Regulating Exposures to NORM in the WA Mining Industry

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https://ro.ecu.edu.au/theses/2642

Today's Presentation

- Radiation and radioactivity: some principles
- Radiation exposure and risk
- NORs in the WA mining industry
- Research project phases and findings
- The WA regulatory framework
- A peek over the horizon – emerging challenges
- Questions

Radiation and Radioactivity

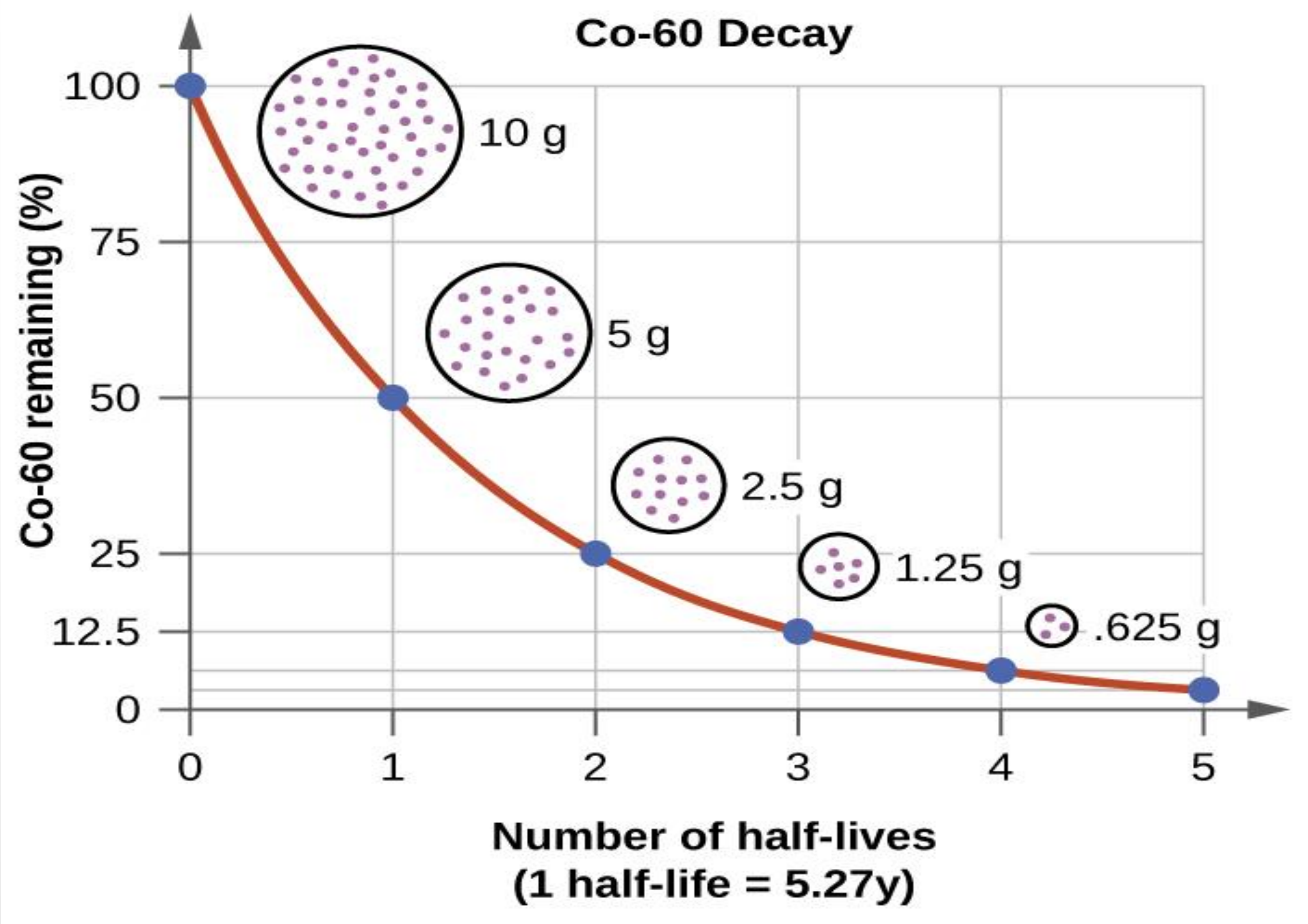
The SI unit of measurement for Activity is the becquerel (Bq).

- **It is a measure of the quantity of radioactive material, but does not indicate how many, or what type of emissions are being released from the nucleus.**
  - The Bq is equivalent to one nuclear disintegration per second.

- Activity Concentration relates to the concentrations of radioactivity within a substance:
  - Solids: Becquerels per gram (Bq/g)
  - Liquids: Becquerels per litre (Bq/l)
  - Airborne: Becquerels per cubic metre (Bq/m^3)

Radiation and Radioactivity: Half Life ($T_{1/2}$)

- The length of time for half of a given quantity of radioactive atoms to undergo radioactive decay
- The half life is constant for a specific radionuclide.



Radiation and radioactivity: Measurement

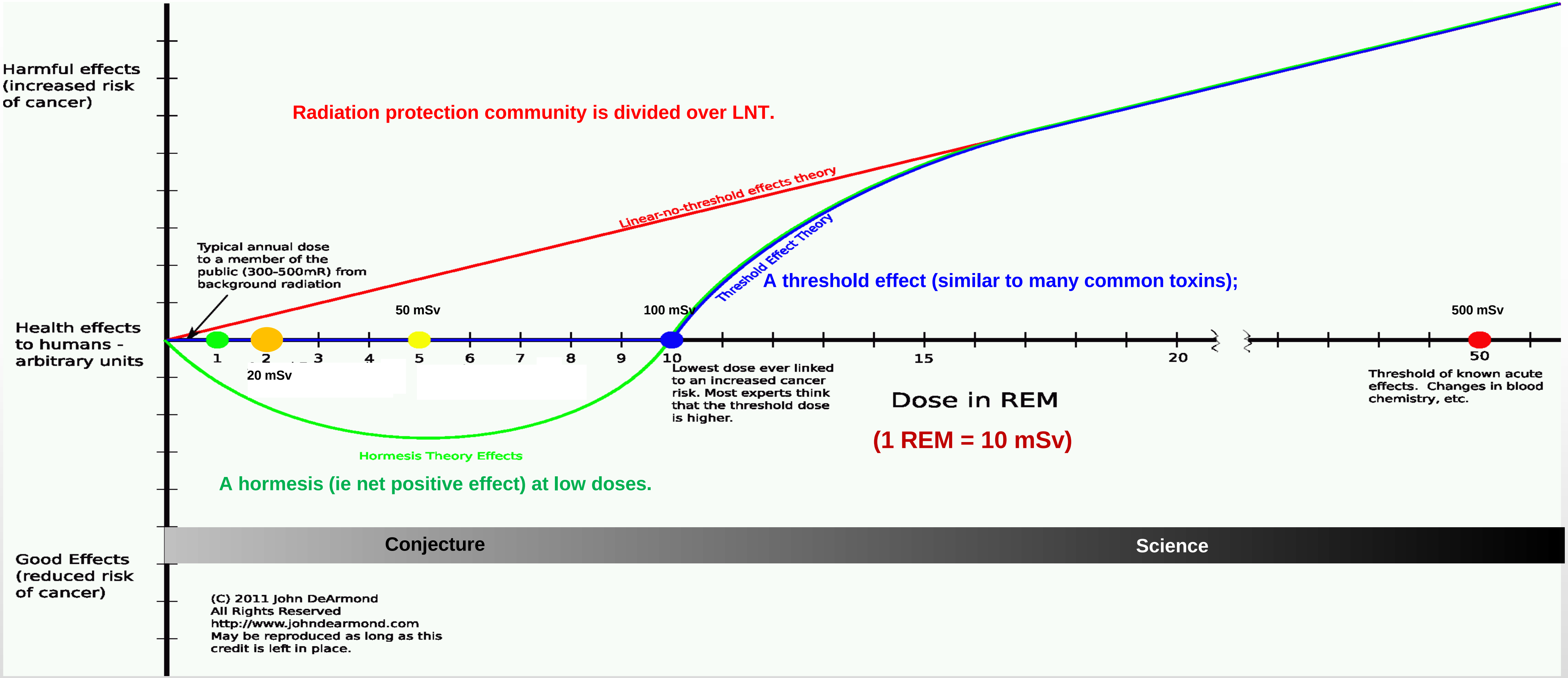
Radiation doses are a function of the transfer of energy to the body, and are measured by 3 fundamental parameters:

1. Exposure:
   - Measured in coulombs per kilogram (C/kg)
2. Absorbed Dose:
   - Measured in grays (Gy)
   - In mining applications, dose rate is measured in microGrays per hour (uGy/h).
3. Dose Equivalent:
   - Measured in Sieverts (Sv)
   - It makes allowance for the type of radiation (the Quality Factor) and the radio-sensitivity of the part of the body exposed.
   - In mining applications, dose equivalent is measured in milliSieverts (mSv).

Radiation exposure and risk: Doses in perspective

Dose Equivalent (mSv)	Effect
10,000	100% mortality
6,000	Early death
4,000	50% mortality
2,000	Threshold for early death
500	Nausea & reduced white blood cell count
131	NATURAL annual background dose$_{peak}$ in Ramsar, Iran
100	Limit for exposure of a radiation worker over a 5 year period.
20	Derived Limit for exposure of a radiation worker in 1 year*
5	Whole body CT scan, single
2	Average annual exposure from NATURAL radiation
1	Limit of exposure of a 'member of the public' in a single year
0.05	Exposure from 7 hour flight
0.02 – 0.10	Typical sequence of chest x-rays

Radiation and Risk: Linear Non-Threshold Hypothesis



Outcome = every exposure carries a risk …

Radiation Exposure and Risk

ARPANSA (2018) states:

- Risk from <u>acute</u> exposures (as might occur with accidents)

  = 1 in 10,000 per mSv

- Risk from chronic exposures (as occur in the mining industry)

  = 1 in 20,000 per mSv

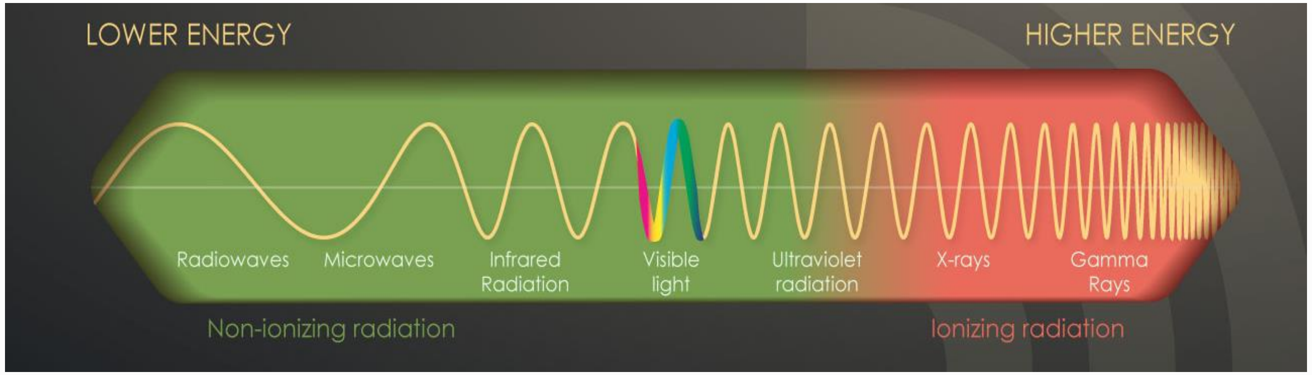
  - Therefore, at 20 mSv annual derived limit, risk is equivalent to <u>1 in 1000</u>

- United Kingdom Health and Safety Executive risk model* suggests that this level of risk is intolerable …

* Cited in Hopkins, Safety Culture and Risk: the organisational causes of disasters (2005)

Ionizing radiation in mining

- Electromagnetic
  - X-rays; or
  - Gamma (γ) rays.

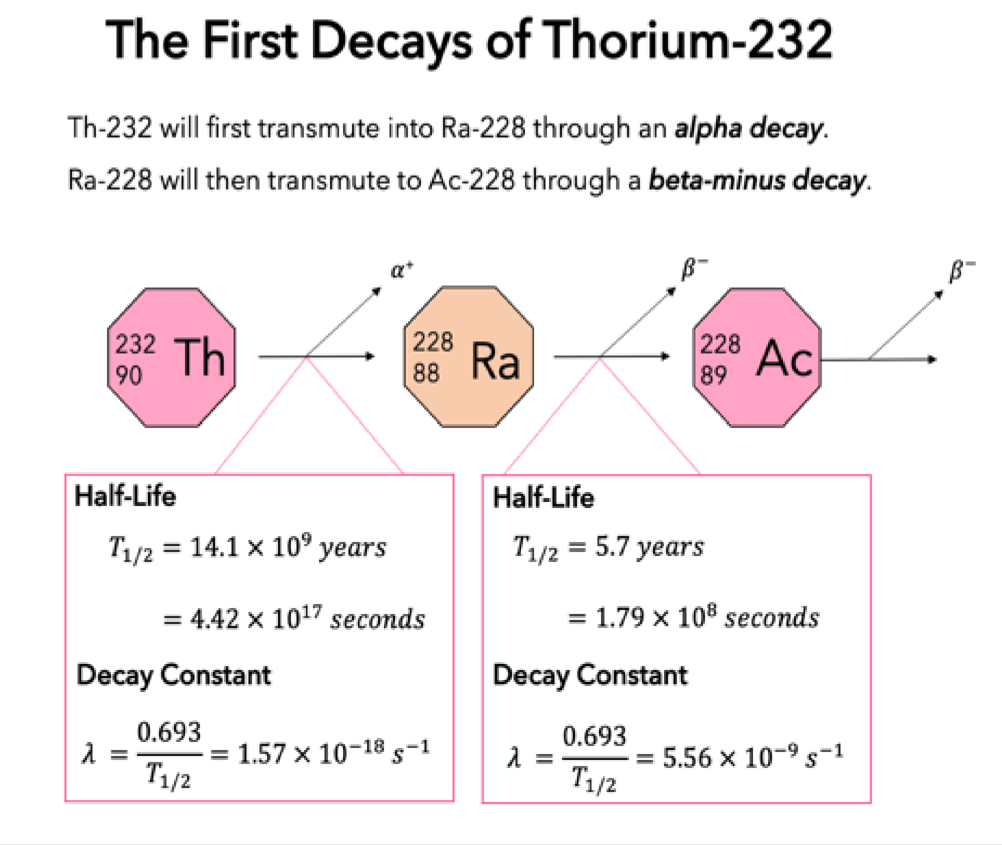


- Particulate
  - Alpha (α) particles;
    - Ionised Helium Nucleus ($_2He^{4\,++}$)
  - Beta (β) particles;
    - High Speed electron from neutron ($_0n^1$) decay

What happens during the decay process?

1) Thorium-232 decays via emission of an alpha particle

- The mass number decreases by 4
- The atomic number decreases by 2
- A new atom of radium is formed



2) The newly formed atom of radium-228 decays via beta emission

- The mass number remains the same
- But – the atomic number increases by 1
- A new atom of actinium is formed …

What are mining NORs?

- The primordial radionuclides
  - Uranium (^{238}U series) and
  - Thorium (^{232}Th series)
- Naturally radioactive
- Heavy metal toxins
  - Will cause death by poisoning before inducing harm via radioactivity
- Consist of complex series' including many radioactive decay products

NOR: The U-238 Decay Series

Uranium-238
4.47 billion yrs.

α

Thorium-234
24.1 days

β

Protactinium-234
1.17 minutes

β

Uranium-234
245000 years

α

Thorium-230
8000 years

α

Radium-226
1600 years

α

Radon-222
3.823 days

α Noble Gas

Radon Progeny

Polonium-218
3.05 minutes

α

Lead-214
26.8 minutes

β

Bismuth-214
19.7 minutes

β

Polonium-214
0.000164 seconds

α

Lead-210
22.3 years

β

Bismuth-210
5.01 days

β

Polonium-210
138.4 days

α

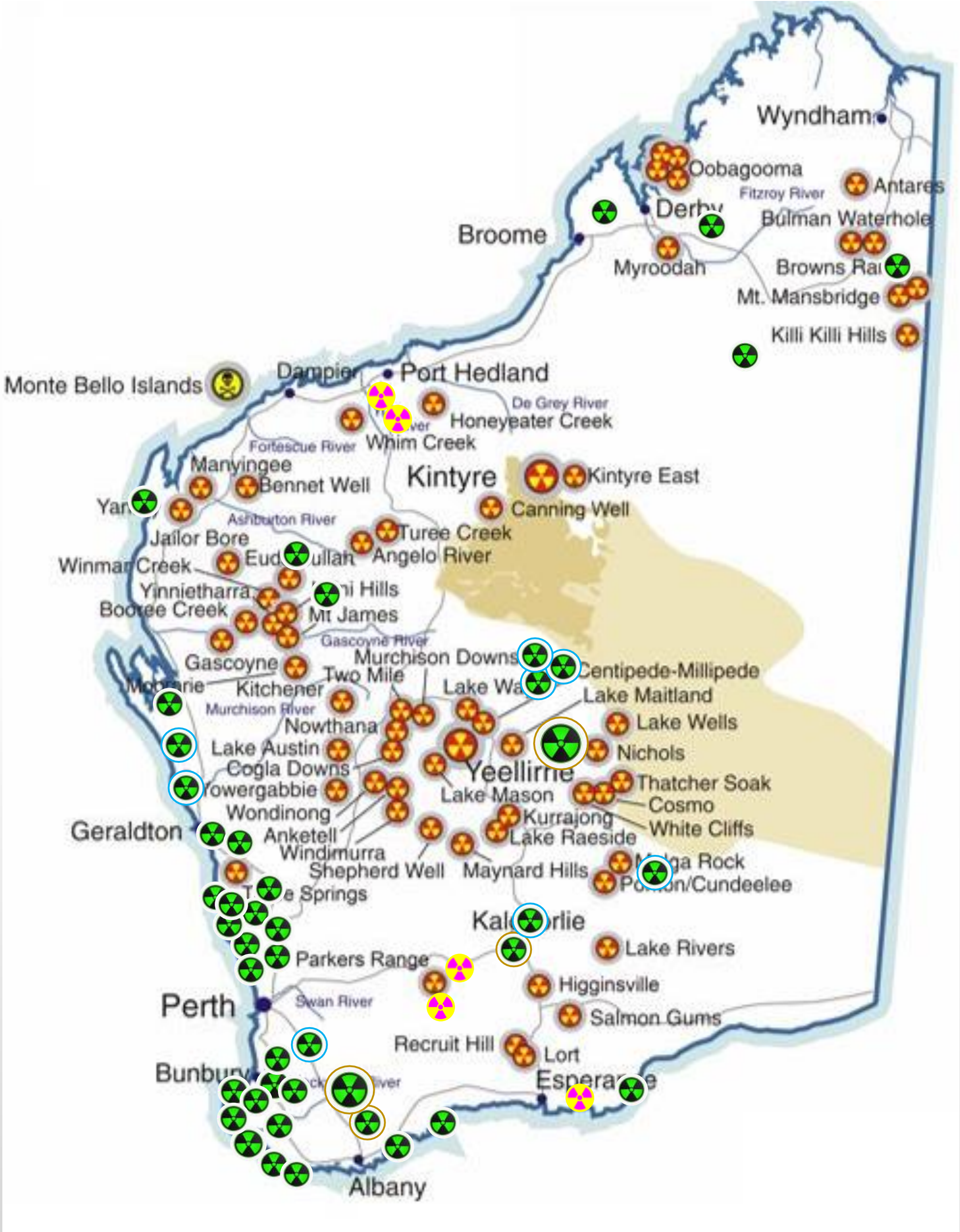
Lead-206
stable

5 Long Lived Alpha-Emitting isotopes

Each β is accompanied by a Y ray

What are mining NORs?

- The primordial radionuclides
  - Uranium (^{238}U series) and
  - Thorium (^{232}Th series)
- Naturally radioactive
- Heavy metal toxins
  - Will cause death by poisoning before inducing harm via radioactivity
- Consist of complex series' including many radioactive decay products
- Occur in trace concentrations in rocks & soils in the earth's crust
  - WA's geology is replete with minerals that contain ^{238}U and ^{232}Th
  - Darling Scarp 10 x more activity than the global crustal average



WA hosts:

^{238}U

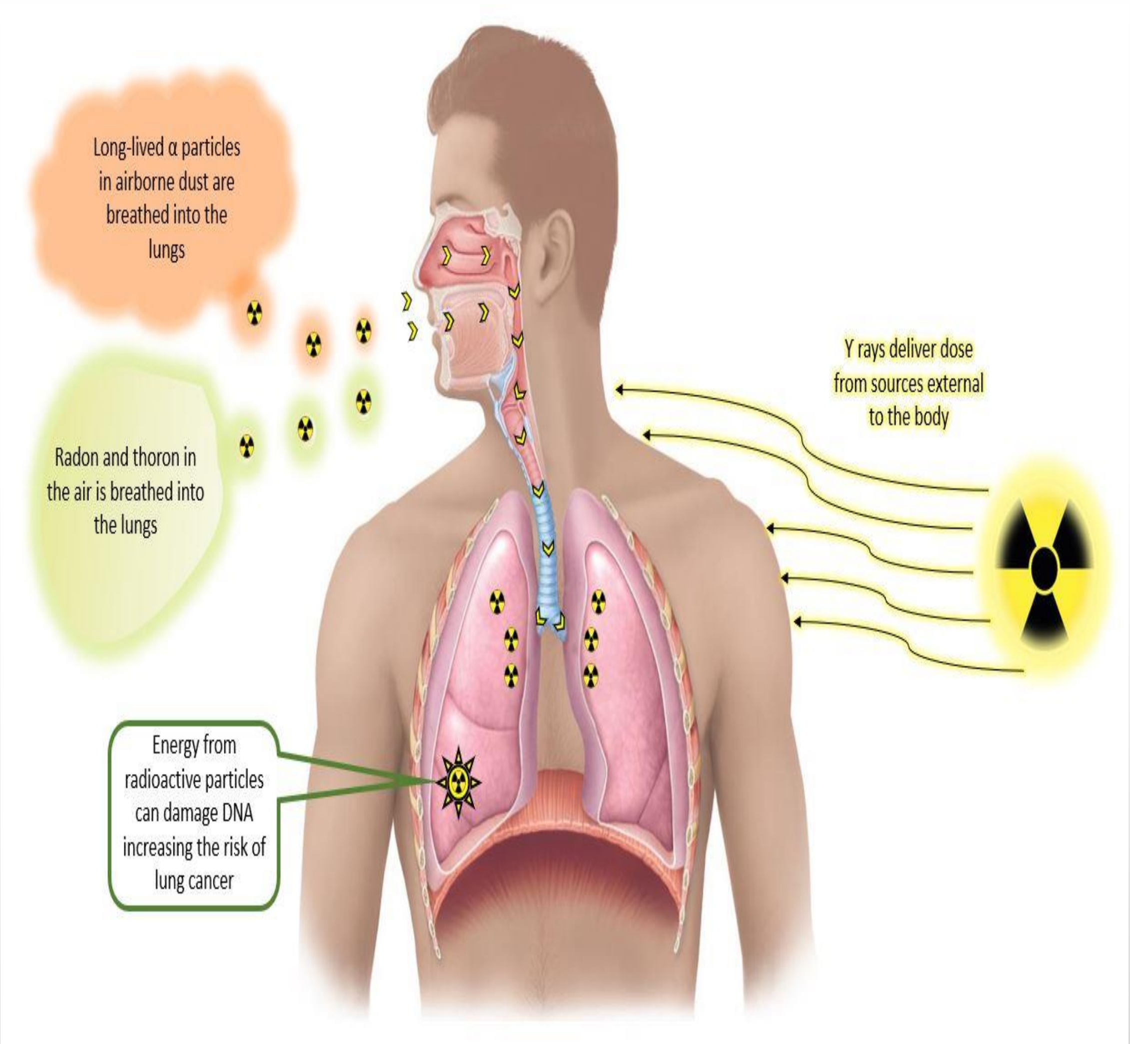
- >60 known potential uranium mines
  - Most deposits adjacent to gold and base metal mines

^{232}Th

- Worlds largest mineral sands producer
- 47 known deposits of monazite; and
- 10 deposits of xenotime
  - Many coincident with base metal operations
  - Significant sources of rare earth elements

- Tantalum-lithium projects
  - Associated with NOR-contaminated groundwater

Why is NORM Important?



- *'In the past the mining and extraction industries have been associated with the highest individual occupational exposures to [NORs]'* Steinhausler (1993, p.38)

- Excess of cancer incidence and / or respiratory system illness observed in studies of mine workers around the world… Steinhausler (1993)

Timeline - Radiation Protection in WA Mines

1966: RCWA advises MSI that monazite is radioactive

1970's

AL = 50+ mSv

1977: ALARA principle formalised

1978: RCWA begins inspections of MSI

1980's

AL = 50mSv

1982: Mineral Sands Code of Practice

1983-90: Intense media scrutiny

1984: Winn Report

1988: ICRP 2 superseded. DCFs revised

1990's

AL = 50mSv

Emerging Awareness

- Monazite production increases.
- Fed. 'Mining' Code implemented.
- Radiation Safety Act prevails.

Media Coverage: Was the hysteria warranted?

In the mid to late 1980's the maximum dose in the mining industry in WA was ~165 mSv

and the mean dose, received by 270 designated radiation workers was 31 mSv.

80% of the dose was delivered via inhalation of Long Lived Alpha particle emitters in radioactive dusts.

Rn, Tn and their progeny were not included in dose estimates …

Media Coverage: Was the hysteria warranted?

- *The discovery that tailings from a mineral sands processing plant had been used as landfill in Capel, a town in southern Western Australia, indicated the need for a survey of the gamma radiation levels within the town site.*
  - *Eleven houses were found to have elevated backgrounds and a further 27 residential properties had elevated levels outside the house.*
  - *The highest dose rate recorded in a residential area was 4µSv per hour**

- Radioactivity in mineral sands in Western Australia

King, Toussaint and Hutchinson (1983)

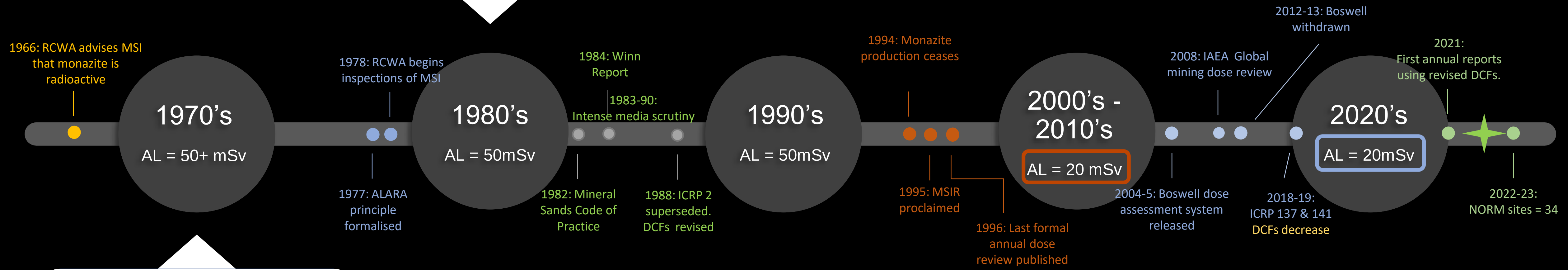
* Equivalent to approximately 35mSv per year.

The annual limit for a member of the public is 1mSv.

Timeline - Radiation Protection in WA Mines

Community Concern

- Some workers doses >150 mSv.
- Dramatic reduction in DAC's.
- Interim Mines Radiation Committee.



Emerging Awareness

- Monazite production increases.
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Research Question

Given the rapidly changing geopolitical landscape for the supply of critical minerals (including uranium) and Western Australia's unique lithology:

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

Research Phase 1: Meta-analysis of historical data

- Systematic monitoring of mine worker doses commenced in **1977**
- Prior to my research, the last report on mine worker occupational radiation exposures was compiled in 1995 (Hewson, 1996a).
- Of the 220 annual reports in the intervening period (until 2018-19) only 2 could not be located:
  - A commendable compliance rate of **99.1%**
- Although some demographic data from the late 1970’s and early 1980’s is not available, the historical record from ~1984 is remarkably intact…

Research Phase 1: Meta-analysis of historical data

Parameter	1977 to 2018-19
Reporting Entities (Site.years)	355
Reports Assessed	335
Sum of workforce by year [2]	***34,240***
Maximum dose (mSv)	**163.4**
Collective dose (man.mSv)	108,850
Mean Worker dose (mSv y^{-1}) [5]	**3.2**
0 and 1.0mSv	10,811
1.01 and 2.0mSv	1,566
2.01 and 3.0mSv	668
3.01 and 4.0mSv	321
4.01 and 5.0mSv	144
Workers receiving less than 5.01mSv [6]	***29,898***
Workers receiving between 5.01 and 10mSv	1,340
Workers receiving greater than 10.01mSv [7]	745

Research Phase 2: Calculating Internal Dose

ICRP develops dose coefficients to simplify the calculation of equivalent dose and effective dose for inhaled or ingested radionuclides.

In simplest terms, calculating the dose from an intake involves multiplying the total amount inhaled or ingested (e.g. in Bq) by the right dose coefficient:

Effective dose (mSv) = intake (Bq) × dose coefficient (mSv/Bq)

The dose coefficient depends on the radionuclide and:

- Whether it's inhaled or ingested
- The particle size (for inhalation)
- The chemical form

http://icrpaedia.org/Calculating_Doses_from_Intakes_of_Radionuclides

Research Phase 2: Internal Dose from Rn & RnP

- *'Radon gas is by far the most important source of ionising radiation amongst those that are of natural origin … radon is the second [highest] cause of lung cancer in the general population after smoking.'*

- *'…there is no known threshold below which radon exposure presents no risk. Even low concentrations of radon can result in a small increase in the risk of lung cancer'*

World Health Organisation (2009)

Dose coefficients for radon, thoron and their progeny were revised in 2018

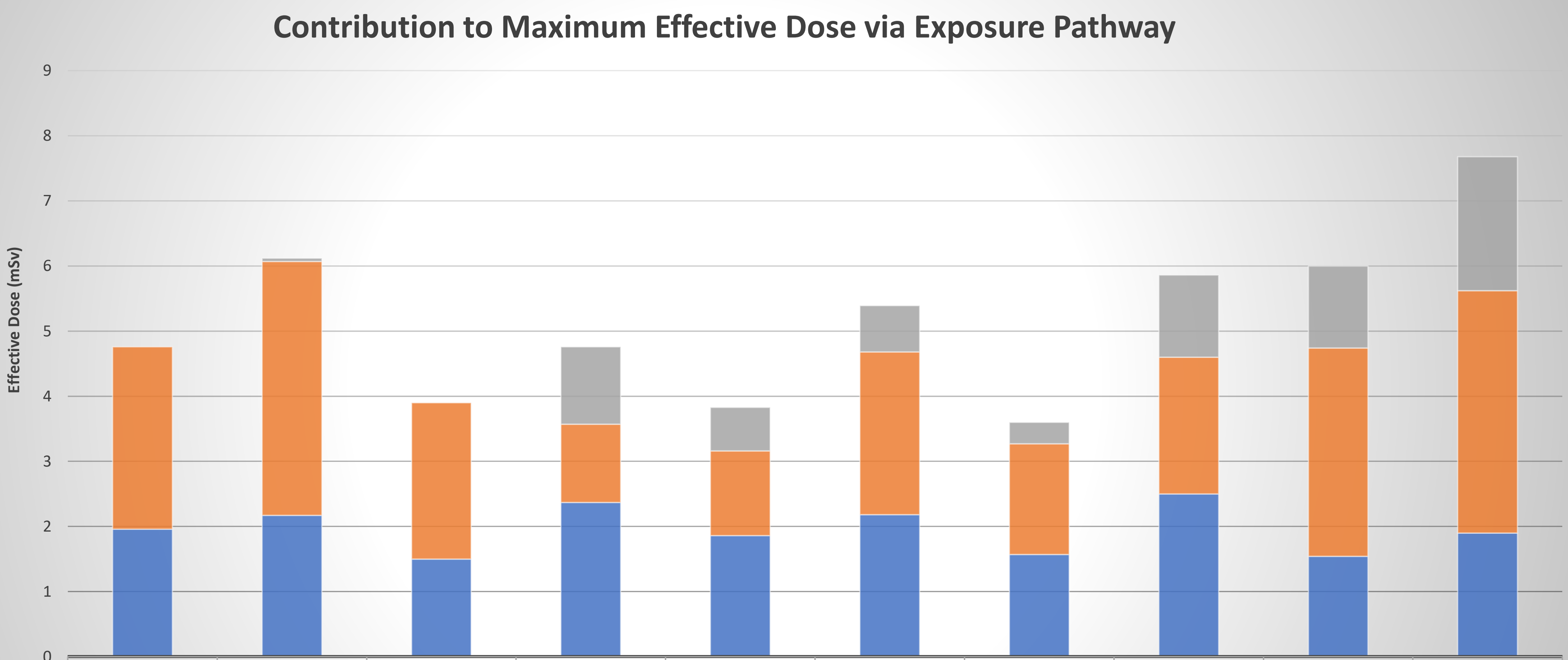
Research Phase 2: Internal Dose from Rn & RnP

- Impact of revised dose coefficients for Radon and Progeny on doses received by WA underground mine workers?

Commodity	Hewson and Ralph (1994) (F=0.5)			2020 Data (F=0.52)		
	Workforce Population	Mean Dose (mSv)	Collective dose (man.mSv)	Workforce Population	Mean Dose (mSv)	Collective dose (man.mSv)
Gold	1,075	1.3	1,400	6,610	1.61	10,642
Nickel / Gold	697	0.8	560	830	0.87	722
Coal	297	2.9	860	-	-	-
Lead / Zinc	122	0.7 [1]	85	860	2.22	1,909
Diamonds	-	-	-	297	1.33 [2]	396
Total	2,173		**2,905** [3]	8,597 [4]		**13,669**

7767 underground miners receive doses above the regulatory intervention level

Research Findings: Contribution from Rn & RnP



	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20
Maximum RnP + TnP	0	0.05	0	1.19	0.67	0.71	0.33	1.26	1.26	2.06
Maximum LLA	2.8	3.9	2.4	1.2	1.3	2.5	1.7	2.1	3.2	3.72
Maximum Gamma	1.96	2.17	1.5	2.37	1.86	2.18	1.57	2.5	1.54	1.9

Research Phase 3: Dose Conversion Factors

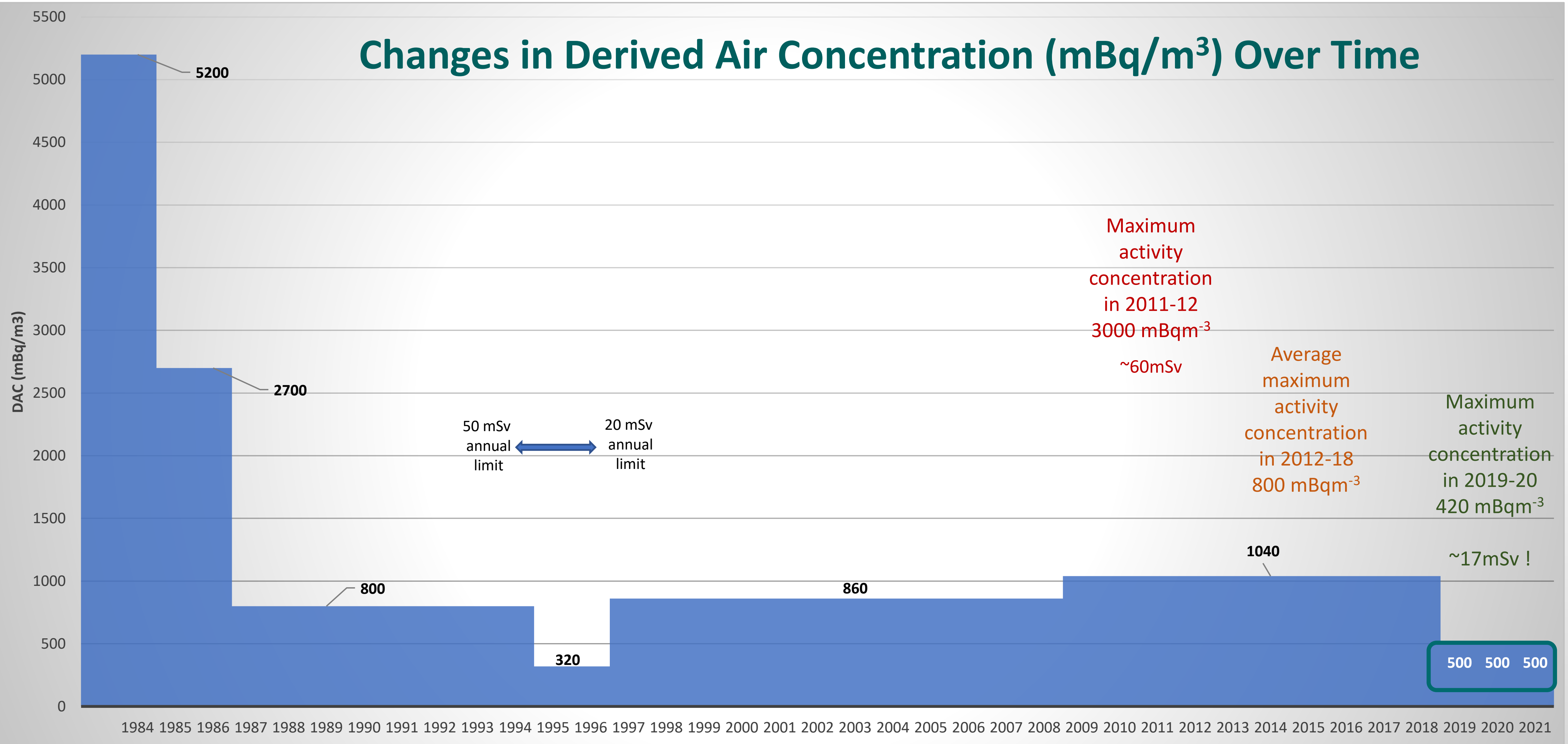
Particle Size	DCF by Particle Size ($mSvBq_{\alpha}^{-1}$)					
	^{232}Th decay series			$^{238+235}U$ decay series		
	A NORM-5	B ICRP-137 & 141	Change, as a ratio B : A	A NORM-5	B ICRP-137 & 141	Change, as a ratio B : A
1 µm	0.0113	0.0290	2.6	0.0050	0.0143	2.9
5 µm	0.0080	0.0167	2.1	0.0035	0.0084	2.4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

- Dose Conversion Factors are derived from dose coefficients.
- Research forecast WA worker doses increase by a factor of between 0.74 and 1.26 times from those reported in 2018-19.
- Maximum annual dose forecast to increase from 4.4mSv to 7.9mSv.

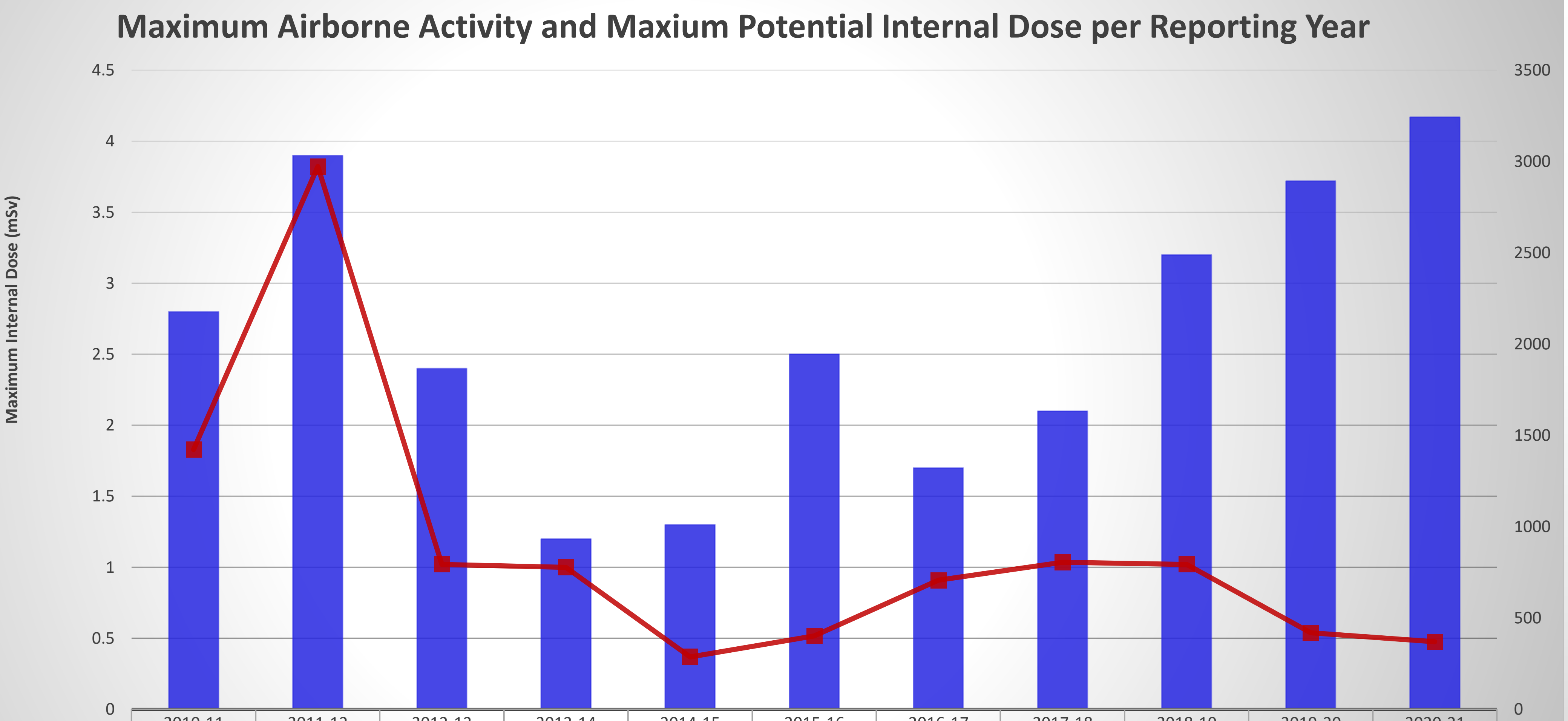
Research Phase 4: 2019-20 Annual Reports

- **19** reporting entities required to submit annual reports submitted
- **1963** total workers
  - 323 “monitored workers”
  - 16.5% of total workforce monitored
- Mean annual dose 1.1mSv
- Maximum annual dose **6.0mSv**
  - 4.4 mSv in 2018-19 – **increase ~36%**
  - First time for 20 years that annual doses have exceeded 5 mSv
- Questionable veracity of dose assessments
  - 0.37 samples per worker (declining from 3.0 in 1995-96)

Impact of DCFs on DACs

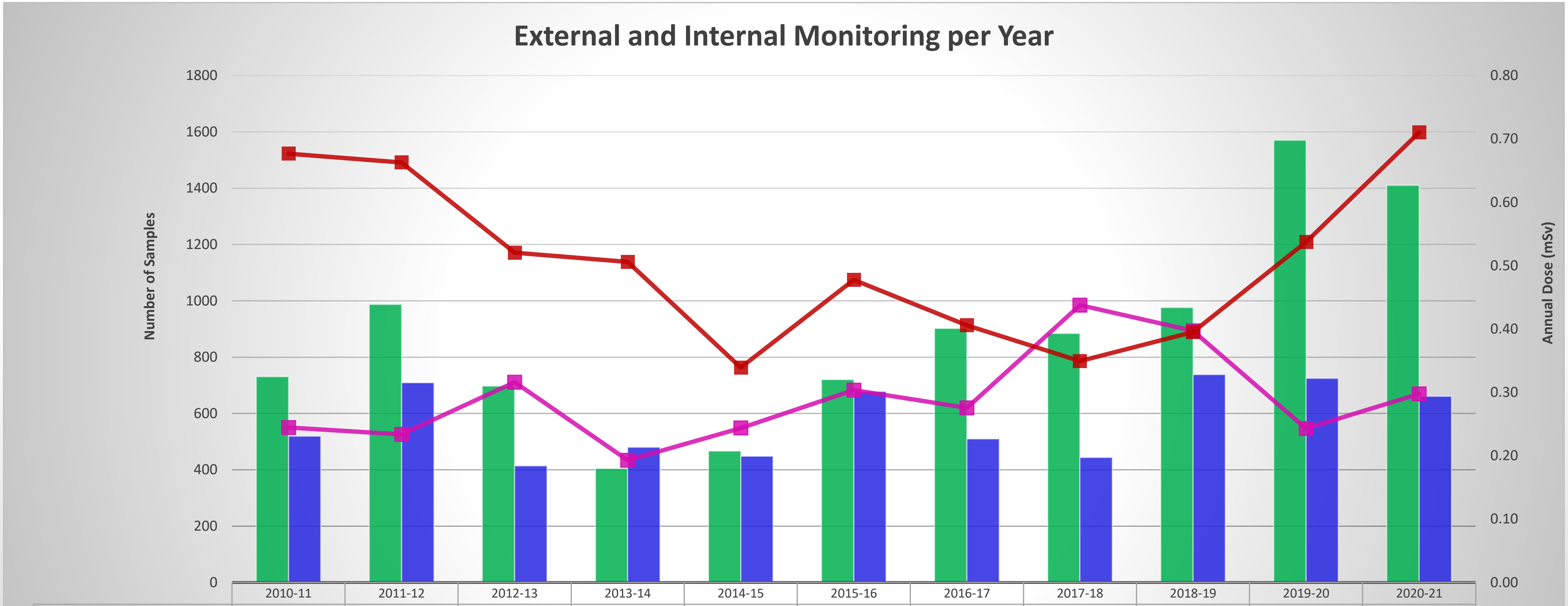


Research Phase 5: Trend Analysis (1)



	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21
Maximum Internal Dose (mSv)	2.8	3.9	2.4	1.2	1.3	2.5	1.7	2.1	3.2	3.72	4.17
Maximum Airborne Activity (mBq/m3)	1423	2973	794	778	287	402	707	806	794	419	370

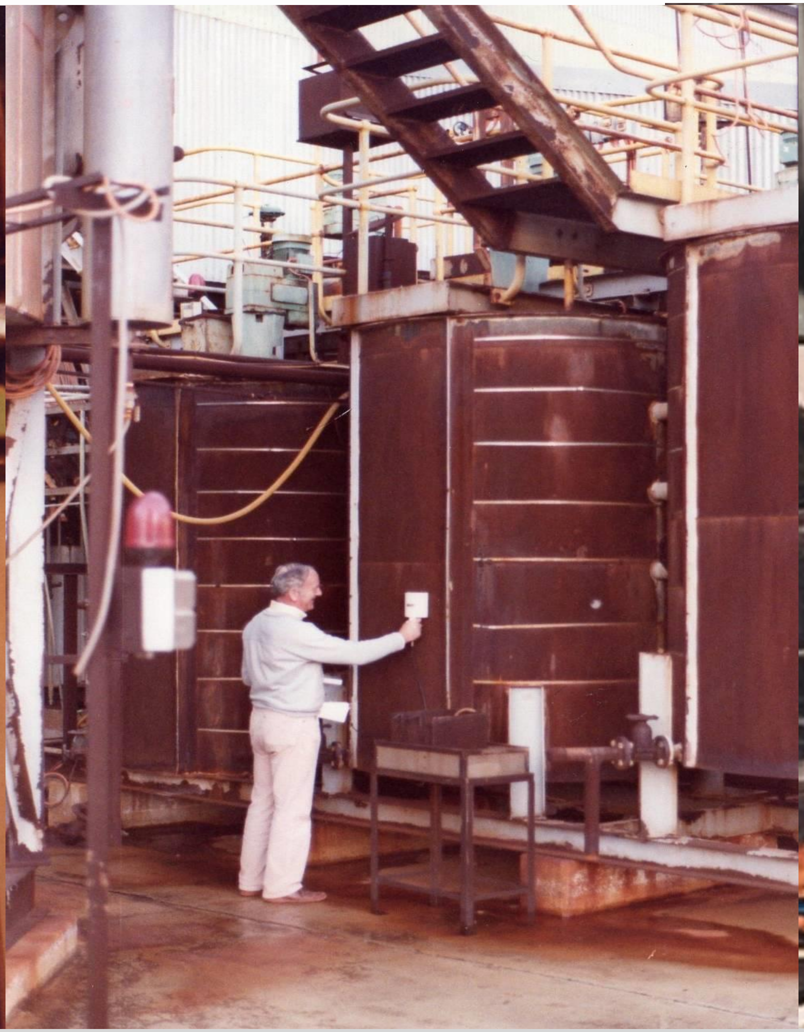
Research Phase 5: Trend Analysis (2)



	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21
Personal Gamma Monitors	731	987	697	404	467	720	902	884	976	1570	1410
Personal Dust Samples	519	709	414	480	448	678	510	444	738	725	661
Mean External Dose	0.24	0.23	0.32	0.19	0.24	0.30	0.28	0.44	0.40	0.24	0.30
Mean Internal Dose	0.68	0.66	0.52	0.51	0.34	0.48	0.41	0.35	0.40	0.54	0.71

Field Research: Managing Radioactive Waste

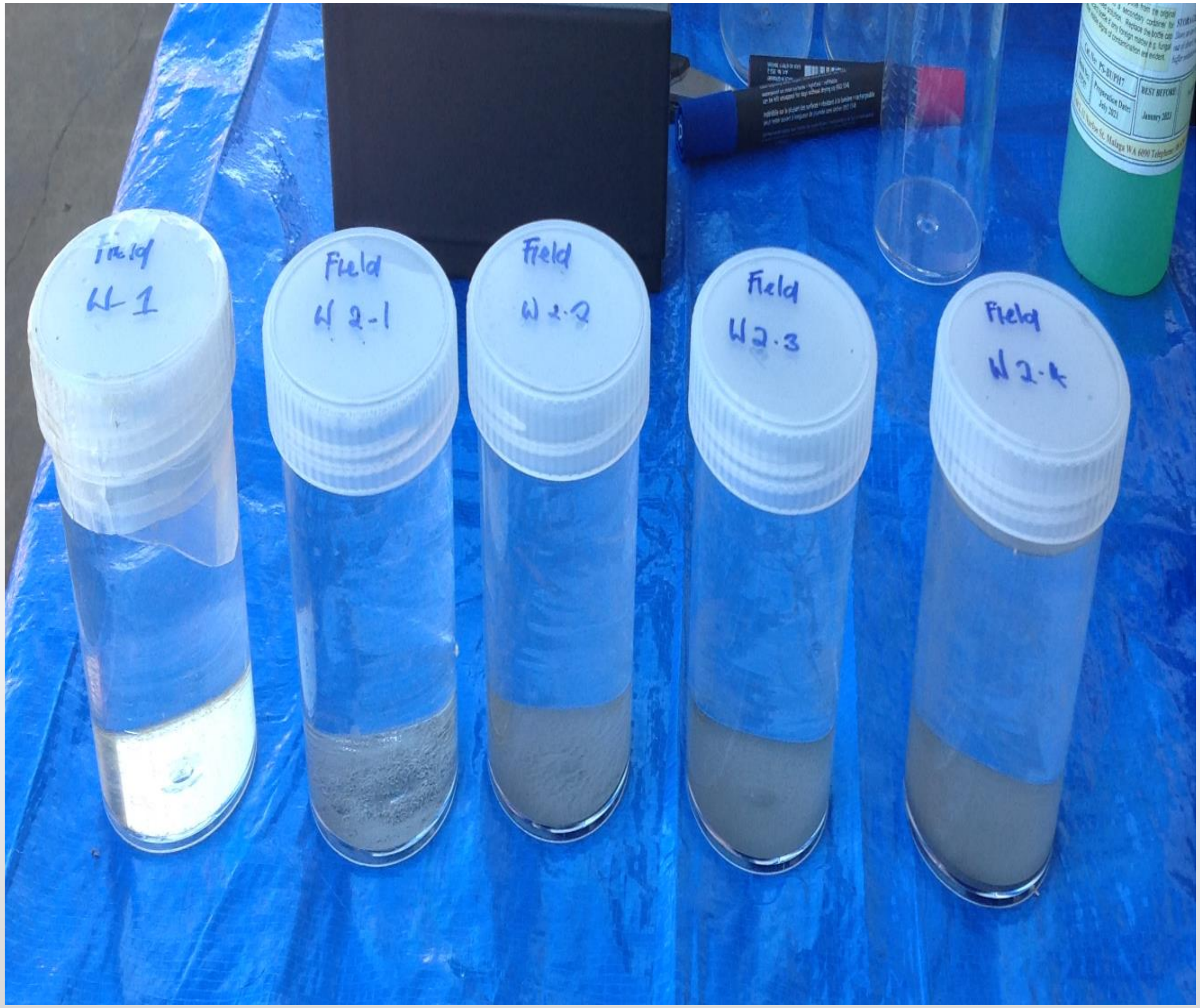
Radium Affinity for Steelwork (especially scale) and Polonium volatility



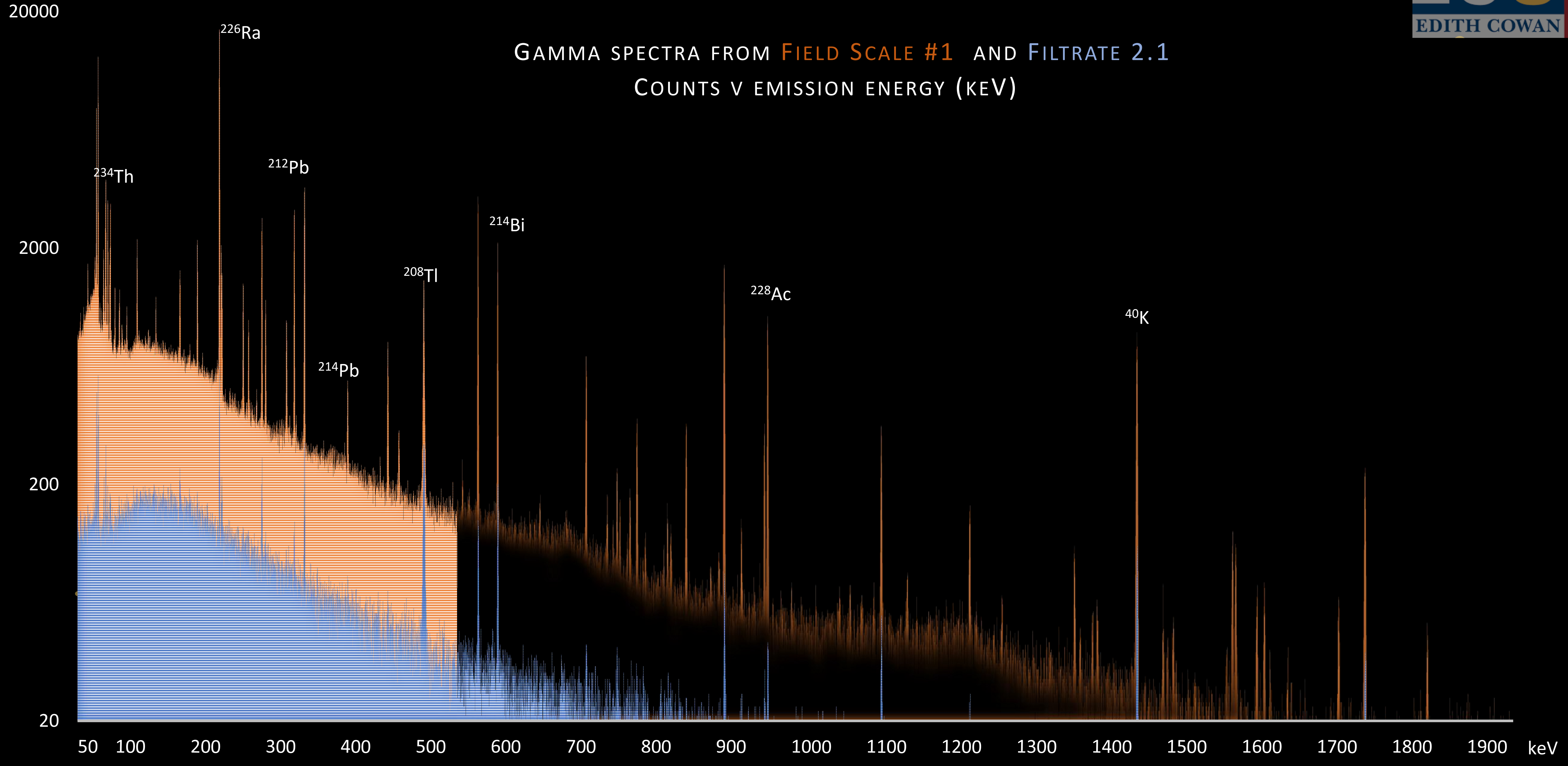
Field Research: Managing Radioactive Waste




Field Research: Managing Radioactive Waste



Results



GAMMA SPECTRA FROM FIELD SCALE #1 AND FILTRATE 2.1
COUNTS V EMISSION ENERGY (KEV)
20000
2000
200
20
^{226}Ra
^{234}Th
^{212}Pb
^{214}Bi
^{208}Tl
^{214}Pb
^{228}Ac
^{40}K
50 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 keV

Summary of Field Trial Results

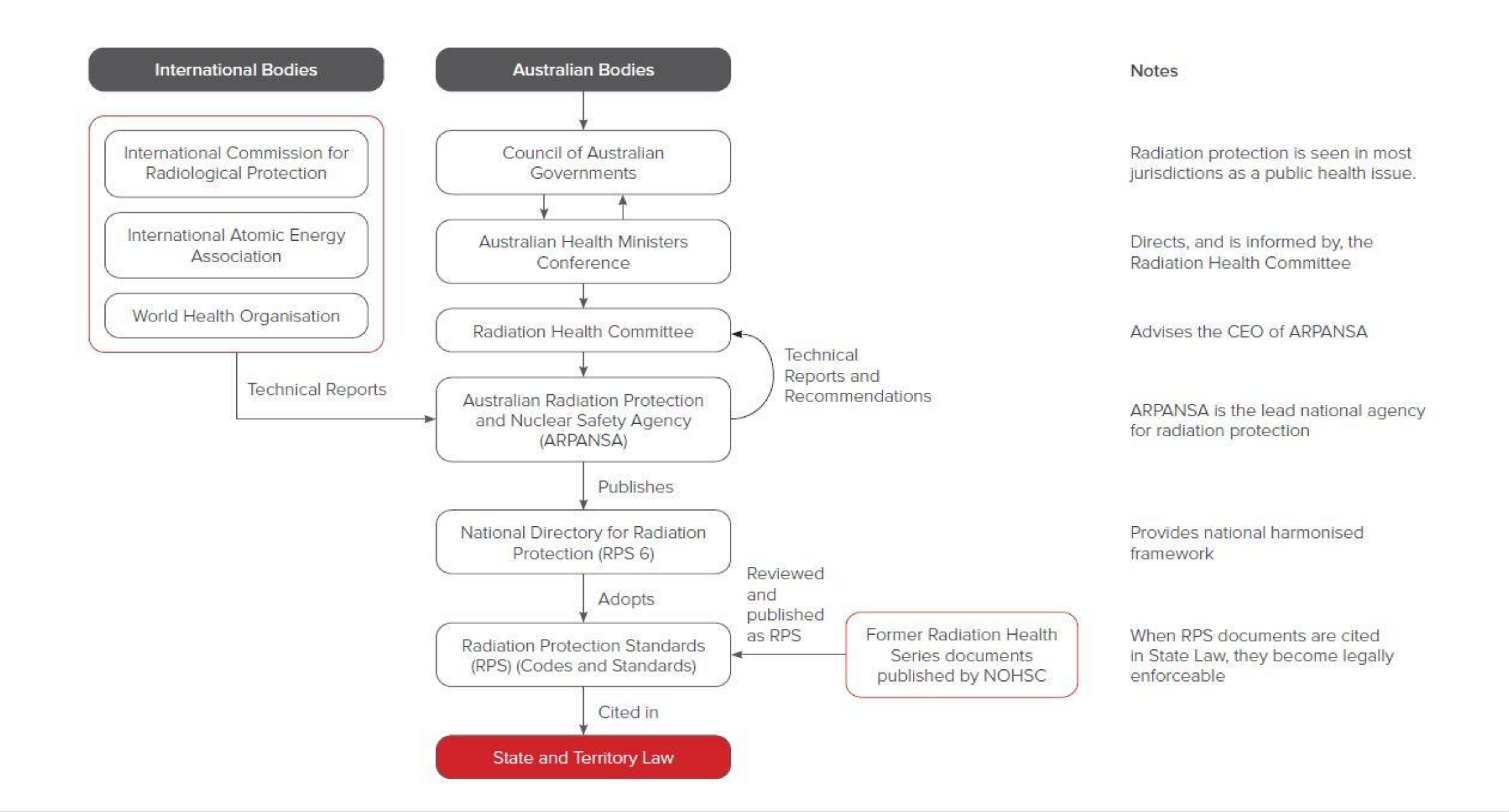
Parameter	^{232}Thorium series (Bqkg^{-1})		^{238}Uranium series (Bqkg^{-1})			Total Activity Concentration (Bqkg^{-1}) [1]
	^{228}Ac	^{228}Tl	^{234}Th	^{214}Pb	^{210}Pb	
Mean of 2 scales	2,147 (± 225)	2,682 (± 159)	<610	2,253 (± 231)	17,767 (± 3,787)	25,459 (± 3,804)
Mean of 4 top filtrates	1	3	<4 [3]	3	203 (± 106)	214 (± 106)
Scale mean + top filtrate mean	2,148 (± 225)	2,685 (± 159)	<614 [3]	2,256 (± 231)	17,970 (± 3,788)	25,673 (± 3,805)
Retention in SFD: Top Filtrate (%)	**100 ± 14.8**	**99.9 ± 8.4**	**99.3**	**99.9 ± 14.5**	**98.9 ± 29.6**	**99.2 ± 20.9**
Mean of 4 bottom filtrates	70 (± 12)	92 (± 18)	<6 [3]	79 (± 17)	3,115 (± 1,290)	3,362 (± 1,290)
Scale mean + bottom filtrate mean	2,217 (± 225)	2,774 (± 160)	<616 [3]	2,332 (± 232)	20,882 (± 4,001)	28,821 (± 4,017)
Retention in SFD: Bottom Filtrate (%)	**96.8 ± 14.1**	**96.7 ± 8.0**	**99.0**	**96.6 ± 13.8**	**85.1 ± 24.4**	**88.3 ± 18.0**
Mean of 8 filtrate samples	36 (± 12)	47 (± 18)	<5 [3]	41 (± 17)	1,537 (± 1,294)	1,666 (± 1,294)
Scale mean + filtrate mean	2,183 (± 225)	2,729 (± 160)	<615 [3]	2,294 (± 232)	19,304 (± 4,002)	27,125 (± 4,018)
Overall retention in SFD (%)	**98.4 ± 14.5**	**98.3 ± 8.2**	**99.2**	**98.2 ± 14.1**	**92.0 ± 27.4**	**93.9 ± 19.8**

The Radiation Protection Framework

IAEA General Safety Requirements: Radiation protection and safety of radiation sources (GSR3, 2014)

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

Australian Regulatory Framework



DCCEEW

Dept. of Climate Change, Energy, the Environment and Water

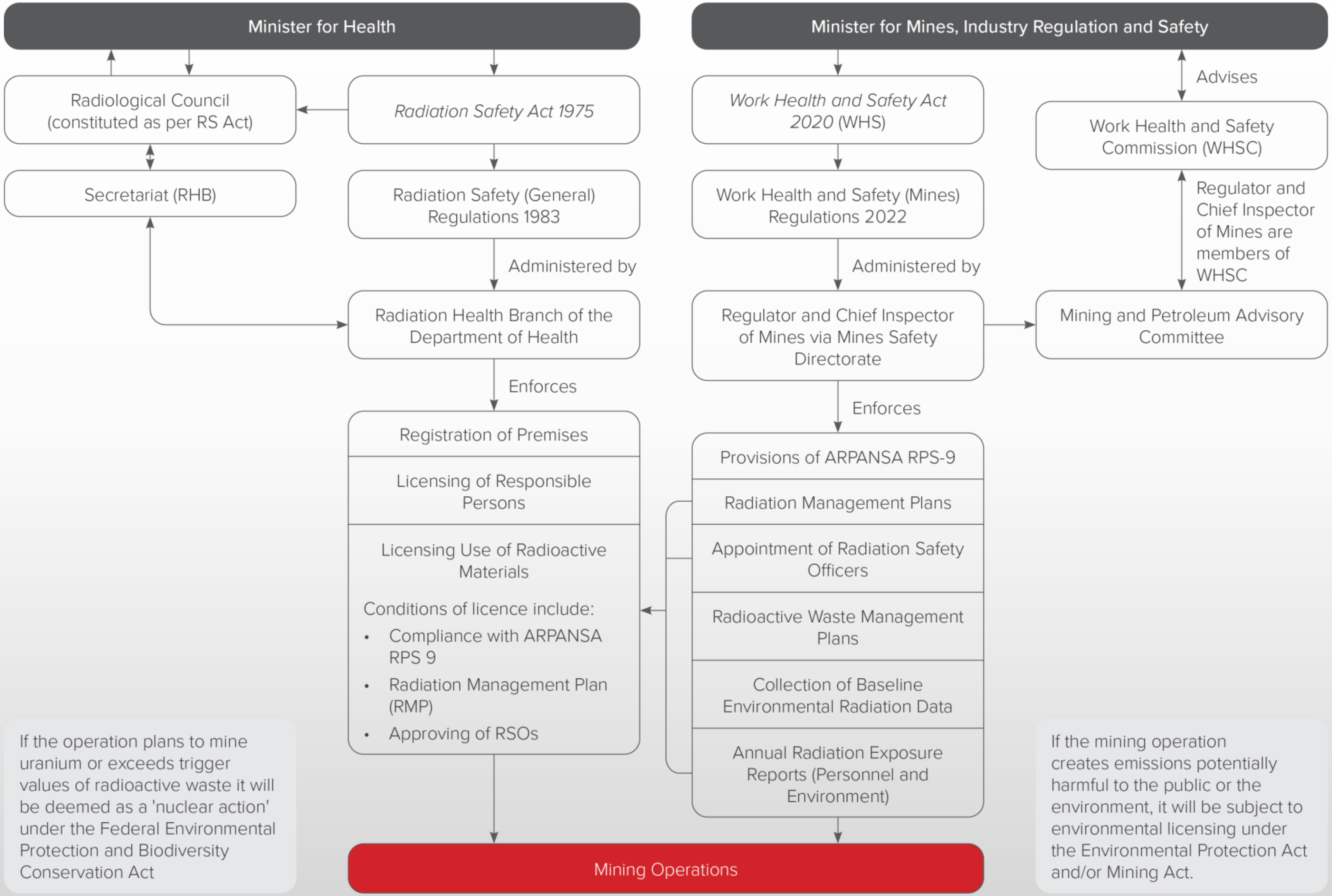
EPBC Act

Nuclear Action

ASNO

Australian Safeguards and Non-Proliferation Office

West Australian Regulatory Framework



WHS (Mines) Regulations: Overview

NORM Covered in Part 10.2, Division 3, Subdivision 3B

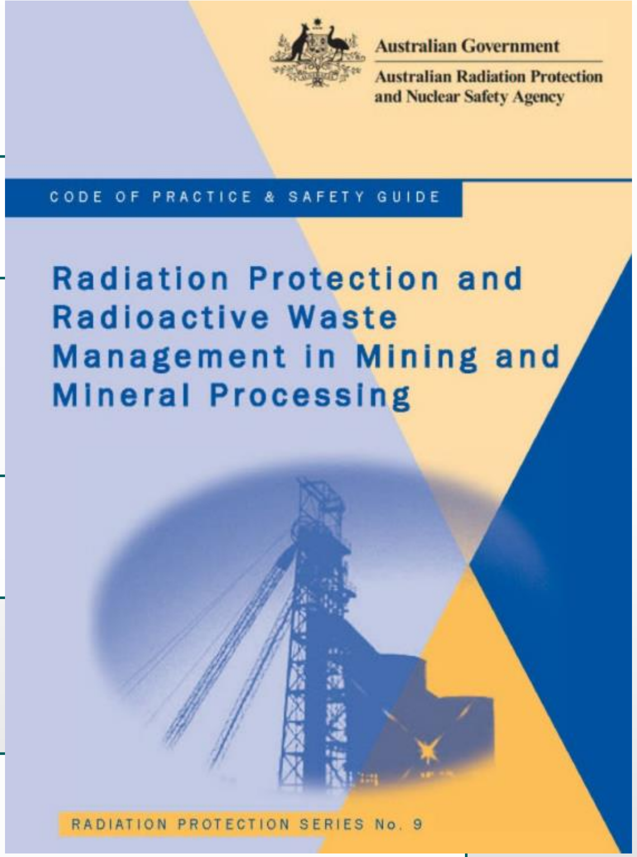
Regulations 641I to 641Y

Risk based approach to application of regulations:

Radioactivity criteria and worker (public) dose criteria

Invokes Federal ARPANSA document RPS-9

Invokes national dose limits



- Radiation Management Plan (RMP)
- Radioactive Waste Management Plan (RWMP)
- Radiation Safety Officer (NORM).

r.641K – Meaning of radioactive material

Actvity concentration >= 1 Bqg^{-1}.

Any part of the mining process, including residues and tailings streams …

All mineral sands products exceed the 1 Bqg^{-1} criteria …

Operations pursuing rare earth or pegmatite-hosted lithium minerals may exceed the 1 Bqg^{-1} criteria …

WHS (Mines) Regulations - r.641L

Risk-based approach applies to radiation protection regulations

If the 1 Bqg^{-1} is exceeded, doses to workers or public must be likely to exceed the limits in r. 641L (b)(i) or (ii) for the regulations to apply

Onus is on the mine operator to demonstrate to the regulator:

- Radioactive materials are not encountered; and
- Doses to workers are not likely to exceed 1 mSv per year; and
- Doses to the public are not likely to exceed 0.5 mSv per year.

WA’s nascent uranium industry challenge

4 approved uranium projects

1 project ~290km north east of Kalgoorlie is well advanced.

Media announcements suggest it will be shovel-ready by Q2 2024.

Regulatory agencies will be under duress once the project commences.

WA's rare earth elementchallenge

Most rare earths deposits in WA contain NORs (some very elevated)

168 WA-based, ASX-listed mining companies with REE in their portfolio

(https://stockhead.com.au/resources/bargain-barrel-10-cheap-asx-rare-earths-stocks-to-jump-into-right-now)

54* exploration operations have made announcements since 1/7/2022… meaning geologists and exploration teams are in the field now!

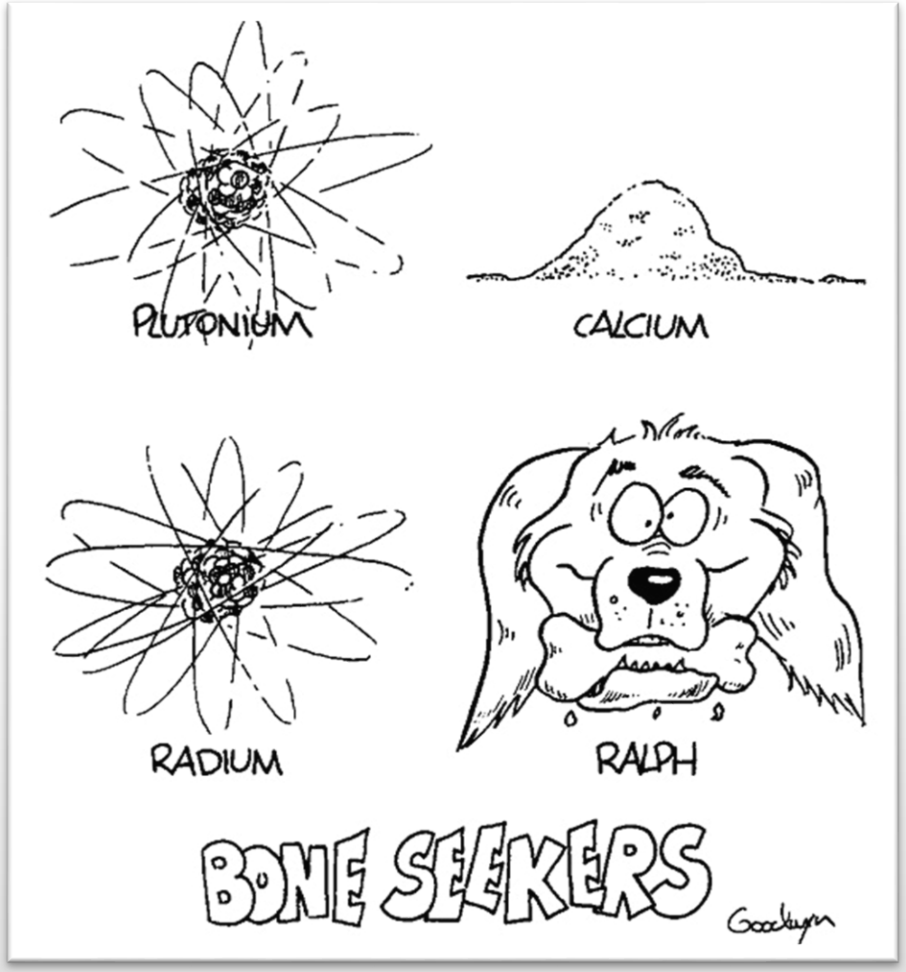
- * As at 25/11/2022

Research Thesis

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

listed on Research Online at https://ro.ecu.edu.au/theses/2642

Thank you … and Questions?



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Research Outputs: 7 peer-reviewed journal articles

1. ***Reassessment of radiation exposures of underground non-uranium mine workers in Western Australia***
   - Published in Radiation Protection Dosimetry Volume 191, Issue 3, September 2020, Pages 272–287
1. ***Impacts of revised dose coefficients for the inhalation of NORM-containing dusts encountered in the WA Mining Industry***
   - Published as a Practical Matter Article in *Journal of Radiological Protection*, Volume 40, Number 4, 1457
3. ***A review of radiation doses and associated parameters in Western Australian mining operations that process ores containing naturally occurring radionuclides for 2018–19***
   - Published as a Practical Matter Article in Journal of Radiological Protection, Volume 40, Number 4, 1476
4. ***Managing the radiation exposures of W.A. mine workers from naturally occurring radionuclides: An historical overview (Part I)***
   - Published in Radiation Protection in Australia, ISSN 1444-2752, Volume 38, Number 1, Pages 53-93
5. ***Managing the radiation exposures of W.A. mine workers from naturally occurring radionuclides: An historical overview (Part II)***
   - Published in Radiation Protection in Australia, ISSN 1444-2752, Volume 38, Number 2, Pages 4-51
6. ***A review of radiation doses and associated parameters in Western Australian mining operations (2018–20)***
   - Published as a Practical Matter Article in Journal of Radiological Protection, Volume 42, Number 1, 012501
7. ***Reducing the environmental footprint of disused radioactively contaminated steel mining equipment by geotextile filtration of residues from high-pressure water-cleaning***