Managing the Radiation Exposures of WA Mine Workers from Naturally Occurring Radioactive Materials: An Historical Overview (Part 1)

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Abstract

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

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

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

The authors have endeavoured to complete the record of radiation doses to WA mine workers from 1977 to 2018-19. This first instalment provides an overview of the legislative framework that governs the management of radiation exposures from minerals containing NORS in Western Australia, and a synopsis of doses to mine workers in Australia and internationally. The paper concludes by outlining the context that led to, and the findings of, the Winn Commission of Inquiry which reported on radiation exposures to workers in the Western Australian minerals sands industry in the late 1970's and mid 1980's.

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1 Preamble

In 1997, the Senate Select Committee on Uranium Mining and Milling reported "Just as the standards of a generation ago are no longer seen as acceptable so it may be expected that the standards in the next generation will rise. It is essential to have a regulatory structure which ensures that the results of research are promptly reflected in enhanced standards" [3].

The authors contend that the deliberations of the Senate Select Committee should apply to any mining activity that encounters naturally occurring radionuclides (NORs), and that this research contributes to the historical record in order that future standards are enhanced.

2 Introduction

The NORs thorium-232 (^{232}Th) and uranium-238 (^{238}U) are widely distributed in the environment and are present to some extent in all rocks and soils [4-11] [1]. Thorium-232 and ^{238}U are the parent isotopes of decay series comprising of different radioactive isotopes, the emissions from which present potential sources of radiation dose to exposed workers [4, 12, 13]. The significant pathways of exposure (overlooking the negligible contributions from inhalation of dusts containing beta-particle emitting isotopes, and intake via the ingestion pathway) are [10, 13-17]:

i. External irradiation from exposure to gamma radiation (γ) emitted by most members of each decay series;

ii. Inhalation of dust which contains long-lived alpha (LLα) emitting isotopes;

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

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

The International Atomic Energy Agency (IAEA) state "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" [10].

According to Steinhausler [4] "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 Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) states "Although the concentrations of [naturally occurring radioactive materials] NORM in most natural substances is low, any operation in which material is extracted from the earth and processed can potentially concentrate NORM in product, by-product or waste (residue) streams ... has potential to lead to exposures to both workers and members of the public ..." [13].

The Australian Radiation Health and Safety Advisory Council (RHSAC), the IAEA and the International Commission on Radiological Protection (ICRP) have identified a range of ores and minerals in which NORs are encountered [5, 10, 11], many of which are mined and processed within Western Australia (WA), such as 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. Further, over the past few years, WA has begun to exploit its significant reserves of "battery minerals" including lithium, cobalt, graphite, manganese, vanadium [18] and rare earths [19] and has recommenced the production of the radioactive mineral monazite for the first time since the mid-1990s [20]. These developments add to the portfolio of minerals that are likely to encounter NORs and will expand the workforce potentially exposed to radiation in the course of their work.

According to the Minerals Council of Australia (MCA) "Australia needs to become known as a

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

high quality reliable producer with a stable, efficient, science-based regulatory environment" [21]. The MCA commentary was made in relation to the nation's uranium industry, and is applicable, by extension, to any sector of the mining industry in which NORs are encountered.

This paper aims to contribute towards the attainment of the objectives as espoused by the MCA by providing an historical overview of radiation protection in the Western Australian mining industry, up to the report of the Winn Commission of Inquiry which reported on radiation exposures to workers in the Western Australian minerals sands industry in the late 1970's and mid 1980's. A companion publication completes the record of radiation doses to WA mine workers from the first systematic evaluation in 1987, to the most recent research by Ralph, Chaplyn and Cattani [1], who analysed data for the 2018-19 reporting period.

3 Legislative Framework For Radiation Protection In WA

In Australia, regulation of workplace radiation protection is the responsibility of the individual States and Territories. In practice, regulation is best described as a complex interaction between Federal and State regulatory agencies, which are influenced by "the international obligations and expectations expressed by bodies such as the IAEA, ICRP and [the World Health Organisation] WHO" (D. Smith, personal communication September 24, 2019).

National uniformity in regulation is driven by the ARPANSA National Directory for Radiation Protection (NDRP) [22], however, as highlighted by the IAEA in 2018 "many issues of uniformity remain unaddressed" and "relevant safety standards have not been implemented consistently by all jurisdictions and harmonisation and uniformity within the Australian legal and regulatory framework has not been achieved at the necessary level" [23].

As outlined below, the WA 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 manner in which the NDRP was established – its first iteration, published in August 2004, did not apply to the mining industry.

Subsequent amendments to the NDRP, made in December 2009, coincided with the national Workplace Relations Ministers Council endorsing a Model Work Health and Safety (WHS) Act [24] which, if adopted, would have significantly altered the WA mining regulatory landscape, and allowed for the adoption of the NDRP into the mine safety legislation. Subsequent delays in the adoption of the Model WHS legislation in WA have resulted in inertia in the adoption of the NDRP [2] [25].

3.1 The contemporary WA radiation protection legislative framework

In Australia, a substance that has a head of decay chain (^{232}Th, ^{238}U or a combination of ^{232}Th and ^{238}U) activity concentration >1 Bqg^{-1} , is considered as radioactive [22].

In WA, the management of radioactive materials is primarily governed by the Radiation Safety Act 1975 (RSA) and Radiation Safety (General) Regulations 1983 (RSGR) [26, 27], whereas specific provisions relating to the management of naturally occurring radioactive materials (NORM) in mining operations are included in the Mines Safety and Inspection Act 1994 (MSIA) and Regulations 1995 (MSIR) [28, 29].

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 Radiological Council of WA (RCWA), the peak body for radiation protection in the State.

In mining operations, occupational exposure of workers, and the disposal of wastes containing NORs are specifically regulated under Part 16, Divisions 1 and 2 of the MSIR. Hereinafter

2 - Royal Assent was given to the WA Work Health and Safety Bill 2019 on the 10th November 2020 mining operations that are required to comply with Part 16, Divisions 1 and 2 of the MSIR are referred to as "reporting entities".

The State mining engineer (SME) is the statutory authority appointed under the MSIA and MSIR. The SME is supported in regulating the mining industry by a team of Inspectors, appointed under the MSIA which is referenced in this manuscript as the "Mines Inspectorate". The Mines Inspectorate is part of the Department charged with oversight of mine safety, which has undergone numerous name changes in the period covered by this research, and for the purposes of this research is referenced as "the Department".

Since the proclamation of the MSIA in 1994, the dual regulatory approach has been problematic for the mining industry [30]. The RSGR deferred to the MSIA in the event of any inconsistencies, but paradoxically, the MSIA deferred to the RSA! Because the MSIA was proclaimed at a later date than the RSA, the State's Crown Law agency advised that the RSA took precedence over the MSIA [31]. The inconsistency was eventually addressed in 2016 when an amendment to the RSGR [26, 32] was made, providing precedence to the MSIA, and by extension, the MSIR.

The RCWA and SME collaborate in order to minimise the regulatory burden on reporting entities, and avoid, where possible, the duplication of effort by the regulatory agencies. However, the success (or otherwise) of the dual regulator approach is largely dependent upon the will of the individual regulatory agencies, due to what Hewson describes as "A complex regulatory surveillance structure ... and detailed inter-relationships ... between the various regulatory agencies" [33]. Those regulatory agencies include 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 Mines Radiation Safety Board (MRSB). The membership of both the IMRC and MRSB included representation from the RCWA [33, 34].

In July 1996, in response to questions raised in the Parliament of WA, Hewson noted "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 provisions relating to the establishment of the [MRS] Board when the opportunity arose to establish a broader Mines Occupational Safety and Health Board [MOHSAB]" [35]. A specialist sub-committee dealing with radiation-related matters was recommended to be established under the MOHSAB structure. However, it is not apparent that the sub-committee ever eventuated, as it's existence is absent from the historical record.

The dissolution of the MRSB in 1996 marked the end of the formal oversight of radiation matters in mining by an independent authority. Despite endeavours to formalise a relationship between the SME and RCWA dating as far back as 2002 [30] a Memorandum of Understanding, which established the Radiation Liaison Committee (RLC) was not formalised until January 2013 [36]. After its initial meeting in April 2013 the RLC made some early progress, but failed to achieve consensus on several critical issues, and seemingly lost momentum. Subsequently, the RLC has remained dormant since its last meeting in early 2016 [36].

Despite the failings of the RLC, the RCWA and SME endeavour to reflect a national approach to radiation protection by promoting the principles contained in various Codes of Practice published by ARPANSA, to be adhered to by reporting entities, the most applicable being:

- Radiation Protection Series No. 6: National Directory for Radiation Protection (NDRP) [22]; and

- Radiation Protection Series No. 9: Code of Practice and Safety Guide: Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (RPS 9) [37].

The RCWA has made compliance with RPS 9 mandatory for reporting entities by including compliance with the Code as a condition of their registration. A similar mechanism does not formally exist under the MSIR [3] .

The RSA and MSIA specify the same annual dose limits for exposed workers, for example, Regulation 16.18 of the MSIR [30] states:

"The manager of a mine must ensure that an employee ... does not receive a dose of radiation exceeding ...

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

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

In accordance with IAEA and ARPANSA recommendations [10, 38], a graded approach to regulation of exposures to NORM is applied in WA. Mining operations that can demonstrate that radiation doses to their workforce are less than 1 mSv per year or have radon (^{222}Rn or ^{220}Rn) concentrations consistently less than 1000 Bqm^{-3} , are exempt from compliance with the MSIR [29] [4]. *Ipso facto* a mining operation in which workers receive doses greater than 1 mSv per year, or exceed ^{222}Rn or ^{220}Rn concentrations greater than 1000 Bqm^{-3} , are required to comply with the MSIR and are categorised as reporting entities.

The MSIR imposes stringent requirements upon reporting entities, including the appointment of duly qualified and experienced Radiation Safety Officers (RSOs); development of radiation management plans (RMPs); and the submission of annual reports of worker doses to the SME for review and comparison against dose limits and other statutory requirements.

The MSIR requires employees to be classified as either "designated" (DE) or "non-designated". A DE is "an employee who works, or may work, under conditions such that the employee's annual effective [sic] dose equivalent might exceed 5 millisieverts ..." [29]. DEs "are then monitored more intensively (including, where appropriate, personal monitoring), and their doses are assessed individually" [39].

For context, it is important to note that although the derived annual ED limit is now 20 mSv, in 1987 the equivalent limit against which worker doses were assessed was 50 mSv [40]. Despite the significant reduction in the annual dose limit, the definition of DE has remained consistent as being any worker who receives over 5 mSv per year, increasing from ten percent of the annual limit in 1987 to 25 percent of the derived annual limit in 2021.

3.2 Historical overview of the development of the radiation protection legislative framework

Radioactive minerals have been extracted in Australia for over 100 years [41], and it is important for this historical overview that the context of the development of the approach to legislative control of radiation protection in the mining industry is established.

Sonter [41] reflects that "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 1940's, in the North Flinders Ranges in South Australia, [and after additional discoveries] then Queensland and the Northern Territory, continuing into the early 1960's, for the United Kingdom and United States weapons programs. It is little realized nowadays that in the late 1940's there were still only 3 uranium suppliers in the 'western world' ... Hence Radium Hill [in South Australia] (which operated from 1952 to 1961), and Rum Jungle [Northern Territory] (which operated from 1954 to 1970), were seen as of great strategic significance".

Sonter adds "These early operations were under tight government [agency] control. The fact

3 - At time of writing, a mechanism has been included in draft regulations to support the Work Health and Safety Bill 2019 (refer to Footnote 1).

4 - At time of writing the reference level for radon is under review.

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 at Radium Hill and Rum Jungle" [41]. It is prudent to contend that the legislative framework, in the respect of uranium mining, was largely absent, or was subject to confidentiality provisions due to national security concerns.

The Department appears to confirm this state of affairs by stating that "The WA Health Department's 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" [31].

According to Hewson, Kvasnicka and Johnston [42] "The mineral sands industry (MSI) in WA commenced in the late 1950's and since this time has been subject to some form of regulatory control". Hewson [33] 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 [WA] Health Department". The regulatory framework was an extension of that applied to uranium mining under the Radioactive Substance Act 1954, and replaced by the Radiation Safety (General) Regulations when they were assented to in August 1983.

Prior to the introduction of specific regulations in the MSIR, radiation protection in the mining of radioactive ores was supplemented via Codes of Practice. The earliest version of a specific mining Code was the Code of Practice in the Mining and Milling of Radioactive Ores [43]. The Code was published by the Commonwealth Department of Health in 1975, but failed to receive support of the WA MSI because it was specifically aimed at uranium mining [44, 45]. As is highlighted by Sonter "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*" [41].

The 1975 Code was superseded in 1980 by the Commonwealth Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores [46], 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 [44] 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 mineral sands industry 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" [45].

Subsequently, the Health Department of WA and the MSI produced separate revisions of the 1980 Code. The MSI revision of the 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 Health Department of WA [45], 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 applied to the development and endorsement, in 1982, of the Code of Practice on Radiation Protection in the Mining and Processing of Mineral Sands [44, 47] (colloquially referenced as the Mineral Sands Code). In January 1983, the Mineral Sands Code was adopted under the Mines Regulation Act 1946 [31], the fore-runner to the MSIA. The Mineral Sands Code was also included in the RSGR.

An updated Commonwealth Code of Practice on Radiation Protection in the Mining and Processing of Radioactive Ores [40] was produced in 1987 (colloquially referenced as the Radiation Protection Code) and was adopted under the Mines Regulation Act Regulations 1976, in January 1989 [31], 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 (colloquially referenced as 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 [42].

The Radiation Protection Code was based upon ICRP 30 [48], which introduced SI units and confirmed the ICRP position supporting the Linear, No-Threshold (LNT) hypothesis that infers that all doses of radiation carry some level of risk. Hewson, Kvasnicka and Johnston [42] 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 sources of irradiation were treated as separate exposures, and the combinative effects were not considered.

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 [27].

Part 16, Divisions 1 and 2 of the MSIR are largely based upon the Radiation Protection Code and Waste Management Code, but also incorporate internationally and nationally accepted practises, including those recommended in ICRP 60 [31]. Despite some minor amendments in 1996, 1998 and 2009 [29] the WA mining-industry-specific legislative requirements have applied, largely unchanged, from December 1995 until the present day. At time of writing, a specific section on radiation protection in mines has been included in draft regulations to support the Work Health and Safety Bill 2019, which received Royal Assent on the 10 th November 2020 [25].

3.3 Historical overview of the basis of worker dose estimates and regulatory limits

Because of the extended periods between this research and the information available in the 1970's and 1980's, it is important to consider the changes that have occurred to dose calculation methodologies and regulatory limits of exposure in the intervening period.

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.

Also, in 1977 the ICRP approved Publication 26, which introduced 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 [49]. 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 [50].

Prior to 1986, internal dose calculations were based upon ICRP-2 [51]. ICRP-2 was superseded by the Publication 30 series, and Publications 54, 68 and 78 [52-55], released progressively between 1980 and 1988.

SWDA reports that at this time the MSI was able to meet the 50 mSv annual dose limit under the Mineral Sands Code by "adjustment of work practices" [45]. Despite these early assurances, it eventuated that the methodology for calculating worker doses as per the Mineral Sands Code was based upon an incorrect interpretation of the ICRP recommendations for inhalation of dusts containing the ^{232}Th decay series published in ICRP Publication 2. 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 [33, 45].

According to Hartley and Hewson [34] "After much deliberation and investigation the Interim Mines Radiation Committee recommended the application of the ICRP Publication 30 annual limits of intake which were significantly more restrictive than previous inhalation limits for thorium". The maximum allowable intake, based upon ICRP 26 [56] and its companion document ICRP 30 [48] 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 50 mSv limit" [45].

Hewson 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 Publication 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 [33]. Hartley and Hewson summarise the impact 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" [34].

In 1992 Hewson, Kvasnicka and Johnston 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. The authors added "The NHMRC's current recommended radiation protection standards and system of radiological protection are based on ICRP Publication 26" [42].

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 [56] and released new recommendations in Publication 60 [57] in 1990. The impacts of ICRP 60 included the reduction of the annual limit for ED from 50 mSv to 20 mSv [57], and altering the dose coefficients (DCs) for the members of the ^{238}U and ^{232}Th decay series [58].

In 1991 the NHMRC published Radiation Health Series 33 that advised that following the recommendations made in ICRP 60, the annual limit of exposure was set to decrease to 20 mSv [50]. However, until the time of proclamation of the MSIA and MSIR in the mid-1990's the State radiation protection regulatory framework remained relatively unchanged. The national 'Mining and Milling Code' [40] applied, and guidance was provided in IAEA Safety Guide No. 95 [59]. Reporting entities that assessed worker internal dose estimates did so in accordance with the NORM Guidelines [60] which reference the ICRP Publication 30 series, using the guidance provided in Publications 54 and 78, and applying the DCs listed in Publication 30 [52-55].

In the early 1990's further research was being performed on the hazards of radon exposure, and improving the model of the human respiratory tract. Australian Radiation Protection Society [61] and Clarke [62] forewarned of impending changes to ICRP modeling for Rn and RnP, followed by the publication of ICRP 65 (Protection against Radon) and ICRP 66 (Respiratory Tract Model) in 1994 [63, 64]. In relation to the global mining industry, Clarke 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" [62].

The Recommendations in ICRP 60 were originally published jointly by NHMRC and National Occupational Health and Safety Commission (NOHSC) in 1995 as Publication No. 39 in the NHMRC Radiation Health Series [65].

The ICRP 60 recommendations were implemented in WA mining legislation in 1995 [29].

From the time of proclamation of the MSIA and MSIR in the mid-1990's the State radiation protection regulatory framework remained relatively unchanged. Reporting entities that assessed worker internal dose estimates did so in accordance with the NORM Guidelines [65] which reference the ICRP Publication 30 series, using the guidance provided in Publications 54 and 78, and applying the DCs listed in Publication 30 [52-55].

In 1999, the Australian Radiation Laboratory, which had been the authorising body governing radiation across Australia since 1973, [66] 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). Two bodies were formed in conjunction with ARPANSA: the RHSAC, which is charged with identifying emerging issues relating to radiation protection and nuclear safety; and the Radiation Health Committee (RHC) the membership of which includes technical representatives from each State and Territory, and whose functions include developing national standards for radiation protection, for the adoption by State and Territory jurisdictions [66].

In 1999 the term NORM formally entered the radiation protection lexicon, when it was used in paragraph 6 of ICRP Publication 82: “Protection of the public in situations of prolonged radiation exposure” [11].

Research on the hazards of exposure to radon and refinement of the models for assessing internal exposures continued through the 2000’s and early 2010’s. Following an extensive period of consultation and advice of impending changes [68], a comprehensive review of the links between Rn exposure and lung cancer was published as ICRP 115 [68] and was followed by ICRP 126 [69] which provided guidance on protection against Rn.

During this period ARPANSA, via the RHSAC and RHC assumed responsibility for the administration of the former Radiation Health Series published by the NHMRC as well as the Codes developed under the Environment Protection (Nuclear Codes) Act 1978 [50]. The publications were progressively reviewed and republished as part of the Radiation Protection Series, commencing in March 2002 when the joint NHMRC and NOHSC Publication No. 39 in the Radiation Health Series was retitled as Radiation Protection Series (RPS) No. 1 to reflect the discontinuation of the Radiation Health Series of publications [70]. RPS 1 was produced as a joint publication between NOHSC and ARPANSA.

The ICRP published updated recommendations in its 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103 [71]. 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.

In 2014 RPS 1 was superseded by the ARPANSA publication Radiation Protection Series F-1; “Fundamentals for Protection Against Ionising Radiation”. ARPANSA 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” [38, 70].

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 [72].

Part 1 of the OIR (published as ICRP Publication 130) [73] provides an introduction to the methodology used in the revision of revised DCs for occupational intakes of radionuclides by inhalation and ingestion. The models used include the Human Alimentary Tract Model (published as ICRP Publication 100 [74]), a revision of the Human Respiratory Tract Model, and revised models for the systemic distribution of radionuclides absorbed to blood. OIR Part 2, issued as ICRP Publication 134 in 2016 [75] 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 [18].

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" [70] colloquially known as the Basic Safety Standards (BSS), which in turn drew upon the ICRP's recommendations made in ICRP 103. The Scope of RPS C-1 is of importance to the WA 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 are deemed as Planned Exposures, and RPS C-1 forms relevant guidance.

The ICRP published Part 3 of the OIR as ICRP-137 [76] in 2017.

In January 2018, ARPANSA [77, 78] endorsed the ICRP revised DC's for RnP [79], based upon ICRP findings on lung cancer risks in the earlier ICRP reports [68, 69] and ICRP 137 Occupational Intake of Radionuclides: Part 3 [76]. As forecast by ARPANSA in [80], 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 [78, 81]. Paquet [82] highlighted the nearly order of magnitude increase in the DC for ^{232}Th, while Hondros and Hondros 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" [83].

ARPANSA also 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 [72].

ICRP-141 [84], which included data for radioisotopes of actinium and protactinium became available in December 2019. The revision of the DCs for all of the members of the ^{232}Th and $^{238+235}$U decay was therefore complete, allowing Ralph, Tsurikov and Cattani [18] to follow up the alerts provided by Hondros and Hondros [83] and evaluate the potential impacts of the revisions on the WA mining workforce. The Mines Inspectorate commenced a review of the NORM-5 Guideline [85] to reflect the updated DCs, and promoted the SME's expectations that worker doses in the 2019-20 annual reporting period and beyond would be calculated using the revised DCs.

Hewson [33] and the Department of Mines Western Australia [85] summarised the impact of the changes in the DC's applicable to the MSI, as expressed by the limit of Derived Air Concentration (DAC) of LLα, by way of a graphical illustration. The data is updated to reflect the changes post-1990, and is illustrated in Figure 1 [5] .

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" [11]. The release of ICRP-142 was not without controversy, a point reinforced by Lecomte [86]. 24 submissions are listed on the ICRP-142 comments web page, five of which were made by Australian institutions [87]. The five submissions are consistent in their criticisms of the draft document, most notably in the exclusion of exposure to Rn and RnP from the document; and the treatment of exposures to NORMs as an Existing Exposure (as opposed to a Planned Exposure, as outlined above). Significantly, one of the five submissions was from ARPANSA [88] 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

5 - The 320 mBqm^{-3} is a best estimate, based upon the introduction of the 20 mSv derived annual CED limit in 1995, whilst not adjusting the DCF. In reality, this limit may never have been applied, but cannot be verified from the historical record.

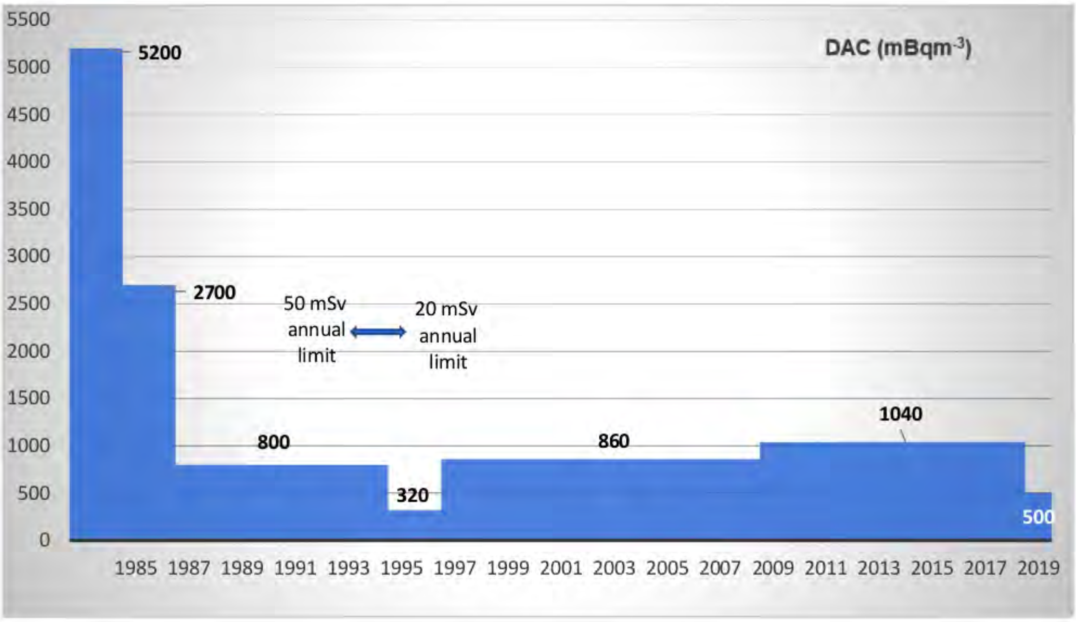

Figure 1: Changes in derived air concentration (DAC) limit (mBqm^{-3})

Australia for Radiation Protection in Existing Exposure Situations, RPS G-2 and IAEA GSR Part 3". RPS G-2 [89] is the companion document to RPS C-1 [38], which, as outlined above constitutes important guidance for the Australian mining industry. 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 exposure scenario has been to adhere to definitions that were found in ICRP-103 (specifically paragraphs 284 and 288) [90], 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" [11]. Lecomte 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" [86].

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*. However, the importance of achieving an expedited resolution for the WA 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.

4 Radiation Exposures Of Mine Workers

The global mining industry is extensive, with the extraction and processing of radioactive ores and minerals carried out in a number of countries throughout the world. According to UNSCEAR [91] "By far the largest category of workers exposed to ionising radiation are those employed in the extractive and processing industries" and 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" [91]. This situation exists despite:

- the hazards associated with the mining and processing of NOR's being the subject of international forums since 1965 [92];

- the publication of the first edition of the IAEA document "Radiation Protection in the Mining and Milling of Radioactive Ores" [93] in 1968; and

- a technical manual on identification of hazards and exposure controls published in 1976 [92].

The level of exposure depends upon a number of factors including the type of mine (whether it is underground or on the surface), the geology, the radionuclides involved, the physical and chemical characteristics of the processing activity, and the working conditions (with a particular emphasis on ventilation).

The activity concentration of NOR's in the orebody, products or tailings streams can be a useful indicator of potential worker exposures. The IAEA cite an extensive list of NOR-containing sources of exposure in the global mining industry in the Appendix VIII of Safety Reports Series Number 68 [94], which illustrates the influence of geology on potential exposures:

- Table 99 of [94] cites typical values of NOR activity concentration in Heavy Mineral Concentrate (HMC) in the MSI for several countries, indicating that HMC ranges up to 3.8 Bg^{-1} in Australia; 7.3 Bg^{-1} in Bangladesh; 9.7 Bg^{-1} in Brazil; and 14.7 Bg^{-1} in Vietnam.

The IAEA report that the tantalite concentrate produced in Ethiopia has an activity concentration of up to 89 Bg^{-1} ; whilst in Finland a niobium-rare earths deposit up to 15 Bg^{-1} , two gold-cobalt mines report up to 4.3 Bg^{-1} ; and a gold deposit nearly 1000 times the activity concentration of the gold-cobalt mine, reporting up to 4000 Bg^{-1} [95].

The importance of the physical and chemical aspects of the processing operations are highlighted by Kim et al [96] who reported a maximum CED of 2.24 mSv 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 ...".

Notwithstanding the important contribution from the geology of an orebody and the physical and chemical processes applied to extract the mineral, Harris summarises the challenge for managing doses from NOR as "It is often not a question of specific activity (sic) 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 ..." [97].

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 (approximately 100 mSv $year^{-1}$ in very few underground mines)" [11].

UNSCEAR [91, 98] advises 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 2.4 mSv; and

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

UNSCEAR [91] states that average annual CEDs in: surface copper mines in Poland are about 1.5 mSv; in a surface gold mine in Ghana were 0.26 mSv; workers in the Brazilian extractive and processing industries receive an average of slightly greater than 1 mSv per year; and 98 percent of surface workers in South African non-gold operations receive annual CEDs of less than 5 mSv, with the highest doses being recorded in copper mines.

Iwaoka et al [99] reported annual worker CEDs in a Japanese monazite processing plant as being 0.62 mSv, whilst the maximum annual CED in zirconium refractory plants was 0.43 mSv [100]. Udompornwirat [101] estimated CEDs to workers in amang[6] plants in Malaysia, Indonesia and Thailand to be between 18 mSv and 19 mSv;

6 - Amang is a general descriptor used in South East Asia for the tailings from the tin processing industry.

and in 2007 Omar et al [102] reported worker CEDs in 16 amang plants in Malaysia ranged from 1.7 mSv to 10.9 mSv, with a mean of 4.1 mSv. Mollah and Rahman [103] estimated CEDs in a Bangladeshi mineral processing plant to average 6.9 mSv; and Ademola [104] found CEDs to the gonads of workers in a Nigerian tin mining area to be 92.4 mSv. The IAEA report annual CEDs in dry mineral separation plants in India ranged from 1.1 mSv to 10 mSv and average CEDs in a similar plant in Vietnam were 6 mSv. [94]

Hartley reports that a study conducted by Boothe (1980) from the use of zircon in the United States implied CEDs arising from external exposure were of the order of 3.4 mSv per annum, with contributions from Rn and RnP and LLα not being assessed [105]. Hartley also cites a 1985 study by the Italian National Group for Studying Radiological Implications in the Use of Zircon, and reports that the annual CED was approximately 5 mSv, largely arising from LLα in fumes generated by the smelting process [105].

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 NORM's, as summarised in Table 1 [98].

UNSCEAR 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 2.9 mSv and the estimated collective effective dose is 37,260 man Sv, which is about seven times higher than the previous estimate" [91].

The preceding examples illustrate that although exposures in surface mining and mineral extraction processes can be effectively controlled to limit worker CEDs to less than 2 mSv, potential doses, if exposures are not effectively controlled can exceed statutory limits.

4.1 Radiation exposures to underground mine workers

The ICRP 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" [106].

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 [107-109].

In its Publication 115 [68], the ICRP 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. In 2019, Laurier, and in a

Table 1: Exposure profile of European workers exposed to NORM

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

later publication with co-authors Marsh, Rage and Tomasek confirmed the earlier ICRP determinations, concluding there is “strong evidence for an association between radon and lung cancer risk, even at low levels of exposure” [110, 111].

Importantly for non-uranium underground mines, Sahu et al [112] 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 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” [17].

Excursions over the regulatory exemption levels have been reported in underground non-uranium mines in international jurisdictions. By way of example, an investigation into radon in underground workplaces in Western Germany found 40% had radon concentrations in excess of 1000 Bqm^{-3} (10 mSv for 2000 hours per year exposure) and 10% of mines exceeded 5000 Bqm^{-3} (50 mSv for 2000 hours per year exposure) [113].

UNSCEAR [91] reports the average annual effective dose (ED) to workers in underground operations in Canada and Germany range from 1.07 to 4.13 mSv; in South African gold mines the average ED was 7.0mSv; in Turkish coal mines the average ED to 12,510 workers was 4.9 mSv; and in an Irish lead / zinc mine EDs ranged from 1 to 6 mSv.

Workers in six coal mines in Pakistan received EDs from Rn between 2.1 mSv and 7.0 mSv; and in Egyptian phosphate mines, EDs ranged from 12.2 mSv to 136.9 mSv, with an average of 70.2 mSv. The maximum ED received by Polish workers in coal mines (in 1997) was 3.5 mSv, whereas the maximum ED in four metal mines was 9.6 mSv with an average of 2.5 mSv. The ED to workers in 80 coal mines in China averaged 2.4 mSv, with a maximum in excess of 10 mSv [91].

Other researchers report annual EDs of 1.83 mSv in a Ghanaian gold mine [114]; 8.3 mSv in an Iranian manganese mine [115]; 5.53 mSv in metal mines in China [116]; up to 21 mSv (from Rn alone) in six underground mines in Brazil, with a mean of 9 mSv [117]; in the United States the cohort of workers that receive the highest occupational exposures is 10,000 “miners” who receive, on average, 8.4 mSv per annum [7] [118]; and Hewson et al [119] cite a maximum annual dose estimate of 240 mSv in an underground copper mine in Poland.

Liu and Pan report that approximately 10 million mine workers were occupationally exposed to NORM in China in 1996-2000, averaging 2.1 mSv per year. The authors provide a case study of an iron and rare earth mine in Inner Mongolia, and estimated the annual dose to ore mining workers to be 3.38 mSv [116].

It is highlighted that all of the studies cited above pre-date the ICRP changes to the risk factors for Rn and RnP as published in ICRP-137 [76] in 2017 and endorsed by ARPANSA in 2018, [77, 78]. As was highlighted in Section 2.3, the changes in DCs were significant, and could lead to doses from Rn and RnP increasing by factors of between two and four-and-a-half times those determined by previous DC conventions [78]. Therefore, many of the CEDs reported in this Section could be understated, with some approaching or exceeding the 20 mSv annual limit.

4.2 Radiation exposures to Australian surface mine workers in jurisdictions outside of WA

Holmes and Stewart [120] advise that in April 1965, surveys were conducted of six mining and processing plants in New South Wales (NSW) and Queensland in response to an approach by the International Labour Organisation and IAEA which were planning to “convene a meeting of experts to prepare a Code of Practice for Radiological Protection in Mining and Milling of

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

Radioactive Ores". Measurements were made for 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 are provided in Table 1 and 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 are provided in Table 3 and demonstrate that the maximum permissible concentration of thorium (sic) was consistently exceeded by a factor of approximately six times.

Similar evaluations of the four remaining operational mining and processing operations were reported in 1973 by Morris [121], who revealed that airborne contamination levels were approximately 7.4 Bqm^{-3} (about an order of magnitude higher than contemporary DAC) and surface contamination levels at one plant exceeded the maximum permissible concentration by factors ranging from 1.7 to 3.7 times. In a similar fashion to Holmes and Stewart [120], Morris did not attempt to estimate worker CEDs.

The Winn Inquiry [122] cite 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 [123] considered potential exposures, concluding "annual doses in excess of 15 mSv 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 50 $mSvy^{-1}$ (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 operations, it is prudent to contend that worker doses would have exceeded (potentially, significantly) the current annual derived dose limit.

Mason et al [124] 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 reported that their preliminary findings indicated very low levels of thoron; no LLα concentrations in excess of the WA DAC of 1.1 Bqm^{-3} ; and external doses "typically kept below 25 mSv per year for the most exposed workers, with about 75% of the monitored workforce receiving less than the public limit of 5 mSv per year (sic)".

Carter and Coundouris [125] evaluated the potential for worker doses in the 1965 study by Holmes and Stewart [120] and the 1973 study by Morris [121] and reported that data collected in 1965 indicated annual doses were "likely to have exceeded 100 mSv", and the 1973 data indicated annual doses were of the order of 70 mSv. The authors 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 20 mSv annual limit".

A summary of the radiological impact of the Queensland MSI by Alexander et al [126] 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 15 mSv", 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 20 mSv".

In 1988, Mason et al [127] reported on radiological assessments on beach sand-mining operations on the west coast and east coast of Australia, conducted by the Australian Radiation Laboratories. The authors report:

- Radon concentrations up to 200 Bqm^{-3} and thoron concentrations up to 1200 Bqm^{-3} were measured in latter stages of the secondary concentration plant;

- Thoron concentrations up to 5000 Bqm^{-3} were measured near a bulk monazite stockpile;

- Most employees receive less than 5 mSv per year from external radiation, but some may receive up to 20 mSv in a year;

- Activity Median Aerodynamic Diameters (AMADs) of airborne dusts range from 2 microns (µm) to 12 µm, with an overall 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 conclude their findings by stating "Inhalation of radioactivity in dust during mineral sands processing is clearly a very significant exposure pathway" [127].

In 1990 Fry reported that maximum EDs to workers in an open pit uranium mine in the Northern Territory were 7.9 mSv, with a mean of 5.9 mSv. Eighty five percent (5.0 mSv) of the mean dose was attributed to LLα [128].

In 1993 Fitch [129] provided a summary of radiation doses to workers in Australia's two operating uranium mines:

- Workers in the open pit mine reported EDs of 5.7 mSv, whilst mill operators at the same operation received mean EDs of 6.0 mSv. Fitch advises that "Maximum doses were less than twice these [mean] values";

- Workers in the metallurgical plant associated with the underground mine received a mean ED of 2.4 mSv, with a maximum of 18.1 mSv. Fitch reflects that "approximately 85% [of the ED] is due to the inhalation of radioactive dust".

Hartley conducted research into worker exposures in five zircon milling plants in Australia (including WA) indicating a theoretical worst-case ED of 5.5 mSv, comprising 3.3 mSv from inhalation of LLα and 2.2 mSv from external γ. Measurements indicated annual doses, based on normal work practises, ranging from 0.66 mSv to 1.03 mSv. Despite the low measured doses, Hartley cautions "the bagging of zircon flour represented a significant source of exposure to dust" [105].

In 2015 ARPANSA published Technical Report Series No. 165 [80], which provided an overview of the Australian MSI (including WA) and reported that in early 2013 regions outside of WA hosted seven operations, comprising two in South Australia; one in Victoria; one in NSW; two in Queensland and one in Tasmania.

Appendix E of TRS-165 [80] includes an analysis of workers doses from external γ for the years 2004, 2008 and 2012, derived from Personal Radiation Monitoring Service (PRMS) provided by ARPANSA. The maximum doses for all three years were recorded by the worker category dry plant operator and ranged from 6.4 mSv in 2004 to 9.5 mSv in 2008. The mean doses in the dry plant operator category ranged from 0.4 mSv (166 workers) in 2012 to 1.0 mSv (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.

According to the 2018 annual radiation protection report for Australia's only underground uranium mine, the maximum ED to workers in the surface operations was 4.4 mSv, received by the smelter shutdown worker category. This category of workers received a mean ED of 3.6 mSv, approximately 90% of which was contributed by LLα [130]. The report indicates that of the 1601 surface operation workers, 757 (47.3%) received

EDs of less than 1 mSv.

4.3 Radiation exposures to Australian underground mine workers in jurisdictions outside of WA

Sonter [41] reflects that underground mining of radioactive ores in Australia began at Radium Hill in South Australia, where a uranium deposit, first discovered in 1906, was mined in order to extract radium for the treatment of cancer. Sonter adds that after the initial campaign of mining at Radium Hill ceased in 1914-15, other deposits in the North Flinders Ranges in South Australia were exploited until the early 1930's. After a hiatus, uranium exploration increased rapidly in the post-World War 2 years, leading to the discovery of the Rum Jungle, Mary Kathleen and South Alligator uranium deposits in the 1950's. The Radium Hill fields in South Australia were reopened at this time, producing about 850 tonnes of U_3O_8 between 1954 and 1961 [41]. Sonter pointedly states "there was not much monitoring done ...", and describes working conditions that were sub-standard by contemporary requirements, and cites research by Woodward et al [131] who conducted a retrospective study of 2574 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. 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.

The ICRP highlights 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.*" [106].

Robinson [132] 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 4.8 mSv (using a DC of 10 mSv per WLM).

In 1989 Sonter and Hondros modelled the potential doses to workers in Australia's only underground uranium mine and forecast a median annual dose of 4.8 mSv with 10% of the workforce receiving greater than 12 mSv [16]. In the following year Fry (largely) confirmed the forecasts, reporting a maximum of 13.7 mSv and a mean of 7.0 mSv, with approximately equal contributions from γ, Rn and RnP and LLα. Fitch [129] reported EDs to underground workers in 1991-92 as having a mean of 6.1 mSv, and a maximum of 12.8 mSv. The proportion of contributions in Fitch differed from those reported by Fry, with 45% of the dose being delivered by RnP; 40% from external γ; and 15% from LLα.

The 2018 annual radiation protection report for Australia's only underground uranium mine demonstrated that the maximum ED to underground workers (the mine production drilling category) was 4.9 mSv [130]. The mean ED for this worker category was 3.8 mSv, with approximately half the mean dose being due to external γ exposure and a similar contribution from Rn and RnP and LLα contributing ~ 5%. The report indicates that of 2066 underground workers, 451 (21.8%) received EDs of less than 1 mSv.

The data includes an estimate of the mean exposure as a result of application of the changes to DCs introduced with ICRP-137 and ICRP-141. The mean dose to the underground mine production drilling category is forecast to increase to 5.8 mSv, an increase of 2 mSv, equivalent to 53% [130], supporting the hypotheses of Hondros and Hondros and Ralph et al [18, 83] in relation to the potential significance of the changed DCs on calculated worker doses.

4.4 Context: Why the need to address radiation exposures in WA mining operations?

In 1992, Hewson, Kvasnicka and Johnson [42] presented a review of the regulatory instruments and agencies that oversaw the radiation protection of mining operations across Australia. This is an important document in this research as it establishes the basis as to why WA became the pre-eminent State in evaluation of radiation doses to miners in the Australia, and why the findings had global significance.

The authors estimate that there were "approximately 124 underground non-uranium mines [across Australia] that may require some form of surveillance" and "nearly all 'designated employees' ... [are] in WA, [the] Northern Territory and South Australia". They advise that at the time, there were three mineral sands in New South Wales and two such operations in Queensland. This was in comparison to one uranium mining operation (and associated processing operation) and four underground non-uranium mine in the Northern Territory; and one underground uranium mine (and associated surface processing operation) in South Australia.

Significantly, the WA regulatory authorities were "concerned with seven mineral sands separation plants, four synthetic rutile pats; one tin processing and smelting operation, approximately 40 underground non-uranium mines, one zirconia plant, two titanium dioxide pigment plants, one prospective rare earths plant and four prospective uranium sites" [42].

In summary, not only were the WA regulatory authorities dealing with a significantly larger number of mining operations (potentially 60 as opposed to the next 'most challenged' authority, the Northern Territory, which had five mining operations) but the radiological properties of the MSI ore, as highlighted in 1988 by Mason et al [127] was an order of magnitude higher than that encountered in similar MSI operations on the eastern seaboard.

5 Radiation Exposures To WA Mine Workers

5.1 An overview of the WA mining industry

Mining in WA commenced with the extraction of lead from the "Northampton Block" in the 1840's, 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*" [133]. Since that time the mining industry has been a significant component of the State's economy, contributing approximately $107 billion in 2018-19, equivalent to 58% of the Gross State Product [134]. In 2018-19, 21,348 mineral tenements covering 47,189,000 hectares were applied across WA, equivalent to approximately 19% of the mainland area [135]. Of the tenements, 5862 are active mining leases [135] which host 557 actively producing mining operations [134].

WA is one of the world's top contributors to the global commodity market, and according to United States Geological Survey data, ranked amongst the top five countries for the production of eight different major minerals and in the top ten of a further three minerals [134].

The measurement of radiation doses commenced being systematically addressed in WA in the 1986-1987 reporting period [136], and therefore 1987 has been selected as the base from which to draw a comparison with the contemporary mining industry. The size of the WA mining workforce between 1987 and 2019 is illustrated as Figure 2.

As shown in Figure 2, the WA 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.

In the 2019-20 financial year, the WA mining industry employed 104,993 full time equivalent workers, with these roles filled by 133,094 individuals [134] [8] .

The distribution of the WA mining workforce by commodity in 1987 is compared to the 2019-20 financial year distribution in Table 2 [134]. As was outlined in the Introduction, commodities identified by RHSAC, IAEA and ICRP [5, 10, 11] to encounter NORs are marked with an asterisk.

8 - Preliminary information released by the Department indicates the growth continued in 2020-21, with an estimated 112,057 full time equivalent workers employed, filled by 139,790 individuals [138].

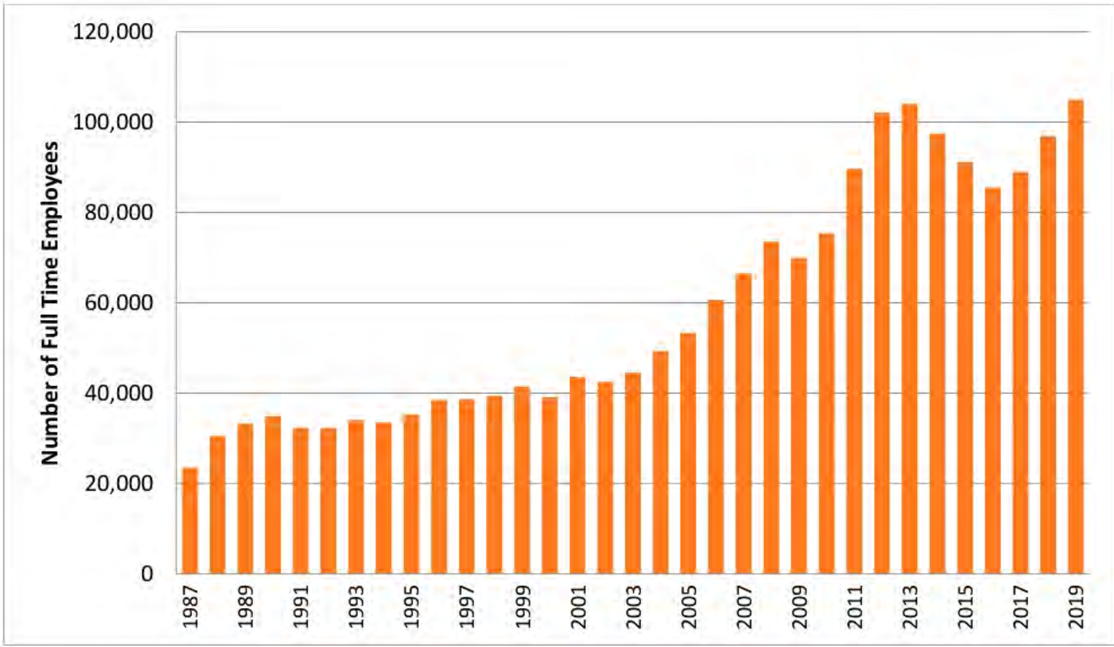

Figure 2. Size of WA Mining Workforce

As can be seen from Figure 2 and Table 2, 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 550 workers in the rare earths sector (see notes to Table 2), approximately 23,800 mine workers are potentially exposed to NORs – equivalent to the size of the entire WA mining workforce in 1987.

The geology of WA has been extensively detailed by the Geological Survey of Western Australia (GSWA), and the major geological features identified [138], as illustrated in Figure 2. There are three 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 [138] 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° degrees west;

2. a series of formations described in the WA Atlas of Human Endeavour [133] 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 as illustrated in Figure 3 [138], which lie to the west of;

3. 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 kilometers from the coast. The Darling Ranges are an expression of the Darling Fault, which runs approximately 1000 kilometers 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.

As illustrated in Figure 4 [139], many of the major mineral deposits in WA are found in these three geological formations. Notably, those commodities that are deemed as likely to encounter NORs, as highlighted in Table 2, are more likely to be located in the Tidal Flats or Darling Ranges, whilst those commodities less likely to encounter NORs are generally found in

Table 2: WA mining workforce by commodity mined 1987 and 2019-20

Commodity Mined (or Activity)	1987		2019-20 [3]	
	Full Time Equivalent Workforce	Percentage of Workforce	Full Time Equivalent Workforce	Percentage of Workforce
Alumina / Bauxite [1]	4022	17.2	7057	6.7
Base metals [1]	160	0.7	2285	2.2
Coal [1]	1163	5.0	707	0.7
Construction Materials	Not reported		725	0.7
Diamonds	128	0.5	756	0.7
Gold	3368	14.4	26033	24.8
Iron ore	9920	42.4	48108	45.8
Mineral sands [1]	628	2.7	1984	1.9
Nickel [1]	2911	12.4	7097	6.8
Salt	401	1.7	644	0.6
Tin - Tantalum – Lithium [1]	Not reported		4151	4.0
Other [2]	720	3.1	2259	2.2
Exploration	Not reported		3186	3.0
Full-Time Equivalent Workers in the WA Mining Sector	**23421**		**104,993**	

[1] Identified by RHSAC, IAEA and ICRP [5, 10, 11] to encounter NORs.
[2] The ‘Other’ category includes workers in the rare earth’s sector, which accounts for (at best estimate) 25% of this cohort, which equates to approximately 550 workers.
[3] The reporting of workforce distribution by commodity by financial year commenced in 2001-02. Prior to this period, reporting was by calendar year.

the Great Plateau.

As can be interpreted from Figure 4, mineral deposits have been identified outside of the three major formations, however despite their prospectivity (for example, potentially commercially sustainable mineral sands deposits have been identified in the Tidal Flats of the Canning Basin in the north-west of WA [140]), they constitute a minor proportion of the State’s current operating mining projects.

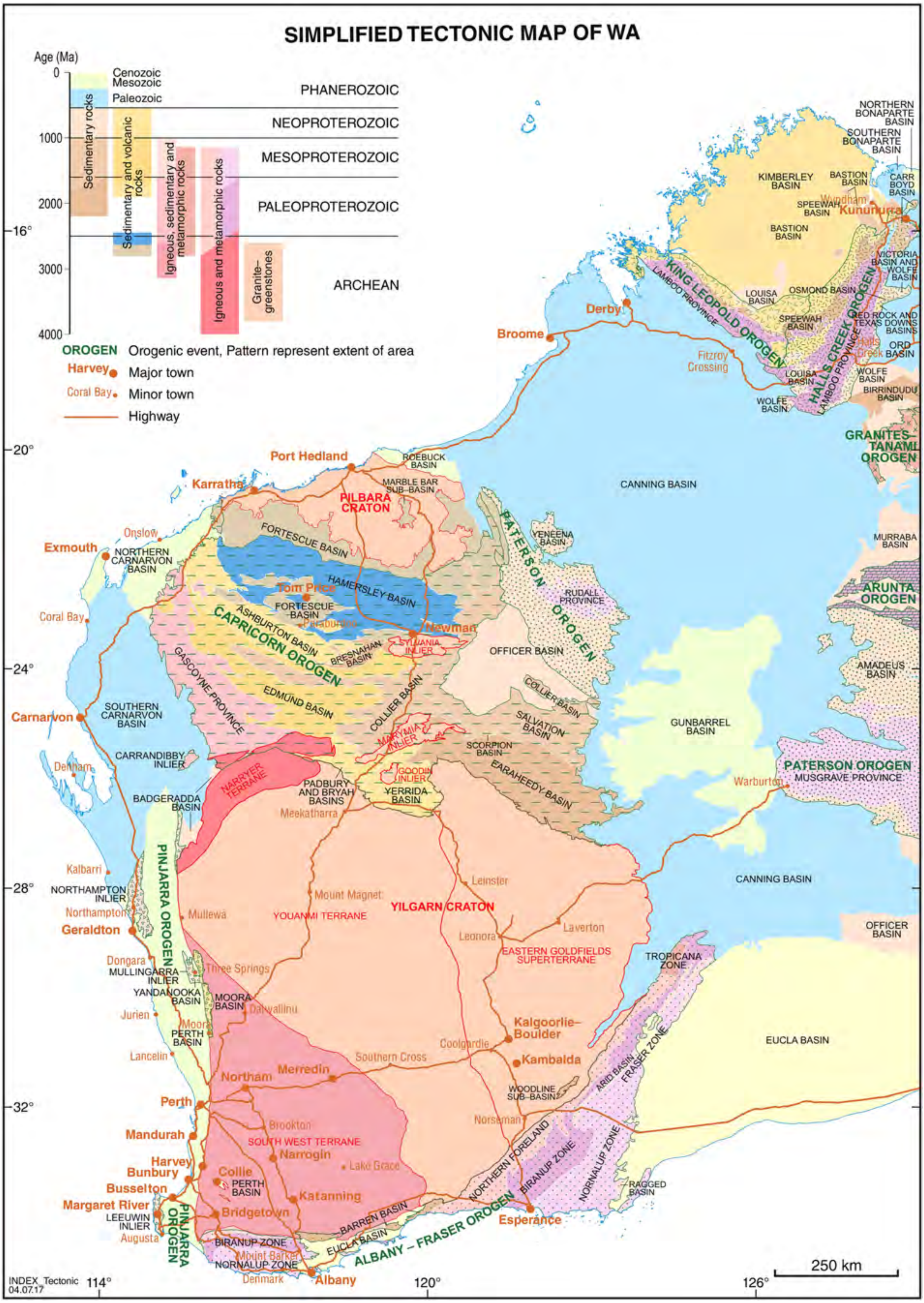

Figure 3. Geology of Western Australia

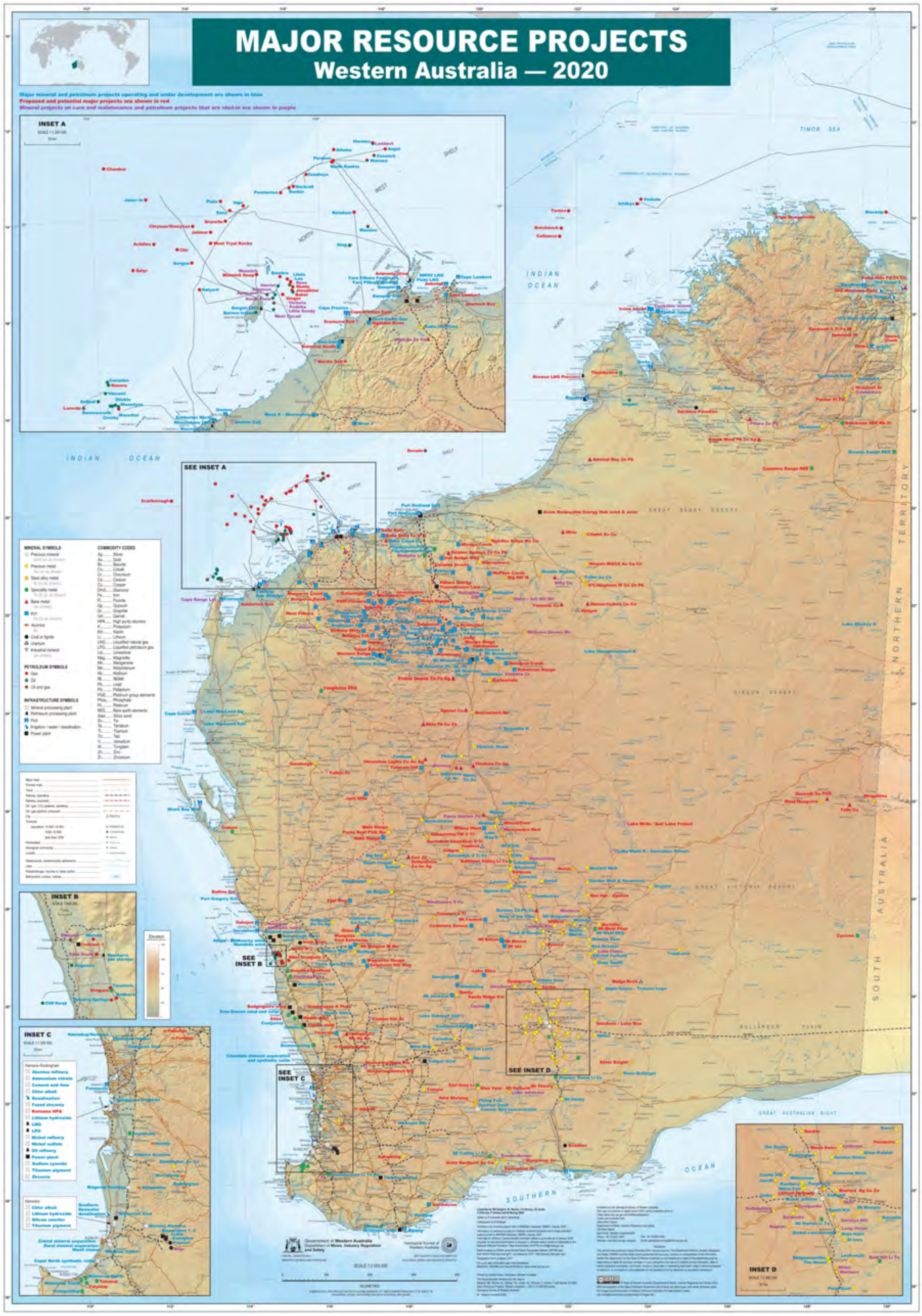

Figure 4. Location of Major Mining Resource Projects in WA [138]

5.2 Uranium mining and milling in WA

Uranium is a lithophilic element, present in approximately five percent of all minerals [141]. According to Eisenbud and Gesell [142] "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.

Mainland WA hosts in excess of 60 known potentially commercially sustainable uranium deposits [143], totaling a known resource of 250,000 tonnes of triuranium octoxide (U_3O_8) [144], supporting the statement "[in Australia] the state with the largest prospect for future uranium development is WA" [145].

Ralph et al [81] highlight that many of the uranium deposits in WA 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 4, the identified uranium deposits are congruent with many of the State's existing mining operations. The authors postulate that the congruence may indicate mines in the Great Plateau will exhibit elevated concentrations of uranium in the rocks that host the minerals being mined. By extension, workers in those mining operations have the potential to receive elevated radiation doses as a result of their exposure to NORs from the ^{238}U decay series. The authors highlight that there is an absence of data to refute their hypothesis.

As the State government has changed over the past four decades, a moratorium has been intermittently applied to the nascent uranium industry. The WA government lifted the moratorium in November 2008 [146], and 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" [144]. At time of preparing this manuscript none of the four approved operations have commenced mining [41], and as a result uranium is a notable absentee from the commodities listed in Table 2.

However, WA has trialed uranium mining and processing in the past, with several projects advancing to a pilot production phase, the two most notable being:

i. 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 [147]. The uranium concentrate was reinjected into the wells.

ii. Yeelirrie, which was discovered in 1972 and was mined in 1980 to supply approximately 13,000 tonnes of uranium ore (average grade of 2200 ppm U_3O_8) [148] for metallurgical testing at the attendant Kalgoorlie Research Plant (KRP), which was commissioned in 1980, and operated until the test work was completed in 1983 [149, 150].

The Yeelirrie operations were subject to several research projects conducted by the Australian Radiation Laboratories [151-154]. One report [155], from field trials conducted in mid-August 1980, whilst mining operations were being conducted. Two significant observations were made, that indicated the potential for elevated worker doses:

- A maximum Rn concentration of 4900 Bqm^{-3}, almost five times the current regulatory exemption concentration was measured at 04:00 hours on an upper level of the mine pit;

- 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 16 mSv;

Workers were monitored for radiation exposure at the Yeelirrie mine site during 1980, and at the KRP from the time of startup in August 1980 to shut down in 1981 [151, 152]. As was the standard of the day, doses were divided into two categories:

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

The advent of the operations pre-dated the implementation of additivity of exposure pathways. An annual limit of 5000 milliRem (50 mSv) applied to "Whole Body" doses and 15000 milliRem (150 mSv) to "Lung" doses [151, 152].

A summary report of worker doses was submitted to the RCWA by the reporting entity [152] [9]. 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. In order to extrapolate the reported data to an annual dose, the data in [152] has been multiplied by 12.5, equivalent to a 2000 hour working year.

Estimates of the annual doses to workers, derived from [152] are given in Table 3. As can be seen from the data presented in Table 3, applying the additivity principle, the potential maximum CED (in contemporary terminology) is 15.6 mSv whilst the mean is 3.3 mSv.

Rehabilitation and revegetation of the Yeelirrie mine site was completed between June and December 2004. 50 individuals were involved in the rehabilitation project, and were monitored for radiation exposure. The majority of workers received CED's of less than 0.2 mSv (mean 0.04 mSv) and the maximum CED was 0.33 mSv by a truck driver who worked the highest number of hours (768) on the project. The project proponents declare " The report identifies that completion criteria to satisfy a return to pastoral land use have been met" [156].

The Kalgoorlie Research Plant was progressively decommissioned between 1986 and 2003. In 2003 an assessment of the radiological properties of the site [149] 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".

5.3 Potential for radiation exposures in mining operations in the Great Plateau

In the late 1980's, as a result of the release of ICRP-47, a heightened level of interest developed globally in evaluating the potential for radiation exposures in underground mines. Specifically, the ICRP stated "… the 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." [106].

As was highlighted in Section 4.2, many of WA's known uranium deposits lie within the Great Plateau, and are congruent with established mining operations. The majority of WA's 57 underground mining operations (E. Rakich, personal communication April 30, 2018) lie within the Great Plateau, and therefore, in accordance with the ICRP's recommendation, the radiation exposures to the underground workers in WA were of particular interest.

Two research projects were undertaken to evaluate the potential doses to workers in the WA underground mining sector were performed in the early 1990's by Hewson et al [119] and Hewson and Ralph [157]. The research found that the average annual CED across 26 mines, employing 2173 workers was 1.4 + 1.0 mSv, ranging from

9 - 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 as indicative of actual exposures.

0.4 mSv in a nickel mine to 4.2 mSv in a coal mine. Rn and RnP contributed approximately 70% of the doses to workers. The authors concluded "On the basis of this preliminary investigation it was concluded that no regulatory controls are specifically required to limit radiation exposures in WA underground mines" [157].

Despite the findings of the preliminary study, the authors stated "There is also a release of Rn in underground non-uranium mines, albeit at a more modest rate, due to the trace amounts of uranium in the host rock. Rn therefore has the potential, given poor ventilation conditions, to accumulate within non-uranium mines to levels which may be unacceptable for continuous exposure" [119].

Significantly, the Hewson and Ralph [157] 1994 study predated the implementation of ICRP-60 in WA, and therefore the conclusions were based upon the maximum dose estimate being less than 10% of the applicable annual dose limit of 50 mSv.

In 1992, Hewson, Kvasnicka and Johnson 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 4.5 mSv, with a maximum of 8.2 mSv. By 2005, this operation had developed an underground component and had added rare earths to the suite of minerals being exploited. Auld [158] reported on three surveys in the underground operations, of between 84 and 123 days in duration. The author measured Rn concentrations ranging from 9 Bqm-3 in a fresh air way to 358 Bqm-3 in a working area of the mine. The mean concentration across the three surveys was 103 Bqm^{-3}. The maximum worker CED was estimated to be 0.7 mSv.

In 2020, Ralph et al [81] revisited the Hewson and Ralph (1994) study [157] and applied the revisions to the DC's for Rn and RnP published in ICRP-137 to the 1994 data. The authors found that mean CEDs increased by 5.4%, and that 12 of the 23 still-operating underground mines, employing an estimated 5400 workers would exceed the 1 mSv threshold, requiring them to comply with the MSIR.

The doses estimated by Auld in 2005 will increase significantly as a result of the application of the revised DC's for Rn and RnP published in ICRP-137. Assuming the ARPANSA prediction of doses from Rn and RnP increasing by factors of between two and four times that determined by previous DC conventions [78] the maximum CED (ignoring contributions from external γ and LLα) would lie between 1.4 mSv and 3.2 mSv, similarly exceeding the 1 mSv threshold, requiring the operation to comply with the MSIR.

Notably, other than two rare earths mining operations, located in the Terraine formations of the Yilgarn Craton (refer to Section 4.1), as illustrated in Figure 3 [138], there is limited data on the abundance of, and radiation doses arising from, minerals containing ^{232}Th in the Great Plateau.

5.4 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 geological formations that abut the Great Plateau were extensively researched in the 1980's and 1990's. Thompson [159] found the major contributor to doses received by Perth residents was gamma rays, however Efendi and Jennings (using electronic detectors) found that the major contributors to the estimated 3.5 mSv annual CED received by residents in e Perth Metropolitan Area were ^{222}Rn and ^{220}Rn [160]; and Toussaint [161] found that annual doses to residents living on the Daring Scarp were 4.6 mSv, nearly 2.5 times the dose to residents living on the Swan Coastal Plain. A significant finding was that reported by Alach et al [162] who found the specific activity (sic) of soils in the Darling Scarp were ten times the global average.

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. The weathering process towards the west, aided by wind and wave action developed mineral sands deposits, and

Table 3. Annual Worker Dose Estimates for the Yeelirrie Operations (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	1.8	0.5	11	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

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 (dealt with in the next Section), but also led to commercially sustainable bauxite deposits within the Darling Ranges.

Although bauxite mining in the Darling Scarp commenced in the early 1960's, the potential for NORs to be encountered in WA bauxite/alumina operations was not investigated until 1982 [163]. The Bayer process uses bauxite as a feedstock to produce alumina, and as a result of the process, the NORs in the feedstock, derived from the soils and rocks of the Darling Ranges are concentrated. However, the NOR's 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 Bq/g activity concentration threshold. However, the NOR concentration in "red mud" is increased by 100% of the bauxite feedstock, and consistently exceed the 1 Bq/g activity concentration threshold.

In 1997 Terry [164, 165] reported the results of four monitoring campaigns conducted from September 1995 to November 1996 to determine the concentrations of Rn and Tn in the residue storage areas. Rn ranged from 11 Bqm^{-3} to 222 Bqm^{-3}, with a mean concentration of 56 Bqm^{-3} and Tn ranged from 11 Bqm^{-3} to 229 Bqm^{-3}, with a mean concentration of 78 Bqm^{-3}. The author 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', predictions of estimates of worker exposures are such that the 1 mSv threshold criteria is not exceeded [163, 164, 166]. O'Connor [163] reported in 2004 that annual doses to operators ranged from 0.28 mSv to 0.9 mSv, with an estimate for all workers being 0.5 mSv. In 2012, O'Connor et al [163] reported that a "typical … refinery employee has a combined background and incremental exposure of about 0.8 mSv per year, obtained over [a working year of] 1920 hours".

Sutar states 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" [167]. Several attempts to introduce "red mud" into industrial processes have occurred in WA over the recent past, and have proved to be controversial due to its radiological properties. The Red Mud Project [168] cites the use of bricks made from bauxite residue being used to build homes in the South-west of WA in the 1980's and advises "However, 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 WA [169-172]. However, Summers et al caution that "the 1 mSv limit … for the general public is reached … at an amendment rate of 1500 tonnes per hectare of bauxite residue" [173]. According to Ryle [174] the WA Agricultural Department conducted a series of field trials on farming properties in the South West of WA in the early 1990's. 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" [175]; "The great red mud experiment that went radioactive" [174]; and "Residents fear radioactivity" [176].

The trials concluded in 1996, and to the best of the author's knowledge, no further large-scale trials of "red mud" as a soil amendment have occurred, and the disposal of the solid waste residues remains largely unresolved.

5.5 Potential for radiation exposures in mining operations in the Tidal Flats

Semeniuk [177] 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 WA are the deposits of garnet and heavy mineral sands, 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" [45].

One of the most significant deposits of garnet in the world occurs at Port Gregory, approximately 520 kilometres north of Perth [178]. 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. However, worker exposures are such that CED's do not exceed 1 mSv per year [179], and the operations have been granted a conditional exemption from the MSIR, on the proviso that estimates of worker doses are submitted to the SME every two years. Garnet in Bangladesh has been reported to have an activity concentration of 11.9 Bg-1 [94], indicating the need for ongoing surveillance of potential worker exposures.

'Heavy mineral sands' is the term used to describe those minerals mined by the MSI which have a specific gravity greater than 2.96. Silica sand is a gangue material prevalent in all mineral sands deposits has a specific gravity of 2.7, and is therefore readily removed by gravity separation techniques. The major valuable heavy mineral sands in the deposits in WA 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).

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 [45, 122]. 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 kilometers south of Perth in 1956, whereas deposits in the Northern Swan Coastal Plain were first mined in 1973, initially at Eneabba, 270 kilometers north of Perth [45].

In 1984 the Winn Inquiry 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" [122]. By 1993, Marshman and Hewson [2] 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 4, NORs are present to some degree in the suite of heavy mineral sands produced by the WA MSI (after Koperski [13] and IAEA [88]).

As can be seen from the activity concentration data presented in Table 4, 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 WA MSI ceased in May 1994 [180]. However, the NORMs monazite and xenotime are still present in the ore, and accompany the other minerals, through the various processing circuits, thereby making the risk of exposure to NORs omnipresent in the processing operations. 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} [181].

The potential for radiation doses to workers and the members of the public arising from the

Table 4: 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 235U is negligible, and has been omitted from the Table.
[3] Calculated by adding the maximum activity concentrations for 232Th content and 238U content.
[4] The activity concentration has been updated to reflect Appendix VIII of IAEA SRS-68 [83], however the weight concentration is as reported in Koperski [13].

NORM content of MSI products led the WA Minister for Health to commission a Committee of Inquiry (the Winn Inquiry) in July 1983 [122].

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

6 THE WINN INQUIRY

SWDA [45] advise that in 1947 “the Geological Survey of WA 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”. It should not have come as a surprise therefore that the mineral sands deposits exploited in WA from the initial operations at Cheyne Bay in 1949 and for the 35 years until the Winn Inquiry had radiological characteristics.

However, it was not until July 1966 that an operation in the MSI in the south west of WA was informed by the RCWA that “the monazite had a thorium oxide content [and] was radioactive” [182]. The Winn Inquiry found the Radiological Advisory Council (at the time the singular regulatory authority) “began systematic inspections of … [the MSI] only in 1978” and whilst some companies adhered to the regulatory authority’s (RA) advice, “Others have in the past shown some diffidence towards complying” [122].

6.1 The societal context

Sonter provides a valuable context in relation to the status of the radiation protection profession in the 1970’s. Sonter states “It is easy to forget just how little was known about the behavior 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” [41]. Sonter reflects that the Australia’s first (and only) nuclear reactor, the Hifar facility at Lucas Heights, New South Wales, first went critical on Australia Day, 1958, and was supposed to herald the dawning of the nuclear age in Australia. Sonter further adds

"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" [41].

It is of importance to note the zeitgeist of the period leading up to the commissioning of the Winn Inquiry. By no means is the following list complete, however, the authors trust that it serves as a useful historical anchor:

1979: March 16th, the movie 'China Syndrome' is released in the USA;

1979: On the 28th March, the Three Mile Island accident occurs in the USA (giving the China Syndrome movie prescience);

1981: Release of 'Radiation & Human Health' by John W. Gofman [183], colloquially known as the 'Father of the Anti-Nuclear Movement';

1984: On the 9th February, release of the movie 'Silkwood'.

Whilst in WA:

1979: In what is perhaps WA's worst industrial accident involving a source of radiation, an Ohmart Density Gauge containing radioactive Caesium-137 was lost from a WA mining entity's operation. The gauge was consigned in a waste metal shipment to Singapore where it subsequently contaminated a scrap metal furnace. The contaminated brick work and contents of the furnace were returned, with much media attention, to Kambalda for burial in a concrete bunker on 8th December 1981 [184]; and

1980: commissioning of a purpose-built pilot plant north of Kalgoorlie (the Kalgoorlie Research Plant) to ascertain the feasibility of the Yeelirrie uranium project occurred.

In Chapter 3.3 of the "Heavy Mineral Sands Handbook" [185], Keys et al cite several print media articles dealing with cases in Geraldton and Capel where "schools, houses and playing fields where tailings had been used for landfill, were found to have unacceptably high radiation levels". The authors also 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 1990, reflecting upon the societal context of the time, Hartley and Hewson [34] 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 later in their introduction state "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 [Regulatory Authority]" [34].

In summary, there was a global anti-nuclear sentiment developing; the local MSI appeared oblivious to the issues; the State's (arguably still) worst radiation-oriented industrial accident had occurred; and yet regulatory support had been provided to evaluate the prospectivity of a potential State uranium mining and milling industry.

6.2 General Findings of The Winn Inquiry

Since commencing in 1950, the MSI had fallen under the regulatory remit of the RSA (and its preceding legislation), enforced by the Radiation Health Section of the Health Department. 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 was conducted [34].

Through the 1970's 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" [34].

The lack of appropriate legislative authority is evident in the submission made by the RCWA to the Winn Inquiry. The RCWA reports that the site advised of radiological issues in 1966 was inspected on numerous occasions through the 1970's, 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 50 mSv, 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" [182].

In 1982, the Cabinet of the Government of WA agreed to form the IMRC to oversee the implementation of actions to overcome the regulatory impasse [182].

In its report (the Winn Report) to the Minister of Health, the tripartite Winn Committee of Inquiry states "Following widespread concern about the levels of ionising radiation in the MSI, the WA government established [this] committee in mid-1983 to report and make recommendations to the Minister of Health 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 … " [122].

The Winn Inquiry agreed that the regulatory structures were inadequate up until the adoption of the Mineral Sands Code [31] in 1983, stating in the Winn Report "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 need statutory basis" [122].

Despite these findings, the Winn Inquiry 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" [122].

The Winn Report identified several areas of improvement in the regulatory structures and how to address their "fragmentary nature". One of the more trenchant comments was "a further cause of concern has been the inadequacy of training facilities for companies' Radiation Safety Officers [RSO] (a position required under the code)" [122]. The Winn Inquiry 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.

The major finding of the Winn Inquiry 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" [122].

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" [122].

6.3 *Worker radiation dose estimates cited in the Winn Inquiry*

As outlined in Section 5, the Winn Inquiry reported that systematic inspections of the MSI commenced in 1978. Using 1978 as a reference point, the Commissioners constructed a timeline of worker doses up until the commencement of the Winn Inquiry in 1982.

The focus of the analysis was doses arising from γ radiation. Personal monitoring was conducted by a film-badge service (presumably offered by the RCWA which offered a service at the time). The number of badges assessed and the number of workers is not provided in the Winn Report, however Hartley and Hewson [34] report that in 1981 there were 61 workers monitored for external γ exposures, of a workforce estimated to be 1000 in the Winn Report. Although monitoring was only 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.

In recognition of the significance of potential doses from inhalation of LLα the Winn Commissioners stated that, based upon 46 dust samples collected prior to 1983, doses from inhalation of LLα were similar to those from external γ [122, 186].

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 [122].

The findings from the Winn Inquiry [115] are used to construct the CED estimates presented in Table 5.

The CEDs listed in Table 5 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 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" [122].

As was outlined in Section 3.3, the ALI's based upon ICRP 26 [56] and ICRP 30 [48] were introduced in 1986. As predicted by the Winn Commissioners, according to Hartley and Hewson, "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] [34].

Poignantly, Hartley and Hewson highlight "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" [34].

Table 5: Estimates of Committed Effective Doses 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
CED	13.6	12.6	7.0	6.8	8.8

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8 DECLARATION OF INTEREST

The corresponding author, Mr. Ralph, is an employee of the Western Australian Department of Mines, Industry Regulation and Safety. Mr. Ralph was the author of Ralph [187]; one of the co-authors of Ralph, Chaplyn and Cattani [1]; Ralph, Tsurikov and Cattani [18]; Ralph, Hinckley and Cattani [81]; Hewson, Tippet [119]; Hewson and Ralph [157], [188]; and a contributor to Chamber of Minerals and Energy of Western Australia [12]; and Mason, Carter [186].

Mr. Tsurikov is the author of Tsurikov [189-192] and a contributing author to IAEA 68 [94].

Dr Cattani is a co-author of Ralph, Chaplyn and Cattani [1]; Ralph Tsurikov and Cattani [18];and Ralph, Hinckley and Cattani[81].

REFERENCES

1. Ralph, M.I., A. Chaplyn, and M. Cattani, A review of radiation doses and associated parameters in Western Australian mining operations that process ores containing naturally occurring radionuclides for 2018–19. Journal of Radiological Protection, 2020. 40(4): p. 1476-1496.
2. Marshman, I.W. and G.S. Hewson, Radiation doses and associated parameters in the Western Australian mineral sands industry 1986 to 1993. Radiation Protection in Australia, 1994. 12(2): p. 7.
3. Commonwealth of Australia. Report of the Senate Select Committee on uranium mining and milling (1996-97). 1997 [cited 2nd January 2021]; Available from: www.aph.gov.au/Parliamentary_Business/Committees/Senate/Former_Committees/uranium/report/c02-6.
4. Steinhausler, F., History of occuational exposures to natural radioisotopes. Radiation Protection in Australia, 1993. 11(2): p. 9.
5. Radiation Health and Safety Advisory Council, Naturally occurring radioactive material (NORM) in Australia: Issues for discussion. 2005, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 36.
6. International Atomic Energy Agency, Technical Reports Series No. 419: Extent of environmental contamination by naturally occurring radioactive material (NORM) and technological options for mitigation. 2003, Vienna.
7. United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and effects of ionizing radiation, Volume 1: Sources, in UNSCEAR 2000 Report to the General Assembly with Scientific Annexes. 2000, United Nations: New York. p. 654.
8. Australian Radiation Protection and Nuclear Safety Agency. What is background radiation? 2020 [cited 15 January 2020]; Available from: https://www.arpansa.gov.au/regulation-and-licensing/safety-security-and-transport/radioactive-waste-disposal-and-storage/what.
9. Rajaretnam, G. and H.B. Spitz, Effect of leachability on environmental risk assessment for naturally occurring radioactive materials in petroleum oil fields. Health Physics, 2000. 78(2): p. 8.
10. International Atomic Energy Agency, Safety Report Series No.49: Assessing the need for radiation protection measures in work involving minerals and raw materials 2006, Vienna, Austria. 56.
11. International Commission on Radiological Protection, Radiological protection from naturally occurring radioactive material (NORM) in industrial processes. Annals of the ICRP 48 (4), 2019. ICRP Publication 142: p. 67.
12. Chamber of Minerals and Energy of Western Australia, Textbook for Radiation Safety Officers in the Titanium Minerals Industry, ed. M. Carter. 1994, Perth, Western Australia: The Chamber of Minerals and Energy Western Australia.
13. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series No. 15. Safety Guide: Management of naturally occurring radioactive materials (NORM). 2008, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory.
14. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series No. 9.1. Safety Guide: Monitoring, assessing and recording

occupational radiation doses in mining and mineral processing. 2011, Chief Executive Officer, ARPANSA, Commonwealth Department of Health,: Barton, Australian Capital Territory.
15. Koperski, J., Radiation protection in the mining and milling of mineral sands. Radiation Protection in Australia, 1993. 11(2): p. 7.
16. Sonter, M. and J. Hondros, Personal dose estimations for Olympic Dam's first year of production. Radiation Protection in Australia, 1989. 7(3): p. 5.
17. International Atomic Energy Agency, General Safety Guide No. GSG-7: Occupational radiation protection. IAEA Safety Standards for protecting people and the environment. 2018, Vienna, Austria: International Atomic Energy Agency. 360.
18. Ralph, M.I., N. Tsurikov, and M. Cattani, Impacts of revised dose coefficients for the inhalation of NORM-containing dusts encountered in the Western Australian mining industry. Journal of Radiological Protection, 2020. 40(4): p. 1457-1475.
19. Reporting Entity 15. Projects. 2020 [cited 19th September 2020]; Available from: Reporting Entity 15 web site.
20. Reporting Entities 1; 2; 3; and 5. Engage / [mining operation]. 2020 [cited 19th September 2020]; Available from: Reporting Entities 1; 2; 3; and 5 web site.
21. Davidson, S. and A. De Silva, Policy Paper: Realising Australia's uranium potential. 2015, Minerals Council of Australia: Forrest, Australian Capital Territory. p. 37.
22. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series No. 6. National directory for radiation protection. 2017, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 72.
23. International Atomic Energy Agency, Integrated regulatory review service (IRRS) mission to Australia, P. Tiippana, Editor. 2018, Department of Nuclear Safety and Security: Yallambie, Australia. p. 133.
24. Safe Work Australia. The development of model WHS Laws. 2020 [cited 17th January 2021]; Available from: https://www.safeworkaustralia.gov.au/law-and-regulation/development-model-whs-laws.
25. Parliament of Western Australia. Work Health and Safety Bill 2019. 2020 [cited 17th January 2021]; Available from: https://www.parliament.wa.gov.au/Parliament/Bills.nsf/BillProgressPopup?openForm&ParentUNID=8F320741B83643A8482584BF000CF89B.
26. Government of Western Australia, Radiation Safety (General) Regulations 1983, Department of Premier and Cabinet, Editor. 1983, State Law Publisher: Perth, Western Australia.
27. Government of Western Australia, Western Australian Legislation. 2021, Department of Justice, Parliamentary Counsel's Office,: Perth, Western Australia.
28. Government of Western Australia, Mines Safety and Inspection Act 1994, Department of Premier and Cabinet, Editor. 1994, State Law Publisher: Perth, Western Australia.
29. Government of Western Australia, Mines Safety and Inspection Regulations 1995, Department of Premier and Cabinet, Editor. 1995, State Law Publisher: Perth, Western Australia.
30. Department of Minerals and Energy, File: Hazardous Materials - Radiological Council Correspondence, Including Examination and TLD Badge Results - Radiation Health Branch. 1994, File: 913-99-Vol 03, Mining Operations Division, Department of Mines and Energy: Perth, Western Australia.
31. Mining Engineering Division, Uranium exploration, mining and processing: radiation protection controls in place in Western Australia. 1997, Box File RSDST 2011-89, Report 192, Department of Minerals and Energy,: Perth, Western Australia. p. 90.
32. Government of Western Australia, Western Australian Government Gazette, Perth, Tuesday 20 September 2016. No. 167. 2016, Government Printer: Perth, Western Australia.
33. Hewson, G.S., Radiation exposure status of mineral sands industry workers (1983 - 1988). Radiation Protection in Australia, 1990. 8(1): p. 10.
34. Hartley, B.M. and G.S. Hewson, Contribution of regulatory programs to radiation risk reduction in the mineral sands industry, in Minesafe International 1990. 1990, Chamber of Minerals and Energy Western Australia: Perth, Western Australia. p. 255-268.
35. Hewson, G.S., Memorandum to Director General, Department of Minerals and Energy: response to Questions on Notice raised in the Legislative Council, October 15, 1996. 1996, File: 913-94, Volume 3, Folios 162-167, Department of Minerals and Energy: Perth, Western Australia. p. 14.
36. Department of Industry and Resources, Radiation Liaison Committee. 2013, File: A1079/201301: Perth, Western Australia.
37. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series No. 9. Code of Practice and Safety Guide: Radiation protection and radioactive waste management in mining and mineral processing. 2005, Chief Executive Officer,

ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 55.
38. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series C-1 (Rev. 1). Code: Radiation protection in planned exposure situations. 2020, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 34.
39. Australian Radiation Protection and Nuclear Safety Agency and National Occupational Health and Safety Commission, Recommendations for limiting exposure to ionizing radiation [NOHSC:1013 (1995)], Radiation Protection Series No. 1. 2002, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 48.
40. Commonwealth of Australia, Department of Arts, Sport, the Environment, Tourism and Territories, Code of practice on radiation protection in the mining and milling of radioactive ores, 1987. 1987, Australian Government Publishing Service: Canberra, Australia.
41. Sonter, M.J., B. Worthley Oration: A heath physicist's history of mining uranium nd other ores in Australia. Radiation Protection in Australia, 2014. 31(1): p. 7.
42. Hewson, G.S., J. Kvasnicka, and A.D. Johnston, Regulation of radiation protection of mining in Australia, in International workshop on the health effects of inhaled radionuclides. 1992, Australian Radiation Protection Society: Jabiru, Northern Territory. p. 25.
43. Australian Government Department of Health, Code of Practice on radiation protection in the mining and milling of radioactive ores, 1975. 1975, Australian Government Publishing Service: Canberra, Australia.
44. Watson, I.D. and R.K. Taylor, The development of separate radiation protection regulations for monazite production in Western Australia. Radiation Protection in Australia, 1984. 2(1): p. 9.
45. South West Development Authority, South west mineral sands industry report: An information handbook 1990. 1990, South West Development Authority: Western Australia. p. 200.
46. Australian Government Department of Health, Commonwealth Code of practice on radiation protection in the mining and milling of radioactive ores, 1980. 1980, Australian Government Publishing Service: Canberra, Australia.
47. Department of Mines, Code of Practice on radiation protection in the mining and milling of mineral sands (1982). 1982, Mining Engineering Division, Department of Mines: Perth, Western Australia. p. 19.
48. International Commission on Radiological Protection, Limits for intakes of radionuclides by workers. Annals of the ICRP 30, 1979. ICRP Publication 30: p. 442.
49. Clarke, R.H. and J. Vanlentin. The history of ICRP and the evolution of its policies: ICRP Publication 109. 2008 [cited 1st August 2020]; Available from: https://www.icrp.org/docs/The%20History%20of%20ICRP%20and%20the%20Evolution%20of%20its%20Policies.pdf.
50. Dessent, K. Australia's Radiation Protection Standards: The Planned Exposure Code. Australian Radiation Protection and Nuclear Security Agency: 2017 License Holder Forum 2017 [cited 17th August 2020]; Available from: www.arpansa.gov.au/sites/default/files/2017-licence-holder-forum-planned-exposure-code-keith-dessent.pdf.
51. International Commission on Radiological Protection, 1962 Supplement to report of committee II on permissible dose for internal radiation. Annals of the ICRP, 1964. ICRP publication 2(1): p. 37-70.
52. International Commission on Radiological Protection, Individual monitoring for intakes of radionuclides by workers: Design and interpretation. . Annals of the ICRP 19 (1-3), 1988. ICRP Publication 54: p. 23.
53. International Commission on Radiological Protection, Dose coefficients for intakes of radionuclides by workers. Annals of the ICRP 24 (4), 1994. ICRP Publication 68: p. 110.
54. International Commission on Radiological Protection, Individual monitoring for internal exposure of workers. Annals of the ICRP 27 (3-4), 1997. ICRP Publication 78: p. 164.
55. International Commission on Radiological Protection, Limits for intakes of radionuclides by workers, part 1, 1979. Annals of the ICRP 4, 1980. ICRP Publication 30: p. I-I.
56. International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection., in Annals of the ICRP 1 (3), H. Smith, Editor. 1977, Pergamon: Sydney, New South Wales. p. 80.
57. International Commission on Radiological Protection, 1990 Recommendations of the International Commission on Radiological Protection. Annals of the ICRP 21 (1-3), 1990. ICRP Publication 60: p. 201.
58. Hartley, B.M., Dose conversion factors for inhalation applicable to the mining and milling of radioactive ores. Radiation Protection in Australia, 1992. 10(4): p. 7.
59. Australian Radiation Protection Society. Special Issue: Proceedings of the first international

symposium on radiation protection in the mining, milling and downstream processing of mineral sands. 1993. Bunbury, Western Australia: Australian Radiation Protection Society.
60. Clarke, R.H., ICRP Recommendations for Occupational Exposure to Natural Radiation. Radiation Protection in Australia, 1993. 11(4): p. 5.
61. International Commission on Radiological Protection, Human respiratory tract model for radiological protection. Annals of the ICRP 24 (1-3), 1994. ICRP Publication 66: p. 488.
62. International Commission on Radiological Protection, Protection against radon-222 at home and work. Annals of the ICRP 23 (2), 1994. ICRP Publication 65: p. 45.
63. National Health and Medical Research Council, NOHSC:3022 Recommendations for limiting exposure to ionizing radiation (1995), in Radiation Health Series No.39. 1995, National Health and Medical Research Council and Safe Work Australia. p. 50.
64. International Atomic Energy Agency, Safety Series No 95: Radiation monitoring in the mining and milling of radioactive ores. IAEA Safety Guides, ed. J.U. Ahmed. 1989, Vienna: International Atomic Energy Agency. 97.
65. Department of Mines, Industry Regulation and Safety. Search Results: NORM Guideline. 2020 [cited 27th May 2020]; Available from: http://www.dmp.wa.gov.au/Utilities/search.aspx?query=norm+guidelines&btn-search-query=Search.
66. Australian Radiation Protection and Nucear Safety Agency. Advisory Council and Committees. 2020 [cited 21st December 2020]; Available from: https://www.arpansa.gov.au/about-us/advisory-council-and-committees.
67. International Commission on Radiological Protection. International Commission on Radiological Protection statement on radon. 2009; Available from: http://www.icrp.org/page.asp?id=16.
68. International Commission on Radiological Protection, Lung cancer risk from radon and progeny and statement on radon. Annals of the ICRP 40(1), 2010. ICRP Publication 115: p. 60.
69. International Commission on Radiological Protection, Radiological protection against radon exposure. Annals of the ICRP 43 (3), 2014. ICRP Publication 126: p. 5-73.
70. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series C-1. Code: Radiation protection in planned exposure situations. 2016, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 36.
71. International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection. Annals of the ICRP 37 (2-4), 2007. ICRP Publication 103: p. 332.
72. Australian Radiation Protection and Nuclear Safety Agency. Changes to dose coefficients for occupational exposures. 2018; Available from: https://www.arpansa.gov.au/understanding-radiation/sources-radiation/radon/changes-dose-coefficients-occupational-exposures.
73. International Commission on Radiological Protection, Occupational intakes of radionuclides: Part 1. Annals of the ICRP 44 (2) 2015. ICRP Publication 130: p. 180.
74. International Commission on Radiological Protection, Human alimentary tract model for radiological protection. Annals of the ICRP 36 (1-2), 2006. ICRP Publication 100: p. 336.
75. International Commission on Radiological Protection, Occupational intakes of radionuclides: Part 2. Annals of the ICRP 45 (3-4), 2016. ICRP Publication 134 p. 352.
76. International Commission on Radiological Protection, Occupational intakes of radionuclides: Part 3. Annals of the ICRP 46 (3-4), 2017. ICRP Publication 137: p. 486.
77. Australian Radiation Protection and Nuclear Safety Agency. Statement on new radon dose coefficients: implications for worker dose assessments. 2018; Available from: https://www.arpansa.gov.au/tags/radon.
78. Australian Radiation Protection and Nuclear Safety Agency. How will the new dose coefficients for radon progeny affect your doses? 2018 [cited 1st March 2018]; Available from: https://www.arpansa.gov.au/news/how-will-new-dose-coefficients-radon-progeny-affect-your-doses.
79. International Commission on Radiological Protection. Summary of ICRP recommendations on radon. 2018; Available from: http://www.icrpaedia.org/images/f/fd/ICRPRadonSummary.pdf.
80. Australian Radiation Protection and Nuclear Safety Agency, Proposed expansion of the Australian national radiation dose register to the mineral sands mining and processing industry., Sarsha Collett, et al., Editors. 2014, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 76.
81. Ralph, M.I., S. Hinckley, and M. Cattani, Reassessment of radiation exposures of underground non-uranium mine workers in Western Australia. Radiation Protection Dosimetry, 2020. 191(3): p. 16.
82. Paquet, F., et al., ICRP Task Group 95: Internal dose

coefficients, in ICRP's 4th international symposium on the system of radiological protection, I.C.o.R. Protection, Editor. 2017: France.
83. Hondros, J. and R. Secen-Hondros, Minor changes leading to major impacts: Practical implications of ICRP137 on industries with NORM. Radiation Protection in Australasia, 2019. 36(2): p. 6.
84. International Commission on Radiological Protection, Occupational intakes of radionuclides: Part 4. Annals of the ICRP 48 (2-3), 2019. ICRP Publication 141: p. 9-501.
85. Department of Mines, The Western Australian mineral sands industry: Radiation protection, Mining Engineering Division, Editor. 1989, Department of Mines: Perth, Western Australia. p. 17.
86. Lecomte, J.F., ICRP approach for radiological protection from NORM in industrial processes, in Annals of the ICRP: 2019 Proceedings of the Fifth International Symposium on the System of Radiation Protection C.H. Clement and H. Fujita, Editors. 2020, Sage: Adelaide, Soth Australia. p. 14.
87. International Commission on Radiological Protection. Radiological protection from naturally occurring radioactive material (NORM) in industrial processes: comments. 2019 [cited ICRP Publication 142 3/6/2020]; 67]. Available from: https://www.icrp.org/consultation.asp?id=17B51F60-CBF9-476C-825A-401935223E87.
88. International Commission on Radiological Protection. ICRP Publication 142: Radiological protection from naturally occurring radioactive material (NORM) in industrial processes - comments from Rick Tinker on behalf of ARPANSA. 2019 [cited 3rd June, 2020]; Available from: https://www.icrp.org/consultation_viewitem.asp?guid={EAB987EB-654B-40C3-AA98-9005182ADBD7}
89. Australian Radiation Protection and Nuclear Safety Agency, Radiation Protection Series G-2. Guide: Radiation protection in existing exposure situations. 2017, Chief Executive Officer, ARPANSA, Commonwealth Department of Health: Barton, Australian Capital Territory. p. 36.
90. International Commission on Radiological Protection. Resolution of public consultation comments for: radiological protection from naturally occurring radioactive material (NORM) in industrial processes, 14th January 2020. ICRP ref 4844-6934-3153 2020 [cited 3rd June 2020]; Available from: https://www.icrp.org/docs/P142%20Resolution%20of%20Comments.pdf.
91. United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and effects of ionizing radiation, Volume 1: Sources, in UNSCEAR 2008 Report to the General Assembly with Scientific Annexes. 2010, United Nations: New York.
92. International Atomic Energy Agency, IAEA Safety Series No 43. Manual on radiological safety in uranium and thorium mines and mills. 1976, Vienna: International Atomic Energy Agency, International Labour Organisation and World Health Organisation. 82.
93. International Atomic Energy Agency, IAEA Safety Series No 26. Radiation protection of workers in the mining and milling of radioactive ores 1983 Edition Code of Practice and Technical Addendum. 1983, Vienna: International Atomic Energy Agency, International Labour Organisation and World Health Organisation.
94. International Atomic Energy Agency, IAEA Safety Report Series No. 68: Radiation protection and NORM residue management in the production of rare earths from thorium containing materials 2011, Vienna, Austria: International Atomic Energy Agency. 149.
95. International Atomic Energy Agency, Proceedings of an international symposium, in Naturally Occurring Radioactive Material (NORM VII). 2016, IAEA, International Atomic Energy Agency: Rio de Janiero, Brazil. p. 16.
96. Kim, K.P., et al., Influence of particle size distribution on inhalation doses to workers in the Florida phosphate industry. Health Physics, 2006. 91(1): p. 10.
97. Harris, F., The challenges of mining, processing and transporting naturally occurring radioactive materials, in ICRP 2019 - 5th International symposium on the system of radiological protection. 2019: Adelaide, South Australia.
98. van der Steen, J., et al. Final report of the SMOPIE Project carried out under contract No FIGM-CT2001-00176 by order of the European Commission. 2004; 69]. Available from: https://www.eu-alara.net/images/stories/Pdfdivers/SMOPIE/smopie-final.pdf.
99. Iwaoka, K., et al., Investigation of natural radioactivity in a monazite processing plant in Japan. Health Physics, 2017. 113(3): p. 5.
100. Iwaoka, K., et al., Occupational exposure to natural radiation in zirconium refractory plants in Japan. Health Physics, 2013. 104(2): p. 7.
101. Udompornwirat, S., A review of radiological hazards associated with the by-product mineral processing industry in the SEATRAD Centre member countries. Radiation Protection in

Australia, 1993. 11(3): p. 5.
102. Omar, M., et al. Radiation dose assessment at amang processing plants in Malaysia. Radiation Protection Dosimetry, 2007. 124, 7.
103. Mollah, A.S. and M.M. Rahman, Evaluation of radiological hazards in the beach sand mineral procesing plant at Cox's Bazar. Radiation Protection in Australia, 1993. 11(3): p. 5.
104. Ademola, J.A., Exposure to high background radiation level in the tin mining area of Jos Plateau, Nigeria. Journal of Radiological Protection, 2008. 28(1): p. 7.
105. Hartley, B.M., The measurement of radiation levels in Australian zircon milling plants. Health Physics, 2001. 80(1): p. 8.
106. International Commission on Radiological Protection, Radiation protection of workers in mines. Annals of the ICRP 16 (1), 1986. ICRP Publication 47: p. 21.
107. Australian Radiation Laboratory, Radiation protection in the mining and milling of radioactive ores. Lecture Notes from a 2 week course conducted at the Australian Radiation Laboratory, February 2-13 1981, ed. J.F. Boas. Vol. 1. 1981, Yallambie, Victoria: Australian Radiation Laboratory. 164.
108. George, A.C., World history of radon research and measurement from the early 1900's to today, in The Natural Radiation Environment: 8th International Symposium (NRE VIII). 2008, AIP Conference Proceedings: Brazil. p. 20-33.
109. World Health Organisation, WHO Handbook on Indoor Radon: A Public Health Perspective, ed. H. Zeeb and F. Shannoun. 2009, Geneva, Switzerland: WHO Press.
110. Laurier, D., Miner studies and radiological protection against radon, in ICRP 2019 - 5th International symposium on the system of radiological protection. 2019: Adelaide, South Australia.
111. Laurier, D., et al., Miner studies and radiological protection in Annals of the ICRP: 2019 Proceedings of the Fifth International Symposium on the System of Radiation Protection C.H. Clement and H. Fujita, Editors. 2020, Sage: Adelaide, Soth Australia. p. 20.
112. Sahu, P., D.C. Panigrahi, and D.P. Mishra, A comprehensive review on sources of radon and factors affecting radon concentration in underground uranium mines. Environmental Earth Sciences, 2016. 75(7): p. 1-19.
113. Schmitz, J. and R. Fritsche, Radon impact at underground workplaces in Western Germany. Radiation Protection Dosimetry, 1992. 45(1-4): p. 3.
114. Darko, E.O., G.K. Tetteh, and E.H.K. Akaho, Occupational radiation exposure to NORMs in a gold mine. Radiation Protection Dosimetry, 2005. 114(4): p. 8.
115. Ghiassi-Nerad, M., et al., Exposure to 222Rn in ten underground mines in Iran. Radiation Protection Dosimetry, 2002. 98(2): p. 3.
116. Liu, H. and Z. Pan, NORM situation in non-uranium mining in China. Annals of the ICRP, 2011. 2012: p. 9.
117. Santos, T.O., et al., Radon dose assessment in underground mines in Brazil. Radiation Protection Dosimetry, 2014. 160(1-3): p. 4.
118. Sinclair, W.K., Dose limits for astronauts. Health Physics, 2000. 79(5): p. 6.
119. Hewson, G.S., et al., MERIWA Report No: 79. Preliminary study of radon in underground mines In Western Australia. 1991: Perth, Western Australia. p. 95.
120. Holmes, R.J. and J.R. Stewart, Radiological and airborne mineral dust hazards in the beach sand mining industry, Australian Atomic Energy Commission, Editor. 1965, File M0060-201201, Department of Mines and Petroleum: Perth, Western Australia. p. 8.
121. Morris, A.J., Radiation hazards in the mining and processing of beach sands. 1973, Report by Radiation Branch, Division of Occupational Health and Radiation Control, Health Commission of New South Wales. File M0060-201201, Department of Mines and Petroleum: Perth, Western Australia. p. 4.
122. Winn, W., J. Mathews, and A. Tough, Report to the Minister of Health of Western Australia on radiation protection from ionising radiation associated with the mineral sands industry. 1984, Health Department: Perth, Western Australia. p. 105.
123. Hewson, G.S., Occupational radiological aspects of the downstream processing of mineral sands. Radiation Protection in Australia, 1993. 11(2): p. 7.
124. Mason, G.C., et al., Evaluation of radiological hazards associated with mineral sandmining, in Occupational radiation safety in mining, H. Stocker, Editor. 1984, Internatonal Atomic Energy Association: Canada. p. 607-611.
125. Carter, M.W. and A.N. Coundouris, Radiation protection in the mineral sands industry in New South Wales. Radiation Protection in Australia, 1993. 11(3): p. 7.
126. Alexander, E.G., N.D. Stewart, and B.J. Wallace, The radiological impact of past and present practises of the mineral sands industry in Queensland. Radiation Protection in Australia, 1993. 11(3): p. 5.
127. Mason, G.C., et al., Radiological assessment of mineral sandmining in Australia, in 7th.

international congress of the International Radiation Protection Association H. Stocker, Editor. 1988, International Radiation Protection Association: Sydney (Australia). p. 1347-1350.
128. Fry, R.M., Implications of the 1990 ICRP Recommendations for the mining industry. Radiation Protection in Australia, 1992. 10(3): p. 10.
129. Fitch, J., Radiation protection in uranium mining in Australia, in Asia congress on radiation protection. 1993, China Society of Radiation Protection: Beijing (China). p. 76-79.
130. BHP Billiton Pty Ltd. Olympic Dam - Annual radiation protection report: 1 July 2017 to 30 June 2018. 2018; 15]. Available from: https://www.epa.sa.gov.au/files/14430_olympic_annual_2018.pdf.
131. Woodward, A., et al., Radon daughter exposures at the Radium Hill uranium mine and lung cancer rates among former workers, 1952–87. Cancer Causes & Control, 1991. 2(4): p. 213-220.
132. Robinson, R., Radon daughter concentrations in Northern Territory non uranium mines. Radiation Protection in Australia, 1992. 10(1): p. 3.
133. Education Committee WAY '79, Western Australia 1829 - 1979: An atlas of human endeavour, ed. N.T. Jarvis. 1979: Education and Lands and Surveys Department of Western Australia. 144.
134. Department of Mines, Industry Regulation and Safety. 2019-20 Economic indicators resources data. 2020 [cited 9th December 2020]; Available from: https://www.dmp.wa.gov.au/About-Us-Careers/Latest-Statistics-Release-4081.aspx.
135. Department of Mines, Industry Regulation and Safety. 2018-19 Spatial and regional resources data. 2019 [cited 12th January, 2020]; Available from: https://www.dmp.wa.gov.au/About-Us-Careers/Latest-Statistics-Release-4081.aspx.
136. Hewson, G.S., Radiation safety in the mineral sands industry (Report No. GHCQS388). 1989, File: 840-90, Folios 60-69, Department of Mines: Perth, Western Australia. p. 10.
137. Department of Mines, Industry Regulation and Safety. Industry activity indicators: Mineral and petroleum industry activity review 2020 - Employment. 2021 [cited 12 April 2021]; Available from: http://dmp.wa.gov.au/About-Us-Careers/Latest-Resources-Investment-4083.aspx#:~:text=Western%20Australia%27s%20mining%2C%20mineral%20exploration,single%20calendar%20or%20financial%20year.
138. Department of Mines, Industry Regulation and Safety. Geology of Western Australia. 2020 [cited 3rd March, 2020]; Available from: https://www.dmp.wa.gov.au/Geological-Survey/Geology-of-Western-Australia-1389.aspx.
139. Department of Mines, Industry Regulation and Safety. Major resources projects: Western Australia - 2020. 2020 [cited 26th January, 2021]; Available from: https://dmpbookshop.eruditetechnologies.com.au/product/major-resource-projects-western-australia-2020.do.
140. [WA mining project proponent]. Thunderbird Project. 2021 [cited 26th January, 2021]; Available from: [WA mining project proponent] website.
141. Závodská, L., et al., Environmental chemistry of uranium. HV ISSN, 2008: p. 1418-7108.
142. Eisenbud, M. and T. Gesell, Environmental radioactivity from natural, industrial and military sources. 4 ed. 1997: Academic Press. 656.
143. Government of Western Australia, Department of Mines and Petroleum, Guide to uranium in Western Australia. 2013, State Law Publisher: Perth, Western Australia. p. 42.
144. Government of Western Australia, Department of Mines and Petroleum, State Government no uranium statement. 2017, State Law Publisher: Perth, Western Australia. p. 1.
145. National Energy Resources Australia, Uranium industry competitiveness assessment. Report on the framework, baseline score, insights and opportunities. 2017, Australian Department of Industry, Innovation and Science: Australian Resources Research Centre: Kensington, Western Australia. p. 26.
146. Clarke, T. Barnett lifts WA uranium ban WA Today 2008; Available from: http://www.watoday.com.au/wa-news/barnett-lifts-wa-uranium-ban-20081117-68vl.html.
147. Bautin, F. and C. Hallenstein, Plans for uranium mining by COGEMA, in ANA 97 Conference on Nuclear Science and Engineering in Australia. 1997, Australian Nuclear Association Inc.: Sydney, Australia. p. 20-24.
148. Laidlaw, M., Detailed site investigation, (M26/781) former Kalgoorlie Research Plant, Kalgoorlie, Western Australia,. 2006, URS Australia Pty Ltd. p. 110.
149. Crouch, P., Radiological issues affecting the closure of the Kalgoorlie Research Plant. 2003, [WA mining project proponent]: Perth, Western Australia. p. 16.
150. Sinclair Knight Merz, Yeelirrie Uranium project: Kalgoorlie Research Plant: Annual Environmental Report for 2004. 2005, [WA Mining Project Proponent],: Perth, Western Australia. p. 60.
151. Department of Health, [WA Mining Project Proponent] - Radioactive ores - mining and or

processing - Part 1 2018, File: RAD-17493 - 00534, Environmental Health - Radiation Health, Department of Health: Perth, Western Australia.
152. Department of Health, [WA Mining Project Proponent] - Kalgoorlie Research Plant - Yeelirrie Expl. Site 47/80 - radioactive ores - mining and or processing - Part 2. 2018, File: RAD-16996 - 00534, Environmental Health - Radiation Health, Department of Health: Perth, Western Australia.
153. Department of Health, [WA Mining Project Proponent] - radioactive ores - mining and or processing - Part 3. 2018, File: RAD-18010 - 00534, Environmental Health - Radiation Health, Department of Health: Perth, Western Australia.
154. Department of Health, [WA Mining Project Proponent] - Kalgoorlie Reseach Plant - radioactive ores - mining and or processing - Part 4. 2018, File: RAD-19649 - 00534, Environmental Health - Radiation Health, Department of Health: Perth, Western Australia.
155. Leach, V.A., S. Solomon, and W. Gan, Australian Radiation Laboratory: Radon / radon daughter survey at the [WA Mining Project Proponent] uranium pilot plant of Kalgoorlie and Yeelirie mine site. 1980, Department of Health WA, Environmental Health File RAD 17493 p. 26.
156. Bradshaw, C., [WA Mining Project Proponent] Yeelirrie supervised area closure finalisation works: Project close-out report. 2004: Perth, Australia.
157. Hewson, G.S. and M.I. Ralph, An investigation into radiation exposures in underground non-uranium mines in Western Australia. Journal of Radiological Protection, 1994. 14(4): p. 12.
158. Auld, B., Greenbushes operations: Radon monitoring, in Radon monitoring from 29th April 2005 to 10th March 2006. 2005, [WA Reporting Entity]: Greenbushes, Western Australia. p. 2.
159. Thompson, A.W., Radiation exposure to the population of Perth, Western Australia. Radiation Protection in Australia, 1995. 13(2): p. 6.
160. Efendi, Z. and P. Jennings, An assessment of the environmantal radiation dose for residents of the Perth metropolitan area. Radiation Protection in Australia, 1994. 12(1): p. 5.
161. Toussaint, L.F., Measurements to determine the radiological impact of uranium and thorium in soils in the darling scarp. International Congress Series, 2005. 1276(2005): p. 4.
162. Alach, Z.J., et al., Radionuclide concentrations in the Darling Scarp of Western Australia. Radiation Protection in Australia, 1996. 14(2): p. 4.
163. O'Connor, B.H., Bayer process radiological evaluation - status review 2004 prepared for [WA reporting entity]. 2004, File: 1174-88, Folio: 505, 498 and 501, Department of Mines: Perth, Western Australia. p. 74.
164. Terry, K.W., Katee Enterprises: Summary on operational radiation monitoring programme - residue storage areas by [WA reporting entity] 1997, File: 001-000871 Report: 496, Department of Mines and Petroleum: Perth, Western Australia. p. 29.
165. Upton, H., RSSC paper 12/2 - The radiological management at bauxite residue. 1995, File: 1174-88, Folios 18-24: Department of Minerals and Energy, Perth, Western Australia. p. 7.
166. O'Connor, B.H., et al., Radiological assessment for bauxite mining and Alumina refining. Annals of Occupational Hygiene, 2013. 57(1): p. 14.
167. Sutar, H., et al., Progress of red mud utilisation: An overview. American Chemical Science Journal, 2014. 4(3): p. 25.
168. Red Mud Project. Industrial uses. 2014 [cited 2nd July 2014]; Available from: https://redmud.org/utilisation/industrial-uses/.
169. Summers, R.N., N.R. Guise, and D.D. Smirk, Bauxite residue (Red Mud) increases phosphorous retention in sandy soil catchments in Western Australia. Fertilizer Research, 1992. 34: p. 12.
170. Grant, S., Garden guru opens up, in Fremantle Herald. 2014: Fremantle, Western Australia. p. 1.
171. Government of Western Australia, Department of Water Water quality protection note 50: Soil amendment using industrial by-products to improve land fertility. 2015. 23.
172. Harris, S. and B. Howard, Bauxite Residue (Alkaloam) Sustainability Assessment: Technical, Community Consultation, Benefit-Cost and Risk Assessment. 2010.
173. Summers, K.J., B.H. O'Connor, and D.R. Fox, Radiological consequences of amending soils with bauxite residue gypsum mixtures. Australian Journal of Soil Research, 1993. 31(4): p. 6.
174. Ryle, G. The great red mud experiment that went radioactive The Sydney Morning Herald, 2002.
175. Bell, L., Red mud a dirty disappointment, in Fremantle Herald. 2014: Fremantle, Western Australia.
176. Adolph, F., Residents fear radioactivity, in The Sunday Times. 2004, News Limited: Perth, Western Australia. p. 1.
177. Semeniuk, V., Tidal Flats. Encyclopedia of Coastal Science, ed. C.W. Finkl and C. Makowski. 2019. 991.
178. Geoscience Australia. Garnet. Australian Mineral Facts 2021 [cited 29th January 2021]; Available from: http://www.ga.gov.au/education/classroom-resources/minerals-energy/australian-mineral-facts/garnet.

179. Gundry, A., [WA reporting entity] radiation safety manual - Geraldton dry plant - supervised area. 2008, File M0166/201001 Folio 505, and supplementary folios 498 and 501: Perth, Western Australia. p. 29.
180. Hewson, G.S. and H. Upton, Operational and regulatory aspects of the management of radioactive wastes arising from mineral sands processing. Radiation Protection in Australia, 1996. 14(3): p. 8.
181. Department of Mines, Industry Regulation and Safety, Annual radiation reports 2007-08. 2019, Records Manager: Results of Search on Occupational Radiation Reports (2007-08): Perth, Western Australia.
182. Radiological Council of Western Australia, Radiation protection in the mineral sands industry: Submission to the committee of inquiry by the Radiological Council. 1983, File M0044/201201, Folio 1-47, Department of Mines: Perth, Western Australia. p. 47.
183. Gofman, J.W., Radiation & human health. 1981, San Francisco, USA: Sierra Club Books. 866.
184. Stewart, J.D., [WA Mining Entity], Kambalda [Site]: The Singapore saga (loss of a radioactive gauge), in Company Records. 1982, [WA Mining Entity] Online History Collection (nla.gov.au).
185. Keys, N., J. Grace, and R. Humphries, The heavy minerals sands industry handbook. 1988, the Office of Senator Jo Vallentine: Perth, Western Australia. 36.
186. Mason, G.C., M.W. Carter, and J.R. Johnson, Technical audit of radiation safety practises in the mineral sands industry: A report to the Minister for Mines, Western Australia. 1990, Government of Western Australia: Perth, Western Australia. p. 99.
187. Ralph, M.I., Summary of radon daughter analyses, G.S. Hewson, Editor. 1988, Department of Mines: Perth, Western Australia. p. 6.
188. Hewson, G.S. and M.I. Ralph, Determination of program protection factors for half-mask respirators used at a mineral sands separation plant. American Industrial Hygiene Association Journal, 1992. 53(11): p. 713-720.
189. Tsurikov, N., Mineral sands mining and processing, Australia - general. Consultant's report to the International Atomic Energy Agency. 2009, Calytrix Consulting: Perth, Australia. p. 13.
190. Tsurikov, N., WA Reporting Entity: Australia, consultant's report to the International Atomic Energy Agency. 2009, Calytrix Consulting: Perth, Australia.
191. Calytrix Consulting, Microsoft Excel File: MSI Dose History 1993-94 to 2007-08, N. Tsurikov, Editor. 2019: Perth, Western Australia. p. 1.
192. Tsurikov, N., NORM in Western Australia - plenty of mineral but not enough human resources, in 9th International Symposium on Naturally Occurring Radioactive Material, Occupational Radiation Protection Network, Editor. 2019: Denver, Colorado, USA.

ARPS Webinar Series

In order to promote member and radiation protection community engagement, the ARPS Executive have commenced quarterly webinars held via Zoom that are open to ARPS members (free of charge) and the general public (for a small fee). We have successfully run two webinars, and they are available/accessible to view via the members portal of the ARPS website. Upcoming webinars will be promoted via the website, emails to members and social media pages.

The webinars are structured such that we have an expert/s talk on a specific topic followed by a moderated Q&A session, but if the topic/theme would benefit from a panel discussion this will also be utilised. They are roughly 30-45 minutes plus the Q&A session, this allows for them to be held during lunchtime.

We welcome suggestions for presenters, topics and themes. At present we have the following topics/themes:

- Medical
- Environmental
- Mining
- Industrial
- Non-Ionising Radiation
- Regulatory
- Incident / Emergency
- Education / Training / Research

Suggestions and feedback can be submitted via the email or web address below:

webmaster@arps.org.au or https://arps.org.au/Contact