returned to the norm for the post 2011-12 period, at approximately 800 mBqm^{-3}.

- This value is 60% higher than the revised DAC and indicates that doses considerably in excess of the 20mSv annual limit are possible if exposure controls are not effectively implemented and maintained

As was shown in Table 23, a total of 47,720 personal dust samples were collected since 1983 (when the number of samples were first reported) until 2018-19, an average of 1,325 per year, peaking at 2,575 samples in 1989. However, 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 all REs.

Another way of assessing the efficacy of the industry's LLα monitoring programme is the number of samples collected per worker per year, illustrated as Figure 15 [43]. 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 worth noting 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).

The trend of personal γ assessments vis-a-vis personal dust samples was discussed in Section 5.11.3 and is illustrated in Figure 15. It was noted that in the post 2009-10 period, the number of gamma assessments was significantly greater than those for LLα. Given the contribution of LLα to the worker collective dose, it is argued that this is indicative of a misallocation of monitoring resources that requires addressing across the industry.

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[43] Note that the number of personal gamma samples began being reported in 1993-94, whilst the number of personal dust samples can be traced to 1986. The comparison in Figure 13 commences at 1993-94.

Further, it is contended that the decrease in the number of personal dust samples per worker, as illustrated in Figure 15, 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 REs.

5.11.5 Designated workers (employees) and dose distribution

An estimated 34,240 worker-years were assessed in this research. This value is not a count of individuals, as many workers would have been employed for more than one year, but is indicative of the number of workers for which either personal or SEG dose assessments had 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 5.4, it has become apparent over the passage of time that a non-standardised approach has evolved in the application of the definiton of DW (DE). As reported in the notes prior to Table 14, the divergence required the researcher 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 8, 9. 10, 11, 12 and 13 is based upon DWs who worked greater than 500 hours per year, the informaton for Monitored Workers reported in Table 14 onwards applies a minimum 200 working hours per year criteria.

Applying the above criteria, 8,960 worker-years, equivalent to 26.2% of the total worker-years were categorised as either DWs 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 particicipated in a monitoring programme, as either a DW or a Monitored Worker.

As shown in Tables 22 and 23, the mean worker dose over the 42-year period from 1977 to 2018-19 was 11.0mSv, calculated by adding the mean contribution from external Y; LLα; and RnP / TnP.

The mean is biased by the excessively 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 unable to be accounted for). An alternate method for determining the mean of the entire working population in Section 5.11.6.

As was discussed in Section 5.3, from 2000-01 the suite of annual reports submitted by REs were able to be accessed, enabling a detailed analysis of the distribution of workers receiving doses less than 5.0mSv. Prior to 2000-01 doses less than 5.0mSv were considered as having little significance and were amalgamated into a single cohort by the REs and Mines Inspectorate. To accommodate as much of the available information as possible, the analysis in this research provides an amalgamated report of doses less than 5.0mSv in the period leading up to and including the 1999-2000 reporting period, and a more detailed analysis of the distribution of the less than 5.0mSv doses thereafter.

The workforce data for the period from 1977 to 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 5.0mSv data was conducted between 1986 and 1999-00.

The distribution of doses for the workforce (where data was available) is provided in Table 22, which shows that the doses of 31,983 workers were able to be stratified, with 10,811 (33.8%) workers assessed as receiving doses of less than 1.0mSv per year. A further 2,699 workers received doses between 1.01 and 5.0mSv per year. When combined with the 16,388 workers who were categorised as receiving less than 5.0mSv between 1986 and 1999-00, the total number of workers who received less than 5.0mSv was 29,898, or 93.5% of the distributed dose estimates.

A total of 2,085 workers (6.5%) received doses greater than 5.0mSv in the period from 1986 to 2018-19; of these, 745 (2.3%) received doses greater than 10mSv; and further, of these, 132 (0.4%) received doses greater than 50mSv.

The maximum reported dose was 163.4mSv, reported in 1987.

- In the 1990s the maximum reported dose was 32mSv in 1994-95,
- In the 2000s the maximum reported dose was 15.7mSv in 2002-03; and
- In the 2010s the maximum reported dose was 4.4mSv in 2010-11, 2011-12 and 2018-19.

The downward trend of maximum dose is noteworthy, and an important finding of this research.

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

5.11.6 Collective dose

The MSIR introduced the concept of collective effective dose which is defined as "the total radiation exposure of a group of people calculated by reference to the sum of their individual effective doses" (GWA, 1995, p. 330). Regulation 16.15 of the MSIR required "the manager of a mine must ensure … the collective effective dose (sic) of radiation to employees generally is reduced to levels that are … [ALARA]" (GWA, 1995, p. 339) [44].

A discussion on the arguments in favour of, and against the use of collective dose is beyond the scope of this research, but it is noted that while it is a methodology applied since the 1970s, concerns have been raised over its use for risk assessment purposes (ICRP, 2007). Nonetheless, an analysis of collective dose to 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 contributions from external γ, LLα and RnP / TnP to determine the mean worker dose, which is then multiplied by the workforce for each reporting entity to provide the RE collective dose. The sum of the collective doses from each RE provides the collective-dose-per-year, as given in Tables 8 to 21.

A slightly different methodology to estimate the collective dose was deployed in Table 23. In order to derive the contribution from each exposure pathway the collective-dose-per-year from the respective exposure pathways are added. It is acknowledged that this approach loses some of the detail apparent in the year-by-year analysis, but contend that it represents an efficient method to derive an exposure pathway contribution analysis.

As can be seen in Table 23, over the period covered by the research, worker doses are dominated by the contribution from LLα (80%);, whilst external γ contributes 19.7%; and the contribution from RnP / TnP is negligible. However, as shown in the comparison data drawn from 2006-07 (the time at which

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[44] Collective dose has been omitted from the WHSR(Mines), but remains in effect by virtue of its use in RPS-9.1 (ARPANSA, 2011a), the companion document to RPS-9 (ARPANSA, 2005).

RnP / TnP commenced), when doses have reduced significantly from those in the 1980s and 1990s, the contribution from LLα has decreased to 58.4% of total dose; external γ has increased to 38.7%; and the contribution from RnP / TnP has increased 10-fold to three percent, with a maximum contribution of 1.3mSv (which accounted for 30% of annual dose at the operation where the 1.3mSv was calculated).

Figure 16 compares the collective dose to the size of the workforce since 1986-87, and starkly illustrates the decline in collective dose since the Winn Committee of Enquiry (Winn et al., 1984). After declining in the late 1980s, the peak collective dose of 10,233mSv occurred in 1992, 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 1990s that contained elevated concentrations of monazite. The most recent reversal of the 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 REs was 108,850mSv (108.85 Sv).

Dividing the collective dose by the Sum of the Workforce by year (34,240) provides an estimate of the mean annual dose per worker, which as shown in Table 22 is 3.2mSv.

The decreasing trend in collective dose, as illustrated in Figure 16 is noteworthy, and can be inferred as the REs 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 Y over LLα; and the emerging importance of monitoring for Rnp / TnP serve as caveats to the positive trend identifed in the collective dose analysis.

5.12 CONCLUSIONS

Although arising from eclectic sources, the historical record of mine worker radiation doses from their exposure to NOR(M)s has been able to be compiled for the period from 1977 to 2018-19.

A total of 34,240 assessments of worker exposures have been analysed. 8,960 workers actively participated in personal radiation exposure monitoring programmes.

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

in the 42-year period, 93.5% of all workers received a dose of less than 5.0mSv per year. The most recent reported exceedance over 10mSv (10.3mSv) was reported in 2009-10, some 15 years after the cessation of monazite production, indicating the potential for elevated doses to occur despite the absence of monazite, the mineral with the highest content of NORs.

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

The trend in collective dose presents a positive picture of the management of worker exposures to NOR(M)s. However, as the Western Australian mining industry has become accustomed to lower worker dose, monitoring of potentially exposed workers has decreased, as indicated by the steep decline in the number of personal dust samples collected across the industry over the past two decades.

At the time of publication of Ralph, Tsurikov and Cattani (2021), the researcher cautioned that the advent of increased DCFs that were to apply in subsequent reporting periods, would require a renewed focus on representative personal dust sampling.

The basis for the cautionary statement is evaluated in Chapter Seven, and the findings of a subsequent investigation into the impacts of the revised DCFs are the subject addressed in chapter Eight.

5.13 ACKNOWLEDGEMENT OF ASSISTANCE

Thanks go to Ms. Hazel Upton and Mr. Duncan Surin from the Radiation Health Branch of Western Australia for assisting with access to historical files, and to the RSOs of the currently operating REs for their willingness to scour their organisational record-keeping systems to retrieve historical annual reports.

The contributions of Ms. Michelle Ralph for her assistance in collating and organizing the many files that were assessed as part of the research, and to Mr. Roley Fletcher for proof-reading early versions of the manuscript, are appreciated.

The research is indebted to the Records Officers of the Department, in particular Ms. Jaya Veluppillai, for their tireless assistance and diligence in identifying, locating, and retrieving files from numerous storage locations around Western Australia.

This Chapter successfully addresses the heretofore lacuna in the body of knowledge of radiation exposures to Western Australian mine workers up to the 2018-19 reporting period.

A Rubicon occurred for this research with the publication of ICRP-137 (ICRP, 2017) and subsequent endorsement of the revised dose coefficients for radon, thoron and their progeny by ARPANSA (2018a, 2018c). The Rubicon became entrenched when the ICRP published ICRP-141 (ICRP, 2019a) completing the revision of dose coefficients for all members of the ^{232}Th and ^{238}U decay series.

The next three Chapters in this research explore the impacts of the revised dose coefficients on contemporary, and future worker doses in Western Australian mines.

CHAPTER SIX: EVALUATING THE IMPACTS OF REVISED DOSE COEFFICIENTS FOR THE INHALATION OF RADON AND RADON PROGENY IN UNDERGROUND NON-URANIUM MINES

The radioactive gas radon (radon-222) is a ubiquitous source of exposure and a recognised source of lung cancer, second only to smoking.

Radon can be inhaled; … as it is inert, nearly all of the gas inhaled is subsequently exhaled. However, the inhaled short-lived radon progeny aerosol can deposit within the respiratory tract, Two of these short-lived progenies, polonium-214 and polonium-218 emit alpha particles and the energy deposited by these alpha particles … represent the major contributor to radiation exposure that may lead to health effects.

[Radon] is present in … underground locations, but levels can vary considerably from location to location depending on factors such as underlying geology … For many individuals, including some workers it is the main contributor to radiation exposure.

International Commission for Radiological Protection, Publication 126

Radiological protection against radon exposure

(ICRP, 2014, p. 5 and 15).

As was discussed in Section 3.4, the highest concentrations of Rn tend to occur in underground workplaces (IAEA, 2018a), and although the radiation environment in non-uranium (such as coal or metalliferous) mines is complex and variable, the main source of exposure is the inhalation of ^{222}Rn and its decay products (ICRP, 1986). Laurier (2019) and Laurier et al. (2020) found “strong evidence for an association between radon and lung cancer risk, even at low levels of exposure”, highlighting the risk of exposure to Rn and RnP to the more than 15,000 workers employed in Western Australia’s 57 underground mines.

A critical juncture for this research was reached when the ICRP published Part 3 of the OIR as ICRP-137 (ICRP, 2017) and ARPANSA subsequently endorsed the revised DCs for Rn and RnP [45] (ARPANSA, 2018c).

This Chapter provides an overview of the present underground mining operations in Western Australia and investigates the impacts of the revised DCs on the current workforce by re-evaluating research into worker exposures to Rn and RnP in the underground mines conducted in the 1990s.

6.1 RADIATION EXPOSURES TO UNDERGROUND MINERS IN WESTERN AUSTRALIA: INTRODUCTION

As was introduced in Section 4.1, following investigations by the ICRP on the risks of exposure to sources of radiation in underground non-uranium mines, and the recommendation that “Radiation protection in non-uranium mines should be given more consideration than it has in the past” (ICRP, 1986, p. 3), the Mines Inspectorate conducted research into the potential for radiation exposures in Western Australian underground mines.

The research involved an intensive survey of Rn concentrations and Y flux levels in 26 mines, and RnP and F determinations in nine of the 26 mines was subsequently published as Hewson and Ralph (1994). The Hewson and Ralph (1994) study provide the foundation of this Chapter of the research, and serves as the baseline against which contemporary data is evaluated.

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[45] The DCs for Tn and TnP also changed, but had not been considered in the Hewson and Ralph (1994) research. However, the ramifications were considered in the revision of the NORM-V Guideline (DMIRS, 2021b), and as a result are integral to subsequent dose assessments.

6.2 1994 V THE CONTEMPORARY WA MINING INDUSTRY: COMMODITIES AND DEMOGRAPHICS

As outlined in Section 1.2, the Western Australian mining industry has undergone significant growth in the quarter-of-a-century since the Hewson and Ralph research was published in 1994. Additional mineral commodities are being pursued, and as near-surface mineral deposits have been exploited, there has been an increase in the number of underground mining operations. Working hours, patterns and rosters have changed significantly in the intervening period, and regulations disallowing working underground for more than six consecutive days were removed when the MSIR was enacted in 1995.

Table 24 summarises some of the demographics as reported in 1994, and compares them to data from 2020 (the time of publication of Ralph et al. (2020b)).

TABLE 24: MINING DEMOGRAPHICS IN 1994 COMPARED TO 2020 DATA

Parameter	1994 Data (Hewson & Ralph, 1994)	2020 Data
Total mining workforce	33,529	102,932
No. of underground mines	48	57
Underground workforce	2,574	8,949 [1]
Gold mine workers	1,075	6,610 [2]
Nickel/Gold mine workers	697	830 [2]
Coal mines (workers)	3 (297)	0 (0) [3]
Lead/zinc mines workers	122	860 [2]
Diamond mine workers	0	297 [2]
Assumed annual working hours	2,000	2,000 [4]

[1] 2018 data from (GWA, 2019a) . Note that the total workforce cited is more than the workforce by commodity due to the time delay in sourcing the commodity data.

[2] E. Rakich, personal communication April 30th, 2018.

[3] The underground coal mining operations were closed in 1994 (Premier Coal, 2018).

[4] For consistency with Hewson and Ralph (1994), 2,000 hours exposure was used in this analysis.

As can be seen from the 2020 data presented in Table 24:

- Underground coal mining in Western Australia has ceased; and
- The underground mining workforce has increased by 350% since 1994, largely from a six-fold increase in gold mining.

6.3 METHODOLOGY

The underpinning principles for the measurement and control of worker doses from inhalation of Rn and RnP were discussed in Sections 4.1.1 and 4.1.2.

A number of variables are required to be determined in order to estimate the radiation dose delivered by exposure to Rn and RnP Most importantly, the concentrations of Rn and/or RnP is required and a determination of the condition of equilibrium between Rn and RnP, denoted F, is desirable (George, 2008, p. 3). Other than concentration values, which must be measured, in the absence of date for the other variables, default values to be used in the dose estimates are derived from the models published by international authoritative bodies such as the ICRP and IAEA.

This Section outlines the methodology used to measure the concentration values and determine the impacts of the revised DCs.

6.3.1 Methodology: Rn and external gamma measurements

Twenty six of the 48 underground mines that were operating in Western Australia agreed to participate and collected all of the data required by the Hewson and Ralph (1994) study [46].

To compile data on Rn concentrations, Hewson and Ralph (1994) positioned passive track-etch monitors (PRMs) for periods of up to six months in selected locations in the participating underground mining operations. Alpha particles emitted from Rn create tracks in the surface of the CR-39 film utilised in the PRMs, and once the sampling period, has expired, the PRMs are returned to the issuing laboratory, where the tracks are subsequently counted and the Rn concentration calculated (ARPANSA, 2022e; Bing, 1993).

The PRMs incorporated a calcium sulphate thermoluminescent dosimetry (TLD) disc. When TLDs are exposed to gamma rays, free electrons in the TLD crystals become trapped in lattice imperfections. At

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[46] One underground mine agreed to participate but failed to submit the required information.

the conclusion of the monitoring period the disc is returned to the issuing laboratory where it is heated, releasing light. The amount of light detected is related to the radiation received, enabling an assessment of gamma ray exposure.

At the end of the sampling period, the PRMs were analysed for Rn concentration and γ dose-rate by the Australian Radiation Laboratories, using a standard procedure.

6.3.2 Methodology: RnP measurements

Measurements of RnP concentrations were undertaken by Hewson and Ralph (1994) in nine of the participating mines, adjacent to the PRMs. Measurements were made via a combination of Alpha Nuclear Alpha Prism II instantaneous working level monitors (electronic samplers, manufactured by the Alpha Nuclear Company, Mississauga, Ontario), and manual grab samples based upon the Kusnetz (1956) method. The RnP measurements were made at each of the nine participating mines in intensive, once-off sampling campaigns of one to four days in duration.

The RnP measurements were used in Hewson and Ralph (1994) to determine an equilibrium factor (F) for the area of the mine in which sampling was conducted, by comparing the RnP exposure (Jhm^{-3}) against the measured long-term Rn exposure (Bqhm^{-3}).

6.3.3 Methodology: Impact of revised DCs

This research entailed a revision of the assumptions and inputs used by Hewson and Ralph (1994) and recalculating the published dose estimates to reflect contemporary dose calculation methodologies.

ICRP-137 (ICRP, 2017) is accompanied by a digital annex called the OIR Data Viewer, which includes a series of tables applicable to the calculation of doses from exposure to Rn and RnP. The OIR Data Viewer was downloaded from the ICRP website (ICRP, 2019c), and the data for Rn and RnP in mines was selected, and applied to the data in Hewson and Ralph (1994).

Note that the OIR Data Viewer contains a DC of 3.14mSv per Jhm^{-3} (ICRP, 2019c) to calculate doses in underground mines from RnP, and this value was used in this analysis.

6.3.4 Methodology: Impacts of equilibrium factor

Hewson and Ralph (1994) measured F in nine of the underground mines and applied a mean F value of 0.5 in their dose calculations. This research evaluated the impact of the actual F values, and compared them against the value of 0.4 used by Hewson and Ralph (1994).

The equilibrium factors were revised by applying Equation 3 DMIRS (2021b, p. 16)

$$F = \frac{P_{RnP}}{t \times C_{Rn} \times 5.56 \times 10^{-6}}$$

EQUATION 3: CALCULATION OF EQUILIBRIUM FACTOR (F) FOR RN AND RNP

Where:

- F is the equilibrium factor between Rn and RnP.
- P_{RnP}, is the potential alpha energy concentrations of radon decay products (mJhm^{-3}).
- *5.56 x 10^{-6}* is the combined potential alpha energy concentration for the RnP series from ^{218}Po to ^{214}Po (mJBq^{-1}).
- *t is the exposure time (hours).*
- *C_{Rn} is the radon gas concentration (Bqm^{-3}).*

This analysis acknowledges, but does not re-assess, the detailed error analysis of the sampling and analytical methodologies included in Hewson and Ralph (1994).

6.4 COMPARISON OF RADIOLOGICAL CHARACTERISTICS

At the time of publishing their work, Hewson and Ralph (1994) applied the protocols established in ICRP-47 “Radiation Protection of Workers in Mines” (ICRP, 1986). In 1990 the ICRP revised its radiation risk assessment methodology in Publication 60 (ICRP, 1990), the effects of which included reduction of the annual dose limit from 50mSv to 20mSv, and altering the DCs for the members of the ^{238}U decay series (Hartley, 1992).

- However, the impacts of the changes introduced in ICRP-60 were not implemented until 1994 when ICRP published ICRP-65 (Protection against Rn) (ICRP, 1994a) and ICRP-66 (Respiratory

Tract Model) (ICRP, 1994b) [47]. The implementation date was post the Hewson and Ralph (1994) study.

Table 25 summarises the changes in the dose calculation protocols in the intervening period.

As can be seen in Table 25, the annual derived dose limit has decreased to 40% of the level that applied in 1994; and the F assumed in the 1994 research was 0.5, whereas in ICRP-137 a default value of 0.2 is applied in the absence of other data (ICRP, 2017).

TABLE 25: RADIOLOGICAL PARAMETERS CITED IN HEWSON AND RALPH (1994) AND 2020 EQUIVALENTS

Parameter	Hewson and Ralph (1994)	2020 Equivalent
Annual ED limit (mSv)	50	20
Breathing Rate ($m^{-3}h^{-1}$)	1.2	1.2 [1]
γ Quality Factor	1	1
Equilibrium Factor (F)	0.5	0.2 [1]
Rn Effective Dose per exposure for mines (Sv per $Bqhm^{-3}$)	1.7×10^{-8} [2]	1.8×10^{-10} [3]
RnP Effective Dose per exposure for mines (mSv per Jhm-3)	Not cited	3.14 [4]
RnP Effective Dose Coefficient (mSv Bq-1)	1.4×10^{-5} [5]	1.4×10^{-5} [6]

[1] From Table 12.7 of ICRP-137 (ICRP, 2017)

[2] From Table 2 of ICRP-47 ICRP (1986), where it is cited as "Time-integrated equilibrium equivalent"

[3] From Table 12.5 of ICRP-137 (ICRP, 2017)

[4] From ICRP-137 (ICRP, 2017)

[5] EEC, F = 0.5

[6] Derived by summation of the three RnP DCs from Table 12.6 of (ICRP, 2017), for mines.

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[47] In a footnote added in proofing of Hewson and Ralph (1994) it was noted that the DCs for Rn and RnP were halved in 1994 by the ICRP in publication 65 (ICRP, 1994a).

6.5 SUMMARY OF DATA REPORTED IN HEWSON AND RALPH (1994)

Table 26 summarises the results that were reported in Tables 1 and 2 of Hewson and Ralph (1994, pp. 362, 364).

Twenty-six mines fully contributed to the study. RnP sampling was conducted in nine mines, which are marked with an asterisk (*) in Table 26. The contribution of LLα to the dose estimate was considered negligible and is not included in the results. The original data included annual γ doses for continuous (8,760 hours per year) exposure, and this data has been corrected to 2,000 hours in Table 26 to account for occupational exposures.

TABLE 26: SUMMARY OF DATA AS REPORTED IN HEWSON AND RALPH (1994)

Mine [1,2]	Commodity [1]	Mean Rn Concentration (Bqm^{-3}) [2]	Rn Dose (mSv) [3]	2000-hour γ Dose (mSv) [4]	Total Dose (mSv) [3]
1*	Gold	40	0.67	0.25	0.92
2*	Gold	43	0.72	0.16	0.88
3*	Gold	172	2.89	0.21	3.10
4	Gold	49	0.82	0.30	1.12
5	Gold	108	1.81	0.14	1.95
6	Gold	147	2.47	0.27	2.74
7	Gold	33	0.55	0.43	0.98
8	Gold	43	0.72	0.55	1.27
9	Gold	115	1.93	0.43	2.36
10	Gold	24	0.40	0.41	0.81
11	Gold	29	0.49	0.30	0.79
12	Gold	31	0.52	0.68	1.20
13*	Nickel / Gold	22	0.37	0.21	0.58
14*	Nickel / Gold	65	1.09	0.34	1.43

Mine [1,2]	Commodity [1]	Mean Rn Concentration (Bqm^{-3}) [2]	Rn Dose (mSv) [3]	2000-hour γ Dose (mSv) [4]	Total Dose (mSv) [3]
15*	Nickel / Gold	27	0.45	0.46	0.91
16	Nickel / Gold	25	0.42	0.14	0.56
17	Nickel / Gold	16	0.27	0.32	0.59
18	Nickel / Gold	18	0.30	0.21	0.51
19*	Nickel / Gold	44	0.74	0.21	0.95
20	Nickel / Gold	55	0.92	0.25	1.17
21*	Coal	220	3.68	0.52	4.20
22	Coal	136	2.28	0.46	2.74
23	Coal	68	1.14	0.55	1.69
24*	Lead / Zinc	35	0.59	0.25	0.84
25	Nickel / Gold	34	0.57	0.16	0.73
26	Zinc	142	2.39	0.98	3.37
Mean		**67**	**1.12**	**0.35**	**1.48**

Notes to Table 26:

[1] Extracted from Table 1 of Hewson and Ralph (1994)

[2] Extracted from Table 2 of Hewson and Ralph (1994)

[3] Calculated, based upon F = 0.5; Breathing rate = 1.2 m^{3}h^{-1}; 2,000 hour exposure, as per Hewson and Ralph (1994)

[4] The data in Table 1 from Hewson and Ralph (1994) had been corrected for continuous (ie 24 hours per day exposure). The values reported reflect occupational exposure by multiplying the reported dose by 0.228 (i.e., 2,000/8,760).

As can be seen from Table 26, Rn concentrations in the underground mines ranged from 16 to 220 Bqm^{-3} with a mean of 67 Bqm^{-3}. An F of 0.5 and a DC of 1.4 x 10^{-5}mSv Bq^{-1} were used to calculate the contribution to dose from Rn in the Hewson and Ralph (1994) study.

Annual dose estimates ranged from 0.51mSv in a nickel/gold mine to 4.20mSv in a coal mine. The mean dose across the 26 mining operations was found to be 1.48mSv. The maximum dose was equivalent to 8.4% of the 50mSv derived annual dose limit applicable at the time.

The maximum dose across the 23 non-coal mines was 3.37mSv in a zinc mine, equivalent to 6.7% of the 50mSv derived annual dose limit applicable at the time. The mean dose in non-coal mines was 1.29mSv.

Across all 26 participating mining operations, Rn and RnP accounted for approximately three-quarters of the reported dose, and a similar result was found in the subset of 23 non-coal mining operations.

6.6 IMPACT OF EQUILIBRIUM FACTOR ON DATA REPORTED IN HEWSON AND RALPH (1994)

As was highlighted in Section 6.3.2, RnP measurements were conducted by Hewson and Ralph (1994) in nine of the participating underground mining operations. The RnP measurements were used to determine an F for the area of the mine in which sampling was conducted.

The calculated F, and the impact of applying each mines equilibrium factor on dose estimates, is summarised in Table 27.

Fs ranged from 0.10 to 0.91, with a mean across the nine mines of 0.44. Two mines had Fs less than 0.2, which were questioned by Hewson and Ralph (1994) due to the possibility that the RnP sampling was non-representative. Excluding the two mines, the mean F is 0.52, which, as is reported in Section 8.2.2, provided the support to use F=0.5 in the calculation of doses reported in Table 26.

As can be seen from Table 27, the overall impact from application of measured Fs across the nine participating underground operations is to increase the mean dose by 3.5% from 1.53mSv to 1.59mSv. Doses for seven of the mines decreased, whilst they increased for two mines.

The significant impact that F can have on dose estimates is emphasised by the increase of 3.02mSv (72%) that results from applying the measured F of 0.91 (indicating near-equilibrium conditions) for mine #21.

TABLE 27: DOSE USING MEASURED EQUILIBRIUM FACTOR (F) REPORTED IN HEWSON AND RALPH (1994)

Mine	A γ Dose (mSv) [1]	Mean Rn (Bqm^{-3})	Mean RnP EEC (Bqm^{-3})	Measured F [2]	B ED from Rn (mSv)	ED (mSv) [3]	ED Change (mSv) [4]
1	0.25	40	4	0.10	0.11	0.36	-0.56
2	0.16	43	24	0.55	0.81	0.97	-0.09
3	0.21	172	44	0.26	1.50	1.71	-1.39
13	0.21	22	20	0.91	0.67	0.88	0.30
14	0.34	65	27	0.42	0.92	1.26	-0.17
15	0.46	27	5	0.17	0.17	0.63	-0.28
19	0.21	44	12	0.27	0.40	0.61	-0.34
21	0.52	220	200	0.91	6.70	7.22	3.02
24	0.25	35	12	0.34	0.40	0.65	-0.19
Mean	**0.29**	**74**	**39**	**0.44**	**1.30**	**1.59**	**0.05**

[1] Corrected for continuous (i.e., 24 hours per day exposure). The values reported reflect occupational exposure by multiplying the reported dose by 0.228 (i.e., 2,000/8,760).

[2] Cited from Table 4 of Hewson and Ralph (1994), which included rounded data.

[3] The sum of Columns A and B.

[4] The difference between Column 7 and Column 6 of Table 27.

6.7 2020 DEMOGRAPHIC AND RADIOLOGICAL DATA COMPARED TO HEWSON AND RALPH (1994)

Hewson and Ralph (1994, pp. 362, 364) applied an intake model based on ICRP-47 (ICRP, 1986) and used a DC of 1.4×10^{-5}mSv Bq^{-1} to calculate annual dose estimates.

Conversely, Table 12.7 of ICRP-137 (ICRP, 2017, p. 315) suggests default parameters for calculating effective doses from inhalation of radon, and in the data for mines [48] applies a default F=0.2 and recommends a DC of 3.3mSv per Jhm^{-3}. [49]

The ICRP caution that the default value of F=0.2 should only be used in the absence of data derived for a specific mining operation (ICRP, 2017). Given that Hewson and Ralph (1994) measured a mean F=0.52 in seven mines, this value has been applied across all of the 26 participating mining operations to derive the data presented in Table 28. The following adjustments to the 1994 data (Hewson & Ralph, 1994) in Table 28:

i. Coal mining has been removed.

ii. The impact of F=0.52 and a DC=3.14mSv per Jhm^{-3} is assessed and the resultant dose are compared to the 1994 findings.

TABLE 28: IMPACT OF APPLYING 2020 PARAMETERS TO EDS REPORTED BY HEWSON AND RALPH (1994)

Mine	1994 Data (Hewson & Ralph, 1994)			2020 Analysis		Increase (mSv) [6]
	2000-hour γ Dose (mSv) [1]	Mean Rn (Bqm^{-3}) [2]	Dose (mSv) [3]	Dose from Rn (mSv) [4]	Total Dose (mSv) [5]	
1*	0.25	40	0.92	0.73	0.98	0.06
2*	0.16	43	0.88	0.78	0.94	0.06
3*	0.21	172	3.10	3.12	3.33	0.23
4	0.30	49	1.12	0.89	1.19	0.07
5	0.14	108	1.95	1.96	2.10	0.15
6	0.27	147	2.74	2.67	2.94	0.20

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[48] Table 12.7 includes a default unattached fraction of RnP of 0.01, which also contributes to the derivation of the DC.

[49] Note that this research used the OIR Data Viewer DC of 3.14mSv per Jhm^{-3} (ICRP, 2019c) to re-evaluate dose estimates.

Mine	1994 Data (Hewson & Ralph, 1994)			2020 Analysis		Increase (mSv) [6]
	2000-hour γ Dose (mSv) [1]	Mean Rn (Bqm^{-3}) [2]	Dose (mSv) [3]	Dose from Rn (mSv) [4]	Total Dose (mSv) [5]	
7	0.43	33	0.98	0.60	1.03	0.05
8	0.55	43	1.27	0.78	1.33	0.06
9	0.43	115	2.36	2.09	2.52	0.16
10	0.41	24	0.81	0.44	0.85	0.04
11	0.30	29	0.79	0.53	0.82	0.04
12	0.68	31	1.20	0.56	1.25	0.04
13*	0.21	22	0.58	0.40	0.60	0.03
14*	0.34	65	1.43	1.18	1.52	0.09
15*	0.46	27	0.91	0.49	0.95	0.04
16	0.14	25	0.56	0.45	0.59	0.03
17	0.32	16	0.59	0.29	0.61	0.02
18	0.21	18	0.51	0.33	0.53	0.03
19*	0.21	44	0.95	0.80	1.00	0.06
20	0.25	55	1.17	1.00	1.25	0.08
25	0.16	34	0.73	0.62	0.78	0.05
24*	0.25	35	0.84	0.63	0.89	0.04
26	0.98	142	3.37	2.58	3.56	0.19
Mean	**0.32**	**57.3**	**1.26**	**1.01**	**1.33**	**0.08** [7]

Notes to Table 28:

[1] Corrected for occupational exposure. Refer to Table 27.

[2] From column 3 of Table 27.

[3] From Column 6 of Table 27 (based upon F = 0.5)

[4] F = 0.52

Notes to Table 28 (continued):

[5] Sum of 2000 hour γ dose (Column 2) and dose from Rn (Column 5)

[6] Where the increase is the difference between Column 6 and Column 4

[7] Rounded value.

6.8 COLLECTIVE DOSE

Hewson and Ralph (1994) reported on the collective dose to the underground mine workforce, by commodity mined. A comparison of collective doses as reported in the 1994 research and equivalent 2020 data is presented in Table 29.

- Note that due to a time delay in collecting the population statistics, the total underground workforce by commodity is lower in Table 29 (8,597 workers) than reported in Table 24 (8,949 workers).

TABLE 29: COLLECTIVE DOSES - HEWSON AND RALPH (1994) AND 2020 ANALYSIS

Commodity	Hewson and Ralph (1994) (F=0.5)			2020 Data (F=0.52)		
	Workforce Population	Mean Dose (mSv)	Collective dose (man.mSv)	Workforce Population	Mean Dose (mSv)	Collective dose (man.mSv)
Gold	1,075	1.3	1,400	6,610	1.61	10,642
Nickel / Gold	697	0.8	560	830	0.87	722
Coal	297	2.9	860	-	-	-
Lead / Zinc	122	0.7 [1]	85	860	2.22	1,909
Diamonds	-	-	-	297	1.33 [2]	396
Total	2,173		**2,905** [3]	8,597 [4]		**13,669**

[1] This value appears to be an error in the 1994 publication. Refer to discussion for further details.

[2] Assuming the mean dose across the other commodity sectors (from Table 29).

[3] An error has been identified in this data. Refer to discussion.

[4] The underground workforce exceeds that cited (as per Table 25) and therefore the collective dose will be higher than reported here.

6.9 DISCUSSION

As can be seen from Tables 24 and 25, significant changes have occurred since Hewson and Ralph published their research in 1994:

- The underground workforce has increased and in 2020 was three and half times that reported in 1994.
- Underground coal mining, the major source of radiation exposure to mine workers has ceased; and
- The annual derived dose limit decreased by 60% of the 1994 level, from 50mSv to 20mSv.

As reported in Table 26, none of the dose estimates to underground workers arising from the 1994 research exceeded 5mSv (i.e. 10% of the 50mSv annual limit that applied at the time), leading the authors to conclude “no regulatory controls are specifically required to limit exposure in WA underground mines” (Hewson & Ralph, 1994, p. 359).

After removing the contribution from the underground coal sector, which closed in 1994, the mean dose estimate increased from 1.26mSv in the 1994 research to 1.33mSv in this review. The increase of 0.08mSv (allowing for rounding) represents a mean increase of 5.4% from the 1994 data.

6.9.1 Discussion: Impacts of equilibrium factor

Table 27 summarises the Hewson and Ralph (1994) measurement of equilibrium factors (F) in nine underground mines and reported Fs that varied between from 0.1 (approaching no equilibrium) to 0.91 (approaching full equilibrium), with a mean of 0.44. Two of the nine mines had Fs less than 0.2, and the authors questioned these findings due to the possibility that the RnP sampling was non-representative. When the two mines are excluded, the mean F is found to be 0.52, and this value was used as the basis for this analysis.

Hewson and Ralph’s (1994) findings were based on the dosimetric methodology in ICRP-47 (ICRP, 1986). ICRP-65 (ICRP, 1994a) adopted an epidemiological approach, effectively halving the DCs in ICRP-47. An in-proof footnote appended to Hewson and Ralph (1994, p. 369) acknowledged the changes and recommended that the doses reported in the paper be halved as a result.

ICRP-137 reverted to the dosimetric approach and doubled the DCs from ICRP-65 which had been in use for nearly a quarter of a century. As can be seen from Table 28, applying the mean F=0.52 and the recommended DC of 3.14mSv per Jhm^{-3} in the OIR Data Viewer provides results similar to those reported by Hewson and Ralph (1994).

However, it is highlighted that the discrepancy of approximately five percent between the DCs listed in Table 12.7 of ICRP-137 (3.3mSv per Jhm^{-3}) and the OIR Data Viewer (3.14mSv per Jhm^{-3}) may lead to confusion and should be addressed. The OIR Data Viewer DC was used as the basis for this analysis.

6.9.2 Discussion: Impacts of mine ventilation on equilibrium factor

Use of the F=0.52 is an important assumption in this review because it does not follow the default value of F=0.2 as recommended in ICRP-137 (ICRP, 2017). The ICRP advises that the default F=0.2 and associated parameters are "given for a diesel powered mine with medium to good ventilation. [The F=0.2] is mainly based on the measurements carried out in mines in Australia [by] Solomon 1993,1994 … " (ICRP, 2017, p. 464).

Three-quarters of the underground mines that participated in the preliminary study by Hewson et al. (1991) indicated they used "series" ventilation circuits. Brake (2012, p. 175) describes a series ventilation circuit as "one in which the air is first used in one workplace, then directed to another workplace, and then potentially reused in many other workplaces", and reflects that "series ventilation circuits have become very popular in many, if not the majority, of hard-rock mining operations in Australia over the past 15 years".

According to the Mines Inspectorate "substandard ventilation occurs when the air quantity and quality in work areas are below that to adequately disperse and dilute contaminants in the work environment" and "it is calculated that air quantities six to eight times greater than those currently found in most mines are required … air drawn from haulage and travelways is already contaminated and therefore … only parallel ventilation circuits should be employed" (GWA, 2013b, p. 21).

The research by Solomon cited in ICRP-137 was conducted in an underground uranium mine, the ventilation system of which was designed to control the concentrations of Rn (Kinhill-Stearns Roger Joint Venture, 1982). Therefore, the application of an F=0.2 to underground mines with poorly designed ventilations systems, as frequently encountered in Western Australian mines, is problematic, and in all likelihood, unfounded.

Studies cited by Sahu et al. (2014) demonstrate Rn laden air that remains for a longer period in a mine develops higher RnP concentration, and higher Fs. As series ventilation circuits re-use the air in an underground mine, the air's residence time increases, thereby increasing the likelihood of a build of Rn and RnP leading to elevated F values.

6.9.3 Discussion: Technological change and the impact on dose from RnP

Legislative changes made in Australia in the mid-2000s introduced ultra-low sulphur diesel (ULSD) fuels into the underground mining environment, decreasing sulphur content from above 500 ppm to below 15 ppm (Landwehr, Larcombe, Reid, & Mullins, 2019).

Use of the ULSD fuels and technological improvements have reduced the mass of particulate matter and average particle size in the atmosphere in underground mines (Landwehr et al., 2019). As a result, the typical underground mine atmospheric conditions have changed significantly since the time of the Hewson and Ralph (1994) research. As a result, assumptions made in relation to the unattached fraction of radon progeny, which is an important variable in the selection of the DC are, in all likelihood no longer valid.

ICRP-137 acknowledges these changes when stating "it is acknowledged that the exposure conditions in mines today are significantly different from those 10 to 20 years ago and that the chosen aerosol parameter values are not necessarily representative of mines today" (ICRP, 2017, p. 217).

As a cautionary note to this research, ICRP-137 applies a DC of 6.61mSv per Jhm^{-3} for tourist caves, based upon a perception that caves are typically lacking large volumes of suspended airborne particles, and therefore the unattached fraction of RnP is larger in cave atmospheres than in mines. The DC for tourist caves is greater than double that applied to mines. In the event that the introduction of ULSD and technological advances have changed the parameters in a modern underground mine to those that are similar to a tourist cave, it is possible that the dose estimates in this review could increase by a factor of 2.1 times, due to the application of the tourist cave DC rather than the DC that is currently applied to underground mines.

The researcher contends that the data upon which the DCs included in ICRP-137 are based are not representative of contemporary underground mining environments in Western Australia, and further research of parameters such as particle size and the unattached fraction of RnP is warranted.

6.9.4 Discussion: Collective doses

Hewson and Ralph (1994) included estimates of collective dose to the mining industry workforce, and a comparison of their analysis with the 2020 data was provided in Table 29. It appears as though an oversight occurred in the 1994 publication, in that collective dose for the zinc-lead/zinc sector is understated. There is no maximum dose value cited in Table 4 of Hewson and Ralph (1994, p. 366), indicating only one mine was included in the analysis, despite two mines being involved in the research.

A review of the data presented in Table 1 of Hewson and Ralph (1994, p. 364) indicates that mine #26 recorded a contribution from γ of 4.3mSv, the highest level recorded in the survey. The contribution to collective dose from mine #26 appears to have been omitted, and the mean ED should be 2.1mSv rather than the 0.7mSv given in Table 6 of Hewson and Ralph (1994). The collective dose to the lead-lead/zinc sector would increase by 155 man.mSv (to 240 man.mSv) and the industry collective dose in Table 6 Hewson and Ralph (1994) should increase to 3,060 man.mSv as a result.

Notwithstanding the cautions on the use of collective dose were provided in Section 5.11, however it is noteworthy that the collective dose to the underground workforce has increased by 4.5 times from 3,060 man.mSv (2,173 workers) to 13,669 man.mSv (8,597 workers). The former regulation 16.5 of the MSIR required collective effective doses to be reduced to levels that are as low as is practicable (GWA, 1995, p. 339), and it is contended that, based on this analysis, the underground sector of the Western Australian mining industry has not complied with the former legislative requirement.

6.9.5 Discussion: Issues encountered in the re-evaluation process

The research published by Hewson and Ralph (1994) included several assumptions which have been difficult to explore further in this review, and which may influence the revised dose estimates:

- Sixty-nine PRMs were assessed in the research, allowing doses from Rn and γ to be calculated for each monitor. However, only mean γ doses were reported for each mine, which obviated the opportunity to assess the doses as reported by individual monitors.
- The contribution to annual dose arising from the inhalation of LLα was unable to be effectively evaluated, and as a result, the contribution from the inhalation of LLα was deemed as being negligible in the Hewson and Ralph (1994) study. However, as is outlined in Chapter Seven the DCs for the longer-lived members of the ^{238}U decay chain have been revised, and the DCF has

increased. As a result, the contribution of LLα to annual doses to underground worker warrants further investigation.

6.9.6 Discussion: Key findings of this research

The key findings from this analysis are:

a) Doses in the 23 non-coal, non-uranium mines that participated in the 1994 research range from 0.53mSv in an underground nickel/gold mine to 3.56mSv in an underground zinc mine. The maximum dose represents 17.8% the annual derived dose limit of 20mSv.

b) The mean dose across all 23 mines is 1.33mSv, equivalent to 6.7% of, the annual derived dose limit of 20mSv. The mean dose exceeds the 1mSv per year criterion (as outlined in Section 2.7) for exemption from compliance with mine radiation safety legislation.

c) Twelve of the 23 mines have revised annual dose estimates that exceed, or were equal to, 1mSv per year and are therefore required to comply with Western Australian mine radiation safety legislation.

d) Annual dose estimates for three mines (#3, #9 and #26) exceed 50% of the 5mSv definition of workers being deemed as “designated employees”. Additional monitoring and controls are warranted in these mines to ensure worker doses are minimised (GWA, 1994, 1995).

e) Applying the radiological outcomes to the demographic data presented in Table 24, and assuming equal distribution of the workforce by mine, suggests that as many as 5,400 workers (eight of 12 gold mine workers; three of the nine nickel/gold workers; half of the workers in the lead/zinc sector; and all workers in the diamond industry) will exceed annual radiation doses in excess of 1mSv.

6.10 CONCLUSIONS

Whilst the closure of Western Australia’s underground coal mining sector removed the major sources of radiation exposures to the Western Australian underground workforce, the workforce has expanded considerably in the quarter-of-a-century since the most recent research was published in 1994 by Hewson and Ralph. Many of the new mining operations are located in the Great Plateau and are likely to encounter enhanced ^{238}U concentrations.

This analysis indicates that worker doses will increase in all underground non-coal, non-uranium mines, by an average of 5.4% to a mean dose of 1.33mSv per year, and ranges from 0.53mSv to 3.56mSv. Doses in 12 of the 23 underground mines that participated in the 1994 study will exceed the 1mSv criteria for exemption and will be required to comply with mine radiation safety legislation.

The dose estimates are based upon parameters contained in ICRP-137 which states "There are no published data on aerosol characteristics in modern mines at the current time. However, … there is insufficient information at this time to provide alternative sets of parameters" (ICRP, 2017), and recommends the use of specific data in place of the default F=0.2 for underground mines.

The average F found in the 1994 study was 0.44, and when non-representative samples were redacted from the data set, the mean F was 0.52, emphasising the need to evaluate RnP as per guidance from ARPANSA (2011a, pp. 16,38) and not rely solely on Rn measurements and an assumption of F. This research has reinforced the importance of determining an F that is applicable to the mining operation being studied, in order to ensure that dose estimates are based upon appropriate data, rather than relying upon theoretical models.

The annual dose estimates reported in this analysis do not include a contribution from inhalation of dusts containing LLα. The impact of recent changes to the DCs for the long-lived alpha-emitting radionuclides of the ^{238}U chain on the doses to the underground mining workforce is unknown and should be investigated.

The collective dose to the underground mining workforce in Western Australia has increased by 4.5 times from 3,060 man.mSv to 13,669 man.mSv.

Potential radiation doses to underground workers are related to ventilation methods and the rate of air movement throughout the mine workings. Series ventilation circuits, in which air is re-used in underground workplaces allows air to become aged and may contribute to elevated Rn and RnP concentrations. Series ventilation was the primary ventilation system encountered in the Hewson and Ralph (1994) study, and continue to be in widespread use in the contemporary industry. Whilst series ventilation techniques abound in Western Australian mining operations, the potential for elevated radiation exposures will exist.

There is justification for further research into the ventilation techniques, and characteristics of the underground working atmosphere such as particle size, Rn and RnP concentrations, the degree of equilibrium and the unattached fraction of RnP, especially in deep mines.

This Chapter has evaluated the impacts of the revised DCs for Rn and RnP on underground mining operations in Western Australia and has identified that the sector is likely to have workers that exceed the 1mSv per annum threshold for regulatory intervention. The findings present a compelling argument for renewed research across the sector into the potential for exposures. The research should include evaluations of the unattached fraction of RnP; the extent of equilibrium between Rn and RnP; and the contribution of LLα to worker doses.

The research reported in this Chapter was largely completed in 2018-2019. In December 2019 the ICRP published ICRP-141 (ICRP, 2019a) completing the DCs for the ^{232}Th and ^{238}U series, and the research reoriented from evaluating exposures in the underground mining environment to evaluation of potential doses from inhalation of NOR-containing dusts in surface mining operations.

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CHAPTER SEVEN: EVALUATING THE IMPACTS OF REVISED DOSE COEFFICIENTS FOR THE INHALATION OF DUSTS THAT CONTAIN NORS

The purpose of monitoring for internal exposure to radionuclides is to verify and document that the worker is protected adequately against radiological risks, and that the protection afforded complies with legal requirements.

Individual monitoring of internal exposure uses measurements made for individual workers for the assessment of their dose of record, together with other dosimetric quantities if required.

The principal objectives of individual monitoring in planned and existing situations are:

- *to assess the worker's dose of record and to demonstrate compliance with regulatory requirements; and*
- *to contribute to the safety management and control of the operation of the facility.*

Measurements in a routine monitoring programme are made at predetermined times not related to known intakes, and therefore it is necessary to make some assumptions about the pattern of intakes. National or local legislation or regulations may also set the requirements for systematic routine monitoring that may be needed if exposures could exceed a specified fraction of the dose limit or a dose constraint.

International Commission on Radiological Protection,

Publication 130, Occupational Intake of Radionuclides Part 1

(ICRP, 2015, pp. 51-52)

The catalyst for this Chapter was the research by Paquet et al. (2017), corroborated by Hondros and Secen-Hondros (2019) that the DCs published in ICRP-137 (ICRP, 2017) and ICRP-141 (ICRP, 2019a) were based upon redefined absorption rates of radionuclides in the body, based upon their solubility. The authors forewarned that the DCs for long-lived, insoluble radionuclides would increase significantly, and provided the example of ^{232}Th, the DC for which would increase by an order of magnitude (Paquet et al., 2017).

Dusts commonly encountered in the Western Australian mining industry are (generally) considered as insoluble. It was contemplated that the revised DCs could have a profound effect upon doses to workers as a result of their inhalation of NOR-containing, insoluble dusts.

This Chapter commences with outlining the methods for sampling, and subsequently calculating the doses from inhalation of NOR-containing dusts prescribed in the Western Australian legislation; the methodology for determining dose conversion factors (DCFs) for a range of particle sizes commonly encountered in the Western Australian mining industry; and uses a typically encountered exposure scenario to model the impact on future worker doses that will result from the revised DCs.

7.1 OVERVIEW

In December 2019, the ICRP published Part 4 of the Occupational Intake of Radionuclides as ICRP-141 (ICRP, 2019a) thereby completing the revision of DCs for all members of the ^{232}Th, ^{238}U and ^{235}U [50] decay series. The aim of the research reported in this Chapter was to evaluate the impact of the revised DCs on the radiation doses received by Western Australian mine workers via the inhalation of insoluble dusts containing LLα.

Data from the 15 [51]annual reports submitted to the RRAM by REs in the 2018-19 reporting period was utilised to develop the exposure scenario upon which predictions of future worker doses are based. The annual radiation reports submitted for the 2018-19 reporting were analysed in Chapter Five of this Thesis.

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[50] Whilst in other Chapter of this Thesis, ^{235}U is acknowledged, but overlooked due to its relatively low abundance, when calculating DCFs it is important to include the contribution from the ^{235}U decay series.

[51] Note that Ralph et al. (2020c) state that 11 annual reports were received. An addition four annual reports were received post-publication of the journal article.

7.2 CODIFICATION OF DOSE CALCULATION METHODOLOGIES

The WHSR(Mines) stipulates that the assessment of doses is “carried out in accordance with a procedure approved by the regulator” [52]. As was discussed in Section 2.7, in order to embed a nationally uniform approach to radiation protection, the WHSR(Mines) includes an additional requirement that the approved procedure must align with the objectives stated in clause 2.2 of RPS-9 (GWA, 2022d, pp. 427-428).

The suite of 14 NORM Guidelines (DMIRS, 2020d) introduced in Chapter Two, comprise the approved procedures. Each NORM Guideline addresses specific components of the system of radiation protection in mining and includes details pertaining to the approved procedure for collecting data; calculating radiation doses; and recording and reporting the derived information.

The (former) Guideline NORM-5 entitled “Dose Assessment” (GWA, 2010d) (NORM-5) provided guidance on the calculation of internal dose to mine workers as a result of inhalation of the long-lived members of the ^{232}Th and $^{238+235}$U [53] decay series. NORM-5 was based upon the ICRP Publication 30 series (ICRP, 1980a) and Publications 54 (ICRP, 1988), 68 (ICRP, 1994c) and 78 (ICRP, 1997), and the respiratory tract model as outlined in ICRP-66 (ICRP, 1994b).

Significantly for this research, NORM-5 provided guidance on the derivation of dose conversion factors (DCFs), based upon a methodology in the International Atomic Energy Agency publication RS-G-1.6 (IAEA, 2004, pp. 79-84).

- Note that the methodology requires the summation of DCs for each member of the decay series (where available) which introduces the term “Sum of DCs” in the following analysis.

Note that this research resulted in NORM-5 being updated to reflect the revised DCs published in ICRP-137 and ICRP-141, and has been reissued as NORM-V. The methodology from RS-G-1.6 (IAEA, 2004, pp. 79-84) has been preserved in NORM-V.

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[52] The provision has been carried over from the former MSIR (GWA, 1995, pp. 342-343) with the exception that procedures were approved by the SME.

[53] Note that the DCs for the ^{238}U and ^{235}U decay series are combined to formulate the DCF for uranium.

7.3 METHODOLOGY

The methodology involved sourcing the relevant DCs (where available) for each of the radionuclides in the ^{232}Th and $^{238+235}$U decay series and applying the methodology from RS-G-1.6 (IAEA, 2004, pp. 79-84) to calculate the DCF for a range of sizes of dust particles.

7.3.1 Methodology: Sourcing DCs

As was introduced in Section 6.3, the OIR series of publications is accompanied by a digital annex, called the OIR Data Viewer, which was downloaded from the ICRP website (ICRP, 2019c).

The OIR Data Viewer "contains a comprehensive set of committed effective and equivalent dose coefficients, … for almost all radionuclides included in Publication 107 (ICRP, 2008) that have half-lives equal to or greater than 10 min, and for other selected radionuclides" (ICRP, 2017, p. 18).

This is an important consideration, because some of the members of the ^{232}Th and $^{238+235}$U decay series have very short half-lives and are unable to be allocated a DC and therefore could not be considered in this analysis.

The OIR Data Viewer provides data on individual radionuclides, their half-lives and decay modes; information on chemical forms encountered in the workplace; and data on inhalation and ingestion. The properties of the radionuclide can be selected from drop-down lists, and based upon the selections, data on dose per intake (mSvBq^{-1}) are automatically generated.

7.3.2 Methodology: Derivation of DCs for members of the ^{232}Th and $^{238+235}$U decay series

One of the requirements for generation of a dose per intake value is the solubility of the form of the radionuclide encountered in the working environment.

Research conducted in the Western Australian mining industry in the 1980s and 1990s evaluated NOR-containing dusts and concluded that they were insoluble, and were removed very slowly from the lung once inhaled (Hartley & Hewson, 1993; Hewson & Fardy, 1993; Hewson & Marshman, 1993; Marshman & Hewson, 1994; Terry, Hewson & Burns, 1997; Twining, McGlinn & Hart, 1993). Accordingly, Type S, the slowest absorption rate available in the OIR Data Viewer, was selected, when it was offered in the drop-down list in the OIR Data Viewer.

A number of DC values (for example lead-212 (^{212}Pb), bismuth-212 (^{212}Bi), radium-224 (^{224}Ra) and radium-228 (^{228}Ra), from the ^{232}Th decay series) were formerly based upon absorption Type F or M in

ICRP-30, as type S was not available, but as a result of the modifications to the Human Respiratory Tract Model (ICRP, 1994b) were able to be treated as Type S in this research.

The OIR Data Viewer also allows the user to select the particle size of the inhaled radionuclide(s), as measured by the Activity Median Aerodynamic Diameter (AMAD) measured in microns (µm).

Based upon the recommendations for evaluating doses to workers and critical groups (ICRP, 1994b, 2015) and previous Western Australian research (Hewson, 1988b, 1990b; Marshman & Hewson, 1994), revised DCs for each radionuclide were extracted for AMADs of 1, 5 and 10 microns.

The resultant DCs were exported from the Data Viewer into a Microsoft Excel (2016) spreadsheet. Each of the three AMAD values were allocated a separate spreadsheet, and the DCs as published in NORM-5 as DCFs were included in the spreadsheet for comparison purposes.

7.3.3 Methodology: Overview of the calculation of DCFs

The term "dose conversion factor" (DCF) is used in IAEA (2004) to represent the mean dose per unit intake of alpha activity arising from inhalation of dusts containing members of either the ^{232}Th decay series and / or the $^{238+235}$U decay series [54].

Analysis of the radioactivity of dust samples is performed via gross alpha activity analysis (GAAA) as per NORM Guideline 3.4 "Monitoring NORM – airborne radioactivity sampling" (GWA, 2010c). GAAA counts all alpha particle emissions from the collected dust sample to provide an activity reading in Bq_{α}.

The beta-emissions from the NORM in the collected dust sample are not detected by GAAA, however their contribution to internal dose is accounted for by including their DCs in calculating the DCF for the entire series.

Similarly, where an α-particle emitting radionuclide has a sufficiently short half-life that it is not allocated a DC, its contribution to GAAA must be accounted for by its inclusion in the total number of alpha particle emitters in the decay series.

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[54] Note that the DCs for the ^{238}U and ^{235}U decay series are combined to formulate the DCF for uranium.

7.3.4 Calculation of DCFs for the ^{232}Th decay series

The ^{232}Th decay series includes six alpha particle emitters, and therefore the values for Sum of DCs cited in Tables 30, 31 and 32 are divided by six to provide the DCF values for the ^{232}Th decay series in Table 36.

7.3.5 Calculation of DCFs for the $^{238+235}$U decay series

The ^{238}U decay series has eight members, and the ^{235}U decay series has seven members that decay via alpha particle emission.

- The specific activity of natural uranium is 12,900 Bqg^{-1} of which ^{235}U contributes 593 Bqg^{-1}, or 4.6% (ARPANSA, 2011a).
- In order to account for the relative contribution of the ^{235}U decay series to the total activity from the combined $^{238+235}$U decay series, the DC for each member of the ^{235}U decay series is multiplied by 0.046 (IAEA, 2004).

Therefore, the combination of the seven alpha-emitting radionuclides in the ^{235}U decay series contribute an equivalent of 0.322 alpha particles to the Bq_{α} from natural uranium.

When added to the eight emitters in the ^{238}U decay series, the combined $^{238+235}$U decay series includes 8.322 alpha emitters.

The DCF data in Table 36 for the $^{238+235}$U decay series are calculated from Tables 33, 34 and 35 by applying Equation 4:

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

EQUATION 4: CALCULATION OF DCF FOR A COMBINATION OF ^{238}U AND ^{235}U

7.3.6 Methodology: Compiling and applying the DCFs

The methodology outlined in NORM-5 and IAEA publication RS-G-1.6 (IAEA, 2004, pp. 79-84) was used to calculate a revised DCF for each of the ^{232}Th and $^{238+235}$U decay series, and a table constructed comparing the DCF derived from the OIR Data Viewer to the ICRP Publication 30 series.

To reflect the varying radiological content of the minerals encountered in the Western Australian mining industry, an additional table was constructed in Microsoft Excel (2016) comparing the DCFs for AMADs of 1 µm, 5 µm and 10 µm by varying ratios of concentration of the ^{232}Th decay series to $^{238+235}$U decay series.

An evaluation was made of the potential impact of the revised DCs on a typical worker exposure scenario, to provide a forecast of increased worker doses from inhalation of insoluble dusts that contain radionuclides in the ^{232}Th and $^{238+235}$U decay series.

7.4 REVISION OF DCS FOR MEMBERS OF THE ^{232}TH DECAY SERIES

Comparisons of DCs from ICRP-30 (replicated in the NORM-5 guideline) and ICRP Publications 137 and 141 for the radionuclides that are members of the ^{232}Th decay series for AMADs of 1µm, 5 µm and 10 µm, are presented in Tables 30, 31 and 32.

Note that:

- Thallium-208 (^{208}Tl), polonium-212 (^{212}Po) and polonium-216 (^{216}Po) have half-lives less than ten minutes, and therefore do not have DCs.
- Radon is an inert gas, with constant aerodynamic diameter. The DC does not change between the tables. A DC for ^{220}Rn is published in ICRP-137 but was absent from ICRP-30.

TABLE 30: DCS FOR INHALATION OF 1µM AMAD PARTICLES COMPRISED OF THE ^{232}TH SERIES

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

TABLE 31: DCS FOR INHALATION OF 5µM AMAD PARTICLES COMPRISED OF THE ^{232}TH SERIES

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

TABLE 32: DCS FOR INHALATION OF 10µM AMAD PARTICLES COMPRISED OF THE ^{232}TH SERIES

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

Tables 30, 31 and 32 illustrate that most of the DCs have increased. Whilst several DCs have decreased, the nett effect for all AMADs is that the Sum of all DCs has increased.

7.5 DCS FOR MEMBERS OF THE $^{238+235}$U DECAY SERIES

Comparisons of DCs from ICRP-30 (replicated in the NORM-5 guideline) and ICRP Publications 137 and 141 for $^{238+235}$U decay series radionuclides for AMADs of 1µm, 5 µm and 10 µm, are presented in Tables 33, 34 and 35.

Note that:

- Thallium-207 (^{207}Tl) bismuth-211 (^{211}Bi), polonium-214 (^{214}Po), polonium-218 (^{218}Po) and ^{219}Rn have half-lives of less than ten minutes and therefore do not have DCs.
- Because it has a half-life of 1.17 minutes, Protactinium-234^{m} (^{234m}Pa) does not have a DC. However, ^{234m}Pa can decay to uranium-234 (^{234}U) via protactinium-234 (^{234}Pa) which has a half-life of 6.7 hours, and has DC listed in ICRP-141.
    - The DC for ^{234}Pa is used in Tables 33, 34 and 35.
    - A DC for ^{234}Pa was not listed in ICRP-30.
- Radon is an inert gas, with constant aerodynamic diameter. The DC does not change between the tables. A DC for ^{222}Rn is published in ICRP-137 but was absent from ICRP-30.

The data presented in Tables 33, 34 and 35 illustrate that most of the DCs have increased, and whilst several have decreased, the nett effect is that the Sum of all DCs has increased for all AMADs.

Table 33: DCs for inhalation of 1µm AMAD particles comprised of the $^{238+235}$U series

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

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC ($SvBq^{-1}$)		Change, as a ratio of B : A
			A ICRP-30 series	B ICRP-137 / 141	
radium-223 (^{223}Ra)	Alpha	M	6.90E-06	3.20E-06	0.464
^{219}Rn	Alpha	-	-	-	-
polonium-215 (^{215}Po)	Alpha	-	-	-	-
lead-211 (^{211}Pb)	Beta	F	3.90E-09	1.10E-08	2.82
^{211}Bi	Alpha	-	-	-	-
^{207}Tl	Beta	-	-	-	-
^{235}U decay series: Sum of DCs for 1µm AMAD			**1.22E-04**	**2.22E-04**	**1.81**

TABLE 34: DCS FOR INHALATION OF 5µM AMAD PARTICLES COMPRISED OF THE $^{238+235}$U SERIES

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

Radionuclide	**Particulate Emission**	**NORM-5 lung absorption class**	**DC (SvBq^{-1})**		**Change, as a ratio of B : A**
			A: ICRP-30 series	B: ICRP-137 / 141	
^{223}Ra	Alpha	M	5.70E-06	2.20E-06	0.386
^{219}Rn	Alpha	-	-	-	-
^{215}Po	Alpha	-	-	-	-
^{211}Pb	Beta	F	5.60E-09	1.30E-08	2.32
^{211}Bi	Alpha	-	-	-	-
^{207}Tl	Beta	-	-	-	-
^{235}U decay series: Sum of DCs for 5µm AMAD			**8.34E-05**	**1.27E-04**	**1.53**

Table 35: DCs for inhalation of 10µm AMAD particles comprised of the $^{238+235}$U series

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

Radionuclide	Particulate Emission	NORM-5 lung absorption class	DC ($SvBq^{-1}$)		Change, as a ratio of B : A
			A: ICRP-30 series	B: ICRP-137 / 141	
^{223}Ra	Alpha	M	3.00E-06	1.30E-06	0.433
^{219}Rn	Alpha	-	-	-	-
^{215}Po	Alpha	-	-	-	-
^{211}Pb	Beta	F	4.80E-09	9.20E-09	1.92
^{211}Bi	Alpha	-	-	-	-
^{207}Tl	Beta	-	-	-	-
^{235}U decay series Sum of DCs for 10µm AMAD			**4.59E-05**	**6.81E-05**	**1.48**

7.6 CALCULATION OF DCF VALUES

The DCFs for the 232Th and 238+236U decay series were calculated by applying the methods outlined in Sections 7.3.4 and 7.3.5 respectively. The resultant DCFs for AMADs of 1 µm, 5 µm and 10 µm are provided in Table 36.

TABLE 36: CALCULATED DCF VALUES BY DECAY SERIES AND AMAD

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

The data presented in Table 37 indicate that the DCF for the three selected AMADs increased by between 1.9 and 2.9 times the NORM-5 values because of the revised DCs in ICRP-137 and ICRP-141.

7.7 CALCULATION OF CONTRIBUTION TO DCF BY THORIUM TO URANIUM RATIO

The DCF values listed in Table 36 were applied to a range of ratios (by mass) of ^{232}Th decay series to $^{238+235}$U decay series to represent the contribution made by each decay series and determine an applicable DCF by AMAD.

Examples of the calculated DCF values by the ratio of ^{232}Th decay series to $^{238+235}$U decay series commonly encountered in the Western Australian mining industry are provided in Table 37.

TABLE 37: CALCULATED DCF VALUES BY AMAD AND RATIO OF DECAY SERIES (BY MASS)

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

7.8 DISCUSSION

In order to estimate the radiation dose delivered by inhalation of dusts containing NORs, knowledge of their: concentration; particle size; respiratory deposition; and clearance from the respiratory system is required (George, 2008, pp. 1-17). DCs will differ markedly according to the parameter values selected, and therefore it is important that the data extracted from the OIR Data Viewer are representative of the particles being inhaled.

The most significant input parameter is the choice of absorption rate from the selection of Fast (F), Medium (M) or Slow (S), where Type S indicates insolubility, and accordingly long retention times in the body. As discussed in Section 7.3.2, significant research was conducted into the properties of dusts in the Western Australian mining industry in the 1980s and 1990s and resolved that typically encountered dusts are insoluble. Accordingly, Type S, the slowest absorption rate available in the OIR Data Viewer, was selected as the default in this research.

7.8.1 Discussion: Secular equilibrium

The term “dose conversion factor” (DCF) is used in NORM-5 and IAEA (2004), to represent the mean annual dose per unit intake of alpha activity arising from inhalation of dusts containing members of either the ^{232}Th decay series and / or the $^{238+235}$U decay series. The DCF is significant as it considers the relative contribution from all the members of the decay series to the internal dose.

DCF is calculated by dividing the Sum of DCs for the ^{232}Th and the $^{238+235}$U decay series by the number of LLα radionuclides in each of the decay series to provide a value of $mSvBq^{-1}$ per alpha emission. Of importance to the use of DCF is that all members of the decay series are in secular equilibrium, and, as was discussed in Section 1.5, the activity of one radionuclide is indicative of the activity of all other members of the decay series.

Research into Western Australian-based mineral sands processing operations reported by Hartley and Hewson (1993) found that the loss of radioisotopes of radon from mineral grains was very low, and that the assumption of secular equilibrium was valid.

However, as was discussed in Section 4.4, if chemical or thermal treatment has been applied in the processing of minerals, secular equilibrium may be disturbed, and DCFs for the inhalation of the dispersed radionuclides must be calculated on a case-by-case basis.

7.8.2 Discussion: Changes in DCs from ICRP-30 to ICRP-137 and ICRP-141

As illustrated in Tables 30, 31 and 32, the DCs for four radionuclides in the ^{232}Th decay series decreased in ICRP-137 and ICRP-141 compared to those published in the ICRP Publication 30 series.

- However, correspondingly, the DCs for ^{228}Ra, ^{212}Pb and ^{232}Th increased significantly, ranging from 1.94 times for ^{212}Pb (10 µm particles) to 14.2 times for ^{228}Ra (1µm particles).
- The increases resulted in an increase in the Sum of all DCs for all AMADs.

As shown in Tables 33, 34 and 35, the DCs for the majority of the members of the $^{238+235}$U decay series increased, with only ^{234}Th, ^{214}Bi and ^{210}Po from the ^{238}U decay series and ^{231}Th, ^{227}Th and ^{223}Ra from the ^{235}U decay series decreasing from the DCs in ICRP Publication 30 series to those in ICRP137 and ICRP-141.

- The highest increases were seen in the DCs for ^{210}Pb, ranging from 5.43 times for 10µm particles to 16.9 times for 1µm particles; and ^{226}Ra, ranging from 4.80 times for 10µm particles to 7.19 times for 1µm particles.

7.8.3 Discussion: Impacts on DCFs

The nett effect of the revised DCs, as illustrated in Table 36, is to increase the DCF values from those published in NORM-5:

- For the ^{232}Th decay series by between 1.9 times for 10µm particles to 2.6 times for 1µm particles; and
- For the $^{238 + 235}$U decay series by between 2.1 times for 10µm particles to 2.9 times for 1µm particles.

Significantly, this research finds the increase in derived DCF is inversely related to AMAD, with the increase becoming larger with decreasing AMAD.

7.8.4 Discussion: Application of DCFs

The data presented in Table 37 have significance, as ultimately it is this data, or variants of them, derived in a similar manner, that will be used for calculating the contribution to internal dose from inhalation of NORM-containing dusts in mining operations in Western Australia.

It has been demonstrated that the AMAD of the dust, and the ratio of the ^{232}Th decay series to $^{238+235}$U decay series, can have a marked effect on internal dose calculations, and therefore it is important that each RE characterises these parameters for their mining operation.

The need for dust characterisation studies by REs can be determined from Table 37. The primary minerals produced (by volume) in the Western Australian mineral sands industry are ilmenite and rutile, which, as illustrated in Table 5 (in Chapter Four) have a ^{232}Th decay series to $^{238+235}$U decay series ratio approximating 10:1:

- At this ratio, the DCF decreases by 69% from 0.0256mSvBq$_{\alpha}^{-1}$ (AMAD = 1µm) to 0.0080mSvBq$_{\alpha}^{-1}$ (AMAD = 10µm).

Zircon, another major product from the mineral sands industry has a ^{232}Th decay series to $^{238+235}$U decay series ratio approximating 1:1 (refer to Table 5):

- The DCF decreases by 68% from 0.0179mSvBq$_{\alpha}^{-1}$ (AMAD = 1µm) to 0.0057mSvBq$_{\alpha}^{-1}$ (AMAD = 10µm) at this ratio.

7.8.5 Discussion: Projection of revised DCFs on future worker doses

The majority of the 15 REs annual radiation reports submitted to the RRAM for the 2018-19 reporting period used the default AMAD of 5µm and the ^{232}Th decay series to $^{238+235}$U decay series ratio for ilmenite and rutile of 10:1 to calculate internal dose from inhalation of LLα in NOR-containing dusts.

- As can be seen in Table 37, the DCF applicable to dusts in mining operations that apply these parameters is 0.0148mSv Bq$_{\alpha}^{-1}$.

In NORM-5 the equivalent DCF is 0.007mSv Bq$_{\alpha}^{-1}$, and therefore the revised DCF is greater by a factor of 2.1 than that used by the majority of REs to calculate internal doses in the 2018-19 annual reports.

A preliminary evaluation of the data submitted in the 2018-19 annual reports [55], indicated that the contribution to annual dose from the inhalation of radioactive dusts across the 15 REs ranged from 35% to 60%.

- Applying the default AMAD of 5µm and a ^{232}Th decay series to $^{238+235}$U decay series ratio for ilmenite and rutile of 10:1, internal doses to the workforce as a result of inhalation of the NOR-

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[55] submitted prior to the release of ICRP-141

containing dusts will increase by a factor of between 0.74 and 1.26 times from those reported in 2018-19 as a result of the revised DCs published in ICRP-137 and ICRP-141.

Based on a preliminary review of the dose estimates provided in the 2018-19 annual reports this research forecasts that the maximum annual dose would increase from 4.4mSv to 7.9mSv, with the contribution from LLα increasing by 3.5mSv to 6.7mSv, representing 85% of total dose.

If the projection is realised, and the activity concentration of the inhaled dust remains constant, internal doses would be nearly double those reported in 2018-19. Further, annual worker dose estimates would, in some circumstances, exceed five mSv which is the criteria above which members of the workforce are considered as Designated Workers. Should this occur, it will be the first time since 2009-10 that Designated Workers will be identified in the state's mining industry.

7.9 CONCLUSIONS

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

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

A scenario which applies an AMAD of 5µm and a ^{232}Th decay series to $^{238+235}$U decay series ratio of 10:1, would result in the internal dose to the workforce being greater by a factor of between 0.74 and 1.26 times from those reported in 2018-19 as a result of the revised DCs published in ICRP-137 and ICRP-141. The application of the revised DCFs may result in members of the workforce being categorised as Designated Workers, for the first time since 2009-10.

It is known that the concentration, AMAD, and radiological characteristics of dusts in mining operations will vary with the mineral being processed, and the physical and metallurgical treatment processes being utilised (Hartley & Toussaint, 1986; IAEA, 2006; Mason et al., 1984). This analysis has confirmed the importance of mining operations conducting characterisation studies of the NOR-containing dust to which workers are exposed in order to determine site-specific and process-specific parameter values upon which appropriate committed effective dose coefficients can be applied to dose calculations.

7.10 ACKNOWLEDGEMENTS

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7.11 POST-PUBLICATION NOTES

This research was published as Ralph et al. (2020c). Publication of the research led to:

- Revision of the NORM-5 Guideline and its re-issue under the title of NORM-V (DMIRS, 2021b).
- The 2019-20 annual radiation reports submitted to the RRAM by REs utilised the DCFs in NORM-V, the results of which are discussed in Chapter Eight.
- Updates to RPS-9 (ARPANSA, 2005) which were broadcast by ARPANSA (2022c) and ECU (2022).

This Chapter responds to the exigency arising from the revised DCs for the ^{232}Th and $^{238+235}$U decay series published in ICRP-137 and ICRP-141 and found that the changes would have a profound effect upon the estimated internal doses arising from the LLα emissions from inhaled NOR-containing dusts in Western Australian mining operations.

The findings of the research were broadcast across the REs and other stakeholders in the Western Australia in the anticipation that they would take heed of the implied cautions in the predictions made and react by implementing effective dust controls and increasing personal monitoring of workers to ensure the collected data is sufficient to provide valid estimates of internal doses.

The following Chapter evaluates the impacts of the revised DCFs on the worker doses reported in the 2019-20 annual reports submitted by the REs.

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CHAPTER EIGHT: IMPACTS OF REVISED DCFS: A COMPARISON OF THE 2018-19 AND 2019-20 ANNUAL RADIATION REPORTS SUBMITTED BY REPORTING ENTITIES

A part of good science is to see what everyone else can see – but think what no one else has ever said.

Advice from Amos Tversky (co-founder of the Law of Small Numbers and Prospect Theory) provided to Donald A Redelmeier

A reflection with Michael Lewis in "The Undoing Project"

Lewis (2017, p. 345)

The previous Chapter forecast that some workers may exceed five mSv in the 2019-20 reporting period as a result of revisions to the DCs for members of the ^{232}Th and $^{238+235}$U decay series on DCFs applied to the calculation of internal dose arising from LLα emitted from NOR-containing dusts typically encountered in the Western Australian mining industry.

This Chapter follows up the research reported in the previous Chapter and evaluates the impacts of the revised DCs by comparing the estimates of radiation doses to mine workers, as reported by REs in the 2019-20 annual reporting period, against those reported in 2018-19.

8.1 INTRODUCTION

As was introduced in Section 2.2 and expanded upon in Chapter Seven, publication of ICRP-137 (ICRP, 2017) and ICRP-141 (ICRP, 2019a) signalled an exigency from the international radiation protection authorities that was the catalyst for a revision of the methodology used to calculate internal doses to mine workers arising from the inhalation of NOR-containing dusts.

Subsequently, the Western Australian Guideline NORM-V (DMIRS, 2021b), which drew upon the research reported in Chapter Seven, was published. The RRAM required all REs to calculate the internal doses to workers in the 2019-20 annual reports using the DCs for Rn and RnP and the DCFs for NOR-containing dusts cited in NORM-V.

The 2019-20 reporting period was the first to utilise the revised DCs and DCFs. The reported doses were analysed by the methodology reported in Chapter Five and the 2019-20 industry dose profile was compiled.

The 2019-20 dose profile was then used to evaluate the impact of revised DCs for members of the ^{232}Th and $^{238+235}$U decay series on the dose estimates to Western Australian mine workers by comparison to the 2018-19 annual reporting period, which immediately preceded implementation of the revised DCs.

8.2 METHODOLOGY: REFRESHER FROM CHAPTER FIVE

At the end of the 2019-20 reporting period, 31 REs had been allocated a numerical identifier, which had increased to 41 REs at time of compiling this Thesis. [56].

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[56] A RE located in the district of Jurien ceased operating in 1977, prior to the alpha-coding system being implemented. This RE has been allocated the numerical code “0” and is counted among the 41 REs.

As was outlined in Chapter Five, REs are required to submit an annual occupational radiation report, which includes analysis of the annual internal dose received by workers. The content of annual reports follows the guidance provided in the Western Australian Guideline NORM-6: Reporting Requirements (GWA, 2010e) which has been applied for over a decade, and has been the basis for consistent application of dose estimate methodologies by the REs.

The annual reports assessed in this research were based upon data collected in the monitoring period from 1st April 2019 to 31st March 2020.

- Internal dose from long-lived alpha emitters (LLα) in dusts (hereinafter referenced as Dose $_{LL\alpha}$); and revised DCs for calculation for internal dose from ^{220}Rn, ^{222}Rn, TnP & RnP (hereinafter, referenced as dose$_{TnP\ \&\ RnP}$); were derived from the NORM-V Guideline (DMIRS, 2021b).

Nineteen REs were operational in the 2019-20 reporting period, two of which were exempt from submitting annual reports because of the likelihood that worker EDs would not exceed 1mSvy^{-1}.

- REs #24 and #25 submitted their first annual reports.
- After a hiatus of six years, RE#2 resumed operations; and
- RE#28 went into care and maintenance during the reporting period and was not required to submit an annual report.

A total of 17 annual radiation reports were submitted by REs in the 2019-20 reporting period.

The annual reports were submitted by the REs to the RRAM via the Safety Regulation System (DMIRS, 2020f), and interrogated by the researcher. The Microsoft Excel (2016) introduced in Chapter Five was duplicated, and a spreadsheet for the 2019-20 reports added. Relevant data was drawn from the annual reports and entered into the 2019-20 spreadsheet, from which the consolidated data could be analysed, and graphs constructed.

8.3 REPORTING ENTITIES BY COMMODITY

This research establishes the foundation for future analysis of the profile of mining operations by which NOR-containing commodities are being mined. Table 38 presents the first such attempt at categorizing the REs by commodity in 2019-20 and draws a comparison to the 2018-19 profile.

TABLE 38: REs BY COMMODITY MINED OR PROCESSED

Commodity Mined or Processed	**Reporting Period**	
	2018-19	**2019-20**
Mineral Sands	7	9
Rare Earths	2	2
Tantalum / Lithium	3	2
Other Activities [1]	3	4
Exempt Operations [2]	2	2
Total REs	**17**	**19**
Reports Received	**15** [3]	**17**

[1] The "Other Activities" mining operations that encounter NORs, but do not fall within the three other categories which are defined by their mineralogy.

[2] Exempt REs are not required to submit a report on an annual basis but are required to keep the RRAM informed of their activities and any increases to worker radiation exposures.

[3] Ralph et al. (2020a) disclosed that annual reports were submitted by 14 REs. However, a further RE (#13) submitted a report, post the article being published.

As can be seen from Table 38, the total number of REs increased by two from the 2018-19 reporting period. The number of MSI operations increased by two; the tantalum/lithium sector contracted by one operation; whilst the Other Activities increased by one operation.

8.4 DEMOGRAPHICS AND RADIOLOGICAL PARAMETERS

In Chapter Five, the data from each RE was amalgamated to form a holistic year-by-year synthesis of reported mine worker doses across-the-industry. It is important to this Section of the research to highlight that the individual RE data, collected from 1984 70 2017-18 that is synthesized in Chapter Five remains available to be analysed on a RE-by-RE basis should it ever be required.

As was illustrated in Table 38, 17 REs submitted annual reports in 2019-20, an increase of two REs that submitted annual reports in 2018-19.

As was introduced in Section 5.1, the data presented in Tables 8 to 21 is based upon a template established by Marshman and Hewson (1994), slightly modified from Table 14 onwards to allow a detailed analysis of worker doses previously reported as less than 5mSv. The template enables a consistent approach to presenting and analysing the data extracted from annual reports.

In this Section, the template is also applied, but unlike the data presented in Tables 8 to 21, is based on a RE-by-RE basis. The demographic data and radiation dose profile of the workforce employed at each of the 17 REs that provided annual reports is provided in Table 39 (which extends over the following six pages).

- Data from the 15 reports submitted in the 2018-19 reporting period are presented in parentheses. [57]
- Note that REs #2, #24 and #25 did not report in 2018-19, and therefore their data for 2018-19 is not able to be presented in Table 39.

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[57] Subsequent to the publication of Ralph et al. (2020a), one RE (#13) submitted an annual report, and REs #9, #11, #15, #16, #22 and #23 provided additional data. The data has been assimilated into this research, and as a result, the information reported in parentheses in Table 39 does not align directly with the information provided in Ralph et al. (2020a).

TABLE 39: DEMOGRAPHICS AND RADIOLOGICAL PARAMETERS, 2019-20 REPORTING PERIOD

Parameter	Reporting Entity (De-identified by Numeric Identifier)					
	2 [1]	**3 [1,2]**	**4 [1]**	**5**	**6**	**7 [1,2]**
Workforce	23	123 (119)	35 (34)	13 (14)	75 (45)	250 (22)
Monitored Workers	20	109 (93)	0 (0)	0 (0)	15 (14)	25 (20)
# of Personal Dust Samples	19	106 (117)	44 (57)	16 (16)	48 (44)	33 (15)
Analysis for all workers who worked greater than 200 hours in the reporting period:						
Mean External Dose (mSv)	0.21	0.59 (0.57)	0.76 (0.70)	0.26 (0.27)	0.1 (0.10)	0.37 (0.82)
Maximum External Dose (mSv)	1.5	1.9 (1.4)	1.6 (1.5)	0.59 (0.41)	1.0 (0.40)	0.87 (1.5)
Mean Internal Dose (mSv)	0.02	0.91 (0.72)	1.5 (0.53)	1.3 (0.22)	0.90 (0.40)	1.8 (2.5)
Maximum Internal Dose (mSv)	0.14	2.6 (1.7)	4.9 (0.69)	3.6 (0.61)	1.3 (0.60)	3.7 (3.7)
Mean ED (mSv)	0.20	1.5 (1.25)	2.2 (1.5)	1.7 (0.49)	1.0 (0.50)	2.4 (2.5)
Maximum ED (mSv)	1.6	3.3 (2.2)	6.0 (2.3)	4.1 (1.0)	2.3 (0.9)	3.9 (4.4)
Collective Dose (man.mSv)	4.6	183 (149)	77.7 (50.0)	21.6 (6.9)	75.0 (22.5)	595 (53.9)

Parameter	**Reporting Entity (De-identified by Numeric Identifier)**					
	2 [1]	**3** [1,2]	**4** [1]	**5**	**6**	**7** [1,2]
Distribution of EDs (mSv) for workers who worked > 200 hours in the reporting period:						
≤ 1.0	22	36 (31)	2 (5)	4 (14)	68 (14)	225 (5)
1.1 to 2.0	1	28 (63)	11 (22)	3 (14)	6 (0)	11 (5)
2.1 to 3.0	0	33 (8)	17 (7)	0 (0)	1 (0)	10 (10)
3.1 to 5.0	0	4 (0)	1 (0)	3 (0)	0 (0)	4 (0)
>5.0	0	(0)	3 (0)	0 (0)	0 (0)	0 (0)

Notes to Table 39:

[1] 2019-20 internal dose data includes contribution from thoron, radon, and their progeny

[2] 2018-19 internal dose data includes contribution from thoron, radon, and their progeny

TABLE 39: DEMOGRAPHICS AND RADIOLOGICAL PARAMETERS, 2019-20 REPORTING PERIOD (CONTINUED)

Parameter	Reporting Entity (De-identified by Numeric Identifier)					
	8 [1,2]	9 [1,2]	11 [1]	13	15 [1]	16 [1]
Workforce	62 (30)	28 (28)	40 (40)	90 (10)	83 (83)	340 (340)
Monitored Workers	0 (0)	13 (13)	34 (0)	0 (-)	0 (0)	0 (0)
# of Personal Dust Samples	160 (110)	24 (95)	6 (32)	0 (-)	126 (70)	14 (14)
Analysis for all workers who worked greater than 200 hours in the reporting period:						
Mean External Dose (mSv)	0.10 (0.20)	0.78 (0.78)	0.01 (1.0)	0.5 (-)	0.37 (0.35)	0.05 (0.05)
Maximum External Dose (mSv)	1.0 (0.80)	1.1 (1.1)	0.04 (1.3)	1.2 (-)	1.3 (1.2)	0.08 (0.11)
Mean Internal Dose (mSv)	1.6 (1.0)	1.2 (0.59)	1.1 (0.52)	0.22 (-)	0.86 (0.18)	0.52 (0.52)
Maximum Internal Dose (mSv)	2.6 (2.1)	3.2 (0.88)	1.7 (0.52)	1.3 (-)	1.1 (1.4)	0.53 (0.53)
Mean ED (mSv)	1.1 (2.5)	0.23 (0.65)	1.2 (1.52)	0.72 (0.46)	1.2 (0.82)	0.45 (0.45)
Maximum ED (mSv)	3.7 (4.4)	2.5 (1.8)	1.7 (1.9)	2.5 (1.1)	2.4 (3.7)	0.53 (0.61)
Collective Dose (man.mSv)	68.2 (15.0)	6.4 (7.6)	46.0 (26.8)	64.8 (4.60)	102.1 (68.1)	153.0 (153.0)

Parameter	Reporting Entity (De-identified by Numeric Identifier)					
	8 [1,2]	**9 [1,2]**	**11 [1]**	**13**	**15 [1]**	**16 [1]**
Distribution of EDs (mSv) for workers who worked > 200 hours in the reporting period:						
≤ 1.0	32 (28)	20 (21)	40 (40)	80 (8)	58 (56)	340 (340)
1.1 to 2.0	26 (1)	2 (7)	0 (0)	5 (2)	20 (20)	0 (0)
2.1 to 3.0	3 (1)	6 (0)	0 (0)	5 (0)	5 (7)	0 (0)
3.1 to 5.0	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
>5.0	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

Notes to Table 39 (continued):

[1] 2019-20 internal dose data includes contribution from thoron, radon, and their progeny

[2] 2018-19 internal dose data includes contribution from thoron, radon, and their progeny

TABLE 39: DEMOGRAPHICS AND RADIOLOGICAL PARAMETERS, 2019-20 REPORTING PERIOD (CONTINUED)

Parameter	Reporting Entity (De-identified by Numeric Identifier)				
	20	22 [2]	23 [1]	24 [1]	25 [1]
Workforce	79 (79)	260 (260)	180 (120)	267	15
Monitored Workers	60 (60)	27 (27)	20 (15)	0	0
# of Personal Dust Samples	14 (14)	28 (75)	15 (8)	39	33
Analysis for all workers who worked greater than 200 hours in the reporting period:					
Mean External Dose (mSv)	0.03 (0.03)	0.04 (0.25)	0.053 (0.04)	0.21	0.1
Maximum External Dose (mSv)	0.25 (0.25)	0.20 (0.25)	0.21 (0.06)	0.43	0.4
Mean Internal Dose (mSv)	0.06 (0.06)	0.40 (0.27)	0.62 (0.07)	0.70	1.5
Maximum Internal Dose (mSv)	0.42 (0.42)	0.90 (0.27)	1.2 (0.09)	0.74	1.5
Mean ED (mSv)	0.10 (0.09)	0.44 (0.52)	0.67 (0.13)	0.97	0.28
Maximum ED (mSv)	0.67 (0.67)	1.1 (0.52)	0.83 (0.15)	1.2	1.6
Collective Dose (man.mSv)	7.9 (7.9)	114.4 (130)	149.4 (15.6)	259.0	4.2

Parameter	Reporting Entity (De-identified by Numeric Identifier)				
	20	**22 [2]**	**23 [1]**	**24 [1]**	**25 [1]**
Distribution of EDs (mSv) for workers who worked > 200 hours in the reporting period:					
≤ 1.0	79 (79)	260 (260)	180 (120)	251	10
1.1 to 2.0	0 (0)	0 (0)	0 (0)	16	5
2.1 to 3.0	0 (0)	0 (0)	0 (0)	0	0
3.1 to 5.0	0 (0)	0 (0)	0 (0)	0	0
>5.0	0 (0)	0 (0)	0 (0)	0	0

Notes to Table 39 (continued):

[1] 2019-20 internal dose data includes contribution from thoron, radon, and their progeny

[2] 2018-19 internal dose data includes contribution from thoron, radon, and their progeny

8.5 COMPARISON OF 2018-19 AND 2019-20 DATA

A summary of the 2019-20 and 2018-19 data is reported in Table 40 [58], and the distribution of doses in the 2018-19 reporting period are compared to the 2019-20 data in Table 41 [59].

8.6 CONTRIBUTION VIA EXPOSURE PATHWAY

Thirteen REs provided estimates of the contribution made by all three of the major exposure pathways, viz: external Y; LLα; and Tn / Rn and TnP / RnP.

Table 42 [59] assesses the relative contribution from each of the three exposure pathways to the maximum annual dose as reported by each of the 13 REs.

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[58] Subsequent to the publication of Ralph et al. (2020a), one RE (#13) submitted an annual report, and REs #9, #11, #15, #16, #22 and #23 provided additional data. The data has been assimilated into this research, and as a result, the information reported for 2018-19 in Table 40 does not align directly with the information provided in Ralph et al. (2020a).

[59] With the exception of collective dose, where the reported data allowed, the dose estimates in Tables 40, 41 and 42 have been rounded to two significant figures.

TABLE 40: COMPARISON OF 2019-20 DATA TO 2018-19

Parameter	2018-19 data	2019-20 data	Non-Rounded Difference (%)
Number of REs	17	19	+2
Exempt REs	2	2	0
Number of Annual Reports Received	15	17	+2
Workforce	1,524 [1]	1,963 [2]	+439 (+29%)
Monitored Workers (MWs)	248	323	+75 (+30%)
MWs as % of Workforce	16.3	16.5	+0.2 (1.2%)
Workers Exceeding ED 5mSv	0	3	+3
Personal Gamma Monitors	976	1,570	+594 (+61%)
Personal Monitors per Worker	0.64	0.80	+0.16 (+25%)
Mean External dose (mSv)	0.40	0.30	-0.10 (-25%)
Maximum External Dose (mSv)	1.5	1.9	+0.26 (+17%)
Personal Dust Samples	738	725	-13 (-1.8%)
Personal Dust Samples per RE	49.2	42.6	-6.6 (-13%)
Personal Dust Samples per Worker	0.48	0.37	-0.11 (-23%)
Mean Internal dose (mSv)	0.74 [3,4]	1.0 [3,4]	+0.27 (+36%)
Maximum Internal Dose (mSv)	3.7 [5]	4.9 [5]	+1.26 (+34%)
Mean Internal dose from LLα (mSv)	0.40 [4]	0.54 [4]	+0.14 (+35%)
Maximum Internal Dose from LLα (mSv)	3.2	3.7	+0.52 (+16%)
Mean Internal Dose: TnP & RnP (mSv)	0.34 [4]	0.47 [4]	+0.13 (+38%)
Maximum Internal Dose: TnP & RnP (mSv)	1.3	2.1	+0.80 (+64%)

Parameter	2018-19 data	2019-20 data	Non-Rounded Difference (%)
Mean ED (mSv)	0.71 [4]	0.97 [4]	+0.23 (+32%)
Maximum ED (mSv)	4.4	6.0	+1.58 (+36%)
Collective dose (man.mSv)	720	1,914	+1194 (+166%)

Notes to Table 40:

[1] Best estimate made based upon information provided in previous reporting periods. Note, REs #11 and #13 provided data after the publication of Ralph et al. (2020a).

[2] All REs provided workforce data.

[3] Sum of the mean internal dose from LLα and TnP & RnP.

[4] The reported value is not weighted by workforce.

[5] Sum of the internal dose from LLα and TnP & RnP

TABLE 41: COMPARISON OF 2019-20 DOSE DISTRIBUTION DATA TO 2018-19

Dose Range (mSv)	Workers in Dose Range	
	2018-19	**2019-20**
≤ 1.0	1,371 (90%)	1,702 (87.9%)
1.1 to < 2.0	120 (7.9%)	139 (7.2%)
2.1 to 3.0	28 (1.8%)	80 (4.1%)
3.1 to 5.0	5 (0.3%)	13 (0.7%)
5.1 to 10.0	0	3 (0.2%)
>10.0	0	0
Total	**1,524**	**1,937** [1]

Note to Table 41:

[1] The difference between this value and the workforce number reported in Table 3 (refer to Chapter One) is due to the exclusion of workers who worked less than 200 hours in the reporting period.

TABLE 42: CONTRIBUTION TO MAXIMUM ED PER REPORTING ENTITY FROM EXPOSURE PATHWAY

Reporting Entity	Maximum Dose (mSv)	Maximum Dose from source (mSv) and (%) [1]		
		External γ	Internal LLα	Internal TnP, RnP
#2	1.6	1.5 (95%)	0.07 (4.5%)	0.01 (0.6%)
#3	3.3	1.3 (39%)	1.7 (52%)	0.30 (9%)
#4	6.0	1.6 (26%)	3.7 (62%)	0.68 (12%)
#7	3.9	0.38 (10%)	3.0 (77%)	0.53 (14%)
#8	3.7	1.1 (30%)	1.3 (35%)	1.3 (35%)
#9	2.5	0.69 (28%)	1.2 (47%)	0.62 (25%)
#11	1.7	0.04 (2%)	0.7 (40%)	1.0 (58%)
#13	2.5	1.2 (48%)	1.2 (48%)	0.09 (4%)
#15	2.4	1.3 (56%)	0.67 (28%)	0.38 (16%)
#16	0.53	0.01 (2%)	0.05 (9%)	0.48 (90%)
#23	0.83	0.21 (25%)	0.42 (51%)	0.2 (24%)
#24	1.2	0.43 (37%)	0.55 (47%)	0.19 (16%)
#25	1.6	0.07 (4%)	0.29 (18%)	1.3 78%)
Range (mSv)	0.53 to 6.0	0.01 to 1.6	0.05 to 3.7	0.01 to 1.3
Range (%)	-	2% to 95%	4.5% to 77%	0.6% to 90%
Mean (mSv)	2.4 [2]	0.76	1.1	0.54
Mean (%)	-	31.7%	45.8%	22.5%

Notes to Table 42:

[1] Analysis of the maximum reported ED, and not the maximum from each pathway.

[2] Sum of the means of the maximums.

8.7 DISCUSSION

The mean annual dose reported by the 17 REs increased by 32.4% to 0.94mSv in 2019-20 from 0.71mSv reported in 2018-19.

- This is an important finding, as it is a significant increase, and indicates that the mean annual worker dose is approaching the 1mSv annual dose estimate at which regulatory intervention should be considered.

The maximum reported annual dose in 2019-20 was 6.0mSv, an increase of 36.4% from 2018-19 (4.4mSv).

As is highlighted in Table 41, three workers received annual doses of more than 5mSv, placing them in the category of Designated Worker (DW) [60]. As was discussed in Section 7.8, the last time that the Western Australian mining industry reported having workers with annual doses that placed them in the DW category occurred in the 2009-10 reporting period As is reported in Table 18 in Section 5.8, four DWs were identified in 2009-10, and a maximum annual dose of 10.4mSv (52% of the annual derived limit) was reported.

The 2019-20 reporting period is the first time in a decade in which worker annual doses have been elevated to the point that DWs have been identified.

8.7.1 Western Australian mining workforce potentially exposed to NORs

As was discussed in Section 5.4, the history of the Western Australian mining industry is replete with expansion and contraction of the number of mining operations and the corresponding size of the workforce. The interval between the 2018-19 and 2019-20 reporting periods was not atypical – but the changes that altered the status of the four REs serve to highlight the challenges in tracking the number of REs, the commodity being mined and the size of the NOR-exposed workforce.

The number of REs increased by two, from 17 to 19 between the 2018-19 and 2019-20 reporting periods, with two operations exempt from producing an annual report of worker

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[60] Replaces the term Designated Employee (DE) in the MSIR legislation.

doses. The two new REs comprised of a large employer in the mineral sands category and a small employer in the "Other Activities" category.

The increase of two REs is a nett effect. During the 2019-20 reporting period, former RE#28 (a large employer in the lithium/tantalum category) went into hiatus, whilst RE#2 (a mineral sands operation) recommenced operating after several years of inactivity.

- The 19 REs represent an historical maximum, and as shown in Table 38, are comprised of nine mineral sands operations; two operations in the rare earths sector; two lithium/tantalum operations; and four "other activities" [61].

All 17 REs provided data on the size of their workforce REs for the 2019-20 reporting period. Despite the loss of 300 workers with the cessation of activity at RE#28, the total workforce employed by the REs in 2019-20 increased by 439 (28.8%) to 1,963 from the 1,524 [62] employed in 2018-19. As can be seen from Table 39, REs #6, #7, #8 and #23 all reported significant increases in workforce numbers, reflecting an increasing level of investment in the mineral sands and downstream processing industry sectors.

Chapter Five traced workforce numbers back to 1981, noting that the workforce reached a nadir of 434 employees in the 2015-16 reporting period, and has undergone significant expansion in the years since.

- The 1,963 workers employed by REs in 2019-20 is an historical high.

8.7.2 Designated Workers and Monitored Workers

As was discussed in Section 5.4, confusion over whether a worker is categorised as a DW or not appears to persist across most of the REs. Because there were no DWs reported in Ralph et al. (2020a), the authors opted to treat those workers defined as DWs in annual reports as "Monitored Workers" (MWs) as a way of illustrating the monitoring effort across all REs.

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[61] Described in Ralph et al. (2020a) as "downstream processing of mineral products". However, as the range of activities in this category has expanded, the former descriptor is no longer appropriate.

[62] Includes workforce data received after publication of Ralph et al. (2020c)

As can be seen in Table 40, the number of MWs increased from 248 in the 2018-19 reporting period to 323 in 2019-20, representing a slight increase in MWs as a percentage of the workforce, from 16.3% in 2018-19 to 16.5% in 2019-20.

8.7.3 Analysis of External Y Dose

Table 40 shows that 1,570 personal external Y monitors were issued to workers in 2019-20, compared to 976 in 2018-19, representing an increase of 60.9%. The 2019-20 data equates to 0.80 external Y monitors per worker as compared to 0.64 in 2018-19. In terms of MWs, the 2019-20 data equates to 4.9 external Y monitors per MW, whereas in 2018-19 it was 3.9.

Although the increase is encouraging, a question remains as to the representativeness of collecting data at a rate of less than one external Y monitor per worker per year, especially when a minimum of four personal monitors per year per worker are required to establish an annual dose.

8.7.3.1 Mean external Y dose

The mean external Y dose decreased from 0.4mSv in 2018-19 to 0.3mSv in 2019-20. Of the 13 REs that reported in 2018-19, four (#3, #4, #15 and #23) reported slight increases in mean external Y dose, whilst five (#5, #6, #9, #16 and #20) reported no discernable change. REs #7, #8, #11, and #22 all reported reductions of 50% or greater in mean dose from external Y in 2019-20 from the results provided in 2018-19.

- The decrease reported by RE#22 is explicable. The operation was reporting for only a second year and had embarked upon a monitoring programme aimed at better defining worker exposures.
- The decrease of 90% reported by RE#11 is due to a shift from using time and motion studies to produce “worst-case” theoretical doses to personal workforce monitoring.
- The decreases reported by long-established REs #7 and #8 were not accompanied by an explanation and require further investigation.

In combination, the magnitude of the decreases in mean external Y dose from the four REs (#3, #4, #15 and #23) is sufficient to indicate a declining trend across all REs. However, this is not an accurate representation and is contrary to the increase of 23.4% in the maximum reported external dose, from 1.5mSv in 2018-19 to 1.9mSv in 2019-20.

8.7.3.2 Maximum external Y dose

Seven REs reported an increase in the maximum external Y dose between the two reporting periods. Two REs (#9 and #20) reported no discernable change, and four (#7, #11, #16 and #22) reported a decreased maximum external Y dose.

- In a similar fashion to RE#22 explained above, RE#16 reported for a second time after an extended hiatus, and therefore the dose trend is formative.
- RE#11 has been explained above, whilst
- The >55% decrease reported by RE#7 requires further investigation.

The maximum external γ dose of 1.9mSv in 2019-20 occurred at RE#3, which reported a maximum external Y dose of 1.4mSv in 2018-19.

- Assuming that there were no other contributing factors such as an increase in the NOR-content of the mineral feedstock, the 32% increase can only be attributed to an absence of shielding, or extended periods spent by workers in proximity to NOR-containing materials.
- The increase should serve as a reminder to the REs of the application of good engineering controls and administrative practices that do not allow the build-up of NOR-containing mineral; the need for signposting of areas of elevated γ levels; and reinforcement that workers should limit their periods of exposure to NORs.

8.7.4 Analysis of internal doses

As shown in Table 40, the mean internal dose increased by 28.4% from 0.74mSv in the 2018-19 reporting period to 1.0mSv in 2019-20. The maximum reported internal dose increased by 34%, from 3.7mSv in 2018-19 to 4.9mSv in 2019-20.

8.7.4.1 Contribution by Dose $_{\text{TnP \& RnP}}$

Encouragingly, the number of REs that assessed the contribution of the TnP & RnP exposure pathway increased from seven in 2018-19 to 13 in 2019-20.

As can be seen from Table 40, the mean dose $_{\text{TnP \& RnP}}$ increased by 20.6%, from 0.34mSv in 2018-19 to 0.47mSv in 2019-20, and the maximum dose $_{\text{TnP \& RnP}}$ increased by 63.5% from 1.3mSv in 2018-19 to 2.1mSv in 2019-20.

The maximum dose $_{\text{TnP \& RnP}}$ was reported by RE#9, a downstream processing operation in which fumes containing NORMs are generated. The particle size of fumes is considerably smaller than the dusts encountered in most of the other REs. The 2019-20 dose $_{\text{TnP \& RnP}}$ is in keeping with findings from Ibrahim, Aassy, Ghany, and Gamil (2018), on the influence of particle size on radon exhalation. By way of comparison, in the 2018-19 reporting period, prior to implementation of the revised DCs for this pathway, RE#9 recorded a maximum dose $_{\text{TnP \& RnP}}$ of 0.32mSv, from a limited sampling campaign.

- Assuming all other parameters remained as per 2018-19, the seven-fold increase in maximum dose $_{\text{TnP \& RnP}}$ underscores the impact of the revised DCs on this exposure pathway.
- The 2019-20 data (2.1mSv) indicates that a detailed evaluation of TnP & RnP exposure is warranted at this RE.

The next highest estimate of dose $_{\text{TnP \& RnP}}$ of 1.3mSv (rounded) was reported by RE#25, which handles bulk materials in enclosed warehouses. This reported dose estimate should serve as a timely reminder to all REs of the potential for TnP & RnP build-up in poorly ventilated workspaces where bulk volumes of NOR-containing materials may accumulate.

As was discussed in Section 1.7, monitoring of this exposure pathway is largely performed via the use of passive sampling for ^{220}Rn and ^{222}Rn and making assumptions about the equilibrium factors with TnP & RnP for inclusion into dose estimates using time and motion studies. As discussed in Section 1.7 and reiterated in Section 4.1 this sampling methodology is not a preferred practice. The potential for significant contribution from this pathway is now understood by REs, and as a result, further research using active sampling for TnP & RnP, to test the assumptions in relation to equilibrium factors is encouraged.

8.7.4.2 Contribution by Dose LLα

As shown in Table 40, 725 personal dust samples were collected on workers in 2019-20 compared to 738 in 2018-19, representing a decrease of 1.8%.

- Disconcertingly, the dust samples collected per worker decreased from 0.48 to 0.37 between the two reporting periods.

The decrease of 23% continued a downward trend identified in Chapter Five in which it was observed that the [34 year] average since 1985 has been 1.5 samples per worker per year, peaking of 3.0 samples per worker in the 2005-06 reporting period. Chapter Five highlighted that the minimum of 0.5 (rounded) samples per worker per year occurred in 2018-19, and that disconcertingly, personal dust sampling (on a samples per worker basis) reached a 45-year nadir in 2019-20.

The paradox of the rate of sampling for LLα in dusts being at an historical minimum, at a time when the DCFs for NORs in those dusts have increased (in some cases, significantly) is self-evident.

The mean dose $_{LL\alpha}$ increased by 35% from 0.40mSv in 2018-19 to 0.54mSv in 2019-20.

The maximum dose $_{LL\alpha}$ increased by 16.3% from 3.2mSv in 2018-19 to 3.7mSv in 2019-20.

Of the 17 REs that submitted annual reports in 2019-20, three did not provide reports in 2018-19; one (#13) did not report an analysis of internal doses in 2018-19; and two (#16 and #20) report biennially, and the results did not change from 2018-19.

Of the remaining 11 REs, ten reported *significant increases in mean internal dose estimates*, and all but RE#15 reported significant increases in the *maximum* reported internal dose from exposure to dusts containing LLα.

A comparison of the mean and maximum doses arising from exposure to LLα in dusts, as reported in the 2018-19 and 2019-20 annual reports is provided in Table 43.

As can be seen from Table 43, the increase in mean internal dose from exposure to LLα in dusts varied significantly by RE and ranged from an increase of 32% (RE#4) to 500% (RE#23).

- The mean of the increases in mean doses was 136%, whilst the maximum of the mean doses increased by 145%.

Excluding RE#15, which reported a significant (but unexplained) decrease in maximum internal dose from exposure to LLα in dusts, the maximum for the remaining eight REs increased by between 63% and 956%.

- The mean of the maximums increased by 218%.

TABLE 43: COMPARISON OF 2018-19 TO 2019-20 DOSE $_{LLA}$ DATA

Reporting Entity	Mean Dose (mSv) and Change (%)			Maximum Dose (mSv) and Change (%)		
	2018-19	2019-20	Change	2018-19	2019-20	Change
#3	0.42	0.69	+64%	1.2	2.2	+91%
#4	0.53	0.70	+32%	0.69	3.7	+439%
#5	0.22	1.3	+491%	0.61	3.6	+490%
#6	0.40	0.90	+125%	0.60	1.3	+117%
#8	0.30	0.90	+200%	0.80	1.3	+63%
#9	0.34	0.80	+135%	0.56	1.2	+105%
#15	0.30	0.58	+93%	1.4 [1]	0.67 [1]	-50% [1]
#22	0.25	0.40	+60%	0.25	0.90	+260%
#23	0.07	0.42	+500%	0.09	0.95	+956%
Mean	0.31	0.74	+136%	0.59	1.9	+218%
Maximum	0.53	1.3	+145%	1.2	3.7	+223%

Notes to Table 43:

[1] Excluded from calculations of the mean and maximum values.

REs #22 and #23 were reporting for the second time, and their dose trends are yet to be fully developed. However, the removal of these two REs has a marginal impact on the increase of mean values – the mean of the mean increase reduces to 134% (compared to 136%) and the mean of the maximum increase decreased to 201% (compared to 218%).

- As a result of the marginal impacts, the data from REs #22 and #23 are included in the following discussion.

In Chapter Seven the researcher forecast that by applying a default AMAD of 5µm and assuming secular equilibrium in insoluble dusts that comprised a ^{232}Th to ^{238}U ratio of 10:1, if all other variables, such as activity concentration in the airborne dusts, worker exposure patterns and dust loading in the workplace atmosphere had remained equal, the DCF would increase by a factor of 2.1, from 0.007mSvBq$_{\alpha}^{-1}$ to 0.0148mSvBq$_{\alpha}^{-1}$, and accordingly doses from internal exposure to LLα would have increased by a factor of 2.1.

As can be seen from the data presented in Table 43, the increase in mean internal dose from exposure to LLα in dusts varied significantly by RE and ranged from an increase of 32% (RE#4) to 500% (RE#23).

However, and paradoxically, two REs reported decreases in internal dose parameters. RE#7 reported a decrease of 40% for mean internal dose (2.04mSv in 2018-19 to 1.24mSv in 2019-20), and RE#15 reported a decrease of 50% in the maximum dose. The decreases were not accompanied by explanatory notes, and therefore it is recommended that further analysis of the decreases experienced by these two REs is undertaken.

RE#4 anchors the increase in internal dose to the revised DCs, stating in the 2019-20 annual report "a DCF of 0.0136 [mSvBq$_{\alpha}^{-1}$] has been used to calculate dose from dust inhalation, resulting in significantly higher levels during this reporting period". It is evident from this statement that RE#4 is suggesting that increases in dose estimates are because of the increase in DCF, and not because of an increase in the NOR content of the minerals being processed, or a failure in dose reduction controls.

A coarse analysis of the activity concentration of dusts across the nine REs assessed in Table 43 found that the mean LLα activity concentration in dusts *increased* by 30% to 39 mBqm^{-3} between 2018-19 and 2019-20. The mean of the maximum reported LLα activity concentrations *decreased* by 17% to 197 Bqm^{-3} in 2019-20.

- REs #4 and #5 reported significant increases in both the mean and maximum activity concentrations; and
- REs #9 and #22 reported significant decreases in the mean and maximum activity concentrations.

The variations in activity concentrations between reporting periods makes a quantitative analysis of the impact of the revised DCs across all REs problematic. However, one RE, #6, reported a 10% increase in mean activity concentration and a 6% reduction in maximum activity concentration, indicating a degree of similarity in dust conditions across the two reporting periods. RE#6 reported an increase in mean dose of 125% and a similar increase (117%) in maximum dose across the two reporting periods.

It is prudent to conclude that most of the increase in reported dose $_{LL\alpha}$ witnessed at RE#6 is attributable to the increase in DCs as published in ICRP-137 and ICRP-141. Further, the estimate of an increase of a factor of 2.1 as forecast by Ralph et al. (2020c) served as a useful forward indicator of the potential for increased internal dose estimates as a result of application of the revised DCs.

8.10.5 Distribution of annual doses

The distribution of doses in the 2019-20 reporting period are compared to the 2018-19 data in Table 41.

As can be seen from Table 41, most workers (90% in 2018-19 and 88% in 2019-20) received annual doses of less than 1mSv. However, there is a noticeable increase in the percentage of workers receiving annual doses of greater than 2.1mSv, and importantly three workers were estimated to have received doses more than 5.1mSv, placing them in the Designated Worker (DW) category.

8.10.6 Contributions to annual dose

Thirteen REs provided estimates of the contribution made by all three of the major exposure pathways (external Y, LLα and TnP & RnP). An analysis of the relative contributions from the exposure pathways to the maximum annual dose reported by each of the 13 REs is provided in Table 42

As can be seen from the data in Table 42, the relative contribution by exposure pathway varies significantly between REs, underpinning the need for each RE to conduct bespoke monitoring campaigns for the three exposure pathways.

- It is important to note that each exposure pathway is the predominant source of dose in at least one of the REs.

As a way of modelling the relative contribution to dose from each of the exposure pathways, a hypothetical “mean of the maximum doses” equivalent to an annual dose of 2.4mSv was calculated in Table 42 and included in the bottom two rows of the Table. The hypothetical model demonstrates that across the 13 REs that monitored all three exposure pathways, external Y contributed 31.7%; LLα contributed 45.8%; and TnP & RnP contributed 22.5% of the hypothetical 2.4mSv.

- The modeling serves to emphasise that whilst LLα remains the most significant contributor to annual dose, all three exposure pathways can contribute significantly to annual dose and require appropriate monitoring.

The finding that LLα remains the most significant exposure pathway further reinforces that the disconcerting decline in sampling for LLα in dusts needs to be arrested.

8.10.7 COLLECTIVE DOSE

The issues with collective dose were discussed in Section 5.11, however a comparison of collective dose by reporting period provides a useful indicator of the success (or otherwise) of intervention methods implemented to reduce worker radiation exposures.

As shown in Table 40, the collective dose increased by 1,194mSv in the interval between the two periods, from 720mSv in 2018-19 to 1,914mSv in 2019-20.

The significant increase of 166% is in a large part due to the 29% increase in the size of the workforce, in combination with the increased mean annual dose across all REs, and the increasing recognition of the contribution from the TnP & RnP exposure pathway.

Of the 1,914mSv reported in 2019-20:

- 363mSv (19.0%) arose from external Y (304mSv, 42.2% in 2018-19).
- 972mSv (50.8%) arose from LLα (337mSv, 46.8% in 2018-19); and
- 579mSv (30.2%) arose from TnP & RnP (79mSv, 11% in 2018-19).

The increase in collective dose is attributable in some part to the revised DCs and changes in DCFs for calculating internal dose from LLα in NOR-containing dusts.

Also note that in the analysis of contribution to collective dose, at 50.8%, the contribution to annual dose arising from LLα in NOR-containing dusts is the most significant pathway, further supporting the requirement to arrest the decline in personal dust monitoring across the REs.

8.8 LIMITATIONS OF THIS RESEARCH

An error analysis is not mandated to be included in the annual reports submitted by REs and therefore, an analysis of the errors involved in estimating the doses reported by the REs cannot be included in this review. As a result, the data is cited “as presented” in the submitted reports, with the exception that the estimates of dose have been rounded to two significant figures, where possible.

Marshman and Hewson (1994, p. 61) counselled “the estimates [i.e., annual doses] should be interpreted and used with caution”, and the caution is applicable to this research in interpreting the estimates of internal doses from dust containing LLα and from exposure to TnP & RnP.

The continued trend of decreasing numbers of personal dust samples per worker increases the uncertainty associated with the reported internal dose estimates, and further complicates the assessment of the impacts of the revised DCs.

8.9 CONCLUSIONS

Nineteen mining operations were identified as reporting entities (REs) in the 2019-20 reporting period, two of which were exempt from producing an annual report of worker annual doses. The number of workers employed by the 17 REs that submitted annual reports reached an historical high of 1,963.

The mean annual dose reported increased by 32.4% to 0.94mSv in 2019-20 from 0.71mSv reported in 2018-19. This is an important finding, as it is a significant increase, and indicates that the mean annual dose is approaching the 1mSv annual dose estimate at which regulatory intervention should be considered.

The maximum reported annual dose in 2019-20 was 6.0mSv, an increase of 36.4% from 2018-19 (4.4mSv). The 2019-20 reporting period is the first time in a decade in which worker annual doses have been elevated to the point that DWs have been identified.

The mean dose from exposure to LLα has increased by 35.0% from 0.40mSv in 2018-19 to 0.54mSv in 2019-20. The maximum dose $_{\text{LL}\alpha}$ increased by 16.3% from 3.2mSv in 2018-19 to 3.7mSv in 2019-20. It is contended that the increase is largely attributable to the revised DCs published in ICRP-137 and ICRP-141 but acknowledge that this hypothesis requires testing via further analysis. Significant variations between REs make a generalised conclusion problematic.

Although the frequency of monitoring of the workforce for external Y has improved, the monitoring of workers potentially exposed to LLα has continued a decreasing trend witnessed over the past decade and has reached an historical low. This finding dilutes the confidence that the data provide across the REs is truly representative of exposures across SEGs and undermines the confidence in reported annual doses.

Whilst there appears to be an increase in annual doses across the REs, it is incumbent upon the individual REs to evaluate the contribution from each potential exposure pathway.

This Chapter endeavours to evaluate the impacts of the revised dose coefficients published in ICRP-137 and ICRP-141 on the estimates of worker doses by comparing the data contained in the 2019-20 annual reports with those submitted immediately prior to the implementation of the revised DCs in 2018-19.

The evaluation was made more difficult than otherwise due to the wide variation in results as reported by REs, with some reporting unexplained decreases in annual doses arising from inhalation of LLα in NOR-containing dusts.

However, most REs reported increased doses, and, from these data, general trends could be identified. The research found that mean and maximum doses increased significantly, but not to the extent forecast in Chapter Seven.

The prediction made in Chapter Seven that the changes in DCs would result in some workers receiving doses that would categorise them as Designated Workers was realised - Western Australia's mining workforce included Designated Workers for the first time in a decade.

Disconcertingly, the anticipated response by the state’s mining industry to the findings reported in Chapter Seven did not materialise. Personal dust sampling of workers continued the declining trend highlighted in Chapter Seven, which was a continuation of the trend first identified in Chapter Five. It is doubtful whether the number of samples per worker is sufficient to provide the required level of confidence in the data for internal dose estimates provided by the REs.

A consequence of the research reported in this Chapter is that the historical record as reported in Chapter Five is extended to include the 2019-20 reporting period.

The researcher is confident that the template developed for recording, presenting, and analysing the data extracted from annual reports submitted by REs, will be a useful tool for future researchers. Further, the research presented in Chapter Five, Chapter Seven, and this Chapter, constitutes a baseline against which to benchmark doses to the Western Australian mining workforce in the future.

Having established the protocol for *evaluating* worker doses and making recommendations for improving the veracity of worker dose estimates in Chapters Three to Eight, attention changes to *quantifying and controlling* a potential source of exposure from PRSM in Chapter Nine.

CHAPTER NINE: AN INVESTIGATION INTO CONTROLLING THE RISKS FROM POTENTIALLY RADIOACTIVELY CONTAMINATED MINING PLANT AND EQUIPMENT

It is common that the absence of (external) γ-radiation, in combination with the absence of ^{222}Rn, is used as an indication for the absence of NORs in products, by-products, waste streams and installations or equipment…

… little or no references have been found regarding occurrence and transport mechanism of unsupported lead or polonium.

The only reliable method to obtain information on the presence of unsupported ^{210}Pb / ^{210}Po in equipment, product, or waste streams … is the representative sampling and subsequent analysis by well equipped, experienced radiological laboratories.

Radioactive Lead: An underestimated NORM issue?

Hartog, Knaepen and Jonkers (1997)

As was discussed in Section 1.5.1, the extraction and processing of minerals can disturb secular equilibrium resulting in an uneven distribution of activity concentrations in different parts of the processing cycle; plant and equipment; or in waste streams ICRP (2019b). The dispersed radionuclides may present sources of exposure to workers and the community and a source of environmental contamination.

As was outlined in Section 4.4, the Western Australian mining industry has recent experience involving potentially radioactive scrap metal (PRSM) which fortunately, did not result in an uncontrolled release of the PRSM into the environment or the community. The two incidents involved corrosion scales from (a) a mineral sands “polishing” plant and (b) the triggering of radiation detectors at a scrap metal yard by PRSM from an underground nickel operation.

As was discussed in Section 4.4.3, exceptionally elevated concentrations (up to 15,000,000 Bqkg^{-1}) of specific radionuclides have been encountered in situations where secular equilibrium has been disturbed. Activity concentrations as discussed in Section 4.4 can readily lead to doses that exceed annual limits if inadvertent exposure occurs. Because the lithology of Western Australia is replete with NORs, PRSM presents a potentially significant source of risk to workers, the community and the environment and substantial cost to the Western Australian mining industry to remediate.

Identification of the potential for PRSM to occur is important to its subsequent management. This Chapter explores the application of gamma spectrometry to identify and quantify NORs in PRSM and evaluates a potential solution to reducing the risks of inadvertent exposures.

9.1 BACKGROUND

The nature, occurrence, and challenges for managing radiation exposures arising from PRSM were discussed in Sections 1,5, 1.7 and 4.4. However, little research has been conducted into the control of exposures from, and management of the environmental impacts of PRSM.

The IAEA (2006, pp. 41-42) suggests that the disposal of PRSM may, dependent upon the level and type of radioactive contamination, require specific control measures including “… the need for decontamination using processes such as high-pressure water jet cleaning … in a suitable facility.” Similarly ANSTO Minerals (2017, p. 9) recommended that because of their radioactive content, the scales on the PRSM from the mineral polishing circuit should be "removed by wet cleaning", referenced hereinafter as high-pressure water-cleaning (HPWC).

The recommendations from IAEA and ANSTO Minerals were persuasive, and HPWC was applied in this research.

Whilst HPWC may remove radioactive and other contaminants from PRSM, effective management is required to ensure the contaminants are then not dispersed to the environment. The researcher contended that effective management of the NOR-containing contaminants could be achieved via containment in the form of an engineered passive filtration technology such as a stormwater filtration device (SFD) [63].

Alam, Anwar, Sarker, Heitz, and Rothleitner (2017) evaluated the performance of an SFD designed and manufactured by Urban Stormwater Technologies [64], which utilises a patented synthetic, non-woven, needle punched polypropylene geotextile as a filtration material. Alam et al. (2017, p. 77) concluded that, what is referenced hereinafter as the ARI SFD, "showed higher potential to capture gross pollutants down to 150µm than similar devices described in previous studies" and "[no other] SFD can capture gross pollutants down to these small particle sizes".

The researcher proposed a trial in which the corrosion scale on PRSM is removed by HPWC and is filtered through the ARI SFD. The research hypothesised that if the filtering of the slurry generated in the removal process was successful in removing a significant proportion of the radioactive content of the filtrate the liquids could be either re-used or allowed to report to tailings without unduly influencing the existing radiological characteristics. The radioactive contaminants would be retained in the ARI SFD as a filter-cake, and disposed of as waste,

9.2 REMOVAL AND DISPOSAL OF NOR-CONTAMINATION FROM PRSM

In relation to discharges from industries involving NORM, the ICRP (2019b, pp. 43-44) states "The protection strategy should include preventative actions aimed at eliminating or reducing

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[63] A stormwater filtration device is used to capture wash-off solid wastes (termed gross pollutants) in drainage systems to prevent them from entering water collection infrastructure or natural waterbodies.

[64] Now ARI Water Solutions Pty Ltd (ARI).

the quantity and concentration of discharges as well as mitigation actions aimed at reducing the impacts of discharges in terms of public and environmental exposures".

Removal of the NOR-contaminated scales and sludges from PRSM will reduce (often significantly) the volume of radioactive materials to be disposed, and they can be blended with other (non-radioactive) soil and disposed of in landfill or an unoccupied area, injected into abandoned wells, or discharged to large water bodies (Krieger, 2005).

An objective of the removal and disposal activity is to ensure that surrounding soil or groundwater is not subsequently contaminated as a result of the de-contamination process.

9.2.1 A simple environmental footprint analysis

The environmental benefit of collection of NOR-contaminated corrosion scale from PRSM is demonstrated from the following hypothetical scenario.

Consider a one-metre length of steel pipe with an external diameter of 20 centimetres, and a wall thickness of 0.5 centimetres.

- The pipe will weigh 24.2 kilograms [65] and occupy a volume of 0.0314 m^3.

Assuming one millimetre of corrosion scale is uniformly deposited on the internal surface of the pipe, and the density of the scale is the same as the steel,

- The scale will weigh 4.7 kilograms and occupy a volume of 0.0006 m^3.

If the corrosion scale can be removed, then (24.2) / (24.2 + 4.7) or 83.8% of the mass can be recovered and sold as scrap steel.

The volume of waste, and the corresponding environmental footprint will be reduced to 1.9% of the original volume occupied by the pipe.

Generally, charges are levied by transporters and waste disposal facilities based upon the volume of waste consigned or to be disposed. It is readily apparent from the (simplified) example provided above that significant reductions in the environmental footprint can occur and cost-savings can be made by removing the NOR-contaminated corrosion scale at source.

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[65] Assuming a density of 7,900 kgm^{-3} (Toppr, 2022)

9.2.2 Disposal of NOR-contaminated corrosion scales

The IAEA (2009, p. 35) notes that action is required to reduce doses due to exposure to [radioactive] waste, and that regulatory control is required to ensure safety.

In Western Australia regulatory control of radioactive waste occurs via the Disposal Facilities Code (ARPANSA, 2018d) which applies to the disposal of “contaminated plant and equipment [i.e. PRSM] resulting from the handling or processing of naturally occurring materials which contain radioactive materials in low but non-trivial amounts”.

Western Australia’s only operation approved under Disposal Facilities Code (ARPANSA, 2018d) is located approximately 500 kilometres from state’s capital Perth, and is accessible by road. The risks and costs associated with transportation, in combination with the area of land required to appropriately dispose of the NOR-contaminated plant and equipment, make the disposal in a facility approved under the Disposal Facilities Code, in most circumstances, cost-prohibitive.

An alternative to disposal in an approved facility is to dispose of the NOR-contaminated plant and equipment into an on-site tailings storage facility. However, the NORs will add to the level of radioactive contamination of the tailings, potentially presenting challenges for long-term management and relinquishment of the mining lease. Therefore, it is imperative to reduce the volume and activity of the NOR-contamination to ALARA.

9.2.3 Disposal of filtrate from HPWC

As was introduced in Section 2.7, the definition of whether a material is radioactive or not is based upon its activity concentration, in this Section, measured in $Bqkg^{-1}$. If a material has an activity concentration of less than 1000 $Bqkg^{-1}$ (cited as 1 Bqg^{-1} in the WHSR(Mines)), it is not deemed as radioactive, and is therefore exempt from institutional controls to limit exposure of workers and the community.

- The $1000Bqkg^{-1}$ radioactive material criteria can be considered as the primary reference level against which discharges can be evaluated.

Therefore, if filtration process is effective such that the activity concentration of the radionuclides in the filtrate is analysed as being less than the 1,000 $Bqkg^{-1}$ reference level stipulated in ARPANSA (2017a), the filtrate could be disposed of via natural or artificial drainage systems, or reused in the HPWC process.

9.2.4 Risks to the researcher

The IAEA (2010, p. 113) caution that significant dose rates inside and outside of PRSM can occur and opening the system for maintenance or other purposes, such as removal of residues and scale will increase the dose rates. The IAEA (2010, p. 120) advises that radiation protection measures are required during high-pressure water descaling, to control potential exposures arising from:

- Sludges removed from pipes, vessels, and tanks.
- Solid scale suspended in water.
- Solid scale recovered from wet … abrasive decontamination processes.
- Wastewater resulting from removal of scale by sedimentation and or filtration of water used for wet abrasive methods, in particular HPWC.

The IAEA recommendations were salient to this research and resulted in the strict enforcement of measures to ensure the minimisation of radiation exposure of the researcher.

9.3 AIMS OF THIS SECTION OF THE RESEARCH

Research by Alam (2018) demonstrated that an SFD manufactured by ARI Water Solutions (ARI) “effectively filtered particles at high flowrates”. A further study by Alam, Anwar and Heitz (2018) found that the ARI SFD is capable of filtering solutions and removing particles greater than 63µm at efficiencies up to 96%.

Accordingly, the ARI SFD was selected as the filtration technology.

The aim of this Section of the research was to determine the filtration efficiency of the ARI geotextile filter to collect corrosion scale particulates from the “slurry” created from the water used in, and the scale and sludge removed during, HPWC of radioactively contaminated equipment.

9.4 METHODOLOGY: OVERVIEW

The owners of the decommissioned mineral processing plant introduced in Section 4.4 volunteered to contribute to this research, by way of providing samples of NOR-contaminated scale and facilitating access to the decommissioned mineral separation plant for field evaluations.

This Section of the research involved laboratory-based analysis of the NOR-contaminated scale provided by the owners of decommissioned mineral processing plant to validate that the geotextile filter was capable of filtering the corrosion scale under controlled conditions. The laboratory-based tests were followed by in-field trials conducted at the decommissioned mineral processing plant, using a HPWC appliance to remove radioactive contaminants from a selected item of NOR-contaminated equipment. The resultant slurry was passed through the geotextile filter which was supported in a purpose-built SFD.

Samples of the filter cake (materials deposited upon the geotextile filter), and the filtrate that passed through the geotextile were collected and subject to gamma spectrometry and compared against each other to determine the filtration effectiveness of the geotextile.

9.4.1 Methodology: NOR-contaminated corrosion scale for laboratory assessment

Two bags of corrosion scale (hereinafter called the “connate scale”) weighing one-and-a-half kilograms each were collected by the owners of the decommissioned mineral processing plant, using a spade to scrape the internal walls of a disused vessel, once used in an acid leach process.

The connate scale presented as a heterogenous collection of shapes and sized fragments, with surface areas up to six square centimetres. To ensure a level of consistency in the sample preparation, the connate scale required homogenisation.

Sarin et al. (2001) ground a sample of corrosion tubercule formed in a drinking water system until it passed through a 150um mesh sieve. Whilst the research by Sarin et al (2001) is persuasive, it was hypothesised that high-pressure water-cleaning would generate a larger particle size, and accordingly a 1.70 mm sieve (certified by Glenammer, #21061063, 11th June 2021) was used to homogenise the connate samples. Aliquots of the two connate samples were presented to the 1.70 mm sieve and manually shaken until approximately 500 grams passed through the sieve.

In order to ascertain whether differences existed in the distribution of activity by size range, samples were collected from each of the connate scale samples and then the oversize (>1.70mm) and undersize (<1.70 mm) fractions. As a result, six samples of connate scale were collected, three from each bag, representing the heterogeneous mixture; the greater than 1.70mm fraction; and the less than 1.70 mm fraction.

Forty-seven mm diameter Millipore Petri-Pad^{TM} petri dishes (Merck, 2022), were filled to capacity with an aliquot of each of the six samples and placed in a desiccator for three days before being post-weighed and sealed with Pechiney Parafilm M (Parafilm) plastic packaging (Amcor, 2022). The date and time of sealing with Parafilm were recorded. Each of the six samples were placed into a double-lined plastic clip seal bag to minimise the opportunity for sample losses.

9.4.2 Methodology: In-field trials

The owners facilitated access to the decommissioned mineral processing plant. A suitable site for the trials was identified, adjacent to a disused engineered diversion drain which fed into a sump that had been previously used for collecting contaminated stormwater runoff.

A “background” water sample was collected from the site water supply, which was used in the HPWC trials. The sample was collected in a Techno Plas 65 mm diameter polypropylene jar (Techno Plas, 2022) and filling to the 220 ml graduation mark.

Prior to commencing HPWC, a soil sample was collected from the engineered diversion drain, adjacent to a grate that covered the opening to the sump. At the conclusion of HPWC activities, a further soil sample was collected from the same area, to determine whether any residual radioactivity remained in the vicinity of the diversion drain. The soil samples were prepared for analysis in the same fashion as the scale samples, as described in the following Section.

9.4.2 Methodology: Equipment used in the in-field trials

A 550 mm long stainless-steel pipe “reducer” flange, with visible scale deposited on the surface of the flange and internal walls was identified as a potential candidate for the trial.

The original location of the reducer within the processing plant was unable to be identified with any certainty. However, stainless-steel components were not generally associated with the acid-leach circuit in this mineral processing plant and were more commonly associated with high temperature applications such as extraction systems for flue gases, and transport of hot (>1,000° C) mineral.

NOR-contamination of the “reducer” was confirmed using a Thermo Scientific Radeye GS (serial number 11570), and a Ludlum 44-9 alpha probe (serial number PR352724) interchanged with a Thermo MC71-MHV gamma probe (serial number 19034).

The reducer was supported in a manner that provided access for the HPWC lance to access the contaminated surface(s) and promoted the flow of the water used in the cleaning process to be directed into a purposely selected [66]ARI SFD that was lined with the geotextile.

An Australian Pump Industries high-pressure cold water cleaner (Scud series) rated at 3,500 pounds per square inch (psi) at 17 litres per minute (API, 2022), supplied by the owners was used in the first trial. The pressure was increased to 4,000-psi by the addition of a turbo nozzle for the second trial. This HPWC unit was selected because “under [the] Safety Standards for operators of High-pressure Water Jetters this range is classified as Class A … no operator certification [is] required” (API, 2022), meaning that the trials could be conducted without the need for assistance from certified specialist water-jetting technicians.

As is illustrated in Figure 17, during the HPWC process the ARI SFD was supported on the polypropylene grate of a four-drum chemical-resistant polyethylene containment bund (the bund) with a capacity of 242 litres (GSS, 2022). The perforations on the four walls and base of the SFD allow the filtrate to escape the SFD and enter the bund via the grate. No spillage of the filtrate outside of the bund was observed during the HPWC process [67]. Six, two litre oblong containers (TDL, 2022) were placed within the inner structure of the bund, as close as could be achieved to the SFD.

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[66] Selected to ensure all the runoff water was directed through the geotextile.

[67] Noting that the HPWC process generates significant volumes of scattered water. However, as this water did not pass through the geotextile it is not considered as filtrate.

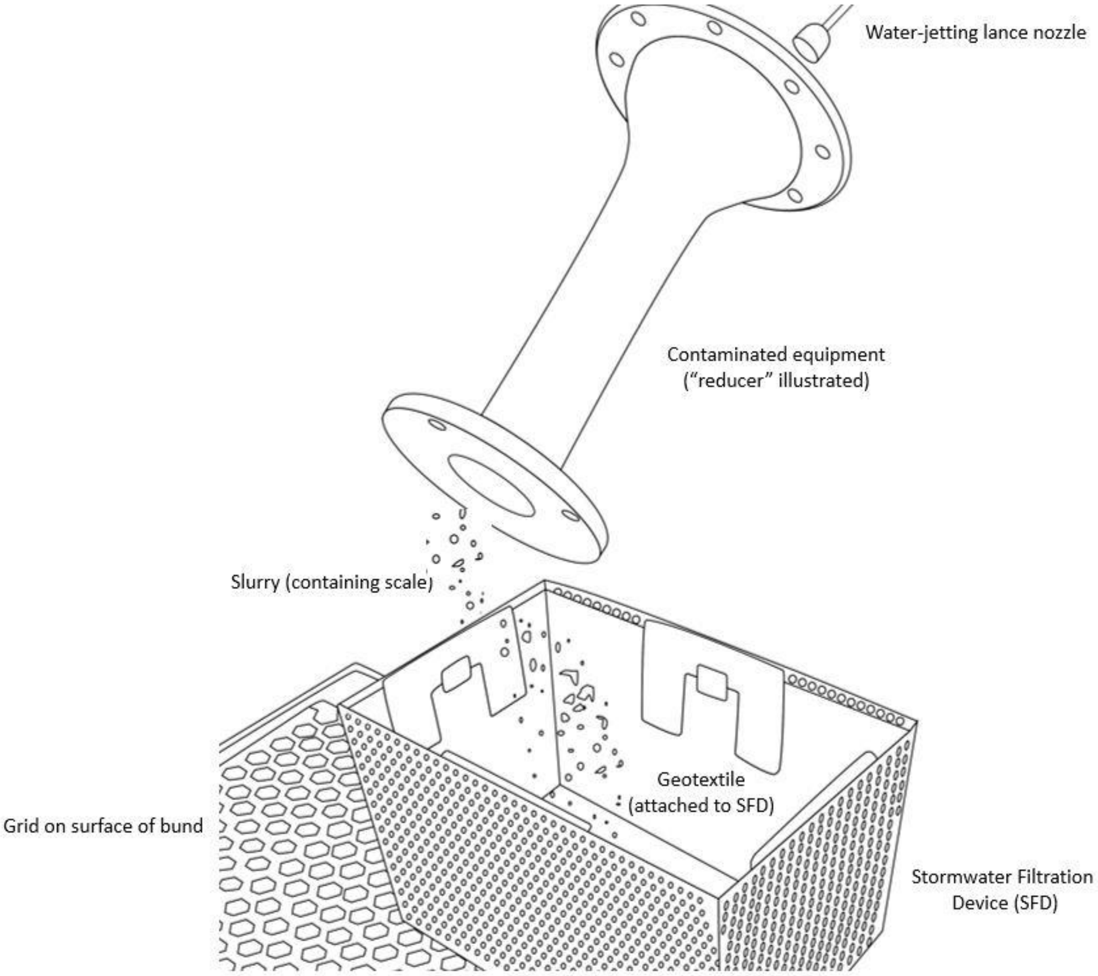

FIGURE 17: SCHEMATIC OF IN-FIELD REMOVAL OF RADIOACTIVE SCALE

At the conclusion of each trial the collected filtrate was consolidated from the two litre containers and allowed to settle overnight. The bottom of the filtrate was slightly discoloured and contained visible small-particles and a viscous "oily" substance. Two samples of the consolidated filtrate were extracted from the top two-thirds, and two from the bottom one-third of the consolidated samples, with care taken to ensure all the small particles and the viscous oily substance were collected. The second sample collected from the bottom one-third of the consolidated filtrate in each trial contained the viscous oily substance.

The filtrate samples were decanted into a Techno Plas 65 mm diameter polypropylene jar, fitted with a screw-on cap (Techno Plas, 2022). The volume of the jar was 250 ml, with 10 ml graduations marked to 220 ml. All liquid samples were standardised by filling each jar to the 220 ml graduation mark.

After collection, the filtrate samples were capped, and sealed with Parafilm, and the date and time of sealing recorded.

The scale samples were collected using a stainless-steel spatula (rinsed in distilled water after each use), placed into a two-litre container and allowed to dry overnight, before randomly selected aliquots were placed into 47mm diameter petri dishes.

Upon return to the laboratory the samples were desiccated for at least three days before being post-weighed, sealed with Parafilm, and placed into a double-lined plastic clip seal bag. The date and times of sealing were recorded for in-growth calculations in the gamma spectrometry analysis process.

9.5 METHODOLOGY: ANALYSIS BY GAMMA SPECTROMETRY

All collected samples were presented to the Edith Cowan University radiochemistry laboratory for quantification by gamma-ray spectrometry. The containers were sealed and stored for at least three weeks before measurement in order to ensure secular equilibrium between ^{226}Ra and its short-lived decay products. The activity in the sample was determined using a high-purity Ge well-type detector (Canberra, Model. GCW3523).

Samples were counted for varying periods, based upon being able to determine the activity concentration of the most active of the analysed radionuclides to an uncertainty of $\underline{+}$ 15%. As a result, counting periods ranged between 500 to 300,000 seconds, determined by the inherent activity in the samples.

Five radionuclides [68], analysed by the gamma spectrometry methodology are reported for each of the supplied water, scale and filtrate samples collected in the field evaluations. Activities of the radionuclides were determined by:

- From the ^{232}Th decay series:

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[68] Potassium-40 (^{40}K) was also quantified via its 1,461 keV emission line. However, the radiation dose to workers and members of the public arising from ^{40}K are insignificant when compared to those from the ^{232}Th and ^{238}U series and its contribution is not discussed in detail in this treatise.

  a. Radium-228 (^{228}Ra) via its immediate progeny, actinium-228 (^{228}Ac) decay at 911 keV.

  b. Thorium-228 ($^{228\text{Th}}$) via its progeny lead-212 (^{212}Pb) 238 keV emission line and thallium-208 (^{208}Tl) 538 keV emission line.

- From the ^{238}U series:

  c. Thorium-234 ($^{234\text{Th}}$) through its emission line at 63.29 keV.

  d. Radium-226 (^{226}Ra) from the 295 keV and 352 keV emission lines of its progeny lead-214 (^{214}Pb) and the 609 keV emission line from bismuth-214 (^{214}Bi).

  e. Lead-210 (^{210}Pb) via its 46 keV gamma emission.

In the instances where the analysis of one radionuclide is determined by the emission from a second radionuclide, an assumption was made that the two radionuclides are in secular equilibrium.

Samples of the materials deposited upon the geotextile filter, and the filtrate that passed through the geotextile were collected and subject to gamma spectrometry and compared against each other to determine the filtration effectiveness of the geotextile.

9.6 CALCULATION OF “FILTRATION EFFECTIVENESS”

Determination of the effectiveness of the geotextile and SFD assembly in removing the NOR-contaminated scale from the slurry created by the HPWC process was calculated by using the activity concentration, as measured in becquerels per kilogram ($Bqkg^{-1}$) for each of the radionuclides in the scale collected by the geotextile and comparing it against the activity concentration for each radionuclide in the filtrate.

The sum of the activity concentrations for all five radionuclides in the scale was also compared to the sum of the activity concentrations in the filtrate to provide a “gross effectiveness” factor.

9.7 RESULTS

The results of the laboratory and field-based evaluations of the NOR-contaminated scale and filtrate are discussed in the following Sections.

9.7.1 Gamma spectrometry of connate scale samples

The results of the gamma spectrometry analysis of the native scale samples are presented in Table 44. Sample masses varied between 29.267g and 38.926g. Counting periods ranged from 496 seconds to 725 seconds, with a mean of 568 seconds.

9.7.2 Gamma spectrometry analysis of "background" samples

The results of gamma spectrometry analysis of the water supplied to the high-pressure cold-water cleaner are presented in the first row of Table 45. The sample was counted for 94,362 seconds.

The values in in the first row of Table 45 are referenced as the "background" contribution of the supplied water to the filtrate samples.

- Note that all subsequent results cited for filtrate samples have been "background corrected" by having the results of the analysis of the supplied water subtracted.

The results of gamma spectrometry analysis of the environmental soil samples are presented in the second and third rows of Table 45. Counting periods were 323,989 seconds for the pre-HPWC sample Env.1 and 91,077 seconds for the post-HPWC sample Env.2.

The results of the soil samples included in Table 45 are discussed in Section 9.10.

9.7.3 Gamma spectrometry analysis of samples collected from HPWC of PRSM

The results of gamma spectrometry analysis of samples of the collected scale and filtrate resulting from the two trials of HPWC of the "stainless-steel reducer", are presented in Tables 46 and 47.

The scale sample collected from the first trial was counted for 18,977 seconds while the scale sample from the second trial was counted for 8,126 seconds.

The counting periods for the eight filtrate samples ranged from 92,716 seconds to 325,097 seconds, with a mean of 191,661 seconds.

- As outlined in Section 9.7.2, all results cited for filtrate samples have been background corrected by having the supplied water results subtracted.

A summary of the two trials, and calculations of the filtration efficiency of the geotextile, based upon activity concentration are presented in Table 48.

In Tables 44, 45, 46, 47 and 48 the following notes apply:

- [1] Sum of the six activity concentrations. If a “less than” value is cited, the minimum detectable activity (MDA) is used in the calculation.
- [2] ND = not detectable, after background has been subtracted.
- [3] Where the cited less than value is the applicable MDA.

Note – additional notations, specific to the individual Tables, are inserted as required.

TABLE 44: GAMMA SPECTROMETRY ANALYSIS OF CONNATE SCALE SAMPLES BY SIZE RANGE

Bag	Description	^{232}Thorium series (Bqkg^{-1})		^{238}Uranium series (Bqkg^{-1})			Total Activity Concentration (Bqkg^{-1}) [1]
		^{228}Ac	^{228}Tl	^{234}Th	^{214}Pb	^{210}Pb	
1	Not sieved	177,801 (± 9,033)	246,112 (± 14,242)	ND [2]	118,006 (± 8,291)	ND [2]	541,919 (± 18,793)
1	Oversize (>1.70mm)	193,896 (± 9,849)	263,329 (± 15,881)	ND [2]	123,016 (± 8,644)	19,620 (± 5,578)	599,861 (± 21,332)
1	Undersize (<1.70mm)	130,848 (± 6,650)	178,163 (± 10,746)	ND [2]	78,590 (± 5,524)	ND [2]	387,601 (± 13,792)
2	Not sieved	145,433 (± 7,404)	195,035 (± 11,773)	ND [2]	85,504 (± 6,014)	ND [2]	425,972 (± 15,152)
2	Oversize (>1.70mm)	165,758 (± 8,479)	222,407 (± 13,446)	ND [2]	104,434 (± 7,351)	ND [2]	492,599 (± 17,513)
2	Undersize (<1.70mm)	118,420 (± 6,076)	158,717 (± 9,605)	ND [2]	65,698 (± 4,632)	ND [2]	342,835 (± 12,273)
Six sample mean		155,359 (± 19,658)	210,627 (± 31,339)	ND [2]	95,875 (± 16,901)	19,620 [4] (± 5,578)	465,131 (± 41,053)

Notes to Table 44:

[4] Because five of the six samples reported no detectable activity, this is likely to be an over-estimate.

TABLE 45: GAMMA SPECTROMETRY ANALYSIS OF "BACKGROUND" FIELD SAMPLES

ID	Description	^{232}Thorium series (Bqkg^{-1})		^{238}Uranium series (Bqkg^{-1})			Total Activity Concentration (Bqkg^{-1}) 1
		^{228}Ac	^{228}Tl	^{234}Th	^{214}Pb	^{210}Pb	
FW.1	Field water blank	<5 [3]	<2 [3]	<11 [3]	<0.7 [3]	<30 [3]	48.7 [5]
Env.1	Soil – prior to trials	209 (± 11)	203 (± 12)	73 (± 11)	81 (± 6)	83 (± 15)	649 (± 26)
Env.2	Soil – post trials	536 (± 27)	568 (± 33)	119 (± 20)	237 (± 17)	281 (± 47)	1,741 (± 69)
Change in soil activity		327 (± 29)	365 (± 36)	46 (± 23)	156 (± 18)	198 (± 49)	1,092 (± 74)

Notes to Table 45:

[5] Because all results were less than the MDA, this is likely to be an over-estimate

TABLE 46: GAMMA SPECTROMETRY ANALYSIS OF REMOVED MATERIALS – TRIAL #1

ID	Weight (g)	^{232}Thorium series (Bqkg^{-1})		^{238}Uranium series (Bqkg^{-1})			Total Activity Concentration (Bqkg^{-1}) [1]
		^{228}Ac	^{228}Tl	^{234}Th	^{214}Pb	^{210}Pb	
Scale	45.56	2,214 (± 114)	2,811 (± 170)	<500 [3]	2,359 (± 166)	19,045 (± 2,857)	26,929 (± 2,869)
Mean: Top 2 Filtrates	220	3 (± 1)	6 (± 1)	<6 [3]	6 (± 1)	393 (± 105)	414 (± 105)
Scale – Top Mean		2,211 (± 114)	2,805 (± 170)	<494 [3]	2,353 (± 166)	18,652 (± 2,859)	26,515 (± 2,871)
Top Retention (%)		**99.9 ± 7.3**	**99.8 ± 8.5**	**98.8**	**99.7 ± 9.9**	**97.9 ± 21.0**	**98.5 ± 15.0**
Mean: Bottom 2 Filtrates	220	117 (± 11)	151 (± 17)	7 (± 7)	125 (± 16)	4,718 (± 1,213)	5118 (± 1,214)
Scale – Bottom Mean		2,097 (± 114)	2,660 (± 171)	<493 [3]	2,234 (± 167)	14,327 (± 3,104)	21,811 (± 3,115)
Bottom Retention (%)		**94.7 ± 7.1**	**94.6 ± 8.3**	**98.6 ± 1.4**	**94.7 ± 9.7**	**75.2 ± 19.8**	**81.0 ± 14.4**
4 Filtrate Mean	220	60 (± 11)	78 (± 17)	<6 [3]	66 (± 16)	2,556 (± 1,218)	2,766 (± 1,218)
Scale – 4 Filtrate Mean		2,154 (± 114)	2,733 (± 171)	<494 [3]	2,293 (± 167)	16,489 (± 3,106)	24,163 (± 3,117)
Overall Retention (%)		**97.3 ± 7.2**	**97.2 ± 8.5**	**98.8 ± 1.4**	**97.2 ± 9.8**	**86.6 ± 20.9**	**88.7 ± 15.0**

TABLE 47: GAMMA SPECTROMETRY ANALYSIS OF REMOVED MATERIALS – TRIAL #2

ID	Weight (g)	^{232}Thorium series (Bqkg^{-1})		^{238}Uranium series (Bqkg^{-1})			Total Activity Concentration (Bqkg^{-1}) [1]
		^{228}Ac	^{228}Tl	^{234}Th	^{214}Pb	^{210}Pb	
Scale	48.43	2,080 (± 111)	2,552 (± 156)	<720 [3]	2,147 (± 152)	16,489 (± 2,485)	23,989 (± 2,497)
Mean: Top 2 Filtrates	220	0 [2]	<1 [3]	<2 [3]	<1 [3]	12 (± 9)	16 (± 9)
Scale – Top Mean		2,080 (± 111)	2,551 (± 156)	<718 [3]	2,146 (± 152)	16,477 (± 2,485)	23,973 (± 2,497)
Top Retention (%)		**100 ± 7.5**	**100 ± 8.6**	**99.7**	**100 ± 10.0**	**99.9 ± 21.3**	**99.9 ± 14.7**
Mean: Bottom 2 Filtrates	220	24 (± 3)	32 (± 4)	<6 [3]	33 (± 4)	1,512 (± 461)	1,607 (± 461)
Scale – Bottom Mean		2,056 (± 111)	2,520 (± 156)	<714 [3]	2,114 (± 152)	14,977 (± 2,527)	22,382 (± 2,539)
Bottom Retention (%)		**98.8 ± 7.5**	**98.7 ± 8.6**	**99.2**	**98.5 ± 9.9**	**90.8 ± 20.5**	**93.3 ± 14.4**
4 Filtrate Mean	220	12 (± 3)	16 (± 4)	4	17 (± 4)	762 (± 461)	811 (± 461)
Scale – 4 Filtrate Mean		2,068 (± 111)	2,536 (± 156)	<716 [3]	2,130 (± 152)	15,727 (± 2,527)	23,178 (± 2,539)
Overall Retention (%)		**99.4 ± 7.5**	**99.4 ± 8.6**	**99.4**	**99.2 ± 10.0**	**95.4 ± 21.0**	**96.6 ± 14.6**

TABLE 48: SUMMARY OF GAMMA SPECTROMETRY ANALYSIS OF THE MATERIALS REMOVED IN THE TWO TRIALS

Parameter	^{232}Thorium series (Bqkg^{-1})		^{238}Uranium series (Bqkg^{-1})			Total Activity Concentration (Bqkg^{-1}) [1]
	^{228}Ac	^{228}Tl	^{234}Th	^{214}Pb	^{210}Pb	
Mean of 2 scales	2,147 (± 225)	2,682 (± 159)	<610	2,253 (± 231)	17,767 (± 3,787)	25,459 (± 3,804)
Mean of 4 top filtrates	1	3	<4 [3]	3	203 (± 106)	214 (± 106)
Scale mean + top filtrate mean	2,148 (± 225)	2,685 (± 159)	<614 [3]	2,256 (± 231)	17,970 (± 3,788)	25,673 (± 3,805)
Retention in SFD: Top Filtrate (%)	**100 ± 14.8**	**99.9 ± 8.4**	**99.3**	**99.9 ± 14.5**	**98.9 ± 29.6**	**99.2 ± 20.9**
Mean of 4 bottom filtrates	70 (± 12)	92 (± 18)	<6 [3]	79 (± 17)	3,115 (± 1,290)	3,362 (± 1,290)
Scale mean + bottom filtrate mean	2,217 (± 225)	2,774 (± 160)	<616 [3]	2,332 (± 232)	20,882 (± 4,001)	28,821 (± 4,017)
Retention in SFD: Bottom Filtrate (%)	**96.8 ± 14.1**	**96.7 ± 8.0**	**99.0**	**96.6 ± 13.8**	**85.1 ± 24.4**	**88.3 ± 18.0**
Mean of 8 filtrate samples	36 (± 12)	47 (± 18)	<5 [3]	41 (± 17)	1,537 (± 1,294)	1,666 (± 1,294)
Scale mean + filtrate mean	2,183 (± 225)	2,729 (± 160)	<615 [3]	2,294 (± 232)	19,304 (± 4,002)	27,125 (± 4,018)
Overall retention in SFD (%)	**98.4 ± 14.5**	**98.3 ± 8.2**	**99.2**	**98.2 ± 14.1**	**92.0 ± 27.4**	**93.9 ± 19.8**

9.8 DISCUSSION

The ICRP (2019b, pp. 37-38) and Hamilton et al. (2004) recommend that identification and characterisation of the NORMs and their activity concentration is required to perform appropriate dose assessments for workers and the public and evaluate the potential impacts on the environment. Accordingly, the radiological characteristics of the connate scale samples; supplied water; and the scale and filtrate samples collected in the field evaluations; were analysed via gamma spectrometry. Five radionuclides were reported for each of the samples [69].

- The radionuclides ^{234}Th and ^{210}Pb were quantified from their emission lines, whilst an assumption was made that:
    - ^{228}Ra was in equilibrium with its immediate progeny ^{228}Ac.
    - ^{228}Th was in equilibrium with ^{212}Pb and ^{208}Tl; and
    - ^{226}Ra was in equilibrium with ^{214}Pb and ^{214}Bi.

Samples were counted for varying periods, based upon being able to determine the activity concentration of the most active of the analysed radionuclides to an uncertainty of ± 15%.

As a result, counting periods were determined by the inherent activity in the samples, and ranged between 500 to 300,000 seconds.

9.8.1 Gamma spectrometry analysis of connate scale sample

The connate scale samples were provided by the owner of the disused mineral processing plant. The disused vessel was not identified, but it has been established that it originated from a different section of the mineral processing circuit from where the stainless-steel reducer was sourced.

The purpose of analysing the connate scale was to provide an indication of the magnitude of the radiological contamination likely to be encountered in the field trials, and evaluate the potential risks posed to the researchers.

As presented in Table 44 the total activity of the five analysed radionuclides was 465,131 ± 41,053 Bqkg^{-1}, an activity concentration not commonly encountered when handling NOR-containing materials,

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[69] As per Footnote 51, Potassium-40 (^{40}K) was also quantified but not discussed here.

prompting the researchers to ensure multiple levels of personal protection when conducting the field trials.

The mass of the six samples varied between 29.267g and 38.926g, and the counting periods were relatively short due to the contained activity, ranging from 496 seconds to 725 seconds, with a mean of 568 seconds.

All six samples demonstrated concentrations of ^{228}Th that exceeded ^{228}Ra by a consistent factor of 1.36 ± 0.02, indicating that ^{228}Ra is not in equilibrium with its parent ^{232}Th, and has decayed to its progeny ^{228}Th.

Similarly, ^{238}U, as measured by its progeny ^{234}Th, was not detectable, whereas ^{226}Ra was present at a consistent ratio of 0.45 ± 0.04 that of ^{228Th} from the ^{232}Th series.

It is contended that the acid-leach circuit from where the connate scale sample was drawn favoured the separation of radium radionuclides from its head-of-chain.

In the case of the ^{232}Th decay series, the activity concentration will decrease to below the reference level of 1,000 Bqkg^{-1} in approximately 45 years. However, this will not be the case for the ^{238}U decay series, as ingrowth of progeny from ^{226}Ra will ensure that contamination levels will remain in excess of the reference criteria for well into the future. This finding suggests that long-term storage, allowing for natural decay processes to reduce activity is not a viable solution to the issue of the PRSM in the disused mineral processing plant.

Encouragingly for this research the homogenisation of the connate scale samples demonstrated that the activity concentration in the undersize (<1.70 mm) samples was significantly less than that for the oversize samples (>1.70 mm).

The ratio of activity concentration in undersize to oversize samples was ~0.66 : 1, suggesting that the majority of activity concentration reported to the larger particle sizes, which, according to Alam et al. (2018) would be readily filtered by the ARI geotextile.

9.8.2 Field water blank

As can be seen from the data presented in the first row of Table 45, the activity concentration for all five radionuclides was reported as less than the MDA for a counting period of 94,362 seconds. However, as recommended by Potter (2001); Potter and Strzelczyk (2008), it is incorrect to assess values reported as less than the MDA as having no activity present. Whilst acknowledging that it may be a limitation to this study, where a value has been reported as less than a specified value, that value is used as the actual result.

Accordingly, although all radionuclides report activity concentrations as “less than” values, the sum of the activity concentrations (hereinafter called total activity concentration) is reported as 48.7 Bqkg^{-1}.

9.8.3 Field evaluations: overview

As discussed in Section 9.4, the stainless-steel reducer derived from a different section of the mineral processing plant to the connate scale. The stainless-steel reducer was selected for the evaluations because it exhibited elevated levels of alpha activity on the surface of the flange, that extended into the throat of the pipe. A maximum reading of 65 counts per second was recorded using a Thermo Scientific Radeye GS (serial number 11570) and a Ludlum 44-9 alpha probe (serial number PR352724), equivalent to a surface alpha activity contamination level of 36 Bqcm^{-2} (R. Browne, personal communication, April 6th, 2022).

Two trials were conducted of HPWC on the stainless-steel reducer, the first using a nozzle rated at 3,500-psi and the second using a 4,000-psi nozzle, in the anticipation that larger quantities of scale would be removed by using the higher-pressure nozzle.

One sample of the scale captured in the ARI geotextile and four samples of filtrate were collected in each trial. In total, two scale samples and eight filtrate samples derived from the field trials were analysed via gamma spectrometry.

9.8.4 Filtration effectiveness, as measured by activity concentration

As discussed in Section 9.2, activity concentration is an important parameter, as it is used as the reference criteria for whether a substance is radioactive (GWA, 2022d, p. 423) and accordingly, whether it is subject to institutional controls or can be released uncontrolled into the environment.

- The reference criterion of significance to this research is 1,000 Bqkg^{-1}, an activity concentration below which a material is deemed as being not radioactive.

The results of the two trials are presented in Table 46 and Table 47, with a consolidated summary of the data provided in Table 48. The scale, which visually presented as a heterogenous distribution of particle sizes, some as large as several square centimetres, reported a mean activity concentration of 25,459 ± 3,804 Bqkg^{-1}. The majority (69.8%) of the activity concentration is contributed by ^{210}Pb (activity concentration = 17,767 ± 3,787 Bqkg^{-1}).

The gamma ray spectrum derived from the scale captured in the geotextile in the first trial is illustrated in Figure 18. The energies used to assess the activities of radionuclides reported in this research are also identified in Figure 18.

- Note that the y-axis in Figure 18 is logarithmic.

Radionuclides in the scale from the ^{232}Th series displayed activity concentrations indicating that secular equilibrium had previously occurred between ^{228}Ra and ^{228}Th, but in the absence of ^{232}Th, activity concentrations of ^{228}Ra had decreased and correspondingly ^{228}Th activity concentrations were consistently 1.25 times greater than its progenitor. This is not the case for the ^{238}U series, where ^{226}Ra is three orders of magnitude greater than the head-of-chain ^{238}U, and ^{210}Pb a further order of magnitude greater activity concentration than ^{226}Ra. These results indicate that the radium and lead have disassociated from the ^{238}U and have been concentrated as a result of the processing of the feedstock mineral.

As was described in Section 9.4, four filtrate samples were collected from each trial, two from (approximately) the top two-thirds and two from the bottom one-third of the settled filtrate, ensuring that any solids that had settled from the slurry overnight were collected in the bottom samples. A viscous "oily" liquid was observed in the fourth sample of each trial, collected from the bottom of the filtrate. All of this substance was collected and included in the last of each of the two bottom samples forwarded for analysis. Note that this oily substance was absent from the other six samples.

A distinct stratification is observed from the results presented in Table 46 and Table 47, in that the samples collected from the top of the filtrate report much lower activity concentrations than those collected from the bottom which contained the visible particles that settled overnight, and in the case of Filtrate 2.4 and Filtrate 2.8 the oily liquid. The stratification of activities between a sample collected from the top of the filtrate (sample 2.1) and the bottom of the filtrate (sample 2.4) is illustrated in Figure 19.

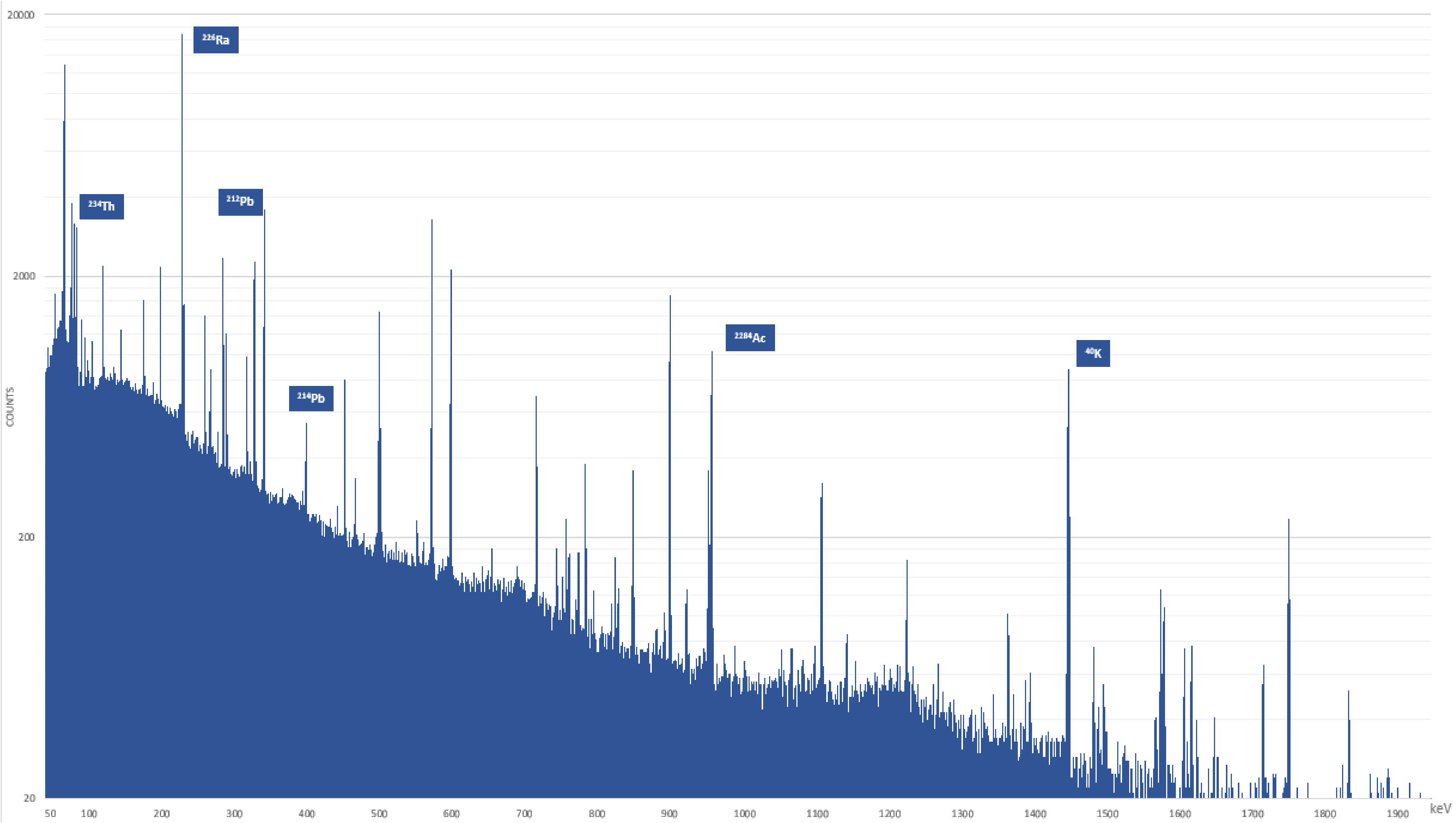

Figure 18: Gamma spectrum of corrosion scale – counts v emission energy (keV)

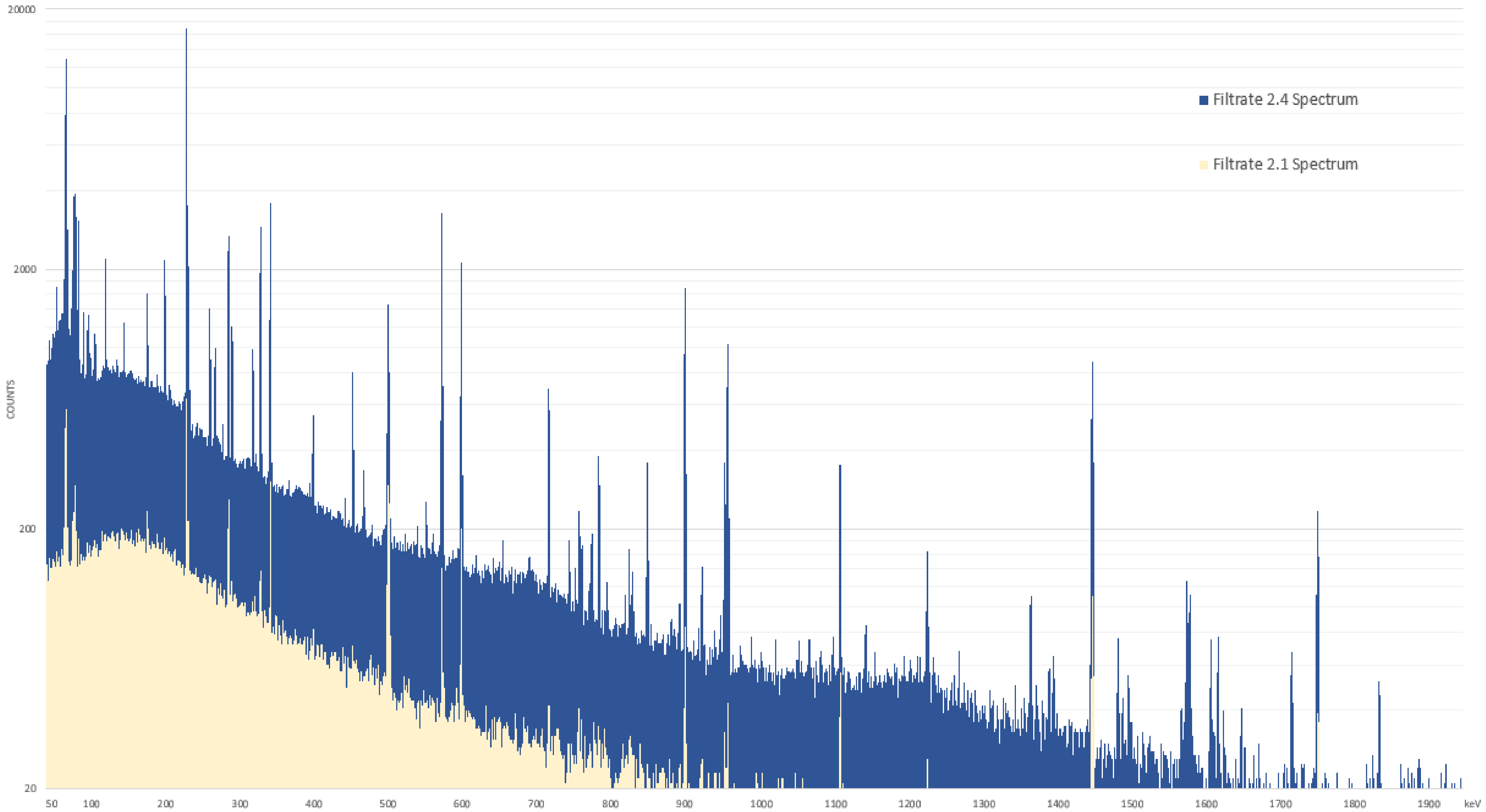

FIGURE 19: GAMMA SPECTRUM OF FILTRATE SAMPLES 2.1 AND 2.4 – COUNTS V EMISSION ENERGY (KEV)

- Note the y-axis in Figure 19 is logarithmic, and the relative activities as demonstrated by the counts in the spectra for most of the energies are at least an order of magnitude lower for the top sample.

Filtrate sample 2.6, collected from the bottom of the filtrate in the second trial appears to be an anomaly, as it too, displayed very low activity concentration. A visual inspection of this sample after gamma spectrometry analysis indicates that it has a much smaller number of visible particles when compared to filtrate samples 2.2, 2.4 and 2.8, perhaps explaining the anomaly.

Lead-210 was the cardinal source of activity concentration in the scale, and predictably, is also the predominant source in the filtrate, for those samples (viz, 2.2, 2.3, 2.4 and 2.8) that displayed elevated activity concentration. Filtrate sample 2.3 is of note – it was extracted from the top centimetre of the filtrate and exhibited an activity concentration of ^{210}Pb of the order of two orders of magnitude greater than the exceptionally low levels reported for the other five radionuclides. The activity concentration of 647 Bqkg^{-1} is 3.4% of the ^{210}Pb in the scale, and possibly indicates that this small portion of the lead remained in solution, or (more likely, it is hypothesised) the particulates had been resuspended during the sample collection process.

Three filtrate samples (viz 2.2, 2.4 and 2.8) reported the highest levels of activity concentration, of 1,665, 8,573 and 3,024 Bqkg^{-1} respectively. In all three samples, greater than 93% of the activity concentration derives from ^{210}Pb, despite the noticeably elevated activity concentrations of ^{228}Ra, ^{228}Th and ^{226}Ra in filtrate sample 2.4. It is not surprising that the activity in filtrate sample 2.8 is less than that of sample 2.4, despite the use of the higher-pressure nozzle - as much of the activity had been removed in the previous trial. However, the congruence of the oily liquid with the two samples of highest activity concentration (viz sample 2.4 and 2.8) raises the question as to the radiological properties of that substance, and whether it is a significant contributor to the activity of the samples [70].

In Table 48, the effect of the geotextile filtration on activity concentration is explored. The mean of the two samples of scale, 25,459 $\underline{+}$ 3,804 Bqkg^{-1} is used as the basis for subsequent calculations. Of note, 69.8% (17,767 $\underline{+}$ 3,787 Bqkg^{-1}) of the activity concentration of the mean of the collected scale samples derives from ^{210}Pb.

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[70] Further analysis of this substance is beyond the scope of this research.

- The first analysis assesses the samples extracted from the (approximately) top two-thirds of the filtrate and indicates that the filtration efficiency in relation to activity concentration is equal to, or exceeds, 98.9%, with a mean for all radionuclides of 99.2 ± 20.9%.
- The second analysis evaluates the samples extracted from the (approximately) bottom one-third of the filtrate, including the visible solids and oily liquid. With the exception of ^{210}Pb, the filtration efficiency in relation to activity concentration exceeds 96.0%. The efficiency for ^{210}Pb is 85.1 ± 24.4%, and the mean for all radionuclides is 88.3 ± 18.0%
- The third analysis consolidates all the eight filtrate samples and uses the mean activity concentration as an indicator of overall filtration efficiency in relation to activity concentration. With the exception of ^{210}Pb (92.0 ± 27.4%), all efficiencies exceed 98%, with the overall activity concentration being 93.9 ± 19.8%.

On the basis of the above data, it is prudent to contend that the ARI geotextile had a profound filtering effect upon the activity concentration of the scale removed by HPWC from the stainless-steel reducer and presents as a possible solution for collection of NOR-contaminated scale, as removed from PRSM via HPWC.

9.9 NEXT STEPS: PRAGMATIC IMPLICATIONS OF THIS RESEARCH

The ARI geotextile has been demonstrated to be an effective filter of the radioactive components of the scale removed via HPWC, especially as measured by activity concentration.

In both trials, it was apparent that most of the radioactivity of the filtrate was associated with the component of the filtrate that settled towards the bottom of the filtrate sample. Samples collected from the upper two-thirds of the filtrate sample contain very low activity concentrations that are below the reference level that would require mandated institutional controls.

A solution to the management of the radioactive components of the scale removed by HPWC is envisaged, whereby the filtrate that passes through the ARI geotextile is captured in a settling tank, that is of sufficient volume to allow the solids to settle. The settling period may be of several days to a week, but during this period, the relatively non-radioactive upper portion of the filtrate could be drawn off for use in the HPWC process (forming an approximated closed-circuit) or because of the low activity concentration, returned to the environment without additional treatment. At some stage the settled solids would require removal from the settling tank, however, as demonstrated by visual observation, these particulates are of such inconsequential volume that only infrequent removal would be required.

9.10 ENVIRONMENTAL CONSIDERATIONS

Intrinsically, high-pressure water cleaning is capable of generating significant quantities of detritus which requires containment as close as practicable to the point(s) of impact of the water with the surface being cleaned. This research was limited in its capacity to contain the dispersion of detritus: the high-pressure water cleaning activities took place in the open and was subject to high winds; the size and shape of the PRSM was unknown until selected; and the mechanism for supporting the PRSM to allow drainage through the SFD and containment options were limited to what was able to be scavenged from the decommissioned site.

The importance of future planning for containment is emphasised by the results of the gamma spectrometry analysis of the environmental soil samples reported in rows two and three of Table 45. Sample Env.1 was collected from the diversion drain, adjacent to the grated opening into a water runoff sump, prior to the trials commencing. Env.2 was collected at the same location at the conclusion of the four days of activity, and after the bund had been drained into the diversion drain. Although radionuclide concentrations are low for both samples, it is noteworthy that activity concentrations of all five analysed radionuclides increased as a result of the HPWC activities, and the total activity concentration in the second sample is approximately twice that of the first sample.

In essence, planning for what was to be encountered during the field evaluations was (necessarily) limited, and the results of the soil samples indicate that a much higher level of planning is required (for example conducting the high-pressure cleaning activities inside a space protected from the elements) in the event that similar activities occur in the future.

9.11 FIELD EVALUATIONS: REFLECTIONS

Although originating from the same mineral processing plant, the connate scale was sourced from the acid-leach circuit whilst the stainless-steel reducer is suspected of originating from a section of the plant in which high temperatures were encountered. The effects of the different physicochemical treatment in the processing of the minerals are demonstrated by the different radiological properties of the connate scale and that removed from the reducer: the connate scale is dominated by radium isotopes (and the ingrowth of ^{228}Th) while the scale removed from the reducer, as predicted by Hewson (1993) and Cook et al. (2018), is dominated by ^{210}Pb.

It is hypothesized that, as a result of radium's solubility the acid-leach process promotes the separation of radium from its parent radionuclide. It is further hypothesized that polonium which is volatile at temperatures as low as 100° C (boiling point of 962° C) may have been evaporated in the heating circuits where temperatures exceeded 1,000° C, and condensed onto cooler surfaces, allowing the ingrowth of ^{210}Pb.

Germane to this research the IAEA (2006, p. 40) state "radionuclide-specific analyses are therefore essential during radiological assessments in wet chemical extraction plants". The different radiological properties of the two sources of scale analysed in this research serve to reinforce the IAEA's counsel and underlines the need for the owners of the processing plant to define the mineral processing treatments previously used in the various sections of the plant in order to predict radionuclide deposition prior to demolition activities commencing.

9.12 LIMITATIONS OF THIS RESEARCH

The objective of this research was to evaluate the efficacy of the ARI geotextile in capturing radioactive scale from PRSM. The researchers had no prior knowledge of the characteristics of the PRSM to be evaluated; the radionuclides or their quantum in the PRSM; or the infrastructure available to support the in-field evaluations. Preparations were made based on the best available information, but, because of the remoteness of the mineral processing site, the researchers could not accommodate all contingencies. As a result, much of the preparations on-site were based on what equipment and support was available rather than best practice, impacting on how much of the slurry could be directed into the SFD, and contained so as to not impact upon the environment.

As acknowledged in Section 9.8.2, the use of the MDA value as a substitute for a "less than" result is not ideal, however, as explained, it is more appropriate than reporting a "no activity" result. In most instances, the use of the MDA has minimal impact on the reported results, and where it does have an impact, it is most-often associated with ^{238}U, which was found to make a minimal contribution to the assessments reported in this research.

Two radionuclides from the ^{232}Th series and three from the ^{238}U series were evaluated via gamma spectrometry. It is acknowledged that these evaluations do not provide a complete assessment of the radionuclide inventory likely to be present in the scale, however the assessment of the full inventory would require sophisticated radiochemistry and analysis by alpha spectrometry which is beyond the scope of this research. It is contended that by the consistent analysis of the five radionuclides identified by gamma spectrometry, the conclusions reached in this research are valid.

9.13 REFLECTIONS: THE NEED FOR POLICY ON REDUCTION OF RISK FROM PRSM

Other than being identified as having radiological properties, the PRSM that was the source of the connate scale, and that used in the field evaluations were randomly selected from many items across the disused mining operation.

Ilmenite is the feedstock for the Becher process. As was presented in Table 5, Ilmenite has a low total activity concentration of 2,400 Bqkg^{-1} (2.4 Bqg^{-1}), but the chemical and thermal processes involved in the Becher process, concentrated the dispersed radionuclides giving rise to a mean activity concentration in the connate scale of 465,000 Bqkg^{-1} (refer to Table 44) and 25,000 Bqkg^{-1} in the field trials (refer to Table 48).

This research has demonstrated that elevated activity concentrations can occur, despite low initial activity materials being consumed in mineral processing circuits. This finding should serve as prompt that a regulatory policy position is required to be established to ensure the risks of exposure to PRSM are minimised.

9.14 CONCLUSIONS

The filtration effectiveness of the ARI geotextile has been evaluated in two trials in which the radioactive contaminants of an item of PRSM have been removed by HPWC, and the resultant slurry passed through the ARI geotextile.

The captured scale and filtrate were subject to gamma spectrometry analysis to determine the extent of the radioactive components that passed through the geotextile into the filtrate.

Filtration effectiveness of the radioactive contamination by the geotextile as evaluated by activity concentration, demonstrated efficiencies for four of the radionuclides exceeding 98% and 92.0 ± 27.4% for ^{210}Pb. The overall efficiency of removal of activity concentration by the geotextile filter was 93.9 ± 19.8%.

It is prudent to conclude that the ARI geotextile presents a potential solution to the emerging issue of the long-term management of NOR-contaminated mining plant and equipment.

It was apparent that most of the radioactivity in the filtrate was associated with the component of the filtrate that settled towards the bottom of the sample. Those samples collected from the upper portions of the filtrate sample contain very low activity concentrations that are below the reference level for further institutional controls.

This leads to the conclusion that the most effective operational solution to the management of the radioactive components of the scale removed by HPWC is via a combination of the ARI geotextile and a subsequent settling tank, whereby the solids in the filtrate are allowed to settle, and the relatively non-radioactive upper portion of the filtrate is drawn off for use in further HPWC or returned to the environment.

In order to minimise the likelihood of inadvertent exposures, regulatory policy is required to raise the level of knowledge across the Western Australian mining sector of the potential risks associated with PRSM.

9.15 ACKNOWLEDGEMENTS

The researcher gratefully acknowledges the assistance of:

- Mr Russell Browne for supplying the samples of connate corrosion scale, and for arranging access and associated support required to conduct the in-field trials.
- Professor Pere Masque-Barre of the Edith Cowan University radiochemistry laboratory for conducting the gamma spectrometry analysis of the collected samples, and for contributing to discussion of the analytical techniques and results.
- Ms Leanne Downie for her support in arranging the facilities and equipment required to prepare the samples for analysis.

The research would not have proceeded if it were not for the generous support of:

- The Minerals Research Institute of Western Australia (MRIWA) which awarded a scholarship to the researcher. Specifically, gratitude is extended to Ms Nicole Rooke and Dr Geoff Batt for their guidance through the scholarship application process and support through the development of the research paper.
- Edith Cowan University which provided a seed grant, allowing the laboratory testing of the connate samples to proceed. The support of Professor Jacques Oosthuizen is appreciated.

9.16 DECLARATION OF INTEREST

Ms Williams-Hoffman is an employee of Edith Cowan University and conducted the gamma spectrometry analysis of samples and prepared the analytical error analysis.

Mr Rothleitner is the Director / Founder of ARI Water Solutions Pty Ltd, which designs and manufactures the stormwater filtration devices and and geotextile filters used in this research. Mr Rothleitner is a co-author of Alam et al. (2017).

This Chapter has established that activity concentrations of some radionuclides of the ^{232}Th and ^{238}U decay can be highly elevated when secular equilibrium is disturbed as the result of processing of minerals by chemical or thermal treatment.

The potential to apply a geotextile to filter the radioactive scale removed by high pressure water cleaning of potentially radioactive scrap metal was evaluated. The laboratory trials indicated that the geotextile would be suitable for the task, and field trials verified that the geotextile could filter the radioactive corrosion scale at efficiencies exceeding ninety percent.

The researcher contends that the application of the geotextile for the purpose as outlined in this Chapter is a potential disruptor to the current deployed techniques used in the treatment of PRSM and has significant upside for the management of exposures to mine workers, members of the Western Australian community and reduction of the environmental footprint of PRSM in the state.

There are possible additional applications of the geotextile filter, that result from the emergence of mining operators that are mining and processing critical minerals. Cook et al. (2018) highlights that "^{210}Pb and ^{210}Po release is set to increase since demand for these commodities, especially rare earth elements is booming, and new mineral sands operations are being established around the globe". It is possible that the geotextile may be repurposed to filter tailings streams from these emergent industries before the radioactive constituents contaminate the processing plant and equipment.

Regulatory policy is required to ensure mining operations are aware of the potential risks to workers, the community, and the environment as a result of the occurrence of PRSM. A discussion on the regulatory policy is included in the next Chapter.

CHAPTER TEN: A PROPOSED MODEL FOR REGULATING RADIATION EXPOSURES FROM NOR IN THE WESTERN AUSTRALIAN MINING INDUSTRY

… the current [WA radiation protection] framework, albeit robust and subject to regular updating with national guidelines, does not fully deliver World Best Practice.

This is primarily due to the overlap between the various agencies operating within the integrated regulatory framework, the uneven adherence to risk-based assessments, the lack of legislative and policy support for open publication of regulatory compliance data, and the lack of the required quality management systems in some agencies.

There are many aspects of the current framework that refer successfully to a World Best Practice approach and specifically to an outcomes-based regulatory framework but, collectively, they do not translate fully into the desired World Best Practice outcome at this stage.

Hon. Norman Moore,

Member of the (Western Australian) Legislative Council,

In a Hansard extract, citing a report by the Uranium Advisory Group

(Hon. Xamon, Hon. Ford & Hon. Moore, 2012).

The complex, and at times dysfunctional relationship between the national and the Western Australian regulatory framework for radiation protection in the mining industry was discussed in Chapter Two. A significant theme emerged from the discussion in Chapter Two, in that whilst Western Australia is a dutiful signatory to the notion of national uniformity in the approach to radiation protection, the state's mining sector is not represented at the national decision-making level, and therefore reacts to, rather than helps to shape national strategies. Further, there appears to be a lack of urgency in the federal approach to the emergence of new mining operations in the state that have the potential to present regulatory challenges in order to effectively manage risks to workers, the community, and the environment.

The researcher contends that the federal response has a disingenuous overtone that inherently snubs the pursuit of national uniformity. As a result, this Chapter provides recommendations to effectively manage potential radiation doses from NORs to future workers, via suggesting a fit-for-purpose regulatory model.

The Chapter takes advantage of a recent experience that has had far-reaching impacts upon managing and monitoring the health of mine workers and uses that experience to build a case for change to the current regulatory framework.

10.1 INTRODUCTION

According to the Minerals Council of Australia (MCA) "Australia needs to become known as a high quality reliable producer with a stable, efficient, science-based regulatory environment" (Davidson & De Silva, 2015). However, the MCA utopian view is far from a reality, as reflected upon by Bell (2017) who describes the regulatory regime that applies to transport of radioactive minerals as "overly complex, repetitious and incapable of responding to international developments…". The comments by the MCA and Bell were made in relation to the nation's uranium industry but is, by extension, applicable to any sector of the mining industry in which NORs are encountered.

According to Bell (2017) and RHC (2018a), various attempts to achieve uniformity in radiation protection laws across the nine jurisdictions in Australia have occurred since the 1950s. The issue received significant attention in the early 1990s, traceable to Hartley (1993) and Swindon (1995) in the lead up to the 1999 Health Minister's conference. Attention was revived in the early 2000s as per ARPS (2000), Koperski (2001) and Robotham (2003) in the prelude to the publication of the NDRP in 2004 (Bell, 2017). Subsequently, Tsurikov (2005) was critical of the failure to achieve national consistency via the NDRP, a theme that was continued with Jeffries (2011), IAEA (2018b) and Furness (2019a, 2019b).

As was discussed in Sections 2.1 and 2.4, the interactions between influential international authoritative bodies and the federal agencies, and in turn the state regulatory bodies, are complex, and compete with issues *du jour* for attention of elected officials. In Australia, and despite the best intentions to achieve harmonisation, these complex inter-relationships have resulted in incongruous laws across the country, and in Western Australia specifically, a dual (and in some cases ternate) regulatory oversight of radiation protection of mining operations. In Section 2.3 the statement by the RHC (2018a, p. 4) highlighted the failure to achieve national uniformity adversely impacts on the effectiveness of the administration of radiation protection among jurisdictions, exemplified by the patchwork framework that currently applies to the Western Australian mining industry (illustrated in Figure 9).

Therefore, it is prudent to contend that after 70 years of endeavour, uniformity across the jurisdictions has not been achieved, and the words of the Hon. Norman Moore (who in 2012 was the Western Australian Minister for Mines and Petroleum) that open this chapter, continue to ring true.

10.2 DIMINUTION OF THE PROFILE OF RADIATION PROTECTION IN THE WESTERN AUSTRALIAN MINING SECTOR

The year 1994 appears to be a salient one that set-in motion the diminution of radiation protection in the WA mining industry. Monazite production ceased in 1994, effectively removing the most radioactive of the minerals produced by the MSI. Concomitantly, Hewson and Ralph (1994) released the findings of their research into radiation exposures of the underground mining workforce in Western Australia, noting that the highest exposures were received by coal mine workers, however, as reported by Premier Coal (2018) the underground coal mining operations were closed in 1994, effectively removing the potentially highest exposed cohort of underground workers.

The congruence of events in 1994 appears to have provided the opportunity for the idiom of “risk equity”, first raised by Cassels and Carter (1992) to become established in the radiation protection lexicon. The concept of risk equity is based upon the precept that those hazards which present higher levels of risk receive the most attention to control. In essence, risk equity seeks to optimise and balance the effort put into the reduction of risks from the hazards in the mining workplace, of which radiation is one of many.

As many of the persons holding the title of RSO in the mining industry have multi-disciplinary roles, it is contended that it is a misnomer to categorise the role as being occupied by a full-time professional. The majority of RSOs in REs also fulfil roles in disciplines as varied as occupational health and safety, geology, metallurgy, industrial hygiene, or environmental management (and in some instances, multiples of these roles). It is contended that risk equity provided the opportunity to reallocate resources from the chronic issue of radiation exposure to the more immediate, acute issues *du jour* such as routine, but high-risk safety issues (for example working at heights or in confined spaces); or more recently, with the re-emergence of coal workers pneumoconiosis , monitoring for silica exposure.

The Coal Workers Pneumoconiosis Select Committee (CWPSC) summarise the challenge of risk equity: "In the field of occupational health and safety, there is often a distinction between efforts to address safety issues, which involve more immediate risks of physical danger, and health issues which typically involve longer term or chronic risks and effects. The committee heard evidence that safety has often been at the forefront of enforcement efforts in Queensland. It was submitted that the skills, resources, and inspection culture of the Inspectorate reflects this historical emphasis" (CWPSC, 2017, p. 14).

Although the diminution of effort, and the skills of those charged with the pursuit of best radiation protection practices, and ALARA in particular, has been highlighted by Higley (2017) and Tsurikov (2019) amongst others, risk equity remains vexatious, as witnessed by attention it continues to receive in radiation protection media, for instance Cologne, Cullings, Furukawa, and Ross (2010); ICRP (2020a, p. 92). The flavour of the risk equity argument is perhaps best captured by Karam (2018) who states "… this may mean reducing our emphasis on reducing radiological risks when the money spent can accomplish far more risk reduction in other areas".

10.3 SCIENCE VERSUS POLICY

It is contended that the preponderance of a policy approach based on risk equity has had an undesired impact upon the science of radiation protection in the Western Australian mining industry, as evidenced by the significant decrease in workforce monitoring illustrated in Figure 12 and discussed in Section 8.7. As is shown in Table 40, a 45-year nadir of 0.37 personal dust samples per worker was reached in 2019-20, continuing a downward trend identified by Ralph et al. (2021, p. 53). It is well-established that the science of personal dust sampling is inexact and requires sufficient data to be collected to overcome sampling biases and errors in order to be effectively applied to assess internal dose to workers. The number of samples required to be collected on a per RE basis needs to meet specific tests for statistical significance, as per DMIRS (2018, p. 18). The paradox of the rate of sampling for LLα in dusts being at an historical minimum, at a time when the DCFs for NORs in those dusts have increased was highlighted in Section 8.7.

The contention is further evidenced in that only one RE is routinely conducting particle size analysis, and the industry-wide default values for thorium to uranium ratio are applied, despite this data being regularly collected as part of export quality control obligations. As was explored in Chapter Seven both parameters are critical to the determination of the intake of LLα, and the calculation of internal dose. The use of default values in the dose calculation process was originally meant as a guide to calculating internal doses, in the absence of data, and not as a reason to abstain from collecting the required data.

10.3.1 Science versus policy: mine worker health surveillance

The policy-first, science-second approach appears to not be limited to the field of radiation protection, but in the broader “health” issues in mining.

In 2013 the Western Australian mine workers health surveillance system, implemented by the Department some 15 years previously was cancelled, without “due consultation” Diss (2013). Professor Lyn Fritschi from the Western Australian Institute of Medical Research at the University of Western Australia challenged the decision, stating “The mine health program was started because people were concerned about the health of miners and we don't know if any problems have come from that data because from what we know it hasn't been analysed properly”, a position supported by the head of Western Australia's Cancer Council Terry Slevin, who stated "… taking that next final step to make sure all of the hard work with the data collection translates into the best possible use of that data is the sensible and responsible thing to do" (Diss, 2013). Clear evidence of the policy-first, science-second approach was provided by the Department’s spokesperson, Mr Mike Rowe, who declared “we don't want to make a mandatory system for something we've shown doesn't give us the best value or best insight" (Diss, 2013).

10.3.2 Science versus policy: coal worker’s pneumoconiosis

Outside of Western Australia an ominous parallel to the policy versus science approach manifested in 2016 when a Parliamentary Select Committee of Inquiry (the CWPSC) into the re-identification of Coal Worker’s Pneumoconiosis (CWP) was commissioned into the mining jurisdiction in Queensland. In May 2015 a worker was diagnosed with CWP, colloquially called “black lung”, in what was described as “the first case of coal workers' pneumoconiosis in a Queensland coal miner in 30 years" (CWPSC, 2017, p. 5).

The CWPSC places the re-emergence of CWP as a result of "what has been a catastrophic failure of the regulatory and health surveillance systems intended to ensure the protection of coal industry workers" (CWPSC, 2017, p. 5). The CWPSC emphasises that prior to the 2015 diagnosis, it was widely accepted by coal mine operators, managers, workers and regulators that Australia had effectively eradicated CWP, and that this myth became self-reinforcing, stating "this pre-conditioned most in the industry to under-estimate the extent of the potential risk that respirable coal mine dust still posed" and "all stakeholders accepted at face value that the health scheme had not identified any cases of CWP in Queensland since 1984, and therefore, that it must have been eradicated here" (CWPSC, 2017, p. 5). These foreboding statements are analogous to issues highlighted through this Thesis in relation to radiation exposures in Western Australia's mining industry.

10.3.3 Science versus policy: "Responsive regulation"

During the mid-1980s to early 1990s the various Australian jurisdictions introduced laws based upon an inquiry into workplace safety and health in the United Kingdom colloquially referenced as the "Roben's report" (Baron Alfred Robens, 1972). The Roben's report changed the *modus operandi* of workplace safety and health, placing the onus of responsibility for control of workplace hazards on employers; decreasing the prescriptive nature of the laws; and steering industry towards "regulatory enforced self-regulation" where regulatory standards are articulated and "self-enforced" by employers, failing which the regulatory agency takes enforcement action against the employer (Bluff, Gunningham & Johnstone, 2004; Johnstone & Sarre, 2004).

"Responsive regulation" is important in Roben's-style legislation in which regulators evaluate how effectively employers are regulating themselves before deciding on whether to escalate intervention. Johnstone and Sarre (2004, p. 5) suggest that self-regulation is not a panacea, stating "Regulators are also beginning to accept that reliance simply on informal measures can easily degenerate into intolerable laxity and a failure to deter those who have no intention to comply voluntarily", the implication being that regulators are required to be vigilant to ensure required standards of performance are met. As reported in CWPSC (2017, p. 14) "Unfortunately there did not appear to be any focus on the part of Queensland public servants on respirable dust mitigation or monitoring technologies."

It is evident that regulator vigilance was not routinely practised in the Queensland coal mining industry, with the CWPSC noting that "The extent to which the mines inspectorate currently undertakes atmospheric dust monitoring inspections and audits the dust sampling results obtained by mine operators is inadequate to ensure public and worker confidence in the integrity of that system" (CWPSC, 2017, p. 32).

The CWPSC excoriated the lack of responsive regulation, stating "The absence of any regulated oversight of respirable dust monitoring or mandatory reporting of exceedances prior to 1 January 2017 allowed a culture of complacency and disregard for the serious risk posed by respirable dust exposure to develop across industry. Risk-based self-regulation of respirable dust as a hazard has failed to protect coal mine workers from repeated and significant exceedances of the [occupational exposure limit] OEL for respirable coal mine dust" (CWPSC, 2017, p. 12).

Compare the CWPSC statement above, to that attributed to Department spokesperson, Mr Mike Rowe, in relation to the cessation of the Western Australian mine health surveillance system "the responsibility has always been on the industry … what we're asking the companies to do is identify those particular risks and to assess the exposures, and companies are happy to do this… " (Diss, 2013). Shortly after the cessation of the health surveillance system, the Department withdrew support for the radiation dose calculation database, Boswell (discussed in Section 6.8), and since that period, REs have (largely) generated annual reports of radiation exposures of their mine workers in the absence of responsive regulation.

10.3.4 Science versus policy: Conclusions

The arguments presented above are not intended to malign the regulatory efforts of the Department, rather it has been to stress the impact that policy may have on science, in the absence of an advocate for maintaining scientific integrity.

As is discussed in detail in Appendix 5, and highlighted by Higley (2017) and Tsurikov (2019), the Department has not been immune to the shortage of experienced radiation professionals, and the general malaise affecting the radiation protection community. It eventuates that this is a global phenomenon, best expressed by Emily Caffrey, Editor in Chief of the Health Physics Society (USA) who advises "the downward trend of health physicists has not been stopped … We see declining workforce numbers due to retirements, declining membership numbers in our professional society, the closing of student programs, fewer certified health physicists, huge numbers of unfilled jobs …" (E. Caffrey, personal communication June 1st, 2022).

It is evident that in order for responsive regulation to be implemented, the need to engage radiation protection specialists, in both industry and the Department is paramount, and forms an integral component of models for future regulatory oversight.

10.4 A PROPOSED MODEL FOR FEDERAL INFLUENCE

As is outlined in Chapter Two, and illustrated in Figure 9, the legislative framework for radiation protection in Western Australian mining operations is influenced by positions adopted by national agencies, in particular ARPANSA, which in turn are influenced by international authoritative bodies, as illustrated as Figure 8.

The Western Australian mining industry hosts the greatest number of potential REs in the country and is evidently a significant stakeholder in the management of exposures to NORM. To some extent, the issues identified in Section 10.1 in relation to the failure to harmonise legislative requirements have been addressed by the inclusion of RPS-9 into the WHS (Mines) regulations, which also rectifies issues raised by Tsurikov (2005).

However, the RRAM is unrepresented at the federal strategic level, on either the RHSAC or the RHC, and is reliant upon informal communications to be apprised of strategic interventions that may impact upon the state's mining industry. As a result, the RRAM reacts to proposed interventions rather than having the opportunity to contribute to shape strategy.

Therefore, the first stage of the proposed model presents three options to ensure the RRAM remains abreast of international and national developments, as presented in Table 49.

It should be noted that the regulator is a member of federal work health and safety regulatory consultation forum, chaired by Safe Work Australia (SWA). Should the matter of a lack of Western Australian representation be sufficient to warrant, SWA could be used to pursue Options 1a or 1b.

TABLE 49: MODEL STAGE 1 – RRAM BEING INFORMED OF INTERNATIONAL AND NATIONAL DEVELOPMENTS

Option	Description
One (a)	RRAM to lobby the RHSAC and/or RHC for recognition as a member, representing workers exposed to NORM, **or**
One (b)	RRAM to lobby RHC and ARPANSA to form a specialist sub-committee on NORM industries. RRAM to be represented by the regulator and a technical specialist, **or**
One (c)	RRAM to act independently [71] of the federal agencies and form a specialist technical group charged with oversight of radiation protection in the state's mining sector. Acting independently is inextricably linked to the Actions listed in Section 14.5 and favoured only if Options 1a and 1b fail to gain traction.

At an operational level, the regulator should consider inviting ARPANSA to be represented on the RLC, as discussed in Recommendation (i) made in Section 10.5.1.

10.5 A PROPOSED MODEL: REGULATING THE WESTERN AUSTRALIAN MINING INDUSTRY THAT ENCOUNTERS NORS

The second phase of the model bifurcates, with the first stream dealing with interactions with the RCWA and other government agencies, and the second dealing with how the RRAM should restructure and resource to effectively regulate the rapidly expanding sector of the state's mining industry with potential to encounter NORs.

10.5.1 Interactions with state agencies

It is important to note that in April 2018 the Minister for Health established a review into Western Australia's Radiation Safety Act (colloquially referenced as the Reynold's review) with the aim of creating a more contemporary legislative framework. The terms of reference included considering a risk-based approach to radiation safety legislation; and the appropriate authority and administrative

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[71] Whilst not in keeping with the pursuit of national uniformity, in essence, this occurred with the requirement that the state's mining industry comply with NORM-V which adopted the revised DCs in ICRP-137 and ICRP-141, two years prior to adoption of the revised DCs by ARPANSA.

arrangements for radiation safety in Western Australia (D. Smith, personal communication September 24th, 2019). The findings of the Reynold's review were initially embargoed from release, and with the advent of the COVID-19 pandemic were de-prioritised. As at time of writing, the report of the Reynold's review has not been released for public scrutiny. Therefore, the following discussion is caveated on the premise that, should the Reynolds review become public and changes to the Radiation Safety Act occur, some, or perhaps all, of the options presented will become redundant.

A significant issue with the state's radiation protection in mining operations legislative framework arises as a result of the dual reporting to the RRAM and the RC, as illustrated in Figure 9. The framework becomes more complex if environmental issues are considered, in which case state and federal environmental protection agencies may also have regulatory oversight. Presently RRAM is not represented on either the RCWA or the EPA but is influenced by the decisions of these two regulatory bodies, a situation that is not conducive to responsive regulation.

In order to rectify the current impasse, the changes as presented in Table 50 are proposed.

Further to the options presented in Table 50, the researcher makes three recommendations to improve the state-based regulatory framework [72]:

<u>Recommendation (i):</u> Regardless of whichever the above-listed pathways are followed, the RRAM needs to reinstitute the radiation liaison committee (RLC) with the Department providing secretariat services.

- The EPA and associated government agencies could be represented either as full members or observers.
- Industry representatives are precluded as members, but invited to present on specific maters, as they arise.

<u>Recommendation (ii):</u> The RLC to report to the regulator.

<u>Recommendation (iii):</u> The RLC publishes Guidance Materials on behalf of the regulator, RCWA and EPA on the management of risks arising from PRSM.

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[72] A further option is possible, in which radiation protection obligations in the WHS (Mines) regulations are removed, with legislative oversight returning to the RCWA via the RSA. This is considered to be a retrograde step, reverting to the legislative oversight pre-Winn Inquiry, and should not be countenanced.

TABLE 50: MODEL STAGE 2 – PROPOSED OPTIONS FOR CHANGES TO WA'S REGULATORY FRAMEWORK

Option	Description
Two (a)	The RSA to be revised such that it does not apply to mining operations, with regulatory accountability allocated to the regulator. Registration of premises and licensing of persons would become the domain of the Department, which has existing capability in this area, **or**
Two (b)	RRAM to lobby the RCWA for permanent membership of a regulatory technical specialist in NORM in mining, **and**
Two (c)	Mines Inspectors to be appointed as inspectors under the RSA and empowered to make decisions in relation to radiation protection in mining operations on behalf of the RCWA.
Two (d)	The regulatory framework is amended to incorporate PRSM as a specific obligation to be addressed in a Radioactive Waste Management Plan as per Clause 2.8.2(h) of RPS-9, viz: *a plan for decommissioning the operation and the associated waste management facilities and rehabilitating the site* [is required to be developed].

10.5.2 Restructure and resourcing the RRAM

Many of the findings of the CWPSC, as discussed in Section 10.3 have resonance for the Western Australian mining industry that encounters NORMs, particularly in the policy versus science context.

The CWPSC called for independence of the regulator, and an independent Mine Safety and Health Authority to be established in Queensland. Regulator independence has been achieved in Western Australia with the advent of the WHSA, however, the State government has in the last four years, opted to merge mine safety and general workplace safety into a singular entity (called the Safety Regulation Group, SRG) and this is unlikely to be re-engineered. The options in this Section are based upon the re-structured of the component of SRG dealing with mine worker health.

Importantly, the CWPSC advocated for the establishment of a Research Division, which has a primary focus of “Health, Occupational Hygiene and Dust Databases” with another element being identification of trends in “Mine Safety” (CWPSC, 2017, Appendix F). This model is proposed to be emulated for Western Australia, with additional resources:

Recommendation (iv): The regulator to form a new division within SRG to focus on mine worker health.

Recommendation (v): The leader of the mine worker health division, a subject matter specialist in worker health, to be appointed at Director level, and report to the regulator.

Recommendation (vi): The mine worker health Division to have a team of radiation protection specialists, including a senior role which focusses upon strategy and international developments; two roles which focus upon compliance with the requirements of RPS-9, and as downstream processing of radioactive minerals approaches certainty, these roles will be supplemented by chemical engineers.

Recommendation (vii): The radiation protection specialists to be supported by a cohort of technical officers who are charged with conducting in-field verification of monitoring results, as per Recommendation 34 of CWPSC (2017) which proffered “the Mines Inspectorate should significantly increase the frequency and extent of its atmospheric dust monitoring inspections”.

Recommendation (viii): The radiation protection specialist team to establish a monitoring and analysis capability to assist the regulator in the discharge of their functions under the WHS (Mines) regulations.

Recommendation (ix): Along similar lines of Recommendation 35 of CWPSC (2017), the radiation protection specialists oversee the development of a new database for recording and reporting worker radiation dose assessments.

Recommendation (x): The new database link directly to the Australian National Radiation Dose Register (ARPANSA, 2014b, 2021b), providing the RHC with line-of-sight of doses to Western Australian mine workers.

Funding for the capital purchases of establishing the monitoring and analysis capability, developing the new database, and the operational expenses of the radiation protection specialists are to be drawn from the Mine Safety Levy, which was established to fund improved services for mines safety regulation, with the objective to generate an amount of revenue that matches expenditure on administering safety and health within the Western Australian mining industry (DMIRS, 2022a).

The Mine Safety Levy is paid per hour worked, and as was discussed in Section 1.2, and illustrated in

Figure **3** 3, the Western Australian mining workforce has expanded considerably over the recent past, and therefore, Mine Safety Funds should be readily available to fund the recommended activities.

10.6 CLOSING COMMENTS

The proposed model is illustrated in Figure 20. A consolidated list of recommendations is provided in Table 51.

Due to the significant momentum developed by the state's mining sector in the pursuit of the Future Battery and Critical Minerals strategies, the proposed actions listed in the preceding Sections of this Chapter should be pursued to their fullest extent and expedited, in order to heed the caution issued by CWPSC (2017, p. 71) which stated "[a] piecemeal approach will not be sufficient to restore workers' trust in the system or in the adequacy of the protection it affords them".

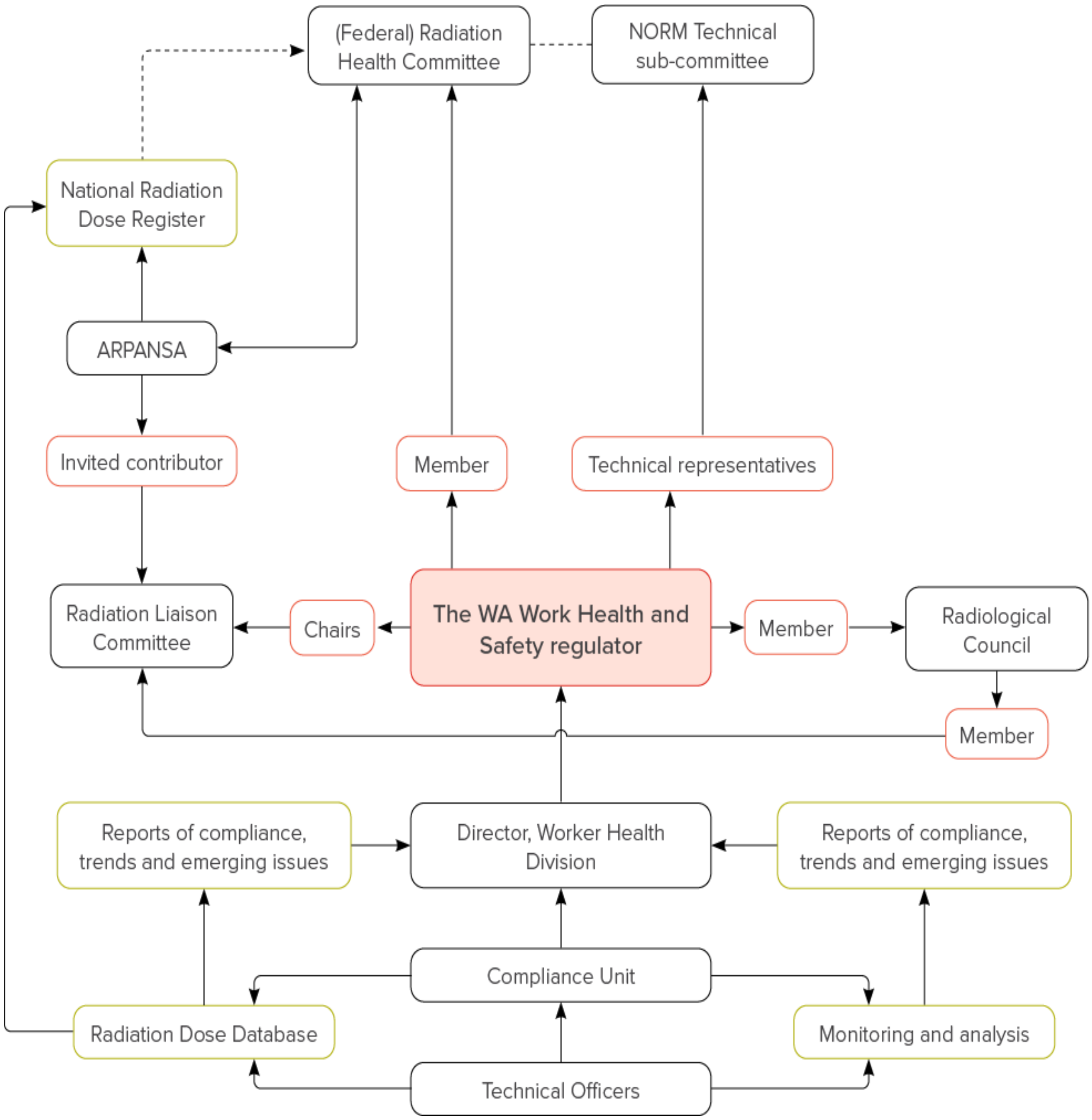


FIGURE 20: PROPOSED REGULATORY MODEL FOR RADIATION PROTECTION IN WA MINES

TABLE 51: CONSOLIDATED LIST OF RECOMMENDATIONS FOR CHANGES TO WA'S REGULATORY FRAMEWORK

Recommendation	Description
(i)	Regardless of which of the options presented in Table 50 are selected, the RRAM reinstitutes the radiation liaison committee (RLC) with the Department providing secretariat services.
(ii)	The RLC to report to the regulator.
(iii)	The RLC publishes Guidance Materials on behalf of the regulator, RCWA and EPA on the management of risks arising from PRSM.
(iv)	The regulator to form a new division within SRG to focus on mine worker health.
(v)	The leader of the mine worker health division, a subject matter specialist in worker health, to be appointed at Director level, and report to the regulator.
(vi)	The mine worker health Division to have a team of radiation protection specialists, including a senior role which focusses upon strategy and international developments; two roles which focus upon compliance with the requirements of RPS-9, and as downstream processing of radioactive minerals approaches certainty, these roles will be supplemented by chemical engineers.
(vii)	The radiation protection specialists to be supported by a cohort of technical officers who are charged with conducting in-field verification of monitoring results.
(viii)	The radiation protection specialist team to establish a monitoring and analysis capability to assist the regulator in the discharge of their functions under the WHS (Mines) regulations.

Recommendation	Description
(ix)	The radiation protection specialists oversee the development of a new database for recording and reporting worker radiation dose assessments.
(x)	The new database link directly to the Australian National Radiation Dose Register providing the RHC with line-of-sight of doses to Western Australian mine workers.

CHAPTER ELEVEN: CONCLUSIONS

… since the 1950s, doubts have been expressed by many regarding their increasing apprehension about the non-credibility of the government, scientists and industry regarding whether or not there is adequate regulation and protection of the public health and environment from carcinogens in the world, especially ionizing radiation …

… it has become apparent that there is no unified basis that allows the international or domestic community to come together to form a coherent policy for radiation protection.

The current state of maelstrom exists because we have confused "science" with "policy".

C. Rick Jones, in "*Radiation protection challenges facing the federal agencies*"

Jones (2004, pp. 273-274)

The preceding Chapters in this Thesis have systematically examined the primary research question "*what is the potential for radiation exposures from NORs to the significantly increased Western Australian mining workforce, and is the regulatory framework fit-for-purpose to ensure radiation doses are kept as low as reasonably achievable?"*

This Chapter discusses how this Thesis has addressed the research objectives; and provides recommendations to effectively manage the radiation exposures of the current and future mining workforce in Western Australia. The limitations of the research, opportunities for further research and the impacts of the research are also discussed.

11.1 INTRODUCTION

The lithology of Western Australia is replete with commercially exploitable mineral resources, but also hosts trace amounts of the NORs thorium and uranium, which may present potential radiation exposures to workers in underground mines and mineral processing operations and pose potential contamination issues as a result of concentrating NORs in the tailings streams.

The mining industry in Western Australia is undergoing a renaissance. Traditional sectors such as gold, iron ore and nickel are resurgent, however, as was discussed in the preliminary section entitled "Influences on the research" and expanded upon in Appendix 4, and illustrated in Figure 2, international demand for minerals to support the renewable energy sector has stimulated significant interest in the mining and processing of uranium and ores that contain rare earths. Western Australia is replete with uranium and rare earths deposits. However, the rare earth deposits commonly associated with the minerals monazite and xenotime which contain notably elevated levels of NORs and consequently present challenges to ensure worker radiation exposure, and impacts upon the environment, are minimised.

The Western Australian regulatory framework, mining industry, regulatory agencies, and worker / environmental representatives must be prepared for the potentially significant increase in workers exposed to NORs and impacts upon the environment that the nascent lithium and rare earths sectors will present.

As was outlined in the Research Aims and Objectives section, the core purpose of the research was to investigate and document the sources, and magnitude of the radiation doses arising from exposure to NORM to the contemporary mining industry workforce in Western Australia. It was anticipated that the outcomes of the research would assist all of the aforementioned stakeholders to manage exposures to NOR from mining operations to below accepted international limits.

Specifically, the research objectives were to:

i. Address the gap in the knowledge of radiation doses from NORs to the Western Australian mining industry workforce.
ii. Evaluate the risks to past workers, by comparing the historical dose records against current exposure standards.
iii. Evaluate the risks to present workers by analysing current data, evaluating the resultant exposure against applicable exposure standards, and applying internationally accepted dose-risk criteria.
iv. Provide recommendations to effectively manage potential radiation doses from NORs to future workers.

The contributions made by the research to theory and practice, and the limitations of the body of the research works are offered in this Chapter.

11.2 ADDRESS THE KNOWLEDGE GAP

In its totality, the research has completed the historical record of worker radiation doses in the state's mining industry; forecast the impacts of revised risk factors on worker dose assessments; evaluated, and verified that the forecast impacts were realised; identified worker cohorts in the state's underground mining sector that require further evaluation; conducted a field investigation that verified elevated activity concentrations of radionuclides can occur when secular equilibrium is broken and validated a potential solution to the emerging issue of NOR-contaminated mining equipment; and proposed a new model for regulating radiation exposures in the state's mining industry.

The research has been published in peer-reviewed publications and has influenced state and national policy.

11.3 COMPLETE THE HISTORICAL RECORD AND EVALUATE PAST WORKER DOSES

This research found that the historical record of radiation doses to workers employed by Reporting Entities, established by the legislative requirement to submit an annual report of worker doses to the RRAM, was remarkably intact, from the time of the Winn et al. (1984) Inquiry to the time of writing.

The research found that whilst the majority of the workers employed by Reporting Entities received radiation doses below the level of regulatory concern, a declining trend over the past decade in representative sampling, especially for the evaluation of internal dose poses questions as to the veracity of the reported dose data.

11.4 EVALUATE THE RISK FROM EXPOSURE TO NORM TO CURRENT MINE WORKERS

During the period of the research, international authoritative bodies revised the risk factors, known as dose coefficients, associated with exposure to radionuclides. The revisions, which were based upon globally significant research, included the members of the thorium-232, uranium-238 and uranium-235 decay series, the results of which were predicted in this research to have material impacts on internal doses via the inhalation pathway.

The research found that as a result the changes to dose coefficients, the mean effective dose across 23 underground mines that participated in research by Hewson and Ralph (1994) is 1.33mSv, which exceeds the 1mSv per year criterion (as outlined in Section 3.5) for exemption from compliance with mine radiation safety legislation. Revisions of worker dose estimates in 12 of the 23 mines exceeded, or were equal to, 1mSv per year and are therefore required to comply with Western Australian mine radiation safety legislation. Dose estimates to workers in three mines exceed 50% of the 5mSv definition of workers being deemed as “designated workers”. Additional monitoring and controls are warranted in the 12 mines, and specifically the three that exceeded the 50% of the designated worker criteria. The research postulated that as many as 5,400 underground mine workers will exceed annual radiation doses in excess of 1mSv and should be subject to further evaluation, if not routine monitoring and dose assessment.

The research also predicted that doses arising from inhalation of dusts with properties typically encountered in the Western Australian mineral sands industry would increase by a factor of between 0.74 and 2.1 times from those previously reported and forecast (other factors remaining constant) that the maximum annual dose would increase from 4.4mSv to 6.7mSv, with the contribution from LLα representing 85% of annual dose.

The research evaluated the worker doses for the year after implementation of the revised dose coefficients and found that the predictions were veracious. The mean dose from exposure to LLα increased by 35.0%; the mean effective dose increased by 32.4%; and the maximum dose increased by 36.4%; from the previous reporting period. Significantly, the maximum reported effective dose was 6.0mSv, the first time in a decade in which worker doses have exceeded the designated workers criteria.

Unfortunately, the declining trend in personal monitoring of workers across the RE cohort was observed to have continued, placing further doubt on the veracity of the data reported by the industry.

The issue of managing worker exposures from, and effective disposal of, potentially radioactive scrap metal is a prescient issue, that was investigated in this research. The research demonstrated that highly elevated concentrations of radioactivity could occur as a result of chemical or thermal treatment that disturbed the secular equilibrium in low-activity feedstock. A potential solution that allows collection of radioactive scale removed by high-pressure water cleaning in a geotextile filter was proven to be effective, and when coupled with a settling tank (a system in extensive use in the Western Australian mining sector) collected in excess of 95% of radioactive solids, dramatically reducing the environmental footprint of the contaminated material.

11.5 RECOMMENDATIONS TO MANAGE POTENTIAL RADIATION DOSES FROM NORS TO FUTURE MINE WORKERS

A significant step towards better radiation protection practice has been made with the advent of the WHS (Mines) regulations, which place equal emphasis on minimising worker doses and the long-term impact on the environment via effective waste management. However, the Western Australian regulatory framework remains stymied by a lack of representation on the state’s lead agency (the Radiological Council) and the federal lead regulatory agency (the Radiation Health Committee). Challenges are anticipated as a result of an embargoed inquiry into the efficacy of the Radiation Safety Act – it is not helpful here to canvass what changes may be made by the government, other than to note that the inquiry has occurred.

The central tenet of this dissertation is that the contemporary Western Australian regulatory capability for radiation protection in the mining industry is ill-prepared for the challenges to be presented in the near-term future as the state embraces the challenge of becoming a significant supplier of minerals to assist in combatting global climate change, and the requirement to ensure that the risks arising from potentially radioactive scrap metal are effectively managed gains traction.

It is contended that although the regulatory framework is much improved, the technical capability in radiation protection resembles that prior to the Winn Inquiry of 1984. The regulatory model proposed in Chapter Ten and illustrated in Figure 20 requires a re-investment in technical skills, and a recognition that whilst the policy of risk-equity is legitimate for acute hazards, a science-based approach is required to effectively govern the risks from chronic hazards. A sustainably-funded mine worker health unit is required to be established and needs to be recognised as a separate entity from the mine safety inspectorate. It is contended that the proposed model will assist the regulator to establish the capability required to effectively regulate the exposure of the state's mine workers to NORs.

11.6 LIMITATIONS OF THE RESEARCH

This research has several limitations that must be acknowledged.

Firstly, the historical record and evaluations of the impact of the revised dose coefficients are based upon the data provided by Reporting Entities in the annual reports of worker doses provided to the State mining engineer. As was introduced in Chapter Two, the impacts of the Winn Inquiry are detailed in Appendix 4. One of the impacts was the implementation of quality control programs to ensure the validity of the data submitted in annual reports by REs. However, there has been a notable absence of quality control programs by the Mines Inspectorate since the mid-1990s, and therefore, the research has used the dose assessment data "*as it was reported*", in full knowledge that it had not been verified via a robust quality control program.

The second limitation has its origins in the first. Since the late 1980s persistent questions have been raised concerning the capabilities of industry-based Radiation Safety Officers. These same RSOs generate the annual reports submitted to the RRAM, and without being subject to quality control, uncertainties in the veracity of the data prevail. This situation is exacerbated by the finding that the Boswell dose reporting system was found to have fundamental flaws but continued to be used across the industry well after the flaws were identified.

The third limitation is related to the assessment of underground worker doses, which were based upon a re-evaluation of research conducted in 1994 by applying contemporary dose coefficients. In order to reach the conclusions presented in Ralph et al. (2020b), a gross assumption was made in that exposure scenarios were unchanged from those in the original research, conducted some 26 years previously. Self-evidently, this was not a truism – those mines that were still operating in 2020 had to have changed in some form – whether they be deeper; better/worse ventilated; or had more/fewer workers, to name but a few variables. The research was not able to conduct in-field experiments to validate the assumptions, and therefore the conclusions as to the number of underground workers potentially exposed, and their exposure profile is subject to question.

Finally, in the field evaluation of the filtration effectiveness of the geotextile to capture NOR-contaminated scale, it must be highlighted that the members of the ^{232}Th and ^{238}U decay series do not all emit gamma rays, and therefore assumptions are made as to the equilibrium between the radionuclide and its progenitor(s). The assumptions can only be tested via alpha spectroscopy, a time-consuming, elaborate, and costly technique that was beyond the capacity of this research to consider. Whilst a limitation, it is alleviated somewhat by consistently analysing for five different radionuclides and comparing their activity concentration. Nonetheless, assumptions of equilibrium were made, and are highlighted as a possible limitation. Further – only one item of equipment was tested. More research is required, applying HPWC to varying items of PRSM in order to test the validity of the findings of the field evaluation.

11.7 FURTHER RESEARCH

This research has identified the need for further investigations into the assessment of doses and evaluation of geotextile capture capability.

In no particular order, further research is required into:

- Exposures to radioactive dust in the underground mines that participated in the Hewson and Ralph (1994) research, and in new underground mines.
- Ventilation techniques, and characteristics of the underground working atmosphere such as particle size, Rn and RnP concentrations, the degree of equilibrium and the unattached fraction of RnP, especially in deep mines.
- Exposures to radon, radon progeny and gamma radiation at new underground mines.
- The veracity of data reported to the RRAM by Reporting Entities. This could take the form of a quality control assessment and in-field sampling to confirm exposure scenarios.
- The observed decrease in airborne activity concentration in the five REs that were operating in the 1990s and are currently in operation.

- Equilibrium factors between thoron, radon and their progeny in mining operations controlled by Reporting Entities. This data is in most parts, lacking.
- The impacts of the revised, but undocumented, changes to the DCF for insoluble dusts following the 2009 revision of the NORM-5 Guideline.
- Activity concentration of the lithology being explored for rare earth content, in order to develop a state-wide library of mining operations with potential NOR-exposure.
- Removal of scale from NOR-contaminated mining equipment across the range of componentry used in a variety of mineral processing activities that use different physical and chemical mineral treatments, such as acid attack or high temperature or pressure.
- The radiological properties of the oily, viscous substance identified in the field trials, and its association with elevated activity concentration should be investigated by the RE, as part of the planning process for demolition of the disused mineral processing operation.

11.8 IMPACT OF THIS RESEARCH

This research was intended to not only investigate and document Western Australian mine workers' exposure to NORs but also to provide the policy foundation for better management of sources of radiation risks arising from exposure to NORs across the Western Australian mining industry.

The research has effectively filled the knowledge gap of mine worker radiation exposures in Western Australia. It has proposed a future regulatory model; influenced the national policy and methodology for determining worker doses; and has been utilised to direct the legislative compliance requirements of the state's mining operations that encounter NORs.

The aim of the research has been achieved, as evidenced by:

- Publication in national and international peer-reviewed journals, and therefore has the potential to influence strategies to minimise mine worker exposure to NORs in jurisdiction outside of Western Australia.
- Being the first published work to address the impact of the revised dose coefficients on internal doses to mine workers arising from inhalation of radon and radon progeny; and NOR-containing dusts.

- Revision of the Western Australian NORM-5 Guideline, and the subsequent publication of the NORM-V Guideline which embraced the revised dose coefficients outlined in Chapter Seven, and published as Ralph et al. (2020c).
- The influence on national policy pertaining to radiation protection in the mining and milling of radioactive ores. The research was adopted in RPS-9 and its companion document RPS-9.1 (ARPANSA, 2022a) and publicised in ARPANSA (2022b) and ECU (2022).
- Establishment of a potential solution to the emerging issue of removal of the radioactive contaminants in disused mining equipment used to process NOR-containing minerals. The solution presented has been demonstrated to be cost-effective and has potential to significantly decrease the environmental footprint of NOR-contaminated waste materials.

11.9 IN CONCLUSION

Western Australia has a long, but chequered history of mining radioactive minerals, that has its origins in the 1950s but escalated significantly in the 1970s when monazite was pursued globally as a source of rare earth elements. However, poor environmental practices which led to some exceptionally high worker doses, and widespread radioactive contamination of rural properties, eventuated in the state government commissioning the Winn Inquiry into radiation protection in the mineral sands industry.

The pronouncement “*History repeats itself, first as a tragedy, then as a farce*” as attributed to Karl Marx applies to some of the findings of this research, which has highlighted persistent issues in relation to the competence of Radiation Safety Officers; and the declining trend in representative dose assessments, reflecting a level of indifference by REs to their obligations to ensure mine worker radiation doses are maintained as low as reasonably achievable. Given this context, it is considered an inevitability that the emerging issue of reducing the risk of exposure to potentially radioactive scrap metal will require amendments to the regulatory framework.

The existing regulatory framework is overly complex; is reactive to national strategies that are often implemented without consultation with the mining sector; does not involve consultation with mine worker representatives; and is reliant upon enforcement by regulatory agencies that are under-resourced. The researcher contends that the Western Australian mining industry is destined to repeat the errors and omissions of the past if these matters are not addressed.

And so … the final word on this research belongs to those who contributed to the Winn Inquiry, the catalyst for those improvements that have been witnessed in the past 42 years: " … we believe the aim to keep occupational doses below 20mSv is achievable within a few years and we urge the industry to accept the challenge in the interests of the health and welfare of its employees" (Winn et al., 1984, p. 50).

The message of the Winn Commissioners is as salient today as when it was first issued in 1984.

This researcher hopes that radiation doses to Western Australian mine worker (and perhaps in national or international mining provinces) arising from their exposure to NORs are better understood, and as a result minimised, because of this research.

* * *

APPENDICES

When one of these particles or rays goes crashing through some material, it collides violently with atoms or molecules along the way … In the delicately balanced economy of the cell, this sudden disruption can be disastrous. The individual cell may die; it may recover. But if it does recover … after the passage of weeks, months, or years, it may begin to proliferate wildly in the uncontrolled growth we call cancer.

The Careless Atom

(Novick, 1969).

2.18. The government shall ensure that a graded approach is taken to the regulatory control of radiation exposure, so that the application of regulatory requirements is commensurate with the radiation risks associated with the exposure situation.

IAEA General Safety Requirements Part 3

(IAEA, 2014, p. 21).

APPENDIX 1: RESEARCH OUTPUTS:

This research is presented as a series of chapters that relate to papers authored by the researcher.

When the ICRP released publication 137 (ICRP, 2017) and the revised dose coefficients for radon were endorsed in Australia (RHC, 2018b) it established the framework for the first paper in this series, with the remaining papers produced as a result of the release of ICRP publication 141 (ICRP, 2019a).

The following seven articles were produced as a result of the research:

i. ***REASSESSMENT OF RADIATION EXPOSURES OF UNDERGROUND NON-URANIUM MINE WORKERS IN WESTERN AUSTRALIA***

Published in Radiation Protection Dosimetry Volume 191, Issue 3, September 2020,

Pages 272–287,https://doi.org/10.1093/rpd/ncaa131

Published: 23 October 2020

Contributors: Martin I Ralph; Steven Hinckley; Marcus Cattani

ii. ***IMPACTS OF REVISED DOSE COEFFICIENTS FOR THE INHALATION OF NORM-CONTAINING DUSTS ENCOUNTERED IN THE WESTERN AUSTRALIAN MINING INDUSTRY***

Published as a Practical Matter Article in *Journal of Radiological Protection*, Volume 40, Number 4, 1457

Published 20 November 2020

Contributors: Martin I Ralph, Nick Tsurikov and Marcus Cattani

iii. ***A REVIEW OF RADIATION DOSES AND ASSOCIATED PARAMETERS IN WESTERN AUSTRALIAN MINING OPERATIONS THAT PROCESS ORES CONTAINING NATURALLY OCCURRING RADIONUCLIDES FOR 2018–19***

Published as a Practical Matter Article in Journal of Radiological Protection, Volume 40, Number 4, 1476

Published 23 November 2020

Contributors: Martin I Ralph, Andrew Chaplyn and Marcus Cattani

iv. *MANAGING THE RADIATION EXPOSURES OF W.A. MINE WORKERS FROM NATURALLY OCCURRING RADIONUCLIDES: AN HISTORICAL OVERVIEW (PART I)*

Published in Radiation Protection in Australia, ISSN 1444-2752, Volume 38, Number 1, Pages 53-93

Accepted for publication 24 April 2021

Contributors: Martin I Ralph, Nick Tsurikov and Marcus Cattani

v. *MANAGING THE RADIATION EXPOSURES OF W.A. MINE WORKERS FROM NATURALLY OCCURRING RADIONUCLIDES: AN HISTORICAL OVERVIEW (PART II)*

Published in Radiation Protection in Australia, ISSN 1444-2752, Volume 38, Number 2, Pages 4-51

Accepted for publication 21 September 2021

Contributors: Martin I Ralph, Nick Tsurikov and Marcus Cattani

vi. *A REVIEW OF RADIATION DOSES AND ASSOCIATED PARAMETERS IN WESTERN AUSTRALIAN MINING OPERATIONS (2018–20)*

Published as a Practical Matter Article in Journal of Radiological Protection, Volume 42, Number 1, 012501

Published 12 January 2022

Contributors: Martin I Ralph and Marcus Cattani

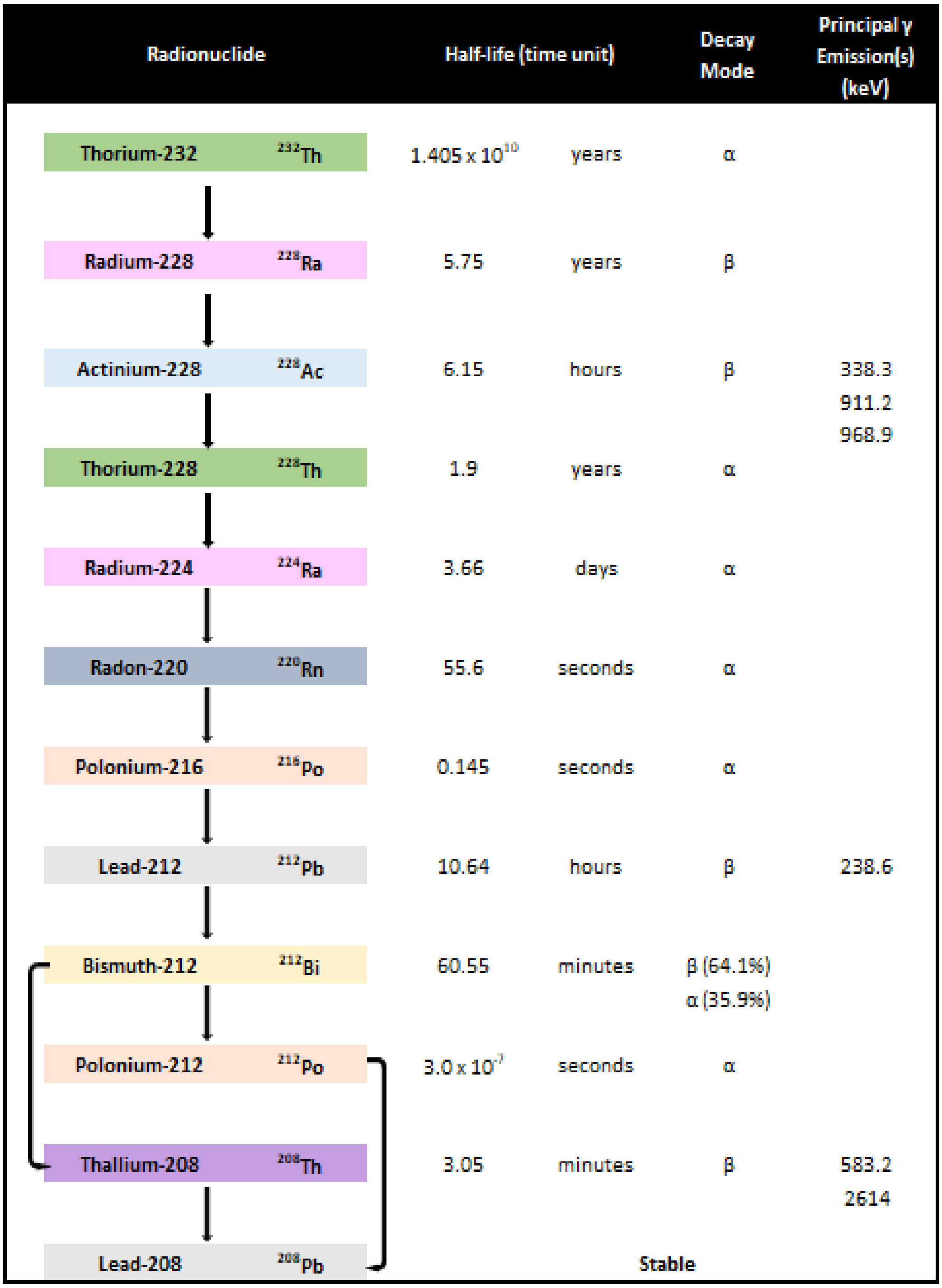
vii. *AN EVALUATION OF A GEOTEXTILE FILTER TO CAPTURE RADIOACTIVELY CONTAMINATED CORROSION SCALE REMOVED FROM DISUSED MINING EQUIPMENT BY HIGH-PRESSURE WATER-CLEANING*

Submitted to Science of the Total Environment, 26 September 2022

Under Editorial Review: Reference STOTEN-D-22-24063

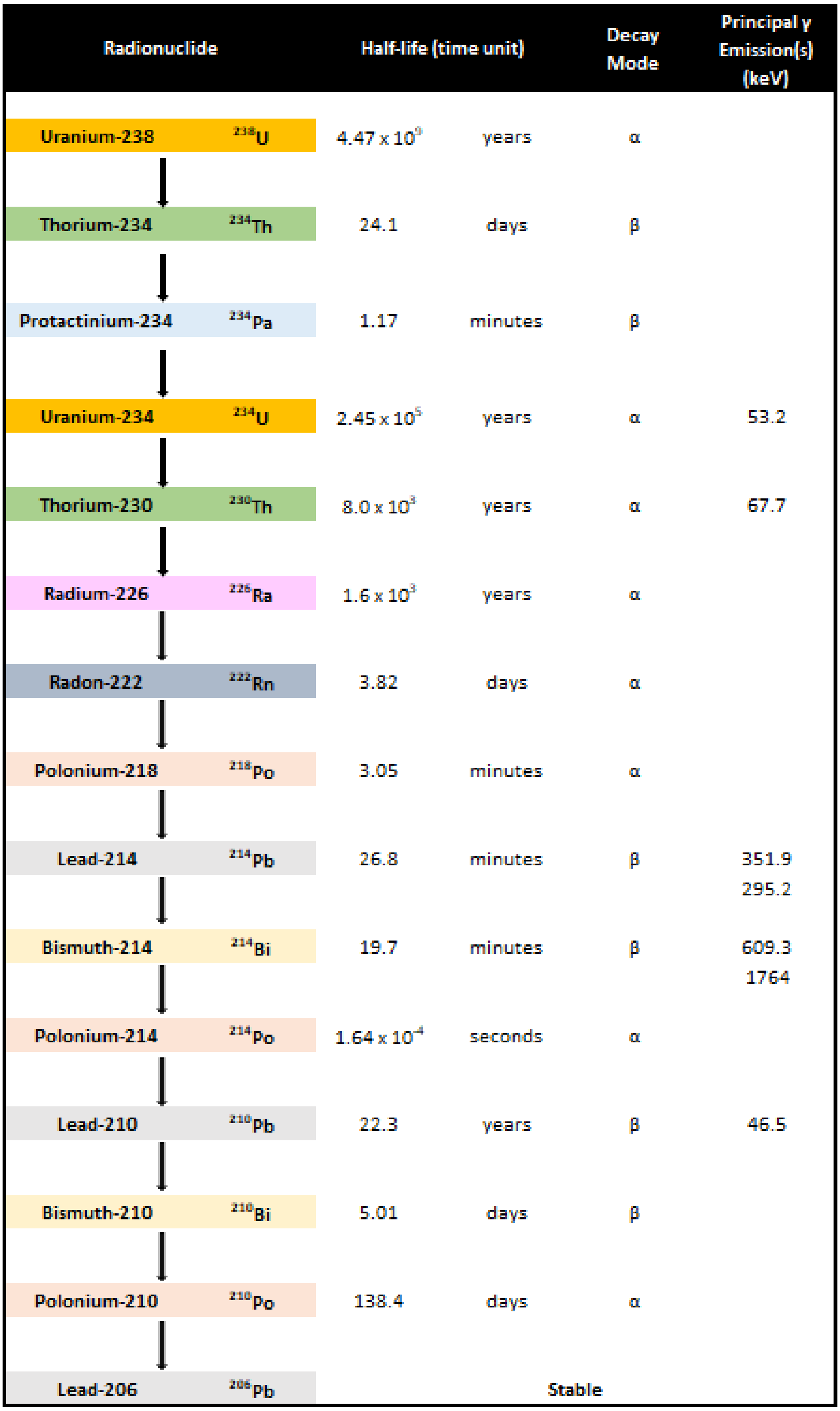
Contributors: Martin I Ralph, Craig Rothleitner, Madison Williams-Hoffman, and Marcus Cattani

APPENDIX 2: THE THORIUM-232 DECAY SERIES



Radionuclide		Half-life (time unit)		Decay Mode	Principal γ Emission(s) (keV)
Thorium-232	^{232}Th	1.405×10^{10}	years	α	
Radium-228	^{228}Ra	5.75	years	β	
Actinium-228	^{228}Ac	6.15	hours	β	338.3 911.2 968.9
Thorium-228	^{228}Th	1.9	years	α	
Radium-224	^{224}Ra	3.66	days	α	
Radon-220	^{220}Rn	55.6	seconds	α	
Polonium-216	^{216}Po	0.145	seconds	α	
Lead-212	^{212}Pb	10.64	hours	β	238.6
Bismuth-212	^{212}Bi	60.55	minutes	β (64.1%) α (35.9%)	
Polonium-212	^{212}Po	3.0×10^{-7}	seconds	α	
Thallium-208	^{208}Th	3.05	minutes	β	583.2 2614
Lead-208	^{208}Pb	Stable			

APPENDIX 3: THE URANIUM-238 DECAY SERIES



Radionuclide		Half-life (time unit)		Decay Mode	Principal γ Emission(s) (keV)
Uranium-238	^{238}U	4.47×10^{9}	years	α	
Thorium-234	^{234}Th	24.1	days	β	
Protactinium-234	^{234}Pa	1.17	minutes	β	
Uranium-234	^{234}U	2.45×10^{5}	years	α	53.2
Thorium-230	^{230}Th	8.0×10^{3}	years	α	67.7
Radium-226	^{226}Ra	1.6×10^{3}	years	α	
Radon-222	^{222}Rn	3.82	days	α	
Polonium-218	^{218}Po	3.05	minutes	α	
Lead-214	^{214}Pb	26.8	minutes	β	351.9 295.2
Bismuth-214	^{214}Bi	19.7	minutes	β	609.3 1764
Polonium-214	^{214}Po	1.64×10^{-4}	seconds	α	
Lead-210	^{210}Pb	22.3	years	β	46.5
Bismuth-210	^{210}Bi	5.01	days	β	
Polonium-210	^{210}Po	138.4	days	α	
Lead-206	^{206}Pb		Stable		

APPENDIX 4: DEVELOPMENTS DURING THE PERIOD OF THIS RESEARCH

The production of the seven research papers was largely driven by the changes to the international models for evaluating worker radiation doses that began in 2015 when the ICRP published the first in a series of five parts of the revised Occupational Intake of Radionuclides (ICRP, 2015).

Coincidentally, the legally binding international treaty on climate change enshrined in the Paris Agreement (UNFCCC, 2015) established the platform for a material increase in global demand for what are collectively colloquially referenced as “battery minerals” used in the manufacture of technology to support reductions in greenhouse gas emissions.

Other significant developments influenced the direction of this research, including (but not limited to):

- December 2016 – Western Australia’s first uranium mine approved (ABC News, 2021).
- March 2017 - The McGowan Government was elected in Western Australia and announced the development of a single Western Australian Work Health and Safety Act to amalgamate the five existing safety and health statutes (Hon. Bill Johnston MLA, 2017).
- April 2018 – the Western Australian Minister for Health established a review into the Western Australian Radiation Safety Act, with the aim of creating a more contemporary legislative framework.
- December 2017 – the ICRP issued publication 137, introducing revised dose coefficients for many members of the ^{238}U and ^{232}Th decay chains.
- January 2018 – ARPANSA endorsed the revised dose coefficients for radon, thoron and their progeny (ARPANSA, 2018a).
- January 2019 – the Western Australian government announced the Future Battery Industry Strategy a vision for the state to become a world leading supplier of battery minerals, many of which are known to have an association with NORM (GWA, 2019b; JTSI, 2019).
- March 2019 – the Australian Federal Government launched the Critical Minerals Strategy targeting a range of mineral commodities known in Western Australia to have an association with NORM (Mining dot Com, 2019).

- December 2019 – the ICRP issued publication 141, completing the revision of dose coefficients for all members of the ^{238}U and ^{232}Th decay chains.

- November 2020 – royal assent given to the Western Australian Work Health and Safety Bill 2019 (Parliament of Western Australia, 2020).

- May 2021 – Revised dose coefficients and the methodology for calculating dose conversion factors for the ^{238}U and ^{232}Th decay chains published in the Western Australian NORM-V Guideline and applied to the 2020-21 annual reporting period.

- September 16th, 2021, the Australian Prime Minister, Minister for Defence and Minister for Foreign Affairs released a joint media statement announcing the AUKUS agreement which will deliver at least eight nuclear-powered submarines to Australia (Hon. Scott Morrison, Hon. Petter Dutton & Hon. Marise Payne, 2021). This will increase demand for radiation protection professionals, who are already in short supply, and will tighten the market for suitably qualified professionals to enter the state's mining industry. The announcement has potential future implications, including increasing the demand for uranium and reigniting the debate on Australia's role in the nuclear energy cycle.

- October 2021 – ARPANSA published the revised version of the National Directory on Radiation Protection, providing a national framework for management of radiation risks to people and to the environment (ARPANSA, 2021c).

- November 26th, 2021 – the State mining engineer approved the operational radiation management plan for the state's first uranium mine and processing plant. Construction works commenced soon after, with the owner indicating production will commence "by 2025" (ABC News, 2021).

- February 24th, 2022 – Russia invaded Ukraine leading to significant disruptions in global supplies of a range of products, including uranium. In combination with renewed interest in nuclear energy as a result of greenhouse gas reduction initiatives encapsulated in the Paris Agreement, material increases in the price of uranium occurred (S&P Global, 2022). In turn, this has led to an increase in exploration for uranium in Western Australia (Stockhead, 2022).

- March 31st, 2022 - radiation safety in mining obligations included in the Work Health and Safety (Mines) Regulations came into effect.
- Late August, 2022 – the European Parliament supported the passage of laws into the European Union labelling investments in nuclear power plants as “climate-friendly” enabling nuclear power to be marketed as “green” from 2023 (Abnett, 2022). This move led to a global increase in the price of uranium, and a commensurate increase in uranium exploration activity in Western Australia.

From Figure 2, it can be seen that developments in relation to the Paris agreement on climate change and the deliberations of the ICRP have in combination resulted in significant increases in commodity prices, driving an increase in the number of mining operations that encounter NORM and a commensurate increase in the potential radiation doses received by an increased cohort of mine workers. An unintended outcome has been an increase in demand for appropriately skilled and qualified radiation safety personnel.

The first Australian case of novel coronavirus (Covid-19) was confirmed in Victoria on the 25th January 2020 (Department of Health and Aged Care, 2020) and throughout the first quarter of 2020 the Western Australian mining industry progressively implemented measures to control the spread of the virus (DMIRS, 2020b). One of the measures, that was maintained for two years, was to restrict non-essential workers such as myself from attending mining operations.

As was discussed in Section 4.4, in late 2019 scrap steel recovered from an underground nickel mining operation in the north-eastern-goldfields region of Western Australia triggered radiation detectors at a scrap metal yard. This event proved pivotal to the direction of the field-based component of this research, as it raised the prospect of radiation exposures to a previously overlooked cohort of workers – those who handle radioactively contaminated steel. It also highlighted the potential for exposures to members of the public and impacts upon the environment if the contaminated items are not effectively managed.

The Covid-19 restrictions and the contaminated steel event, prompted the field evaluations to focus on evaluating a method to safely remove the radioactive contaminants from steelwork, thereby reducing the risks of exposure and minimising the potential for impacts upon the environment.

APPENDIX FIVE: THE WINN INQUIRY AND ITS INFLUENCE ON RADIATION PROTECTION IN THE WESTERN AUSTRALIAN MINING INDUSTRY

The discovery that tailings from a mineral sands processing plant had been used as landfill in Capel, a town in southern Western Australia, indicated the need for a survey of the gamma radiation levels within the townsite.

Eleven houses were found to have elevated backgrounds and a further 27 residential properties had elevated levels outside the house. The highest dose rate recorded in a residential area was 4µSv per hour [73]

Radioactivity in mineral sands in Western Australia

King, Toussaint and Hutchinson (1983).

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[73] Equivalent to approximately 35mSv per year. The annual limit for a member of the public is 1mSv.

The Winn Inquiry signified an exigency for the manner in which worker exposures to NORs were managed by the MSI and regulated by government agencies.

The following Sections provide a synthesis of the societal and regulatory environment that led to, and the ramifications of the Winn Inquiry, many of which endure to the present day.

A.5.1 THE WINN INQUIRY

In 1947 the Geological Survey of Western Australia investigated the beaches and rivers of the State searching for monazite deposits as part of a national program to define Australia's potential radioactive mineral resources SWDA (1990, Ch1-5). As a result, it is prudent to suggest that the radiological characteristics of Western Australian mineral sands deposits were known prior to the initial operations at Cheyne Bay in 1949, and for the subsequent 35 years until the advent of the Winn Inquiry.

From commencement of operations in 1950, the MSI fell within the regulatory remit of the RSA (and its preceding legislation), enforced by the RCWA via the (various) Radiation Health Section(s) of the Health Department.

- However, it was not until July 1966 that an operation in the MSI in the south west of Western Australia was informed by the RCWA (1983) that "the monazite had a thorium oxide content [and] was radioactive".

Winn et al. (1984, p. 6.4) found the Radiological Advisory Council (at the time the singular RA) "began systematic inspections of … [the MSI] only in 1978". Areas of operating plants were surveyed for external γ, and recommendations made to the mining companies for reducing worker exposures. Other than some preliminary measurements of LLα, little surveillance of internal exposures was conducted (Hartley & Hewson, 1990).

Through the 1970s, monazite production expanded significantly and despite the potential for elevated worker exposures, it "became apparent, however, that the RSA did not have suitable powers to enable proper control of radiation on mine sites as it had been designed principally to control medical uses of radiation" (Hartley & Hewson, 1990). Winn et al. (1984) observed that whilst some companies adhered to the regulatory authority's advice, added "Others have in the past shown some diffidence towards complying".

The lack of appropriate legislative authority is evident in the submission made by the RCWA to the Winn Inquiry (RCWA, 1983). The RCWA reports that the site advised of radiological issues in 1966 was inspected on numerous occasions through the 1970s, with officers representing the RCWA noting that "doses in the office area would exceed the ICRP limits for the general public" and "a monazite bagger could receive between 20 and 100 milliRem/week (equivalent to 10 to 50mSv, from external γ, per year). The RCWA commented further "Altogether the operations of this plant have been relatively unsatisfactory over the years … The company has been relatively slow in responding to requests from Council to clean up their procedures … Indeed [according to site management] … no radiation protection measures were thought necessary" (RCWA, 1983).

In 1982, the Cabinet of the Government of Western Australia agreed to form the IMRC to oversee the implementation of actions to overcome the regulatory impasse (RCWA, 1983). However, the issues persisted, leading to the following statement attributed by Winn et al. (1984) to the Western Australian Minister for Health: "Following widespread concern about the levels of ionising radiation in the MSI, the Western Australian government established a Committee of Inquiry (the Winn Inquiry) in mid-1983 to report and make recommendations on:

(b) The adequacy of, and compliance with, codes of practice and legislation regulating radiation in the mining, processing and transport of heavy mineral sands and the disposal of tailings ".

The Winn Inquiry had far-reaching impacts upon the manner in which radiation protection in the Western Australian mining industry was regulated, and its influences continue to be felt in the current regulatory framework.

A.5.2 THE SOCIETAL CONTEXT LEADING TO THE WINN INQUIRY

Sonter (2014) provides a valuable context in relation to the status of the radiation protection profession in the 1970s, stating "It is easy to forget just how little was known about the behaviour of radiation (and especially radon) in uranium mines in the 1960s and early 1970s: we did not have a good handle on how to predict radon in underground mines, or how to control it; we did not have good data for prediction of gamma dose rates; we did not know how to work out internal doses from inhalation of dust".

Australia's first (and only) nuclear reactor, the Hifar facility at Lucas Heights, New South Wales, first went critical on Australia Day, 1958, an event that was supposed to herald the dawning of the nuclear age in Australia. Sonter (2014) reflects "But then social attitudes changed. Serious fears and antipathy towards "things nuclear" developed in the 1970s, driven by concern about worldwide atmospheric weapons testing and the resultant quite significant fallout. This was exacerbated by the arrogance and callousness of the French for blowing up … south sea islands".

The zeitgeist of the period leading up to the commissioning of the Winn Inquiry reflected a growing community angst towards radiation, and the nuclear fuel cycle in particular. The following list is not exhaustive however it serves as a useful historical anchor:

- 1979: March 16th, the fictional movie "China Syndrome", centred upon a theme of safety cover-ups at a nuclear power plant, was released in the USA.
- 1979: On the 28th of March, the Three Mile Island accident occurred in the USA (giving the "China Syndrome" movie prescience).
- 1981: Release of the book "Radiation & Human Health" by John W. Gofman (Gofman, 1981), colloquially known as the "Father of the Anti-Nuclear Movement".
- 1984: On the 9th of February, the movie "Silkwood", themed on the life of a nuclear whistle-blower, was released in the USA.

Whilst in Western Australia:

- 1979: In what is perhaps Western Australia's worst industrial accident involving a source of radiation, an Ohmart Density Gauge containing radioactive Caesium-137 was lost from a Western Australian mining operation. The gauge was consigned in a shipment of waste metal to Singapore where it subsequently contaminated a scrap metal furnace.

  The contaminated brick work and contents of the furnace were returned on 8th December 1981 to Kambalda for burial in a concrete bunker (Stewart, 1982) and attracted significant media attention; and
- 1980: The Kalgoorlie Research Plant (KRP) was commissioned. KRP was designed to ascertain the feasibility of the Yeelirrie uranium project, as is expanded upon in Section 10.2.

In 1990, reflecting upon the societal context of the time, Hartley and Hewson (1990) stated "From the late 1970s the MSI has excited considerable controversy … through increased community concern about environmental issues. Those involving radiation have attracted particular media attention, which in turn has generated anxiety amongst both workers and the broader community" and "... public perceptions about the community radiation hazard arising from MSI operations[s] have tended to escalate with some concern that myths may have been fostered in an effort to polarize public opinion. The intense public scrutiny has at times complicated the functioning of the RA".

The controversy highlighted by Hartley and Hewson (1990) is typified in the "Heavy Mineral Sands Handbook" by Keys, Grace and Humphries (1988, Chapter 3.3), which cites several print media articles dealing with cases in the towns of Geraldton and Capel where "schools, houses and playing fields where tailings had been used for landfill, were found to have unacceptably high radiation levels", findings verified by King et al. (1983) as per the quotation that opens this Chapter.

Keys et al. (1988) discuss two examples of concerns expressed by waterside workers as a result of them handling radioactive minerals, and the discovery that "the Geraldton railway yards' storage and handling facilities had radiation levels up to ten times the permitted levels as a result of monazite and other heavy minerals being spilt", concluding "it became evident that health and safety regulations were not being enforced…".

In summary, at the time the Winn Inquiry was commissioned, there was a global anti-nuclear sentiment developing; the local MSI appeared oblivious to the radiation issues associated with NORMs in their products and tailings; the state's (arguably still) worst radiation-oriented industrial accident had occurred; and yet, seemingly in denial of these issues, regulatory support had been provided to evaluate the prospectivity of a potential state uranium mining and milling industry…

A.5.3 GENERAL FINDINGS OF THE WINN INQUIRY

The Winn Inquiry (Winn et al., 1984, Ch 6.3-6.4) agreed that the existing regulatory structures were inadequate up until the adoption of the Mineral Sands Code (DME, 1997) in 1983, stating "the RCWA and its predecessor the Radiological Advisory Council … have for many years found themselves in a position of administering radiation protection standards in the MSI without any clear legal standards " and "The 1982 WA [Mineral Sands] Code put radiation protection in the MSI on a much needed statutory basis".

Despite these findings, the Winn Inquiry (Winn et al., 1984, Ch 7.1) concluded "there is an obvious and genuine attempt by the industry to run its business in accordance with good common sense, the codes and pertinent legislation", and commended the (then) RA, the State X-ray Laboratories, on their performance, stating “[it] carries out its work efficiently and effectively despite the small size of its work force”.

The Winn Report (Winn et al., 1984, Ch 7.5) highlighted that a shortage of appropriately qualified and experienced RSOs would detract from the MSI’s ambitions to effectively manage the exposure of its workers and the public. One of the more trenchant comments was “a further cause of concern has been the inadequacy of training facilities for companies’ [RSOs] (a position required under the code)”.

The major finding of the Winn Inquiry (Winn et al., 1984) was “The committee has found no major breaches of legislation, regulations or codes of practice”. Whilst this finding was encouraging, the Winn Report contended that the performance could be improved, pointedly stating “the Commissioners believe the goal of bringing radiation levels As Low as Reasonably Achievable, i.e., the ALARA principle; needs to be pursued with more vigour”.

Prophetically the Commissioners stated that they “see a difficulty for the MSI in the future as it attempts to comply with the proposed new maximum limits for the radioactivity of dust” (Winn et al., 1984).

A.5.4 WORKER RADIATION DOSE ESTIMATES CITED IN THE WINN INQUIRY

The Winn Inquiry reported that systematic inspections of the MSI commenced in 1978, and using this time as a reference point, constructed a timeline of worker doses up until 1982.

The focus of the analysis was doses arising from γ radiation. Personal monitoring was conducted by a film-badge service [74]. The number of badges assessed and the number of workers is not provided in the Winn Report, however Hartley and Hewson (1990) report that in 1981 there were 61 workers monitored for external γ exposures, of a workforce estimated to be circa 1,000 in Winn et al. (1984).

- Although monitoring was conducted on less than ten percent of the workforce, nonetheless, there appeared to be sufficient data for the Winn Commissioners to be confident in the doses they reported [75].

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[74] Presumably by the RCWA which offered a service at the time.

[75] There is no indication in Winn et al. (1984) as to the representativeness of the monitoring.

In recognition of the significance of potential doses from inhalation of LLα Winn et al. (1984) stated that, based upon 46 dust samples collected prior to 1983, doses from inhalation of LLα were similar to those from external γ.

The contribution from thoron, radon, TnP and RnP was deemed as "not a problem in the industry" with the Winn Commissioners noting that "the levels are so near to the ultimate sensitivity of the instruments available that the measurements are difficult to perform" and concluded that this was unsatisfactory (Winn et al., 1984, pp. 5.5-5.7).

- The data reported by the Winn Inquiry are used to construct the dose estimates presented in Table 52.

TABLE 52: DOSE ESTIMATES IN THE WA MSI, 1978 TO 1982

Parameter	Committed Effective Dose (mSv)				
	1978	1979	1980	1981	1982
External γ	6.8	6.3	3.5	3.4	4.4
LLα in Dust	6.8	6.3	3.5	3.4	4.4
Thoron / Radon	n/a	n/a	n/a	n/a	n/a
TnP / RnP	n/a	n/a	n/a	n/a	n/a
annual dose	13.6	12.6	7.0	6.8	8.8

The annual doses listed in Table 52 were compared to the applicable legislative dose limit of 50mSv, leading the Winn Inquiry to declare "that radiation levels in the [MSI] are below present limits for workers".

Notwithstanding the findings, and aware of the impending changes to dose conversion factors recommended by international authorities, the Winn Commissioners cautioned "A future compliance problem will come from the move to reduce the ALI [annual limit of intake] of thorium ore dust as recommended by the ICRP and taken up by the IAEA and others. This will be quite difficult for the industry to achieve" (Winn et al., 1984).

As was outlined in Section 2.2, the ALI's based upon ICRP-26 (ICRP, 1977) and ICRP-30 (ICRP, 1979) were introduced in 1986. As predicted by the Winn Commissioners, according to Hartley and Hewson (1990):

- "The effect was that workers who had been previously assessed as having radiation doses less than the annual limits [in 1983] were now assessed as exceeding the limits [in 1986].

Poignantly, Hartley and Hewson (1990) succinctly state "It then became clear that stricter regulation of the industry was needed as well as a program to limit the exposure of workers to radioactive dust".

A.5.5 COROLLARIES TO THE WINN INQUIRY

The recommendations of the Winn Inquiry were implemented, leading to significant changes in the regulatory governance of worker radiation exposures in the MSI, and over time, other mining operations that encountered NORs.

As reported by Hartley and Hewson (1990), 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 (GWA, 1987).
- relocation of regulatory responsibility for radiation protection in Western Australian mines from the RCWA to the SME; and
- commissioning of a specialized Radiation Secretariat within the Mines Inspectorate (later renamed the Radiation Safety Section, RSS).

The changes in regulatory governance laid the foundation for a period in which Western Australia's oversight of radiation protection in the mining industry was recognised to be performing at world's best practice.

Some of the more significant accomplishments are outlined in the following Sections.

A.5.6 EDUCATION OF RSOS AND DEVELOPMENT OF THE 'NORM GUIDELINES'

The Winn Inquiry, and later, Meunier (1987) and Gandini (1990) identified the absence of an articulated pathway for developing appropriately qualified and skilled RSOs as an issue that would negatively impact the pursuit of improved radiation protection across the MSI.

According to Hewson (1989b) 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 (Gandini, 1990), the courses and seminars grew in status and were delivered by the university sector (Hartley & Hewson, 1990), and converted into a formal textbook (CMEWA, 1994).

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 (Hewson, 1989b). A suite of ten Guidelines were endorsed by the IMRC and published between August 1986 and October 1988 (Hartley & Hewson, 1990).

- Over time the Guidelines have been edited and condensed, and have entered the radiation protection lexicon as the “NORM Guidelines” (DMIRS, 2020g).

The NORM Guidelines are cited in ARPANSA Radiation Protection Series No. 9.1 (ARPANSA, 2011a), and according to Ralph et al. (2020c) have been “distributed to numerous regulatory authorities in jurisdictions outside of Australia, some of which have adopted them into their radiation protection legislation”.

The development of NORM-V (based upon (Ralph et al., 2020c)) which embraces the use of DCs published in ICRP publications 137 and 141 was discussed in Section 3.7. The implementation of NORM-V is believed to be the first time that any mining jurisdiction in the world has mandated the use of the revised DCs.

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 REs.

A.5.7 REPORTING REQUIREMENTS IMPOSED UPON REs

According to Hewson (1989b) the requirement for REs to submit annual reports of worker radiation doses was implemented in 1984, with guidance on the contents of the reports provided in NORM Guideline #8 entitled “Reporting Requirements” in November 1987 (Hartley & Hewson, 1990). This date was too late in the calendar year reporting format of the time to align the annual reports from all REs to the new standard.

- 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 Western Australian mine safety legislation in 1986, sample numbers were low, and quality assurance programs were not in place” (Hewson & Marshman, 1993, p. 2). Accordingly, the doses reported prior to 1986, and probably including those in 1987, have an elevated level of uncertainty, and have been treated accordingly.

Increased regulatory scrutiny from 1986 onwards eventually led to a standardised reporting format, and the development of an electronic database, the Mines Dose Assessment System (MIDAS). As is discussed in Section 6.8, MIDAS was used by all REs for the recording of monitoring data and the calculation of worker doses (Hewson, 1989b; Marshman & Hewson, 1994).

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 (GWA, 2010e). 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” which runs from 1st April each year to 31st March in the following year. The first radiation reporting year was 1993-1994; and
- As a result of the withdrawal of support for the Boswell dose reporting system (as discussed in Section 6.8) 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 (Ralph, 2017).

The consistency in reporting format contributed significantly to this research, allowing an assessment of the historical record of exposure scenarios and to identify trends in worker doses as reported in Chapter Ten, and enabling the assessment of the impact of the revised DCs, as reported in Chapters Eleven and Twelve.

A.5.8 COMPUTER-BASED DOSE CALCULATION, RECORDING AND REPORTING SYSTEMS

As was reported by Hewson (1989b), “Another project [by the RSS] involves the development of a computer-based radiation exposure recording and reporting system, so that future investigation of worker exposure trends may be based on reliable data”. According to Marshman and Hewson (1994) the initiative, which had commenced in 1988 as a joint project between the RSS and the Chamber of Mines and Energy of Western Australia (CMEWA) was largely driven by:

- complexities associated with calculating annual doses, particularly doses arising from the inhalation of LLα.
- a general lack of technical expertise of industry RSOs (as identified in the Winn Inquiry) to calculate annual doses effectively and consistently; and
- the requirement for the RSS to audit the dose assessments provided by the REs, which when performed manually, proved to be a laborious and time-consuming exercise.

Marshman and Hewson (1994) reported that a database application referenced as the Mines Dose Assessment System (MIDAS) was installed at each of the REs in October 1992. The use of MIDAS ensured that the dose calculation process was consistent across operations, whilst allowing for 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 (1994) 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-2010s. In some part this was due to the need for REs 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 (Hewson, 1988b; Koperski, 1993a), and in order to standardise the calculation and reporting of this complex data, the RSS developed two Microsoft Access DBIV database routines (Marple and Sierra) and distributed them for use by REs (Ralph, 1990).

The CMEWA funded the development of a software application called Boswell, which utilised the Microsoft Access (2000) platform to replace MIDAS. The application was developed by the Mines Inspectorate, and implemented across the MSI in September 2004, with the expectation that the 2004-05 annual report would be compiled using dose assessment data in Boswell (Knee, 2004).

The transition to Boswell was not smooth, with new functionality seemingly causing confusion amongst MSI RSOs (DMIRS, 2019b) and multiple examples of errors being reported from inception to the late 2000s (C. Bovell, personal communication December 7th, 2020), (DMIRS, 2019c). One such report from an RE 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” (DMIRS, 2019c). In order to overcome the issues some REs reverted to hard-copy submissions and included print-outs or PDF copies of selected sections of the Boswell data. However, this approach was not uniform across the industry, and 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) the Mines Inspectorate opted to withdraw support for Boswell in May 2014 (DMIRS, 2019d). Despite the withdrawal of support, several REs have continued to use Boswell, in the knowledge that many of the reporting functions are flawed. This has created an additional burden on the auditing of dose assessment function for the Mines Inspectorate (C. Bovell, personal communication December 7th, 2020). Some REs 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 et al. (1984) and repeated by the Uranium Industry Framework Steering Group of the Uranium Industry Framework Steering Group (2006, Item 4.1.1). The significant increase in the number of workers potentially exposed to NORs (as indicated in Section 1.2) has exacerbated the RSO competency issue, as highlighted in a 2019 presentation at an international NORM symposium by Tsurikov (2019), 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 Western Australian mining sector was identified by the Winn Inquiry, the issue remains largely unresolved.

A.5.9 MANAGEMENT OF ANNUAL RADIATION REPORTS SUBMITTED BY REs

Operations meeting the RE criteria must have a RMP approved by the RRAM before operations can commence. As was addressed in Section 3.6, a RE must also provide annual reports of estimates of radiation doses received by the workforce to the RRAM, with the report to follow the format as outlined in NORM Guideline No. 6 (GWA, 2010e).

Since 1986 when the Mines Inspectorate became the RA for REs, the Department has been responsible for the keeping of records associated with the radiation exposure of mine workers. With the advent of the MSIR (GWA, 1995), the SME [76] became the approving authority, and was required to store records of the:

- results of baseline radiation monitoring programs submitted by REs.
- radiation management plans (RMPs) and radioactive waste management plans (RWMPs).
- approval and appointment of RSOs.
- dose assessments for workers; and
- removal, importation, storage, stockpile management and disposal of radioactive material.

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 RE.

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[76] Under the WHSR(Mines) legislation this obligation now resides with the RRAM. In the event that a RE ceases operation, copies of personal dose records will also be retained by the RCWA.

As technology improved, the records management officers 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)” (Veluppillai, 2020b). 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-2010s, submissions have been made via email, or the bespoke Mines Inspectorate computer-based record and communication information management system, the Safety Regulation System (SRS) (DMIRS, 2020f). Whilst the transition to SRS was occurring, an ad-hoc process developed whereby some technical specialists opted to forward electronic copies of the annual reports to the records management officers for retention in Records Manager (2005).

As is discussed in Chapters Seven and Chapter Ten, the historical record of worker dose assessments is remarkably intact and bears testament to the record-keeping system implemented by the RA.

A.5.10 EXTERNAL AUDIT OF IMPLEMENTATION OF THE RECOMMENDATIONS OF THE WINN INQUIRY

In order to ascertain the level of progress made in implementing the recommendations of the Winn Committee, in June 1989 the Western Australian Minister for Mines commissioned a Technical Audit of Radiation Safety Practises in the Mineral Sands Industry (Mason, Carter & Johnson, 1990). The Technical Audit accessed papers that were prepared for the IMRC, including reports by Hewson (1989b, 1990a) for the IMRC which continued the reporting of doses established in 1988 (Hewson, 1988a). Mason et al. (1990) commended the improvements that had been made in regulatory oversight of the MSI, commenting “most of the recommendations of the Winn Committee of Inquiry have been implemented”.

Mason et al. (1990) 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”.

Mason et al. (1990) made 23 recommendations to the Minister, the majority of which were administrative in nature (Carr, 1990). 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 15mSv or more in a year" (Mason et al., 1990).

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.

A.5.11 REPORTS OF WESTERN AUSTRALIAN 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 (DoM, 1990; Hewson, 1988a, 1989b; Hewson & Ralph, 1987). Largely, these reports were for internal stakeholders, but following the commencement of the Technical Audit by Mason et al. (1990), and increased pressure for transparency from external stakeholders, the RSS commenced a program of public reporting on the status of worker doses in the MSI.

The first report was published in 1990 by Hewson (1990b) 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 DWs [77], 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 of the Department (MED, 1992). This report established a reporting template that was followed in the third report by Hewson and Marshman (1993) and replicated by Ralph et al. (2020a).

The final peer-reviewed publication of doses to MSI workers occurred when Marshman and Hewson (1994) published what amounts to an update of the original paper by Hewson (1990b) and cites data up to the end of the 1992-93 reporting period.

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[77] Formerly DEs (designated employees) under the MSIR legislation.

The practice of publication in peer-reviewed journals discontinued after 1994 effectively removing the opportunity for operations to benchmark their performance.

In 1996, in response to a request from the RCWA, Hewson (1996a), presented an analysis of doses to MSI workers in the reporting periods from 1993-4 to 1995-96, using the template established in MED (1992).

- Disconcertingly, given that sales of monazite from the Western Australian MSI ceased in May 1994 (Hewson & Upton, 1996), the mean annual dose at one of the REs in 1995-96 was reported as 11.5mSv, and the maximum annual dose [78] is estimated as 32.1mSv.
- As discussed in Section 2.2, these doses were reported several years after the advent of ICRP-60 in 1991, with the maximum dose exceeding the derived annual limit of 20mSv by 60%.

On several occasions through the 2000s the RCWA requested the SME to update the historical record of doses to workers in REs (DME, 1994; Toussaint, 2002), but the information was not provided to the REs or more broadly disseminated.

Fetwadjieff (2005) attempted a benchmarking exercise, writing to individual REs comparing their dose distribution against de-identified REs. This practice was repeated the following year (Fetwadjieff, 2006) but ceased thereafter.

The Departmental record of correspondence between the SME and RCWA in relation to mine worker doses appears to end when Knee (2009a, 2009b) [79] responded to a request for the 2006-07 reporting period.

Cross-agency reporting of mine worker doses only recommenced when a copy of the research by Ralph et al. (2020a) was forwarded to the RCWA by Ralph (2020c).

A5.11.1 IAEA report of Western Australian mine worker dose assessments

In 2008, a Western Australian radiation consultant was commissioned by the IAEA to “compile, from available exposure records … data from the MSI for 1995 to the present … and a specified rare earths

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[78] Estimated by adding the maximum internal dose to the maximum external dose.

[79] The correspondence 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.

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" (IAEA, 2008). The consultant confirmed he obtained a copy of the MIDAS and Boswell databases and exposure summaries from each of the operational REs, and where possible, from those operations that had ceased (Nick Tsurikov personal communication, September 23rd, 2020).

In compiling the information on behalf of the IAEA, the consultant observed "in many cases the Boswell database that was used by the [RE] at the time was not providing accurate doses and the detailed raw data from each MSI site were used to re-calculate the worker doses – using DCs for the inhalation of radioactive dust that were applicable at the time of the report" (N. Tsurikov personal communication, September 23rd, 2020).

The workforce demographics and EDs for the period from 1994-95 to 2007-08, data were summarised in two reports to the IAEA (Tsurikov, 2009a, 2009b) extracts of which were published as Tables 29 and 113 of IAEA Safety Reports Series No. 68 (IAEA, 2011).

- It is noted that although Tsurikov conducted a site-by-site analysis, the Western Australian MSI data cited in IAEA Safety Reports Series No. 68 (IAEA, 2011) is aggregated, and although useful for assessing temporal trends across the entire industry, the richness of the individual RE data is absent.

Notwithstanding Tsurikov's 2008 reports (Tsurikov, 2009a, 2009b) which assessed trends across the MSI, the research by Ralph et al. (2020a), which was based on the MED (1992) template, was the first peer-reviewed analysis that allowed REs to benchmark their worker doses since the article by Hewson and Marshman (1993).

- Therefore, a gap of over a quarter of a century in the peer-reviewed body of knowledge of radiation doses from NORs to Western Australian mine workers existed.

A.5.12 RESEARCH ACTIVITIES OF THE RSS, POST THE WINN INQUIRY

The Winn Inquiry was also the catalyst for an intense period of research into the sources, measurement of, and quantity of exposures to radiation in the Western Australian mineral sands industry.

The major developments are summarised in the following Sections.

A5.12.1 Quality control of LLα analysis

In order to ensure that doses from inhalation of LLα were being assessed consistently, the RSS established a "comparative alpha counting" quality control program whereby dust samples were submitted to RSS [80] for counting and the calculated LLα results were compared (Hartley & Hewson, 1990; Ralph, 1989).

The quality control program was supplemented by a calibration service which entailed an RSS officer travelling to the operating mine sites, and calibrating their alpha particle counting equipment *in situ* (Hartley & Hewson, 1990).

The quality control programs provided confidence in the data supplied by REs.

A5.12.2 Measurement of TnP and RnP

In order to address one of the main technical findings of the Winn Inquiry, an investigation was undertaken in 1988 by the RSS 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 53 (Ralph & Hewson, 1988).

As can be seen in Table 53, the measured mean annual dose from inhalation of the combination of TnP and RnP was 0.23mSv and ranged from a minimum of 0.04mSv to a maximum of 0.39mSv, with a potential maximum of 0.92mSv.

The research indicated that TnP and RnP were present in the MSI working environment and that it could be meaningfully measured. Further, the research indicated that the source of exposure should not be discounted from worker dose estimates.

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[80] Submissions were made on a quarterly basis.

TABLE 53: SUMMARY OF TNP AND RNP SAMPLING IN THE MSI IN 1988

Source	**Range (mWL) [1]**			**Annual dose (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 annual dose (mSv) [3]				0.023	0.92	0.23
Measured Total annual dose (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 m3h^{-1}; DC (220Rn) = 3.6mSvWLM^{-1}; DC (222Rn) = 10.4mSv WLM^{-1}

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

A5.12.3 RSS research activities subject to peer review

As reporting of radiation doses to the IMRC became more robust (Hewson, 1988a), it became apparent that many of the assumptions underpinning the dose assessment process required investigation.

The RSS either conducted research, or supported the research of others, leading to a series of peer-reviewed publications, including:

- characterisation studies of the particle size of dusts inhaled by the workforce (Hewson, 1988b).
- an analysis of the effectiveness of respiratory protection for reducing worker exposures (Hewson & Ralph, 1992).
- investigations into the secular equilibrium of the ^{232}Th series in monazite (Kerrigan & O'Connor, 1990).
- emanation of Tn from monazite (Kerrigan, 1988); and
- uncertainties in the calculation of doses from the inhalation of thorium (Hewson, 1989a; Hewson, 1989c).

A.5.13 WORLD'S BEST PRACTICE?

The volume of research and measurement activity in the early 1990s justified Western Australia to hosting the First International Symposium on Radiation Protection in the Mining, Milling and Downstream Processing of Minerals Sands in 1993 (ARPS, 1993).

During the symposium Hartley and Hewson (1993) provided a status update on a number of projects that were in progress such as thorium metabolism (Hewson & Fardy, 1993) and the use of an integrated personal dose assessment instrument (Terry, 1992). The symposium provided the platform for socialising research on particle size characterisation studies (Koperski, 1993a) and the biological properties of inhaled particles (Twining et al., 1993).

In his report on the proceedings of the Symposium, Koperski (1993c) 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 the President of the Australian Radiation Protection Society, Fitch (1988) 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”.

Over the following handful of years, the SME, via the RSS:

- introduced the requirement for REs to submit a Radioactive Waste Management Plan for their operations (Torlach, 1994).
- identified other potential REs (Terry, 1996).
- supported ing further research into the biological properties of inhaled particles (Hewson, 1995; Terry et al., 1997); and
- provided funding for an investigation into alternate methods for the measurement of internal doses (Terry, 1995, 1998).

A5.13.1 World's best practice: an unsustainable aspiration?

1998 appears to signal the demise for research into dose assessment methodologies. Momentum appears to have dissipated, with the research by Terry into thoron-in-breath as a dose assessment technique (Terry, 1998; Terry et al., 1997) signalling the end of the post-Winn Inquiry research phase.

From 1999, it is apparent that, other than the evaluation of radiological hazards in zircon plants by Hartley (2001), the findings of the research conducted between 1988 and 1998 became mainstream, and the little research, where it occurred, was conducted on an operational basis, and was not published in peer-reviewed journals, or made generally available for public scrutiny, for example an investigation of TnP and RnP on a single MSI operation by Browne (2016).

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APPENDIX 6: PERSONAL THOUGHTS ON MY "*ACCIDENTAL JOURNEY*"

With due homage to the ancient Chinese philosopher Laozi, my personal professional journey did not strictly adhere to the adage "*a journey of a thousand miles begins with a single step*", rather it was an accident that started my career in radiation protection.

I was raised, the eldest of four children, in Kalgoorlie the epicentre of Western Australia's gold mining industry, located on the western edge of the Great Victorian Desert, approximately 600 kilometres east-north-east of the state's capital city, Perth. Mining runs through my veins – my father was an underground miner, and his father before him worked in the coal mines in Scotland and England.

Upon graduating from high school, I ventured to Perth to commence my tertiary studies. Early in the second year of my undergraduate program I received the news that my father had been seriously injured in an underground mining accident, and I would have to return home to Kalgoorlie. I found employment as a laboratory assistant with a major mining company, a role which helped with my scientific pursuits by providing me with invaluable experience in the application of analytical techniques, and access to a host of high-tech instruments.

Shortly after I was recruited to another division of the mining company, to the role of radiation safety technician at the Kalgoorlie Research Plant, the state's first dalliance with uranium processing. I thrived in this working environment, under the tutelage of my first radiation protection mentor, Bill (Old George) Chandler. At one stage Bill had to return to Perth for an extended period, leaving me, barely past my 19th birthday, to provide radiation oversight of the operations. I must have performed satisfactorily, because, as the Research Plant was nearing the end of operations, I was again transferred within the company, to the Olympic Dam Project, a massive underground copper-gold-uranium mine in South Australia located 560 kilometres north of the capital city, Adelaide. The Olympic Dam project was highly contentious, and my new mentor (and life-long friend), Mark Sonter, attended to the socio-political issues, leaving me to run the on-site radiation protection program.

After returning to Perth to recommence my studies, I was recruited by another mentor, Dr Bruce Hartley to join the Physics Division of the State X-ray Laboratories, which, at the time was regulating radiation in the Western Australian mining industry. My return coincided with a series of upheavals for the state's mineral sands industry because of what could be best described as a cavalier approach to radiation protection of their workers, members of the public and the environment, which generated much media interest, and culminated in the Winn Committee of Inquiry (covered in detail in Appendix

5). The Winn Committee recommended that regulation of radiation in mining be transferred to the Department of Mines, and I was duly recruited to the newly formed Radiation Safety Secretariat, and appointed as a Special Inspector of Mines, working alongside another mentor (and life-long friend) Greg Hewson. With the support and vision of the then State mining engineer, Jim Torlach, Greg led the Radiation Safety Secretariat to the point where it received national and international acclaim, and provided the robust regulatory approach required to shift the mineral sands industry towards better radiation protection practices.

After receiving career advice that suggested I “*should make peace with my Geiger counter*” I moved into management consulting, eventually becoming the chief executive officer, and managing director of Australia’s largest not-for-profit occupational safety and health training and consulting enterprise. However, I never really left the radiation protection discipline: being appointed as the radiation safety officer for a major mineral sands mining company; acting as an expert witness on radiation in mining on behalf of the state of Victoria; developing courses in radiation safety; and contributing to a textbook for radiation safety officers and the Australian Institute of Health and Safety’s Body of Knowledge.

After a fruitful and enjoyable twenty years, my career turned almost full circle when I returned to a leadership role with the state’s mining regulator, now called the Department of Mines, Industry Regulation and Safety. To my consternation, the robust processes and systems implemented under Bruce and Greg’s stewardship had deteriorated over the ensuing twenty years and were largely dysfunctional. Research activities had ceased, and any aspirations to leadership in radiation protection had been surrendered. My return coincided with four uranium mines receiving approval to proceed, and the Western Australian government declaring its intention to become a global hub for the supply of critical minerals, without due acknowledgement that many of the state’s critical mineral deposits contain radioactive materials. I viewed the lack of rigour as a radiation regulator as not commensurate with the nascent critical minerals industry, and so began the chain of events that led to my pursuit of a Doctor of Philosophy examining radiation exposures in the state’s mining industry.

I have been very fortunate to have had caring, and technically masterful mentors in my professional career. But without my father incurring his life-changing accident, it may never have eventuated …

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