Accurate prediction of radiation exposures of workers involved in the transport of NORM

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Abstract. The study of actual radiation exposures encountered by workers involved in the transport of minerals and mineral concentrates containing naturally-occurring radioactive materials has been undertaken over a four-year period, between 2008 and 2012. Hundreds of measurements were made in the process of transport of NORM between mining and processing sites in Australia (road, rail and marine transport) and in and between the ports in Australia, People's Republic of China and Japan.
The main subject of the study was thorium and uranium containing minerals and mineral concentrates (such as ilmenite, rutile, zircon, monazite and other minerals) and the study was carried out in three stages:
– The first stage involved measurements in Australia and was jointly sponsored by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), mineral sands industry and Calytrix Consulting;
– The second stage was focussed on obtaining more data from Australian and International transport routes and was jointly sponsored by the mineral sands industry and Calytrix Consulting;
– During the last stages additional monitoring was undertaken addressing materials shipped from Australia in bulk and in containers to overseas ports and was done solely by Calytrix Consulting.
It has been found that –
– The use of the 'exclusion' factor of 10 for the concentrations of radionuclides in natural materials in the IAEA Transport Safety regulations is appropriate and should be maintained;
– The dose rates from all potential pathways of exposure of workers can be accurately predicted, based on the concentrations of thorium and uranium in the transported material; and
– These dose rates remain the same irrelevant of the mode of transport – road, rail or marine.
The information presented in the paper allows, by the use of simple charts, to accurately predict potential doses to workers involved in transport of NORM. It is suggested that it can be used in any assessments of potential exposures of workers that may be required prior to the commencement of the NORM transport process – by both regulatory bodies and by the mining and mineral processing industry.

1. Introduction

This paper summarizes the results of a four-year long study of radiation exposures of workers involved in the transport of naturally occurring radioactive materials, especially in the heavy mineral sands industry. The complete results are complied in a detailed document available from the author's Internet website [1], the summary of the results of the study is presented in this paper.

It should be noted that whilst this paper builds on the Calytrix Consulting report to Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) "Radiation exposure in the transport of heavy mineral sands" published in 2008 [2], neither this paper, nor the associated report [1] can be quoted as reflecting ARPANSA's position, and results and conclusions remain the sole responsibility of the author. For ARPANSA's position the reader should refer to ARPANSA's report [2].

The subject of the study was the mineral sands industry in Australia and overseas. The transport of minerals and concentrates is a significant component of mining and production.

2. Heavy mineral sands mining and processing

The mineral sands ore after its collection is typically screened (to break it down into grains no larger than 2 mm) and carried by the system of pipes and/or conveyors to the primary concentrator.

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At the primary concentrator heavy sands are separated from other sands using a system of gravity separators ('wet magnetic' separation is also occasionally used). In most cases the primary concentrate is further processed through the series of spirals to remove tailings and excess slime. This secondary concentration process may be incorporated into the same plant, or may be carried out in a separate plant constructed to treat the primary concentrate from several mine sites.

The final Heavy Minerals Concentrate (HMC) is then transported to separation plants. After additional screening, magnetic and electrostatic methods are used in the separation of the concentrate into individual minerals. Using electrostatic separation techniques the conductors (titanium minerals ilmenite and rutile) are separated from the non-conductors (zircon and monazite). Magnetic separation is then used to separate the magnetic minerals (ilmenite and monazite) from the non-magnetic minerals (rutile and zircon). Another important industry product is synthetic rutile, which is an 'upgraded' ilmenite after thermal and chemical treatment to remove iron oxides and to produce a material with a higher percentage of titanium.

All mineral sands are considered to be naturally occurring radioactive materials (NORM), due to the presence of thorium and uranium in mineral grains. As a rule, the elements of the ^{232}Th and ^{238}U decay chains are present in the minerals in the state of secular equilibrium and the specific activity of a particular mineral can be assessed using the concentrations of parent radioisotopes only. Typical content of radionuclides in different minerals is presented in the Tables 1 and 2.

Table 1. Typical activity concentrations (industry data)

Material	Th (Bq/g)	U (Bq/g)	Sum (Bq/g)
PART 1: Materials transported between mines and on the route mine – plant – mine			
Heavy minerals concentrate (HMC)	0.5-6.0	0.3-2.5	0.8-8.5
Intermediate products and tailings returned to the mine	2.4-7.2	0.9-2.0	3.3-9.2
PART 2: Materials transported from plants to customers overseas			
Zircon	0.8-1.1	3.2-3.8	4.0-4.9
Ilmenite	0.5-1.9	0.1-0.5	0.6-2.4
Rutile	0.2-0.6	0.1-0.8	0.3-1.4
Synthetic Rutile	0.4-1.9	0.1-0.5	0.5-2.4
Additional material			
Monazite concentrate (radioactive)	82.0-143.5	9.5-20.0	91.5-163.5

Table 2. Typical activity concentrations in the materials in this study

Material	Th (Bq/g)	U (Bq/g)	Sum (Bq/g)
Heavy minerals concentrate (HMC)	1.6	0.6	2.2
Intermediate products and tailings returned to the mine	5.1	1.7	6.8
Zircon	0.9	3.0	3.9
Ilmenite and synthetic rutile	1.2	0.2	1.4
Monazite concentrate (radioactive)	84 – 94	9 – 14	~100

3. Scope of the study

In accordance with the Australian Code of Practice for the Safe Transport of Radioactive Material [3] that adopts International Atomic Energy Agency (IAEA) Transport Safety Regulations [4]:
107. The Regulations do not apply to:
(e) natural material and ores containing naturally occurring radionuclides that are either in their natural state, or have been processed only for purposes other than for the extraction of the radionuclides, and that are not intended to be processed for use of these radionuclides, provided that the activity concentration of the material does not exceed 10 times the values specified in para 401(b), or calculated in accordance with paras 402–406.

In the latest version of the IAEA International Transport Safety Regulations [5], not yet adopted in Australia, minor amendments were made for this definition:
107. The Regulations do not apply to:
(f) Natural material and ores containing naturally occurring radionuclides, which may have been processed, provided the activity concentration of the material does not exceed 10 times the values specified in Table 2, or calculated in accordance with paras 403(a) and 404–407.

Therefore, transport safety regulations do not apply to all materials listed in Tables 1 and 2 (except monazite concentrate), due to the '10-times' exclusion factor provided specifically for 'natural' materials.

Several discussions were held since the publication of the first version of the report in 2008 [2], particularly in regards to the definition of the 'transport worker'. The IAEA International Transport Safety Regulations [4, 5] state clearly, in paragraph 106:
Transport comprises all operations and conditions associated with, and involved in, the movement of radioactive material; these include the design, manufacture, maintenance and repair of packaging, and the ***preparation, consigning, loading****, carriage including* ***in-transit storage, unloading and receipt at the final destination*** *of loads of radioactive material and packages.*

It is understood that it may be difficult to establish an exact 'administrative boundary' between 'processing' and 'transport' at a particular mining or mineral processing site but, in accordance with the definition, an employee whose primary tasks are associated with loading of the material in bulk (or into bags and containers), a loader operator handling the containers at the wharf, and a person unpacking the containers at the destination all need to be considered as 'transport workers'.

To complement the data in the report to ARPANSA in 2008 [2] significant amount of supplementary monitoring data was obtained in 2009 – 2012. In 2009 and 2010 additional funding was obtained from the mineral sands industry and in 2011 and 2012 additional monitoring was undertaken by Calytrix Consulting in several locations both in Australia and overseas, without additional funding.

The main purpose of this study was to determine if the exemption of the transport of materials in heavy mineral sands industry from transport safety regulations is justified and if the exemption factor of 10 used for 'natural' materials is appropriate.

All stages of transport of concentrates, intermediate and final products in the heavy mineral sands industry were studied:
a) Transport routes and modes of transport were identified;
b) Measurements of radiation exposure levels were carried out:
   - Gamma-radiation: using gamma radiation monitors, electronic dosimeters and TLD badges,
   - Airborne dust: using personal and area dust samplers,
   - Radon (^{222}Rn) and thoron (^{220}Rn) concentrations: using portable electronic radon/thoron monitor SARAD-RTM1688-2;
c) Occupational time factors were recorded for the purpose of dose assessments.
Additionally, the relevant information was collected from the industry in 2009 – 2011.

The data for the radiation exposure has been obtained for nineteen transport routes:
- Transport of primary concentrate to a secondary concentrator, two road routes;
- Transport of heavy minerals concentrate (HMC) from mine sites to the separation plants, five road routes (including three with return of the tailings to a mine site), one rail route, one marine route; transport of tailings from the plant back to the mine site – one road route;
- Transport of final products from a separation plant to a wharf, three road routes; assessments of radiation exposures for wharf workers were also carried out;
- Transport of final products to a customer overseas, six marine routes.

Measurements were also undertaken at several Australian and overseas sites for the mineral packed in containers and the information on seven shipments of monazite concentrate is also available.

Additional information is contained in the complete text of the study [1]:

– Detailed description of monitoring data obtained for each transport route,
– Equipment and techniques used in the monitoring,
– Detailed description of dose assessment of workers involved in the transport and handling of minerals for each transport route,
– The assessments of potential exposures of the members of the general public,
– The description of the:
    - Unloading of the mineral in an overseas port,
    - System of the monitoring of surface gamma radiation levels from the trucks,
    - Possibilities of the loss of mineral through spillage during transport, and
    - Relatively high natural background levels in one of the Australian ports.

The overall summary of potential exposures of workers involved in the transport of mineral sands products is provided in Table 3 and on associated charts.

Table 3. The summary of the results of the study

Route No.	Material and mode of transport	Bq/g in the material	Highest exposure, in μSv/year	Highest exposure (nSv/hour)
1#	HMC – road	2.0	107	89
2*	HMC – road	4.1	397	331
3#	HMC – rail	4.3	229	423
4*	HMC tailings – road	8.0	276	552
5*	HMC – road	1.0	253 (driver) 210 (loader)	126 (driver) 233 (loader)
6#	HMC – road	1.5	151	151
7*	HMC – road, tails return	3.9/ ~6.0	604	549
8*	HMC – road, tails return	1.9/6.0 ~4.0	387 (driver) 426 (loader)	194 (driver) 213 (loader)
9*	HMC – road	1.6/3.0 ~2.3	227	162
10#	HMC – marine	5.4	196	490
11*	Zircon – road	4.1	69 (driver) 442 (wharf)	114 (driver) 214 (wharf)
11*	Ilmenite / synthetic rutile – road	1.8	69 (driver) 442 (wharf)	138 (driver) 228 (wharf)
12*	Zircon – road	3.8	59	98
13*	Ilmenite / synthetic rutile – road	1.0	54 (driver) 371 (wharf)	108 (driver) 279 (wharf)
14#	Zircon – marine	3.8	168	140
15#	Ilmenite / Synthetic rutile – marine	1.8	134	112
16#	Ilmenite / Synthetic rutile – marine	1.1	25	52
17*	Synthetic rutile – marine	1.2	74	62
18*	Zircon – marine	3.9	134	111
19*	Synthetic rutile – marine	1.4	86	72
Additional assessments				
A*	Zircon – containers	3.9	48 (driver) 162 (freight)	40 (driver) 135 (freight)
B*	Thorium mineral – containers	4.7	132 (driver) 221 (freight)	110 (driver) 184 (freight)
Comparative assessment for radioactive material (monazite concentrate)				
C*	Lowest exposure (ship loader)	90. 0 – 110.0	150	1250
	Average exposure		512	6887
	Highest exposure (loader in pit)		1406	12508

 # – ARPANSA data [2]

** – New and/or more accurate data available*

Figure 1. Heavy Mineral Concentrate (HMC) transport: data for road, rail and marine transport

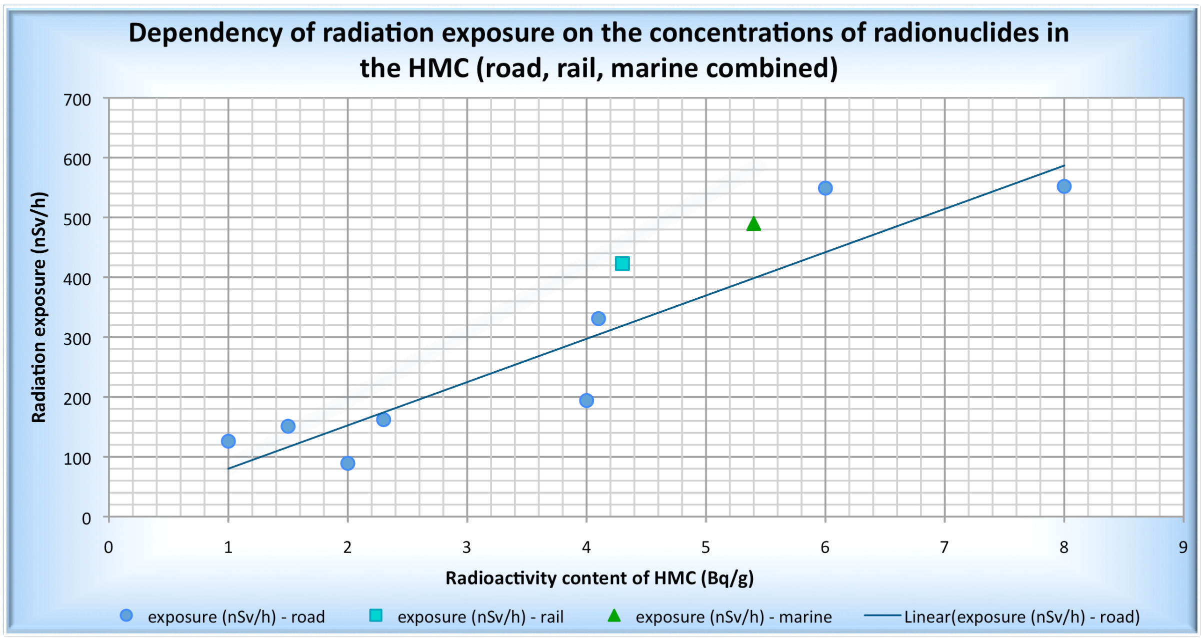
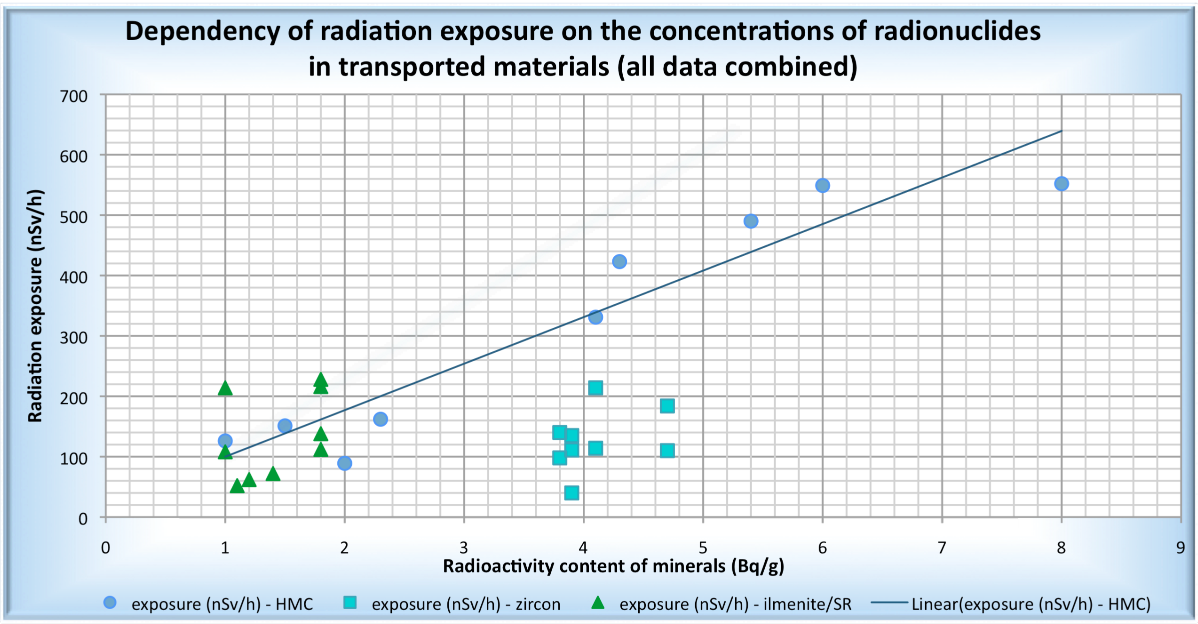


Figure 2. All monitoring data combined



The causes of the difference between ilmenite, synthetic rutile and HMC on one side and zircon on the other side are likely to be:

- Different weight ratios of Th:U in these materials and associated dose conversion factors for the exposure to airborne dust,
- In the case of transport of synthetic rutile, possible exposure of workers due to the inhalation of thoron also needs to be considered as it contributes significantly to an overall exposure level,
- Higher gamma-radiation exposure levels are expected from a 'combined' Bq/g value of HMC, ilmenite and synthetic rutile (predominantly thorium) and zircon (typically more uranium than thorium).

Figure 3. All monitoring data combined (data for monazite concentrate added)

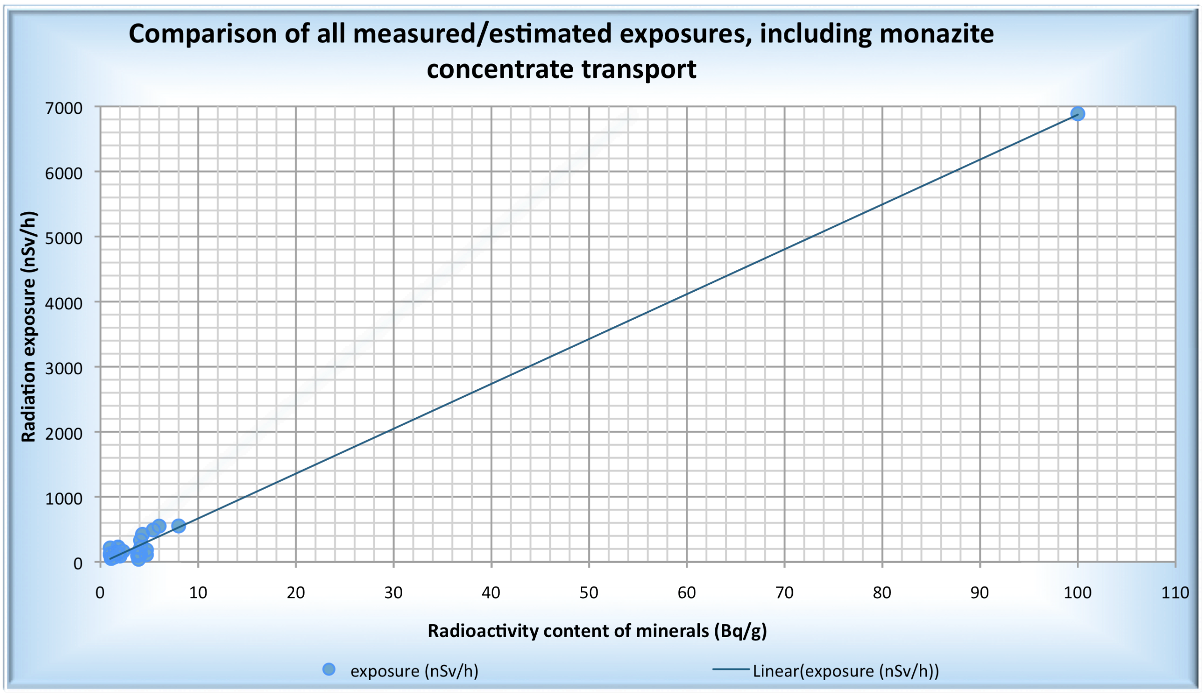
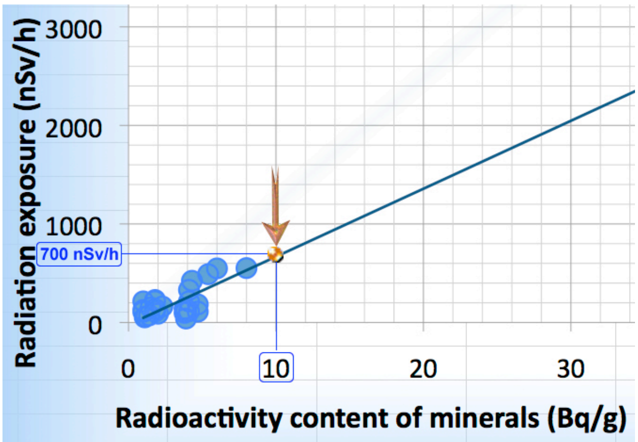


Figure 4. A 'close-up' of the region of interest of Figure 3



It is estimated that a worker typically involved in the transport of materials in the minerals industry for approximately 1200 – 1400 hours in a year. Therefore, to ensure that the overall exposure of a worker does not exceed 1 mSv/year, his/her hourly exposure rate should not be above 715 nSv/h.

After the comparison of this value with Figure 4 it is clear that the factor of 10 appears to be entirely appropriate for the transport of heavy mineral sands.

4. Conclusions

The highest annual radiation exposure of a worker involved in the transport of mineral sands in Australia is 739 μSv/year.

The transport of materials in Australian mineral sands industry does not pose a significant risk to the workers and members of the general public.

The use of the 'exclusion factor' of 10 is entirely appropriate for the heavy mineral sands industry and should be maintained, but this value cannot be increased to 15.

The radiation exposure in the case of the bulk transport of zircon is expected to be significantly lower in comparison with the exposure in cases of the transport of HMC and titanium minerals with the similar activity concentrations.

The highest 'per hour' values were registered for loader operators inside the sheds at different wharves. Due to the fact that in these situations a potential exposure to radon and thoron is more significant than the exposure to airborne dust and to the external gamma radiation, the establishment of regular monitoring programs is advisable.

A clear dependency has been established between concentrations of radionuclides in heavy mineral concentrate (HMC) and titanium minerals (ilmenite and synthetic rutile) and the typically expected exposure levels are summarised in Table 4. It is suggested that this information can be used in the prediction of potential exposures of workers that may be required prior to the commencement of the NORM transport process – by both regulatory agencies and by the mining and mineral processing industry.

Table 4. Predicted radiation exposure levels

Activity concentration (Bq/g)	Predicted radiation exposure level in nSv/hour
Ilmenite, synthetic rutile, heavy mineral concentrate with activity concentrations less than 10 Bq/g (expected variance of $\pm$*10%)*	
1	100
2	180
3	260
4	330
5	410
6	490
7	560
8	640
9	720
Typical zircon (expected variance of $\pm$*15-20%)*	
3.5	140
4.0	170
4.5	200
5.0	230
Ilmenite, synthetic rutile, heavy mineral and monazite concentrates with activity concentrations over 10 Bq/g (expected variance of $\pm$*15%)*	
10	700
20	1400
30	2100
40	2700
50	3400
60	4100
70	4800
80	5500
90	6100
100	6900

Whilst previous author's publications were concerning the issues of application of the regulations to the transport of NORM [6] and potential problems and their solutions in international transport and trade in NORM [7, 8], this paper and report [1] complement previous papers by providing data on *practical* measurements and assessment of *actual* radiation exposures in the transport of NORM.

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