












Radiation exposure in the transport of naturally occurring radioactive materials (NORM) in heavy mineral sands industry

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Australia, April 2013

Report containing supplementary data for the study conducted in 2008 for Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)

Contents

Appendices:

Previous version of the report and additional studies

The results of the monitoring undertaken in 2007 and 2008 were summarised in the previous version of the report in September 2008 [1]. A clear dependency has been established between concentrations of radionuclides in most mineral sands minerals and the typical level of radiation exposure of workers involved in the process of transport of these minerals.

It should be noted that whilst this report builds on ARPANSA's report "Radiation exposure in the transport of heavy mineral sands" published in 2008 [1], this report cannot 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 [1].

The data obtained indicated that the use of the 'exclusion factor' of 10 for the concentrations of radionuclides in natural materials in the Transport Safety Regulations is appropriate and should be maintained.

In 2009 and 2010 additional funding was obtained from the mineral sands industry and a significant amount of supplementary monitoring data was obtained. Therefore, the development of a supplementary document was considered necessary.

The following work was carried in addition to that undertaken previously:

- Monitoring of radon (^{222}Rn) and thoron (^{220}Rn) concentrations in relevant workplaces, particularly in the mineral storage areas;
- Monitoring of four marine shipments of minerals;
- Monitoring of gamma radiation levels from containers with minerals;
- Monitoring of airborne dust levels at several sites;
- Collection and collation of the additional monitoring data obtained by the mineral sands companies in 2009 – 2011.

The monitoring data was also obtained for the several shipments of monazite concentrate (specific activity concentration in order of 90-100 Bq/g), for comparison purposes.

In 2011 and 2012 additional monitoring was undertaken by Calytrix Consulting in several locations both in Australia and overseas, without supplementary funding.

The relevant sections of the original document were amended to include additional data and new parts were developed where necessary.

The instances where ARPANSA data [1] was used in the compilation of this report are clearly marked in the text of this document.

In addition, the assessments of potential exposures of the members of the general public were carried out (Appendix 1), and the final version of the report is also supplemented by:

- The description of the unloading of the mineral in an overseas port (Appendix 2),
- The description of the system of the monitoring of trucks carrying mineral sands (Appendix 3), and
- Supplementary illustrations (Appendix 4).

It is believed that the current version of the report:

- Provides comprehensive data on the possible radiation exposures of workers in the process of transport of naturally occurring radioactive materials (NORM) in the heavy mineral sands industry, and
- Allows, by the use of simple charts, to accurately predict potential doses to workers involved in transport of NORM in the heavy mineral sands and associated industries.

It is suggested that this information can be used in the 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.

Radiation exposure in the transport of heavy mineral sands

The subject of the study was the mineral sands industry in Australia and overseas. Heavy minerals (zircon, rutile, ilmenite, leucoxene, and monazite) are mined and processed in all States of Australia (except Tasmania). The transport of minerals and concentrates is a significant component of mining and production.

1. Mineral sands mining and processing

The mineral sands ore is mined by two methods:

a) Dredging – The dredge floating on a pond digs up the ore which is carried by a system of pipes to the primary concentrator.

b) Dry mining – The ore is collected from the pit using scrapers and/or excavators and placed into a hopper for screening (to break the ore down into grains no larger than 2 mm), and then carried by the system of pipes and/or conveyors to the primary concentrator.

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 as the primary one, 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 transported to separation plants. After additional screening, magnetic and electrostatic separation 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).

All mineral sands are considered to be Naturally-Occurring Radioactive Materials (NORM), due to the presence of thorium and uranium in mineral grains. Three primary products of the mineral sands industry are called 'heavy sands' due to their specific gravity:

- Rutile = 4.2 g/cm^3, typical titanium content ~60%,
- Ilmenite = 4.5 – 5.0 g/cm^3, typical titanium content ~30%
- Zircon = 4.6 – 4.7 g/cm^3, zirconium silicate

Another important product is synthetic rutile, which is essentially an 'upgraded' ilmenite after thermal and chemical treatment to remove iron oxides and to produce a material with a higher percentage of titanium. In some circumstances synthetic rutile is further processed by removing thorium and radium, resulting in a product more readily accepted on international markets due to the lower radioactivity content (about 0.5 Bq/g).

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 below.

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 routes mine→plant→mine			
Heavy minerals concentrate (HMC)	0.5-6.0	0.3-2.5	0.8-8.5
Intermediate products & 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 & 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

Scope of the study

In accordance with the Australian Code of Practice for the Safe Transport of Radioactive Material [2] that adopts International Atomic Energy Agency (IAEA) Transport Safety Regulations [3]:

> *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 International Transport Safety Regulations [4], not yet adopted in Australia, minor amendments were made to this definition – but the principle has remained unchanged:

> *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 Table 1 (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, particularly in regards to the definition of the 'transport worker'. The International Transport Safety Regulations [3, 4] 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 hard 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'.

The main purpose of this study was to determine if the exemption of the transport of naturally occurring radioactive materials (NORM) 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 mineral sands industry were studied:

a) Mine sites and processing plants were chosen in Western Australia, Victoria and New South Wales;
b) Transport routes and modes of transport were identified;
c) Measurements of radiation were carried out:
    - Gamma-radiation – using portable gamma radiation monitors and electronic dosimeters / TLD badges,
    - Airborne dust – using personal and positional dust samplers,
    - Radon and thoron concentrations – using portable electronic radon/thoron monitor SARAD-RTM1688-2,
    - The information was also collected from the companies where available;
d) Occupational time factors were recorded for the purpose of dose assessments;
e) In cases where the exposures could not be measured – they were modelled.

The data for the radiation exposure has been obtained for nineteen transport routes:

a) Transport of primary concentrate to a secondary concentrator, two routes – road;
b) Transport of heavy minerals concentrate (HMC) from mine sites to the separation plants, five routes – road (including three with return of the tailings to a mine site), one route – rail, one route – sea; transport of tailings from the plant back to the mine site – one route, road;
c) Transport of final products from a separation plant to a wharf, three routes – road; assessments of radiation exposures for wharf workers were also carried out;
d) Transport of final product to a customer overseas, six routes – sea.

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.

The study was carried for the transport of minerals at and between mining and processing sites of BeMax Resources (now Cristal Mining), Doral Mineral Sands, Iluka Resources and TiWest Joint Venture (now Tronox) in Western Australia, Victoria and New South Wales; between processing sites and wharves of Geraldton and Bunbury in Western Australia and Portland in Victoria; between ports of Adelaide and Bunbury, Portland and Xiamen (People's Republic of China), Geraldton/Bunbury and Yokkaichi (Japan), Bunbury and Hirohata (Japan), Geraldton and Osaka (Japan), Portland and Osaka (Japan).

Additional readings were taken at several processing sites and in the ports, but on the request of facility operators neither location nor the name of a company can be disclosed. In the text of the report all sites are described only as site 'A', site 'B', etc.

2. Transport of mineral sands products – monitoring results

2.1. Transport of heavy mineral concentrate (HMC) between mine sites

Two routes where a primary heavy mineral sands concentrate (HMC) is transported for further upgrade at a secondary concentrator were studied.

Route 1 – all data was collected for the report to ARPANSA [1]

HMC is transported from site A to site B, at a distance of approximately 200 km by road. The round trip takes approximately 5 hours (2.5 of which carrying HMC), two trips per shift. Driver is also loading the truck with HMC using the front-end loader permanently parked in the stockpile area, loading takes approximately 15 minutes. The typical working hours for a driver on this route would not normally exceed 1200 hours per year.

HMC from this site typically contains 1.4 Bq/g Th and 0.6 Bq/g U (the sum of 2.0 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (10 readings) = 0.07 – 0.17 μSv/h (average of 0.11 μSv/h);
- HMC stockpile area (16 readings) = 0.64 – 1.42 μSv/h (average of 0.97 μSv/h);
- Inside the cabin of the loader in the HMC stockpile area (8 readings) = 0.37 – 0.94 μSv/h (average of 0.61 μSv/h).

Eight drivers were monitored for the duration of one round trip:
Gamma radiation readings from a loaded truck in the 'low background' area (away from the HMC stockpile):

- Level inside truck cabins (12 readings) = 0.13 – 0.16 μSv/h (average of 0.14 μSv/h);
- Outside truck, 1 metre distance (20 readings) = 0.22 – 0.28 μSv/h (average of 0.25 μSv/h);
- Outside truck, 0.1 metre distance (23 readings) = 0.19 – 0.49 μSv/h (average of 0.32 μSv/h).

These eight drivers were provided with electronic dosimeters for the duration of the 5-hour round trip and the readings were between 0.4 and 0.9 μSv (the average was 0.6 μSv). One electronic dosimeter was kept in the mine office to obtain the background reading and in all cases the reading was 0.4 μSv.

Eight personal dust monitors were also provided and the results were as follows: dust concentration = 0.02 – 0.21 mg/m^3, dust activity = 0.004 – 0.012 Bq/m^3 (average of 0.007 Bq/m^3).

Route 2 – additional readings were taken in 2009-2011

HMC is transported within site B (but using a public road) at a distance of approximately 15 km to a secondary concentrating plant. The round trip takes approximately 1 hour (0.5 of which carrying HMC), 8 trips per shift. Driver is also loading the truck with HMC using the front end loader permanently parked in the stockpile area, loading takes approximately 15 minutes. Typical working hours for a driver on this route would not normally exceed 1200 hours per year.

HMC from this site typically contains 3.0 Bq/g Th and 1.1 Bq/g U (the sum of 4.1 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (20 readings) = 0.07 – 0.18 μSv/h (average of 0.12 μSv/h);
- HMC stockpile area (75 readings) = 1.03 – 3.15 μSv/h (average of 1.86 μSv/h).
- Inside the cabin of the loader in the HMC stockpile area (24 readings) = 0.63 – 1.72 μSv/h (average of 1.30 μSv/h).

Five drivers were monitored for approximately six hours:
Gamma radiation readings from a loaded truck in the 'low background' area (away from the HMC stockpile):

- Level inside truck cabins (14 readings) = 0.20 – 0.29 μSv/h (average of 0.24 μSv/h);
- Outside truck, 1 metre distance (22 readings) = 0.20 – 0.46 μSv/h (average of 0.32 μSv/h);
- Outside truck, 0.1 metre distance (25 readings) = 1.01 – 2.23 μSv/h (average of 1.58 μSv/h).

These five drivers were provided with electronic dosimeters for the duration of the 6-hour monitoring period and the readings were between 0.7 and 2.4 μSv (the average was 1.6 μSv). One electronic dosimeter was kept in the mine office to obtain the background reading and in all cases the reading was 0.5 μSv.

Five personal dust monitors were also provided and the results were as follows: dust concentration = 0.03 – 0.14 mg/m^3, dust activity = 0.006 – 0.018 Bq/m^3 (average of 0.012 Bq/m^3).

2.2. Transport of heavy mineral concentrate (HMC) from mine sites to processing plants

Seven routes where a heavy mineral sands concentrate (HMC) is transported for separation into individual minerals in a processing plant were studied.

Route 3 – all data collected for the report to ARPANSA [1]

HMC is transported from site B to site C for processing and separation into individual minerals, at a distance of approximately 150 km by rail. The round trip takes approximately 10 hours. Two people are involved – a locomotive operator who stays inside the cabin and another worker who assists mine personnel in loading of the HMC into railway carriages at site B, for approximately 4 hours. This person is typically changed at the end of the shift and another one assists plant personnel with unloading of the HMC into silos at site C, for approximately 3.5 hours. The typical working hours for these workers would not normally exceed 350 hours per year.

HMC from this site typically contains 3.1 Bq/g Th and 1.2 Bq/g U (the sum of 4.3 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (12 readings) = 0.07 – 0.16 μSv/h (average of 0.12 μSv/hr);
- HMC storage bins (36 readings, both at site B and at site C) = 0.94 – 3.08 μSv/h (average of 1.85 μSv/h).

Four workers were monitored:
Two locomotive operators were provided with electronic dosimeters for the duration of the 10-hour monitoring period and the readings were between 1.1 and 1.3 μSv (the average was 1.2 μSv). One electronic dosimeter was kept in the railway office to obtain the background reading and in both cases the reading was 0.7 μSv. The results of dust monitoring for one of these workers were: 0.11 mg/m^3 and 0.009 Bq/m^3.

The electronic dosimeter reading for the worker involved in loading of the material at site B was 3.0 μSv (background = 0.7 μSv), result of the dust monitoring was 0.44 mg/m^3 and 0.032 Bq/m^3.
The electronic dosimeter reading for the worker involved in unloading of the material at site C was 3.8 μSv (background = 0.7 μSv), result of the dust monitoring was 0.63 mg/m^3 and 0.042 Bq/m^3.

Route 4 – additional readings were taken in 2009-2011

Occasionally, the tailings from site C are returned to site B for the disposal. At the time of the study these tailings were carried by road and their approximate radioactivity content was 6 Bq/g Th and 2 Bq/g U (the sum of 8 Bq/g). The round trip takes four hours (two – carrying tailings from site C to site B, and two – carrying HMC from site B to site C). Typically, only one half of the trucks are used to transport the HMC from site B to site C, and drivers do not work more than 500 hours in a year on this route.

Five drivers were monitored for the duration of four hours (one round trip):
Four drivers were provided with electronic dosimeters for the duration of the 5-hour round trip and the readings were 1.0 and 1.7 μSv (the average was 1.4 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and in all cases the reading was 0.5 μSv.

Nine personal dust samples were obtained and the results were as follows: dust concentration = 0.07 – 0.51 mg/m^3, dust activity = 0.011 – 0.057 Bq/m^3 (average of 0.045 Bq/m^3).

Route 5 – additional readings were taken in 2009-2011

HMC is transported at site D from mine site to the processing plant, at a distance of approximately 70 km by road. The round trip takes approximately 3 hours (1.5 of which carrying HMC), three-four trips per shift. The loading of the HMC is carried out by the loader operator. The typical working hours are 2000 for a driver and 900 for a loader operator.

HMC from this site typically contains 0.7 Bq/g Th and 0.3 Bq/g U (the sum of 1.0 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (12 readings) = 0.04 – 0.11 μSv/h (average of 0.08 μSv/h);
- HMC stockpile area (15 readings) = 0.51 – 1.07 μSv/h (average of 0.74 μSv/h).

Five drivers were monitored for the duration of six hours (two round trips):
These five drivers were provided with electronic dosimeters for the duration of the 6-hour round trip and the readings were between 0.8 and 1.0 μSv (the average was 0.9 μSv). Three loader operators were also provided with electronic dosimeters for 6 hours and the readings were between 1.5 and 1.8 μSv (the average was 1.6 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and in all cases the reading was 0.5 μSv.

Fifteen personal dust monitors were also provided and the results were as follows:

- Truck drivers (nine samples): dust concentration = 0.01 – 0.22 mg/m^3, dust activity = 0.004 – 0.011 Bq/m^3 (average of 0.007 Bq/m^3);
- Loader operators (six samples): dust concentration = 0.03 – 0.37 mg/m^3, dust activity = 0.004 – 0.010 Bq/m^3 (average of 0.006 Bq/m^3).

Route 6 – all data was collected for the report to ARPANSA [1]

HMC is transported at site E from two mine sites to the processing plant, at a distance of approximately 30-40 km by road. The round trip takes approximately 1 hour (0.5 of which carrying HMC), nine-ten trips per shift. The loading of the HMC is typically carried out by the driver and sometimes – by the loader operator. The typical working hours for both driver and loader operator would not normally exceed 1000 hours per year.

HMC from one of mining sites typically contains 0.6 Bq/g Th and 0.2 Bq/g U (the sum of 0.8 Bq/g), from another – 1.6 Bq/g Th and 0.6 Bq/g U (the sum of 2.2 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (10 readings) = 0.05 – 0.10 μSv/h (average of 0.08 μSv/h);
- HMC stockpile area 1 (12 readings) = 0.24 – 0.52 μSv/h (average of 0.39 μSv/h);
- HMC stockpile area 2 (8 readings) = 0.48 – 1.45 μSv/h (average of 0.86 μSv/h);

The transport of HMC at the site E is carried out in campaigns and it was not possible to carry out the actual measurements of radiation exposure. The modelling is used in this case to assess possible radiation doses.

Route 7 – additional readings were taken in 2009-2011

HMC is transported at site F from mine site to the processing plant, at a distance of approximately 110 km by road. The round trip takes approximately 4 hours (2 of which carrying HMC), typically two trips per shift. The typical working hours for a driver would not normally exceed 1100 hours per year.

HMC from this site typically contains 2.8 Bq/g Th and 1.1 Bq/g U (the sum of 3.9 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (25 readings) = 0.07 – 0.14 μSv/h (average of 0.11 μSv/h);
- HMC stockpile area (22 readings) = 0.80 – 2.55 μSv/h (average of 1.72 μSv/h).

Some tailings are returned back from the plant to the mine site for disposal. Average radioactivity content of these tailings is 6-7 Bq/g of Th and 1-2 Bq/g of U (the sum of 8 Bq/g). It should be noted that, occasionally, the radioactivity content in tailings warrants the signposting of the trucks as carrying 'radioactive material' – as the level sometimes may exceed 10 Bq/g.

Five drivers were monitored for the duration of four hours (one round trip), carrying HMC from the mine site to the plant and returning to the mine site with no load:
These five drivers were provided with electronic dosimeters for the duration of the 4-hour round trip and the readings were between 0.6 and 1.6 μSv (the average was 1.2 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and the reading was 0.4 μSv.

Five personal dust monitors were provided and the results were as follows: dust concentration = 0.08 – 0.11 mg/m^3, dust activity = 0.006 – 0.008 Bq/m^3 (average of 0.007 Bq/m^3).

Five other drivers were also monitored for the duration of four hours (one round trip), carrying HMC from the mine site to the plant and returning to the mine site with tailings for disposal:
These five drivers were provided with electronic dosimeters for the duration of the 4-hour round trip and the readings were between 1.8 and 3.8 μSv (the average was 2.4 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and the reading was 0.4 μSv.
Five personal dust monitors were also provided and the results were as follows: dust concentration = 0.06 – 0.30 mg/m^3, dust activity = 0.003 – 0.009 Bq/m^3 (average of 0.006 Bq/m^3).

Route 8 – additional readings were taken in 2009-2011

HMC is transported at site G from mine site to the processing plant, at a distance of approximately 140 km by road. The round trip takes approximately 6-7 hours (3 of which carrying HMC), usually two trips per shift. The typical working hours for a driver would not normally exceed 2000 hours per year.

HMC from this site typically contains 1.3 Bq/g Th and 0.6 Bq/g U (the sum of 1.9 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (11 readings) = 0.05 – 0.12 μSv/h (average of 0.08 μSv/h);
- HMC stockpile area (8 readings) = 0.53 – 1.52 μSv/h (average of 1.07 μSv/h).

Some tailings are returned back from the plant to the mine site for disposal. Average radioactivity content of these tailings is 5 Bq/g of Th and 1 Bq/g of U (the sum of 6 Bq/g).

Six drivers were monitored for the duration of seven hours (one round trip), carrying HMC from the mine site to the plant and returning to the mine site with no load:
Four of these drivers were provided with electronic dosimeters for the duration of the 7-hour round trip and the readings were between 0.5 and 1.4 μSv (the average was 0.9 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and the reading was 0.5 μSv.

Six personal dust monitors were provided and the results were as follows: dust concentration = 0.06 – 0.42 mg/m^3, dust activity = 0.005 – 0.011 Bq/m^3 (average of 0.008 Bq/m^3).

Four other drivers were also monitored for the duration of seven hours (one round trip), carrying HMC from the mine site to the plant and returning to the mine site with tailings for disposal:
These four drivers were provided with electronic dosimeters for the duration of the 7-hour round trip and the readings were between 0.6 and 1.8 μSv (the average was 1.2 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and the reading was 0.5 μSv.
Four personal dust monitors were also provided and the results were as follows: dust concentration = 0.28 – 0.57 mg/m^3, dust activity = 0.004 – 0.023 Bq/m^3 (average of 0.013 Bq/m^3).

In the case of site G, the exposure of drivers and loader operators to the external gamma-radiation is currently monitored with the help of TLD badges. The company data (73 results) indicate that quarterly exposures were as follows:

a) Drivers: range between 0 and 330 μSv, average = 104 μSv (38 results);
b) Loader operators, mine site: between 0 and 390 μSv, average = 127 μSv (15 results);
c) Loader operators, plant site: between 100 and 570 μSv, average = 239 μSv (20 results).

Route 9 – additional readings were taken in 2009-2011

HMC is transported at site H from mine site to the processing plant, at a distance of approximately 160 km by road. The round trip takes approximately 5 hours (2.5 of which carrying HMC), usually two trips per shift. The typical working hours for a driver would not normally exceed 1400 hours per year.

HMC from this site typically contains 1.1 Bq/g Th and 0.5 Bq/g U (the sum of 1.6 Bq/g).

Area gamma-radiation measurements:

- Background level in the area (71 readings) = 0.05 – 0.18 μSv/h (average of 0.11 μSv/h);
- HMC stockpile area (157 readings) = 0.49 – 1.95 μSv/h (average of 1.13 μSv/h).

Some tailings are returned back from the plant to the mine site for disposal. Typical radioactivity content of these tailings is less than 1 Bq/g of Th and U, but relatively often the tailings with concentrations in order of 5-9 Bq/g are also returned to the mine site.

Due to the fact that the gamma radiation levels from the trucks carrying this type of material may be comparatively high, the company has introduced a comprehensive system of monitoring to ensure that no trucks exhibiting surface radiation levels in excess of 5 μSv/h are allowed to leave site.

Therefore, regardless of the radioactivity concentration in the mineral, all material is transported back to the mine site as 'excepted package', in accordance with paragraph 516 of the Australian Code of Practice [2]:

516. The radiation level *at any point on the external surface of an* excepted package *shall not exceed 5 μSv/h.* This system is further described in Appendix 3.

Four drivers were monitored for the duration of five hours (one round trip), carrying HMC from the mine site to the plant and returning to the mine site with no load:

These drivers were provided with electronic dosimeters for the duration of the 5-hour round trip and the readings were between 0.4 and 0.5 μSv (the average was 0.5 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading the reading was 0.4 μSv.

The company also conducts regular assessment of radiation exposure of drivers using TLD badges and the results obtained in the last monitoring year support data obtained with personal electronic dosimeters. The quarterly dose registered on the drivers' TLD badges varies between 0 and 90 μSv, being on average 23 μSv per quarter.

The company also conducts regular assessment of the exposure of drivers to the airborne dust and the results obtained (47 samples) were as follows: dust concentration = 0.04 – 1.18 mg/m^3, dust activity = 0.004 – 0.030 Bq/m^3 (average of 0.012 Bq/m^3).

Note:

In the 2008 report to ARPANSA [1] a special situation on this site was described as follows: the loading of the trucks on the mine site is carried out by specifically designated loader operators, which have other duties but typically spent most of their working day in the 'supervised radiation area' where the HMC is stored, or in its immediate vicinity. The company assesses radiation exposure of these workers using TLD badges (exposure to the airborne dust is not considered, as the material is typically moist and workers operate inside fully enclosed cabins). In 2008 the results of the monitoring of two loader operators indicated that their quarterly exposure to the external gamma *radiation varied between 0.13 and 1.04 mSv (four results), being on average 0.61 mSv/quarter. Registered annual exposures (4 results) were between 1.77 and 2.83 mSv/year, being on average 2.32 mSv/year.*

Further investigations have revealed that the main reason for the elevated readings was the fact that TLD badges were mistakenly located inside the loader on the permanent basis and, therefore, the above results cannot be considered accurate.

Route 10 – all data was collected for the report to ARPANSA [1]

HMC as an intermediate product is transported from site G to site E, firstly by rail to a port in South Australia, where it is loaded onto a ship and transported to a port in Western Australia for further processing at a separation plant.

Radiation exposure of operators loading railway carriages at site G is described above (Route 8).

HMC from this site typically contains 3.5 Bq/g Th and 1.9 Bq/g U (the sum of 5.4 Bq/g).

The shipping takes 7 days (~ 170 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.

Control TLD badge was placed in the mess room and other TLD badges were placed in different locations on the ship carrying HMC, the results were as follows:

Readings close to the mineral:

- Cargo hold 2 – 140 and 190 μSv,
- Cargo hold 3 – 150 and 160 μSv,

Average = 160 μSv.

Other areas of the ship:

- Starboard cabin, B deck – 80 μSv,
- Porthole, laundry – 70 μSv,
- Engine control room – 70 μSv,
- Engine room workshop – 100 μSv,
- Ship's office – 70 μSv,
- Galley – 70 μSv,
- Bridge, starboard – 90 and 100 μSv,
- Engineer's cabin, C deck – 80 and 100 μSv,

Average = 83 μSv (in 170 hours).

The possibility of ship's crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.

2.3. Transport of minerals from processing plants to ports

Three routes where a mineral is transported from separation plant to the wharf were studied.

Route 11 – additional readings were taken in 2009-2011

Minerals are transported from site C to the adjacent wharf.

Measurements were taken from two trucks carrying zircon (1.0 Bq/g Th and 3.1 Bq/g U) and two trucks carrying ilmenite (1.6 Bq/g Th and 0.2 Bq/g U). The return trip to the wharf takes approximately one hour (30-35 minutes with mineral). It is unlikely that any driver will be involved in this work for more than 500 hours in a year.

Four drivers were provided with electronic dosimeters for the duration of 5 hours and the readings were 0.4 and 0.6 μSv for the truck carrying ilmenite (average was 0.5 μSv) and 0.5 and 0.7 μSv for the truck carrying zircon (average was 0.6 μSv). One electronic dosimeter was kept in the plant office to obtain the background reading and the reading was 0.4 μSv.

Eighteen personal dust samples were taken and the results were as follows:

- Trucks carrying ilmenite: dust concentration = 0.06 – 0.41 mg/m^3, dust activity = 0.007 – 0.015 Bq/m^3 (average of 0.011 Bq/m^3);
- Trucks carrying zircon: dust concentration = 0.11 – 0.52 mg/m^3, dust activity = 0.009 – 0.018 Bq/m^3 (average of 0.014 Bq/m^3).

The exposure of wharf employees can be estimated using the company data and several results of personal dust and gamma-radiation monitoring obtained in the course of this study.

The surveys of gamma-radiation are regularly carried out by the company (typically twice a year) and the results are in the range 0.16 – 0.48 μSv/hour, with an average of 0.27 μSv/h (57 monitoring points). The typical background in the area is 0.15 μSv/h.

The company also conducts environmental dust monitoring at the wharf, at two locations using the high-volume dust monitor (70 m^3/hour flow rate). The results at this wharf are typically: dust concentration = 0.02 – 0.91 mg/m^3, dust activity = 0.0003 – 0.0010 Bq/m^3 (average of 0.0006 Bq/m^3).

Personal monitoring of workers involved in ship loading was undertaken at this wharf and the results were as follows:

- Ship operator – ilmenite / synthetic rutile (8 samples): dust concentration = 0.27 – 1.26 mg/m^3, dust activity = 0.009 – 0.039 Bq/m^3 (average of 0.021 Bq/m^3), personal electronic dosimeter (2 readings, 6 hours) – 0.7 and 0.7 μSv (background = 0.5 μSv);
- Ship operator – zircon (7 samples): dust concentration = 0.22 – 0.53 mg/m^3, dust activity = 0.009 – 0.024 Bq/m^3 (average of 0.017 Bq/m^3), personal electronic dosimeter (2 readings, 6 hours) – 0.8 and 1.0 μSv (background = 0.5 μSv);
- Shipping coordinator (2 samples): dust concentration = 0.11 – 0.28 mg/m^3, dust activity = 0.007 – 0.011 Bq/m^3 (average of 0.009 Bq/m^3).

The longest time spent by these workers loading the ships in 500 hours/year, further 400 hours is spent in the areas of the wharf where the material is stored prior to the loading.

Route 12 – all data was collected for the report to ARPANSA [1]

Minerals are transported from site F to the wharf located approximately 100 km from the site.

Measurements were taken from trucks carrying zircon (0.9 Bq/g Th and 2.9 Bq/g U). The return trip to the wharf takes approximately four hours (2 hours with mineral). It is unlikely that any driver will be involved in this work for more than 600 hours in a year.

The results were as follows:

- Dust concentration (4 samples) = 0.08 – 0.16 mg/m^3, dust activity = 0.005 – 0.014 Bq/m^3 (average of 0.009 Bq/m^3);
- Personal electronic dosimeters (2 readings, 4 hours) – 0.5 and 0.8 μSv, average = 0.6 μSv (background = 0.4 μSv).

Route 13 – all data was collected for the report to ARPANSA [1]

Minerals are transported from site D to the wharf located approximately 60 km from the site.

Measurements were taken from trucks carrying ilmenite and synthetic rutile (0.8 Bq/g Th and 0.2 Bq/g U, in both materials). The return trip to the wharf takes approximately two hours (1 hour with mineral). It is unlikely that any driver will be involved in this work for more than 500 hours in a year.

The results were as follows:

- Dust concentration (8 samples) = 0.14 – 1.12 mg/m^3, dust activity = 0.007 – 0.014 Bq/m^3 (average of 0.010 Bq/m^3);
- Personal electronic dosimeter (2 readings, 6 hours) – 0.5 and 0.6 μSv, average = 0.6 μSv (background = 0.5 μSv).

The surveys of gamma-radiation at the wharf are regularly carried out by the company (typically twice a year) and the results are typically in the range 0.07 – 1.26 μSv/h, with an average of 0.26 μSv/h (92 monitoring points). The typical background in the area is 0.11 μSv/h.

The company also conducts environmental dust monitoring at the wharf, at one location, using the high-volume dust monitor. The results at this wharf (22 samples) are as follows: dust concentration = 0.02 – 0.15 mg/m^3, dust activity = 0.0001 – 0.0026 Bq/m^3 (average of 0.0004 Bq/m^3). Typically, working hours of wharf employees do not exceed 1000.

2.4. Transport of minerals from ports in Australia to ports overseas

Six routes where a mineral is transported from a port in Australia to a customer port overseas were studied.

Note:
In the 2008 report to RPANSA [1] where no result was obtained for a TLD badge, it was presented as "0 μSv". It has been commented however that, in accordance with the industry practice, if a radiation monitoring result indicates a dose/concentration that is less than a minimum detection level (MDL) of the equipment used to undertake that particular measurement – the level of this MDL needs to be used in the assessment of the exposure instead of a 'zero value'.
Therefore, both for the measurements undertaken previously and for newly obtained data the lowest value for a TLD badge result was considered to be at the level of 10 μSv.

Route 14 – all data was collected for the report to ARPANSA [1]

Zircon is transported from the wharf associated with site F to the port in People's Republic of China. This zircon typically contains 0.8 Bq/g Th and 3.0 Bq/g U (the sum of 3.8 Bq/g).

The shipping takes 20 days (~ 480 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.
Control TLD badge was placed on the ship's bridge and other TLD badges were placed in different locations on the ship, the results were as follows:

Readings close to the mineral:
- Cargo hold 1 – 340 and 370 μSv,
- Cargo hold 3 – 300 and 330 μSv,

Average = 335 μSv.

Other areas of the ship:
- Captain's office, B deck – 70 μSv,
- Owner's cabin, B deck – 70 μSv,

- Boatswain’s cabin, A deck – 100 μSv,
- Ship’s office, poop deck – 80 μSv,
- Crew’s mess and smoke room, poop deck – 70 μSv,
- Officers’ mess and smoke room, poop deck – 10 μSv,
- Galley, poop deck – 70 μSv,
- Engine control room – 70 μSv,
- Forecastle store – 70 μSv,

Average = 68 μSv (in 480 hours).

The possibility of ship’s crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.

<u>Route 15 – all data was collected for the report to ARPANSA [1]</u>

Ilmenite and synthetic rutile is transported from the wharves associated with sites C and D to the port in Japan. This material typically contains 1.5 Bq/g Th and 0.3 Bq/g U (the sum of 1.8 Bq/g).

The shipping takes 21 days (~ 500 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.
Control TLD badge was placed on the ship’s bridge and other TLD badges were placed in different locations on the ship, the results were as follows:

Readings close to the mineral:

- Cargo hold 1 – 130 and 130 μSv,
- Cargo hold 3 – 140 and 160 μSv,

Average = 140 μSv.

Other areas of the ship:

- Captain’s office – 10 μSv,
- Ship’s office – 70 μSv,
- Crew’s mess room – 90 μSv,
- Officers’ mess room – 70 μSv,
- Bosun’s cabin – 70 μSv,
- Pilot’s cabin – 10 μSv,
- Forecastle store – 10 μSv,
- Galley – 80 μSv,
- Engine control room – 80 μSv,

Average = 54 μSv (in 500 hours).

The possibility of ship's crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.

Route 16 – all data was collected for the report to ARPANSA [1]

Ilmenite and synthetic rutile is transported from the wharf associated with the site E to the port in Japan. This material typically contains 1.0 Bq/g Th and 0.1 Bq/g U (the sum of 1.1 Bq/g).

The shipping takes 17 days (~ 400 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.
Control TLD badge was placed on the ship's bridge and other TLD badges were placed in different locations on the ship, the results were as follows:

Readings close to the mineral:

- Cargo hold 1 – 70 and 70 μSv,
- Cargo hold 3 – 70 and 70 μSv,
- Cargo hold 5 – 10 and 70 μSv,

Average = 60 μSv.

Other areas of the ship:

- Captain's office – 70 μSv,
- Ship's office – 10 μSv,
- Chief officer's cabin – 10 μSv,
- Galley – 10 μSv,
- Crew mess room – 10 μSv,
- Seaman's cabin – 10 μSv,
- Bosun's store – 10 μSv,
- Engine control room – 70 μSv,

Average = 25 μSv (in 400 hours).

The possibility of ship's crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.

Route 17 – new data

Synthetic rutile is transported from the wharf associated with the site C to the port in Japan. This material typically contains 0.5 Bq/g Th and 0.1 Bq/g U (the sum of 0.6 Bq/g).

The shipping takes 19 days (~ 450 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.
Control TLD badge was placed on the ship's bridge and other TLD badges were placed in different locations on the ship, the results were as follows:

Readings close to the mineral:

- Cargo hold 1 – 100 and 70 μSv,
- Cargo hold 3 – 70 and 10 μSv,

Average = 63 μSv.

Other areas of the ship:

- Captain's office – 10 μSv,
- Crew's mess – 10 μSv,
- Bosun's cabin – 10 μSv,
- Ship's office – 10 μSv,
- Galley – 70 μSv,
- Forecastle store – 10 μSv,
- Engine control room – 70 μSv,

Average = 27 μSv (in 450 hours).

The possibility of ship's crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.
A close observation of the unloading of this ship was carried out and further information is presented in Appendix 2.

Route 18 – new data

Zircon is transported from the wharf associated with site F to the port in Japan. This zircon typically contains 0.8 Bq/g Th and 3.0 Bq/g U (the sum of 3.8 Bq/g).

The shipping takes 21 days (~ 500 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.
Control TLD badge was placed on the ship's bridge and other TLD badges were placed in different locations on the ship, the results were as follows:

Readings close to the mineral:

- Cargo hold 1 – 300 and 380 μSv,

Average = 340 μSv.

Other areas of the ship:

- Bridge stairway – 70 μSv,
- Captain's cabin – 10 μSv,

- Pilot's cabin – 70 μSv,
- Chief Officer's cabin – 10 μSv,
- Ship's office – 70 μSv,
- Bosun's cabin – 10 μSv,
- Laundry – 70 μSv,
- Bosun's store – 70 μSv,
- Galley – 70 μSv,
- Mess room – 70 μSv,
- Engine control room – 70 μSv,
- Forecastle store – 70 μSv,

Average = 55 μSv (in 500 hours).

The possibility of ship's crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.

<u>Route 19 – new data</u>

Synthetic rutile is transported from the wharf associated with the site D to the port in Japan. This material typically contains 1.1 Bq/g Th and 0.1 Bq/g U (the sum of 1.2 Bq/g).

The shipping takes 19 days (~ 450 hours) and it is unlikely that the same ship with the same crew will be transporting this mineral more than twice a year.
Control TLD badge was placed on the ship's bridge and other TLD badges were placed in different locations on the ship, the results were as follows:
Readings close to the mineral:

- Cargo holds 1 & 2 – 100 and 70 μSv,

Average = 85 μSv.

Other areas of the ship:

- Captain's office – 10 μSv,
- Ship's hospital – 10 μSv,
- Chief Officer's cabin – 10 μSv,
- Engineer's deck hallway – 10 μSv,
- Seaman's cabin – 10 μSv,
- Mess room – 10 μSv,
- Galley – 70 μSv,
- Engine room store – 70 μSv,
- No.3 crane tower – 70 μSv,
- Entrance door near Hold 2 – 70 μSv,
- Forecastle store – 10 μSv,

Average = 30 μSv (in 450 hours).

The possibility of ship's crew to be exposed to airborne dust during loading, unloading and cleaning of cargo holds considered to be very remote as most of these activities are carried out by the wharf employees.

Additional data for routes 14-19 – all data was collected for the report to ARPANSA [1]

Measurements were also made in one of the overseas ports. On the request of port authority the name and location of the port is not provided.

Gamma-radiation levels at the wharf prior to the unloading of mineral: 0.06-0.10 μSv/h (12 readings), average = 0.08 μSv/h; gamma-radiation levels in the middle of unloading process: 0.34-0.64 μSv/h (8 readings), average = 0.50 μSv/h.

Four dust samples were also taken and the results were as follows:
Two positional samples on board of the ship: dust concentration = 0.44 – 0.53 mg/m^3, dust activity = 0.012 – 0.036 Bq/m^3 (average of 0.023 Bq/m^3), two positional samples on-shore: dust concentration = 0.21 – 0.25 mg/m^3, dust activity = 0.009 – 0.015 Bq/m^3 (average of 0.012 Bq/m^3).

2.5. Transport of monazite concentrate from sites to port – new data

For comparison purposes the data was also obtained for the shipments of monazite concentrate from two processing sites to a port in Western Australia. The main purpose of the establishment of exposure levels was to determine if a dependency established between specific activity of the minerals and the radiation exposure of workers is also valid for situations where much higher doses are expected, due to the fact that mineral's specific activity is in order of 100 Bq/g.

A 'monazite concentrate shipment' typically takes only 3-4 days and the following workers are involved in it:

- Front end loader operators – loading the mineral into the trucks at an interim storage location (pit or shed),
- Truck drivers – transporting the mineral from the storage site to the wharf,
- Vehicle inspectors – inspecting the vehicles before they leave site, ensuring that appropriate signs are present on the truck and that there is no mineral on the outside of the trailers (and removing it where necessary),
- Tailgaters – opening the tail gate of the truck at the wharf, closing the gate after the unloading and removing all spilled material from truck surfaces,
- Ship loader operators – monitoring the delivery of the mineral to the ship,

- Clean-up operators – removing spillages in the process of the ship loading and upon the completion of the project.

The monitoring undertaken during these projects typically consists of personal dust sampling and the assessment of exposure to gamma radiation using personal electronic dosimeters (due to the very short duration of the projects the use of TLD badges is not considered practical).

A significant volume of data has been collected and the summary is presented below:

Table 3 – Results of personal dust monitoring

Work category	No. of samples	Gross alpha activity (Bq/m^3)	
		Range	Average
Loader operators	8	0.010 – 0.154	0.031
Truck drivers	9	0.011 – 0.047	0.020
Vehicle inspectors	8	0.013 – 0.080	0.032
Tailgaters	23	0.012 – 2.130	0.195
Ship loader operators	4	0.012 – 0.019	0.016
Clean-up operators	7	0.010 – 0.044	0.019
SUMMARY	59	0.010 – 2.130	0.047

Table 4 – Results of personal gamma radiation monitoring (normalised to μSv/h)

Work category	No. of samples	Gamma exposure (μSv/h)	
		Range	Average
Loader operators (shed)	11	1.4 – 18.4	4.1
Loader operators (pit)	23	7.2 – 15.9	11.5
Truck drivers	7	0.8 – 3.7	1.5
Vehicle inspectors	9	0.8 – 4.7	2.1
Tailgaters	23	0.5 – 5.7	3.2
Ship loader operators	3	0.5 – 0.7	0.6
Clean-up operators	9	0.5 – 1.4	0.9
SUMMARY	85	0.5 – 18.4	3.1

2.6. Radon (^{222}Rn) and thoron (^{220}Rn) monitoring – new data

It is not a current practice in the mineral sands industry to sample for radon (^{222}Rn) and thoron (^{220}Rn), due to the comparatively low uranium content in mineral sands and very short half-life of thoron.

To support these assumptions, an extensive monitoring of concentrations of radon and thoron in mineral storage areas that are accessed by workers during the loading of material has been undertaken.

The sensitivity of the electronic monitor used for measurements is 10 Bq/m^3, for both radon and thoron. Therefore, this value was used in calculations if the 'zero value' was obtained in a particular measurement.

Due to the similar nature of the minerals all obtained data can be summarised in tables below:

Table 5 – Results of radon monitoring

Mineral	Site	No. of samples	Radon concentration (Bq/m^3)	
			Range	Average
HMC	B	18	10 – 34	22
	C	19	10 – 60	31
	E	7	10 – 42	24
HMC average				**25**
Synthetic rutile	C	16	47 – 128	67
	D	18	24 – 98	59
Synthetic rutile average				**63**
Zircon	C	21	10 – 72	40
	E	7	10 – 32	16
	H	24	10 – 64	18
	I	23	10 – 65	27
Zircon average				**25**
Ilmenite	C	24	10 – 16	12
	D	19	10 – 53	28
	E	8	10 – 62	22
	H	15	10 – 24	18
Ilmenite average				**18**
Monazite concentrate	B	23	10 – 64	44
	E	7	10 – 98	33
	H	14	10 – 44	15
Monazite concentrate average				**31**

Table 6 – Results of thoron monitoring

Mineral	Site	No. of samples	Thoron concentration (Bq/m^3)	
			Range	Average
HMC	B	18	10 – 112	42
	C	19	10 – 54	27
	E	7	10 – 92	36
HMC average				**35**
Synthetic rutile	C	23	101 – 1230	615
	D	25	50 – 978	391
	H	35	10 – 215	103
Synthetic rutile average				**412**
Zircon	C	21	120 – 452	234
	E	7	10 – 312	187
	H	24	149 – 755	346
	I	23	49 – 640	496
Zircon average				**316**
Ilmenite	C	24	10 – 304	96
	D	19	10 – 34	22
	E	8	10 – 45	24
	H	15	10 – 34	21
Ilmenite average				**41**
Monazite concentrate	B (open pit)	23	388 – 2323	1795
	E (shed)	7	698 – 4912	1981
	H (open storage)	14	399 – 1854	1036
Monazite concentrate average				**1604**

The general background measurements for both radon and thoron were in the range between 10 and 38 Bq/m^3 and, therefore, dose assessments are not considered necessary in situations where these concentrations in a workplace do not exceed 40 Bq/m^3.

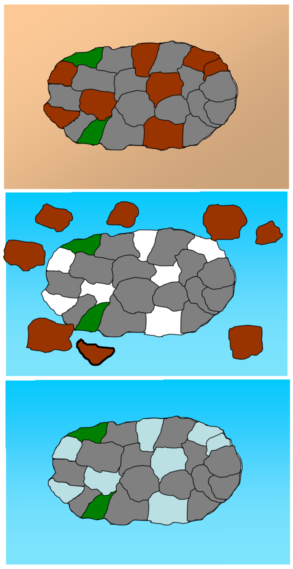
The notable increase in thoron concentrations in the areas of storage of synthetic rutile (in comparison with its ‘source mineral’ ilmenite) can be explained as follows:

Typically, grains of ilmenite contain titanium dioxide and iron in an approximate ratio of 60%:30%. In the production of synthetic rutile iron is removed from the mineral grain, resulting in the product called ‘synthetic rutile’, with the TiO_2 grade in order of 90%. The process is basically a reduction of ilmenite in a rotary kiln with coal as ‘reductant’ and the removal of iron and manganese by aeration and leaching.

Unless additional processing is carried out, the concentrations of thorium and uranium in synthetic rutile are the same as in the 'source' ilmenite.

The grains of synthetic rutile are very porous (in comparison with ilmenite) and it is suggested that this fact may be the reason for significantly increased thoron concentrations. An approximate illustration of the treatment of the mineral grain after 'roasting' in the kiln (reduced ilmenite) is given on Figure 1 below.

Figure 1 – Leaching effect on reduced ilmenite (courtesy of Iluka Resources Ltd)



1. Typical single grain of RI comprised of different particles of TiO_2, Iron and other elements in ratio 60%, 30% & 10%.
2. When exposed to NH_4Cl (process catalyst) particles of metallic iron leach out from grain and become suspended in the solution.
3. Mineral grain now comprises almost 90% TiO_2, although by now it is very porous.

2.7. Monitoring of container shipments – new data

In the course of this study it was considered impracticable to monitor the shipment of minerals in containers on the ships due to the fact that most shipments were in a form of a comparatively small amount of containers (not more than 20), which were placed on a ship carrying around 400 of such containers with different other cargo. It is expected that the potential radiation exposure of the ship's crew will be significantly less than in the case of bulk shipments.

Additional monitoring of the levels of gamma radiation from containers has been undertaken for modelling purposes.

At site I the measurements were taken from several containers containing 20 tons of zircon (3.9 Bq/g) and the results were as follows:

- Close to surface (8 measurements): 0.47 – 1.09 μSv/h, 0.81 μSv/h on average,
- At a distance of 1 m (8 measurements): 0.32 – 0.49 μSv/h, 0.38 μSv/h on average,
- At a distance of 2 m (8 measurements): 0.17 – 0.27 μSv/h, 0.22 μSv/h on average,

- Background in the area: 0.14 – 0.18 μSv/h, 0.16 μSv/h on average.

At sites J, K and L the measurements were taken from a container containing approximately 20 tons of thorium-bearing mineral (4.0 – 5.5 Bq/g, on average 4.7 Bq/g) and the results were as follows:

- Close to surface (38 measurements): 0.66 – 1.86 μSv/h, 1.11 μSv/h on average,
- At a distance of 1 m (34 measurements): 0.31 – 0.67 μSv/h, 0.50 μSv/h on average,
- At a distance of 2 m (42 measurements): 0.18 – 0.26 μSv/h, 0.22 μSv/h on average,
- At a distance of 3 m (41 measurements): 0.26 – 0.40 μSv/h, 0.31 μSv/h on average,
- At a distance of 4 m (37 measurements): 0.15 – 0.23 μSv/h, 0.18 μSv/h on average,
- At a distance of 4 m (38 measurements): 0.11 – 0.15 μSv/h, 0.18 μSv/h on average,
- Typical background in the areas: 0.09 – 0.18 μSv/h, 0.12 μSv/h on average.

It appears that despite higher costs the transport of minerals in containers is becoming more common in the mineral sands industry. One of the primary reasons for this change is the loss of mineral that occurs at all transfer points in the case of bulk shipment (which may also have radiation protection implications).

The mineral could be lost in the process of:

a) Loading of the trucks at the processing site,
b) Loading of the mineral on the ship at a port,
c) Unloading of the mineral from the ship at a destination port,
d) Loading of the trucks/barges at a destination port,
e) Unloading of the trucks/barges at a customer plant.

It is estimated that approximately 10% of the shipment may be lost in transport – several examples are presented in Appendix 4.

2.8. Note for information

It is important to note that dose assessments for port workers could be additionally complicated, as different materials are used for the construction of sea barriers in different ports. In some circumstances natural granite with elevated concentrations of natural radionuclides could be used for this purpose. The gamma dose rate from some of this granite is comparable to the gamma dose rate measured from some minerals that are being transported, and an example in presented in Appendix 4.

2.9. Equipment and techniques used in monitoring

Monitoring of potential exposure to the external gamma-radiation was carried out with the following equipment:

- Radiation Alert 'Inspector' instrument, calibrated by the Radiation Health Branch of the WA Department of Health and by Australian Radiation Services (Victoria),
- Exploranium 'Identifier' instrument, model GR-135Plus, calibrated by SAIC Exploranium (Canada) and Australian Radiation Services (Victoria),
  Where the monitoring data provided by the companies was used, it was confirmed that the monitoring is conducted with the help of appropriately calibrated equipment.
- Canary II Model 4080 portable electronic dosimeters, calibrated by the Radiation Health Branch of the WA Department of Health and by Australian Radiation Services (Victoria),
- TLD badges supplied and assessed by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Victoria.

Monitoring of potential internal exposure due to the presence of airborne dust was carried out with the following equipment:

- Aircheck2000 dust pumps, calibrated each time before use with the help of the 'Defender' calibrator, were used in accordance with Australian Standard AS 3640: 2004. Workplace atmospheres – Method for sampling and gravimetric determination of inhalable dust [5].
  Where the dust monitoring data provided by the companies was used, it was confirmed that the monitoring is conducted in accordance with the above Australian Standard and, in the case of high-volume environmental dust sampling – in accordance with Australian Standard AS 3580.9.3:2003. Methods for sampling and analysis of ambient air Method 9.3: Determination of suspended particulate matter – Total suspended particulate matter (TSP) – High volume sampler gravimetric method [6].
- Dust filters were weighted at MPL Laboratories in Perth and analysed for long-lived alpha activity using Canberra alpha spectrometers (model 7401) in the 'total alpha count' mode. The counters were calibrated weekly using ^{241}Am calibration sources calibrated by the Radiation Health Branch of the WA Department of Health.

Monitoring of potential internal exposure due to the possible presence of radon and thoron was carried out with the following equipment:

- RTM 1688-2 Radon/thoron monitor manufactured by SARAD GmbH, Germany.

It should be noted that the equilibrium factors between radon (^{222}Rn) and thoron (^{220}Rn) and their progeny are expected to be very variable, particularly in the case of thoron. The assessments of potential exposures in this report was carried out using average default equilibrium factors – the companies and/or organisations intending to undertake detailed dose assessments are encouraged to establish site- and plant-specific equilibrium factors.

3. Transport of mineral sands products – dose assessments

3.1. General comments

The assessment of the exposure to the external radiation was made on the basis of the readings obtained with the equipment described in part 2.9 above, using occupational time factors recoded at different sites. Typically, the highest possible exposure levels were assessed.

The assessment of the internal radiation exposure due to the presence of airborne dust was made using the dust monitoring data obtained with the equipment and by methods described in part 2.9 above. The dose conversion factors (mSv/Bq) that were used in dose assessments were derived from ICRP-68 [7] and ICRP-72 [8] for the default dust particle Aerial Median Aerodynamic Diameter (AMAD) of 5 μm, for different thorium and uranium weight ratios.

These factors were calculated for the Guideline NORM-5 – Radiation Dose Assessment (Department of Mines and Petroleum of Western Australia, Resources Safety, 2010) [9] and are detailed below:

Table 7 – Dose conversion factors (DCF) for the exposure to airborne dust

Sites/route	Material	Th:U weight ratio	DCF (mSv/Bq)
A→B/1	HMC	7: 1	0.0067
B/2	HMC	8:1	0.0068
B→C/3	HMC	8:1	0.0068
C→B/4	tailings	9:1	0.0069
D/5	HMC	7:1	0.0067
E/6	HMC	8:1	0.0068
F/7	HMC	8:1	0.0068
G/8	HMC	6:1	0.0065
H/9	HMC	7:1	0.0067
G→E/10	HMC	6:1	0.0065
C/11	zircon	1:1	0.0044
C/11	ilmenite	25:1	0.0075
F/12	zircon	1:1.25	0.0044
D/13	ilmenite & syn.rutile	15:1	0.0073
F/14	zircon	1:1.25	0.0044
C,D/15	ilmenite & syn.rutile	15:1	0.0073
E/16	ilmenite & syn.rutile	25:1	0.0075
C/17	synthetic rutile	15:1	0.0073
F/18	zircon	1:1.25	0.0044
D/19	synthetic rutile	15:1	0.0073

Notes:

1. No respiratory protection factors were taken into account due to the fact that it is uncommon for the workers involved in the transport of mineral sands to wear respiratory protection equipment (except during the unloading of minerals). Where it was worn, the assessment of the efficiency of a site's respiratory protection program was beyond the scope of this study.
2. It is possible that the same drivers may be exposed to radiation in situations described for routes 5 and 6 during one year (contractor company trucks are used for transport of HMC for different companies). The assessments for 2000 hours (full working year) provided for routes 5 and 8 are expected to provide a reasonable dose estimate in these circumstances.

The assessment of the internal radiation exposure due to the presence of radon and thoron was made using the monitoring data obtained using the equipment described in part 2.9 above. The dose estimation was carried out the equations given in the Guideline NORM-5 – Radiation Dose Assessment (Department of Mines and Petroleum of Western Australia, Resources Safety, 2010) [9]:

> *Potential alpha energy exposures to radon progeny and thoron progeny may be determined from the concentrations of radon and thoron gas in the air by using the following formula's derived from Table A.1 of ICRP-47 and paragraph 15 of ICRP-65:*
>
> $$P_{RnP} = 5.56 \times 10^{-6} \times t \times F_{RnP} \times C_{Rn}$$
>
> $$P_{TnP} = 7.57 \times 10^{-5} \times t \times F_{TnP} \times C_{Tn}$$
>
> *where:*
> P_{RnP} *,* P_{TnP} *are the potential alpha energy exposures to radon progeny and thoron progeny, respectively (mJh/m*^{3}*);*
> *t is the exposure time (hours);*
> F_{RnP} *is the equilibrium factor for radon progeny (typically taken as 0.4 for indoor areas and 0.2 for the outdoors);*
> F_{TnP} *is the equilibrium factor for thoron progeny (typically taken as 0.04 for indoor areas and 0.004 for the outdoors);*
> C_{Rn} *is the radon gas concentration (Bq/m*^{3}*); and*
> C_{Tn} *is the thoron gas concentration (Bq/m*^{3}*).*

Dose conversion factors in [mSv/(mJh/m^3)] are given as 1.4 for ^{222}Rn and 0.48 for ^{220}Rn in the Australian Code of Practice [10].

3.2. Transport of heavy mineral concentrate (HMC) between mine sites

Route 1

External radiation exposure:

Each shift a driver spends approximately 30 minutes in the HMC stockpile area loading the truck and 5 hours in the truck cabin carrying HMC, maximum hours per year – 1200 (100 of 12-hour shifts).

Exposure per shift: (0.61 – 0.11) μSv/h × 0.5 h + (0.14 – 0.11) μSv/h × 5 h = 0.4 μSv.
The value is confirmed by the personal electronic dosimeter (average of 0.2 μSv in 5 hours).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.4 μSv × 100 shifts = 40 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.007 Bq/m^3 × 1.2 m^3/h × 1200 h = 10.0 Bq
Using the dose conversion factor from Table 2 (0.0067 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is: 10.0 Bq × 0.0067 mSv/Bq = 67 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 107 μSv/year, and the highest hourly exposure is 89 nSv/h.

Route 2

External radiation exposure:
Each shift a driver spends approximately 2 hours in the HMC stockpile area loading the truck and 4 hours in the truck cabin carrying HMC, maximum hours per year – 1200 (100 of 12-hour shifts).
Exposure per shift: (1.30 – 0.12) μSv/h × 2 h + (0.24 – 0.12) μSv/h × 4 hr = 2.8 μSv.
The value is confirmed by the personal electronic dosimeter (average of 1.2 μSv in 6 hours).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 2.8 μSv × 100 shifts = 280 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.012 Bq/m^3 × 1.2 m^3/h × 1200 h = 17.3 Bq
Using the dose conversion factor from Table 7 (0.0068 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is: 15.8 Bq × 0.0068 mSv/Bq = 117 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 397 μSv/year, and the highest hourly exposure is 331 nSv/h.

3.3. Transport of heavy mineral concentrate (HMC) from mine sites to processing plants

Route 3

External radiation exposure was measured with electronic dosimeters:
Locomotive operator – 0.5 μSv during 10-hour shift,
Operator involved in HMC loading – 2.3 μSv during 10-hour shift,
Operator involved in HMC unloading – 3.1 μSv during 10-hour shift.
Given that the amount of hours worked per year does not exceed 350, annual exposures can be estimated as follows:
Locomotive operator – 18 μSv/year, operator involved in HMC loading – 81 μSv/year, operator involved in HMC unloading – 109 μSv/year.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
Locomotive operator – 0.009 Bq/m^3 × 1.2 m^3/h × 350 h = 3.8 Bq,
Operator involved in HMC loading – 0.032 Bq/m^3 × 1.2 m^3/h × 350 h = 13.4 Bq,
Operator involved in HMC unloading – 0.042 Bq/m^3 × 1.2 m^3/h × 350 h = 17.6 Bq.

Using the dose conversion factor from Table 7 (0.0068 mSv/Bq), the highest annual internal radiation exposures of workers on this route are:
Locomotive operator – 3.8 Bq × 0.0068 mSv/Bq = 26 μSv,
Operator involved in HMC loading – 13.4 Bq × 0.0068 mSv/Bq = 91 μSv,
Operator involved in HMC unloading – 17.6 Bq × 0.0068 mSv/Bq = 120 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of an operator on this route is 229 μSv/year, and the highest hourly exposure varies between 126 nSv/h and 654 nSv/h, being on average 423 nSv/h.

Route 4

External radiation exposure was measured with electronic dosimeters and was on average 0.9 μSv during the 5-hour sampling period (0.18 μSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.18 μSv/h × 500 h = 90 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):

0.045 Bq/m^3 × 1.2 m^3/h × 500 h = 27.0 Bq.
Using the dose conversion factor from Table 7 (0.0069 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is: 27.0 Bq × 0.0069 mSv/Bq = 186 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 276 μSv/year, and the highest hourly exposure is 552 nSv/hr.

Route 5

External radiation exposure was measured with electronic dosimeters and was on average:
0.4 μSv during the 6-hour sampling period for truck drivers (0.07 μSv/h), and
1.1 μSv during the 6-hour sampling period for loader operators (0.18 μSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.07 μSv/h × 2000 h = 140 μSv, and for the loader operator 0.18 μSv/h × 900 h = 162 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.007 Bq/m^3 × 1.2 m^3/h × 2000 h = 16.8 Bq for truck drivers, and
0.006 Bq/m^3 × 1.2 m^3/h × 900 h = 6.5 Bq for loader operators.
Using the dose conversion factor from Table 7 (0.0067 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is 16.8 Bq × 0.0067 mSv/Bq = 113 μSv, and the same for the loader operator 6.5 Bq × 0.0067 mSv/Bq = 44 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 253 μSv/year (210 μSv/year for a loader operator); and the highest hourly exposures are 126 nSv/hr for truck driver and 233 nSv/hr for loader operator.

Route 6

External radiation exposure:
The driver would typically spend approximately an hour during the shift loading the truck. It is known that the dose rate inside the loader cabin is typically 60-70% of the dose rate observed from the HMC stockpile. Therefore, the assessment is carried out on the assumption that the driver spends approximately 100 hours per year on the stockpile where he/she is exposed to gamma-radiation of 0.17 μSv/h above background and another 100 hours – on the stockpile with 0.41 μSv/h above background. Out of typical 1000 hours in

the truck, 650 are spent carrying the HMC. From measurements on other sites it can be estimated that the dose rate in the truck's cabin would be on average 0.02 – 0.03 μSv/h above background.
Therefore, exposure of these drivers would be:
0.17 μSv/h × 100 h + 0.41 μSv/h × 100 hr + 0.03 μSv/h × 650 h = 78 μSv.

Internal radiation exposure is expected to be similar to the one observed at other sites and dust activity concentrations would be in order of 0.007 – 0.009 Bq/m^3. The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.009 Bq/m^3 × 1.2 m^3/h × 1000 h = 10.8 Bq.
Using the dose conversion factor from Table 2 (0.0068 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is 10.8 Bq × 0.0068 mSv/Bq = 73 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 151 μSv/year; and the highest hourly exposure is 151 nSv/h.

Route 7

External radiation exposure was measured with electronic dosimeters and was on average:
0.8 μSv during the 4-hour sampling period for truck drivers carrying HMC to the plant and returning 'empty' to the mine site (0.20 μSv/h), and
2.0 μSv during the 4-hour sampling period for truck drivers carrying HMC to the plant and returning tailings to the mine site (0.50 μSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.20 μSv/h × 1100 h = 220 μSv and 0.50 μSv/h × 1100 h = 550 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.007 Bq/m^3 × 1.2 m^3/h × 1100 h = 9.2 Bq, and
0.006 Bq/m^3 × 1.2 m^3/h × 1100 h = 7.9 Bq.
Using the dose conversion factor from Table 2 (0.0068 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is 9.2 Bq × 0.0068 mSv/Bq = 63 μSv, and 7.9 Bq × 0.0068 mSv/Bq = 54 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 604 μSv/year (283 μSv/year for truck drivers returning 'empty' to the mine site); and the highest hourly exposures are 549 nSv/h and 257 nSv/h for trucks returning 'empty'.

Route 8

External radiation exposure was measured with electronic dosimeters and was on average:
0.4 µSv during the 7-hour sampling period for truck drivers carrying HMC to the plant and returning 'empty' to the mine site (0.06 µSv/h), and
0.7 µSv during the 7-hour sampling period for truck drivers carrying HMC to the plant and returning tailings to the mine site (0.10 µSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.06 µSv/h × 2000 h = 120 µSv and 0.10 µSv/h × 2000 h = 200 µSv.
These values are a slight overestimation of personal monitoring data that is carried out with TLD badges, which is 104 µSv/year on average. The annual exposure of loader operators at the mine site is 127 µSv, and at the plant site – 239 µSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.008 Bq/m^3 × 1.2 m^3/h × 2000 h = 19.2 Bq, and
0.012 Bq/m^3 × 1.2 m^3/h × 2000 h = 28.8 Bq (similar exposures are expected for loader operators).
Using the dose conversion factor from Table 7 (0.0065 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is 19.2 Bq × 0.0065 mSv/Bq = 125 µSv, and 28.8 Bq × 0.0065 mSv/Bq = 187 µSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 387 µSv/year (245 µSv/year for truck drivers returning 'empty' to the mine site); and for loader operators – 314 µSv/year at the mine site and 426 µSv/year – at the plant site. The highest hourly exposures for drivers are 194 nSv/h and 122 nSv/h, and 157 nSv/h and 213 nSv/h for loader operators.

Route 9

External radiation exposure was measured with electronic dosimeters and was on average:
0.1 µSv during the 5-hour sampling period (0.02 µSv/h). The data supplied by the company (TLD badges readings) confirms that the level of exposure is very low but slightly higher than the one measured – average 92 µSv/year (0.05 µSv/h). The reason for the difference could be explained by the fact that these drivers are occasionally involved in returning the tailings back to the mine site.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):

0.012 Bq/m^3 × 1.2 m^3/h × 1400 h = 20.2 Bq.
Using the dose conversion factor from Table 7 (0.0067 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is 20.2 Bq × 0.0067 mSv/Bq = 135 µSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 227 µSv/year; and the highest hourly exposure for drivers is 162 nSv/h.

Route 10

Average exposure of ship's crew is estimated at 83 µSv in 170 hours (0.49 µSv/h), and the annual amount of time carrying HMC would not exceed 400 hours. Therefore, highest possible exposure of a member of the crew of the ship carrying HMC will be 196 µSv/year; and the highest hourly exposure is 490 nSv/h (the exposure to airborne dust is considered to be unlikely in this case).
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

3.4. Transport of minerals from processing plants to ports

Route 11 – drivers

External radiation exposure was measured with electronic dosimeters and was on average:
0.1 µSv during the 5-hour sampling period for truck drivers carrying ilmenite (0.02 µSv/h), and
0.2 µSv during the 5-hour sampling period for truck drivers carrying zircon (0.04 µSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.02 µSv/h × 500 h = 10 µSv and 0.04 µSv/h × 500 h = 20 µSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.011 Bq/m^3 × 1.2 m^3/h × 500 h = 6.6 Bq (ilmenite), and
0.014 Bq/m^3 × 1.2 m^3/h × 500 h = 8.4 Bq (zircon).
Using the dose conversion factors from Table 7 (0.0075 mSv/Bq – ilmenite, 0.0044 mSv/Bq - zircon), the highest annual internal radiation exposure of a driver on this route is:
5.4 Bq × 0.0075 mSv/Bq = 49 µSv (ilmenite), and 7.2 Bq × 0.0044 mSv/Bq = 37 µSv (zircon).
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 69 μSv/year; and the highest hourly exposures for drivers are 138 nSv/h (ilmenite) and 114 nSv/h (zircon).

Route 11 – wharf operators

External radiation exposure was measured with electronic dosimeters and was on average:
0.2 μSv for the 6-hour sampling period for operator loading ship with ilmenite (0.03 μSv/h),
0.4 μSv for the 6-hour sampling period for operator loading ship with zircon (0.07 μSv/h),
The surveys of gamma-radiation in the area of this wharf indicate that the level is 0.11 μSv/h above background.
Therefore, the highest annual exposure to external gamma radiation of a wharf operator is:
0.03 μSv/h × 500 h + 0.11 μSv/h × 400 h = 59 μSv (ilmenite), and
0.07 μSv/h × 500 h + 0.11 μSv/h × 400 h = 79 μSv (zircon)

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.021 Bq/m^3 × 1.2 m^3/h × 500 h + 0.0006 Bq/m^3 × 1.2 m^3/h × 400 h = 12.9 Bq (ilmenite), and
0.017 Bq/m^3 × 1.2 m^3/h × 500 h + 0.0006 Bq/m^3 × 1.2 m^3/h × 400 h = 10.5 Bq (zircon).
Using the dose conversion factors from Table 7 (0.0075 mSv/Bq – ilmenite, 0.0044 mSv/Bq - zircon), the highest annual internal radiation exposure of a wharf operator is:
12.9 Bq × 0.0075 mSv/Bq = 96 μSv (ilmenite), and 10.5 Bq × 0.0044 mSv/Bq = 46 μSv (zircon).

The average levels of radon observed in the zircon storage sheds were 25 Bq/m^3 for radon and 316 Bq/m^3 for thoron, in ilmenite storage sheds – 18 Bq/m^3 for radon and 41 Bq/m^3 for thoron, and in synthetic rutile storage sheds – 63 Bq/m^3 for radon and 412 Bq/m^3 for thoron (background levels taken at 20 Bq/m^3 for both radon and thoron). Therefore, the dose assessment was carried out using the assumption that a worker at the wharf spends approximately the same time (~200 hours per year inside the storage sheds) handling and/or loading zircon, ilmenite and synthetic rutile.

Using the equations described in part 3.1 above, the following estimations can be made:

- Working with zircon: 3 μSv (radon) + 86 μSv (thoron) = 89 μSv,
- Working only with ilmenite: 0 μSv (radon) + 6 μSv (thoron) = 6 μSv,
- Working only with synthetic rutile: 27 μSv (radon) + 114 μSv (thoron) = 141 μSv,
- With an average for working with titanium minerals (ilmenite and synthetic rutile) of ~ 73 μSv.

Overall exposure to radon and thoron of a wharf operator is estimated at 162 μSv/year.

It is important to note that in this particular situation a potential exposure to radon and thoron is much more important than the exposure to gamma radiation and airborne dust.

Therefore, the highest possible exposure of a wharf operator is 442 μSv/year; and the highest hourly exposures are 228 nSv/h (working predominantly with ilmenite and synthetic rutile) and 214 nSv/h (working predominantly with zircon) – being on average 221 nSv/h.

Route 12

External radiation exposure was measured with electronic dosimeters and was on average:
0.2 μSv during the 4-hour sampling period for truck drivers carrying zircon (0.05 μSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.05 μSv/h × 600 h = 30 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.009 Bq/m^3 × 1.2 m^3/h × 600 h = 6.5 Bq.
Using the dose conversion factor from Table 7 (0.0044 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is:
6.5 Bq × 0.0044 mSv/Bq = 29 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 59 μSv/year; and the highest hourly exposure for drivers is 98 nSv/h.

Route 13 - drivers

External radiation exposure was measured with electronic dosimeters and was on average:
0.1 μSv during the 6-hour sampling period for truck drivers carrying zircon (0.02 μSv/h).
Therefore, the highest annual exposure to external gamma radiation of a driver on this route is in order of 0.02 μSv/h × 500 h = 10 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.010 Bq/m^3 × 1.2 m^3/h × 500 h = 6.0 Bq.
Using the dose conversion factor from Table 7 (0.0073 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is:
6.0 Bq × 0.0073 mSv/Bq = 44 μSv.
The assessment of the potential exposure due to the inhalation of radon and thoron is not considered necessary.

Therefore, the highest possible exposure of a driver on this route is 54 μSv/year; and the highest hourly exposure for drivers is 108 nSv/h.

Route 13 – wharf operators

The surveys of gamma-radiation in the area of this wharf indicate that the level is 0.13 μSv/h above background. Therefore, the highest annual *exposure to external gamma radiation* of a wharf operator is expected to be:
0.13 μSv/h × 1000 h = 130 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (breathing rate of 1.2 m^3/h):
0.0004 Bq/m^3 × 1.2 m^3/h × 1000 h = 0.5 Bq.
Using the dose conversion factor from Table 7 (0.0075 mSv/Bq – ilmenite and synthetic rutile, 0.0044 mSv/Bq - zircon), the highest annual internal radiation exposure of a wharf operator is:
0.5 Bq × 0.0075 mSv/Bq = 4 μSv (ilmenite), and 0.5 Bq × 0.0044 mSv/Bq = 2 μSv (zircon).

The mineral at this site is predominantly stored in bins prior to shipment; therefore no reasonable possibility of the exposure of workers to radon and thoron exists, except for the time when the workers are required to enter the conveyor tunnels and several storage sheds. The length of this exposure is not expected to exceed 160 hours per year inside the tunnels and 200 hours inside the sheds.

Using the assumption that half of the working time is spent in the vicinity of synthetic rutile (currently only synthetic rutile is produced at the site D) and another half – in the vicinity of zircon, using typical radon and thoron concentrations measured for route 11, and applying equations described in part 3.1 above, the following estimations can be made:

- Working with zircon: 4 μSv (radon) + 86 μSv (thoron) = 90 μSv,
- Working with synthetic rutile: 31 μSv (radon) + 114 μSv (thoron) = 145 μSv.

Overall exposure to radon and thoron of a wharf operator is estimated at 235 μSv/year.

As in the case of the route 11 above, it is important to note that, despite the fact that this dose is relatively low, it is clear that in this particular situation a potential exposure to radon and thoron is more important than the exposure to airborne dust and exposure to gamma radiation.

Therefore, the highest possible exposure of a wharf operator is 371 μSv/year; and the highest hourly exposures are 279 nSv/h (ilmenite) and 222 nSv/h (zircon), 250 nSv/h on average.

3.5. Transport of minerals from ports in Australia to ports overseas

Route 14

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 68 μSv in 480 hours (0.14 μSv/h), the annual amount of time carrying zircon would not exceed 1200 hours. Therefore, highest possible exposure of a member of the crew of the ship carrying HMC will be 168 μSv/year; and the highest hourly exposure is 140 nSv/h.

Whilst the members of the crew can be exposed to the airborne dust during loading and unloading of the ship, no visible dust was observed in this case and the exposure to airborne dust is considered to be unlikely. The First Mate was present during the opening of ship's holds prior to the unloading of the mineral but due to the time he spent in this area (approximately 15 minutes), his exposure to both airborne dust and radon/thoron is unlikely to be measurable.

Route 15

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 54 μSv in 500 hours (0.11 μSv/h), the annual amount of time carrying ilmenite and/or synthetic rutile would not exceed 1200 hours.
The highest annual exposure of the member of the crew of this ship is:
0.11 μSv/h × 1200 h = 132 μSv.

Internal radiation exposure can to be assessed, as during unloading of the ship several members of the crew were exposed to the airborne dust, for approximately 3 hours.
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h and assuming average dust activity concentration of 0.023 Bq/m^3 on board of the ship, and three unloading operations per year):
0.023 Bq/m^3 × 1.2 m^3/h × 9 h = 0.2 Bq.

Using the dose conversion factor from Table 7 (0.0073 mSv/Bq), the highest annual internal radiation exposure of a crew member on this route is:
0.2 Bq × 0.0073 mSv/Bq = 2 μSv.
Due to the very short-term exposure time the possible doses due to radon and thoron were not assessed.

Therefore, the highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be 134 μSv/year; and the highest hourly exposure is 112 nSv/h.

Route 16

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 25 μSv in 400 hours (0.06 μSv/h), the annual amount of time carrying ilmenite and/or synthetic rutile would not exceed 1200 hours.
The highest annual exposure of the member of the crew of this ship is:
0.06 μSv/h × 1200 h = 72 μSv.

Internal radiation exposure can be assessed, as during unloading of the ship several members of the crew were exposed to the airborne dust, for approximately 3 hours:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h and assuming average dust activity concentration of 0.023 Bq/m^3 on board of the ship, and three unloading operations per year):
0.023 Bq/m^3 × 1.2 m^3/h × 9 h = 0.2 Bq.
Using the dose conversion factor from Table 7 (0.0075 mSv/Bq), the highest annual internal radiation exposure is:
0.2 Bq × 0.0075 mSv/Bq = 2 μSv.
Due to the very short-term exposure time the possible doses due to radon and thoron were not assessed.

Therefore, highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be 74 μSv/year; and the highest hourly exposure is 62 nSv/h.

The exposure of workers carrying out the unloading of the ship can also be assessed. In an overseas port two loader operators work approximately 8 hours in the area where the mineral is unloaded from the ship. Gamma-radiation level is typically 0.42 μSv/hr above background, and in the worst case they are exposed to the airborne dust with concentration of 0.012 Bq/m^3. In the worst case these workers would be involved in unloading of six ships with mineral per year and, therefore, their annual exposure can be estimated as follows:

External radiation exposure:
0.42 μSv/hr × 8 hr × 6 = 20 μSv

Internal radiation exposure: the intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h and assuming six unloading operations per year):
0.012 Bq/m^3 × 1.2 m^3/h × 48 h = 0.7 Bq.
Using the dose conversion factor from Table 7 (0.0075 mSv/Bq), the highest annual internal radiation exposure is:
0.7 Bq × 0.0075 mSv/Bq = 5 μSv.

Due to the very short-term exposure time the possible doses due to radon and thoron were not assessed.

Therefore, highest possible exposure of a worker at the wharf unloading ilmenite and/or synthetic rutile will be 25 μSv/year; and the highest hourly exposure is 52 nSv/hr.

Route 17

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 27 μSv in 450 hours (0.06 μSv/h), the annual amount of time carrying synthetic rutile would not exceed 1200 hours.

The highest annual exposure of the member of the crew of this ship is:

$0.06\ \mu Sv/h \times 1200\ h = 72\ \mu Sv$.

Internal radiation exposure can be assessed, as during unloading of the ship several members of the crew were exposed to the airborne dust, for approximately 3 hours:

The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h and assuming average dust activity concentration of 0.023 Bq/m^3 on board of the ship, and three unloading operations per year):

$0.023\ Bq/m^3 \times 1.2\ m^3/h \times 9\ h = 0.2\ Bq$.

Using the dose conversion factor from Table 7 (0.0073 mSv/Bq), the highest annual internal radiation exposure is:

$0.2\ Bq \times 0.0073\ mSv/Bq = 2\ \mu Sv$.

Due to the very short-term exposure time the possible doses due to radon and thoron were not assessed.

Therefore, highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be 74 μSv/year; and the highest hourly exposure is 62 nSv/h.

Additional details on this shipment are provided in Appendix 2.

Route 18

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 55 μSv in 500 hours (0.11 μSv/h), the annual amount of time carrying zircon would not exceed 1200 hours.

The highest annual exposure of the member of the crew of this ship is:

$0.11\ \mu Sv/h \times 1200\ h = 132\ \mu Sv$.

Internal radiation exposure can be assessed, as during unloading of the ship several members of the crew were exposed to the airborne dust, for approximately 3 hours:

The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h and assuming three unloading operations per year):
$0.050\ Bq/m^3 \times 1.2\ m^3/h \times 9\ h = 0.5\ Bq$ ($0.050\ Bq/m^3$ is the highest dust activity concentration typically observed in zircon milling plants).
Using the dose conversion factor from Table 7 (0.0044 mSv/Bq), the highest annual internal radiation exposure is:
$0.5\ Bq \times 0.0044\ mSv/Bq = 2\ \mu Sv$.
Due to the very short-term exposure time the possible doses due to radon and thoron were not assessed.

Therefore, highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be 134 μSv/year; and the highest hourly exposure is 111 nSv/h.

Route 19

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 30 μSv in 450 hours (0.07 μSv/h), the annual amount of time carrying synthetic rutile would not exceed 1200 hours.
The highest annual exposure of the member of the crew of this ship is:
$0.07\ \mu Sv/h \times 1200\ h = 84\ \mu Sv$.

Internal radiation exposure can be assessed, as during unloading of the ship several members of the crew were exposed to the airborne dust, for approximately 3 hours:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h and assuming average dust activity concentration of $0.023\ Bq/m^3$ on board of the ship, and three unloading operations per year):
$0.023\ Bq/m^3 \times 1.2\ m^3/h \times 9\ h = 0.2\ Bq$.
Using the dose conversion factor from Table 7 (0.0073 mSv/Bq), the highest annual internal radiation exposure is:
$0.2\ Bq \times 0.0073\ mSv/Bq = 2\ \mu Sv$.
Due to the very short-term exposure time the possible doses due to radon and thoron were not assessed.

Therefore, highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be 86 μSv/year; and the highest hourly exposure is 72 nSv/h.

3.6. Transport of monazite concentrate from sites to ports

This assessment was made for comparison purposes. The shipments of monazite concentrate are relatively infrequent and volumes of mineral being shipped at any one time are relatively low, in order of 15 – 20,000 tons. Therefore, the maximum possible time in a year a worker can be employed for the transport of monazite concentrate is estimated to be in order of ten days: three separate shipments – 3 days each (working 12-hour shifts) and one 'extra' day.

Using the data from Table 4 in part 2.5, the annual doses for these workers can be estimated, assuming the time of exposure of 120 hours per year.

External radiation exposure:

- Loader operators (in a shed) – 492 μSv,
- Loader operators (in a pit) – 1380 μSv,
- Truck drivers – 180 μSv,
- Vehicle inspectors – 252 μSv,
- Tailgaters – 384 μSv,
- Ship loader operators – 72 μSv,
- Clean-up operators – 108 μSv.

Internal radiation exposure (dust inhalation):
The dose conversion factor for the typical Th:U=20:1 weight ratio is 0.0074 mSv/Bq for the default particle size of 5 μm. Therefore, this exposure can be estimated using the data from Table 3 in part 2.5, as follows:

- Loader operators (both in a shed and in a pit) – 3 μSv,
- Truck drivers – 2 μSv,
- Vehicle inspectors – 3 μSv,
- Tailgaters – 21 μSv,
- Ship loader operators – 2 μSv,
- Clean-up operators – 2 μSv.

Internal radiation exposure (thoron):
Levels of radon (^{222}Rn) measured in the monazite concentrate storage areas (Table 5) are considered to be too low to warrant a specific dose assessment.
However, relatively high concentrations of thoron (^{220}Rn) were measured in these areas (Table 6), on average above background 1355 Bq/m^3 in open-air storage, and 1961 Bq/m^3 – in the sheds.

Using the equation from part 3.1, for the period of 120 hours in a year the doses can be estimated as follows:

- Loader operators (in a shed) – 338 μSv,
- Loader operators (in a pit) – 23 μSv,
- Truck drivers (40 hours in a pit + 40 hours in a shed) – 121 μSv,
- Vehicle inspectors (open-air) – 23 μSv,
- Tailgaters (open-air) – 23 μSv,
- Ship loader operators (100 h in open-air, 20 h inside) – 76 μSv,
- Clean-up operators (100 h in open-air, 20 h inside) – 76 μSv.

Therefore, annual radiation exposure of workers involved in the shipment of monazite concentrate varies between 150 μSv (ship loader operators) to 1406 μSv (loader operators in a pit). The average exposure of workers is estimated at 512 μSv/year, with hourly exposure of 6887 nSv/h.

3.7. Transport of minerals in containers

It was considered impracticable to undertake actual measurements on ships carrying containers with minerals, due to the fact that containers are placed on the ship randomly and therefore the tests were carried out on two types of containers – with zircon (3.9 Bq/g) and thorium-bearing minerals (4.0 – 5.5 Bq/g, 4.7 Bq/g on average).

In addition to the actual measurements, the following equation could also be used to estimate a possible gamma-radiation exposure from containers:

$$\text{Dose Rate}_{(d)} = \text{Dose Rate}_{(surface)} \times [1 - d/(d^2 + A \times B/3.14)^{0.5}]$$, where:

d – distance to the source, A and B – dimensions of the source (A – height, B – width).

An estimation of potential exposure of *truck drivers*:

Given that the measured average surface radiation level from the containers (1.09 μSv/h for zircon and 1.46 μSv/h for thorium ore), and the 'source profile' of 3×3 meters, the maximum dose rates at a distance of 2 metres (in the cabin of the truck) can be estimated at 0.26 and 0.36 µSv/h (not taking into account any shielding by the cabin of the truck and another equipment located between the cabin and containers).

It would be reasonably conservative to assume that, taking possible shielding factors into consideration, the dose rate in the truck cabin would be approximately $^{2}/_{3}$ of the calculated value (0.17 and 0.24 µSv/h above natural background.
A reasonable value of natural background gamma radiation on bitumen roads (~ 0.13 μSv/h) is also taken into account.

Therefore, assuming 1200 working hours in a year, the dose for the drivers would be 48 μSv (40 nSv/h) and 132 μSv (110 nSv/h).

An estimation of potential exposure of *freight depot workers* and *port workers*:
Typically the containers are stored in '2-up' or '3-up' configurations and it is very unlikely that more than 30 containers are located in a storage depot or at a wharf at any time.

Given that the measured highest surface radiation level from the containers (1.09 μSv/h for zircon and 1.46 μSv/h for thorium ore), and the maximum 'source profile' of 21×6 meters the maximum dose rates at a distance of 1 metre can be estimated at 0.92 and 1.23 μSv/h, and at a distance of 5 meters – at 0.41 and 0.55 μSv/h above natural background.

For the handling of single container at a port the 'source profile' size would be 7×2 meters and maximum dose rates are expected to be in order of natural background (~ 0.10 μSv/h) at a normal operating distance of 3-4 meters.

Freight depot workers receive containers and prepare them for delivery to the port. It is assumed that such worker is located within 1 meter of the containers for 100 hours/year, and a distance of 5 meters – 200 hours/year, and additional 900 hours in general vicinity of the containers where dose rate may be higher than the natural background by only 0.01-0.02 μSv/h.
Zircon: 0.82 μSv/h × 100 h + 0.31 μSv/h × 200 h + 0.02 μSv/h × 900 h = 162 μSv (135 nSv/h).
Ore: 1.13 μSv/h × 100 h + 0.45 μSv/h × 200 h + 0.02 μSv/h × 900 h = 221 μSv (184 nSv/h).

Handling and loading of containers in a port is unlikely to result in any measurable radiation exposure of *port workers*, as both measurements on sites and the theoretical calculations confirm that the gamma radiation levels will be at a natural background level at the distances where these workers are located.

Container handling has been observed in three Australian and two overseas ports and it is very unlikely that any worker spends enough time in a close vicinity of a container with mineral that will allow for personal monitoring to be undertaken, particularly in one overseas port where container handling is fully automated.

3.8. Exposures during emergency situations (transport accidents and spillages)

In the case of a transport accident it is not believed likely that any worker will be involved in the clean-up operation for more than 12 hours and his/her possible exposure to external radiation can be estimated.

The data used in the calculations below represents a worst-case scenario of a spillage of HMC (heavy mineral concentrate) with gamma-radiation levels above 5 μSv/hour (40% higher then the highest level observed in the study) and dust concentrations 2 times higher than the highest level observed in the study.

5.10 μSv/h [the highest level that was measured from the HMC] minus 0.10 μSv/h [average natural background value].
The result (5.0 μSv/h) is multiplied by 12 hours = 60 μSv.

When similar calculations are performed for the typical concentrates and products transported in the mineral sands industry the values of this exposure would be:
HMC (typical) – between 5 and 18 μSv, with an average of 12 μSv;
Zircon – between 5 and 13 μSv, with an average of 9 μSv;
Ilmenite and/or synthetic rutile – between 3 and 8 μSv, with an average of 6 μSv;
Monazite concentrate (radioactive) – between 300 and 612 μSv, with an average of 456 μSv.

It is not believed that the internal radiation exposure to the HMC or other mineral sands dust will be a significant exposure factor, as the recommendations are always to dampen the material with water prior to cleaning and wear appropriate respiratory protection. However, in a worst-case scenario when these protective measures are not taken, a potential internal radiation exposure of a worker involved in the clean up may be conservatively estimated as follows:

Time of exposure: 12 hours, Dust concentration: 3 mg/m^3 [2 times higher than the highest level observed in the study],
Dust particle size: 3 μm [conservative value, in comparison with default 5 μm],
Specific activity of the concentrate dust: 8 Bq/g (7 Bq/g Th and 1 Bq/g U).

The intake of the radioactivity is calculated as follows:
12 hours [time of the exposure]
multiplied by:
1.8 m^3/h [breathing rate of a worker, normally it is assumed to be 1.2 m^3/h, bit it is typically higher in emergency situations]
multiplied by:
0.008 Bq/mg [specific activity of the dust]
multiplied by:
3 mg/m^3 [adjustment factor for the dust concentration]
= 0.52 Bq.

The value is multiplied by an appropriate dose conversion factor: 0.078 mSv/Bq (Th:U weight ratio of 7:1, particle size = 3 μm), and the result is = 4 μSv.

When similar calculations are performed for the typical concentrates and products transported in the mineral sands industry and using the default particle size value of 5 μm, the values of this exposure would be:

HMC – between 0 and 2 μSv, with an average of 1 μSv;
Zircon – between 1 and 2 μSv, with an average of 1 μSv;
Ilmenite and/or synthetic rutile – between 0 and 1 μSv, with an average of 1 μSv;
Monazite concentrate (radioactive) – between 44 and 51 μSv, with an average of 48 μSv.

The total radiation exposure of the worker involved in the clean up of an accidental spillage of the concentrate would be 13 μSv, zircon – 10 μSv, ilmenite and/or synthetic rutile – 7 μSv.

Additional attention must be paid to the clean up of spillages of monazite concentrate, as the typical 12-hour radiation exposure would be in order of 550 μSv (also taking into account a relatively small contribution from the inhalation of thoron).

3.9. Summary

The general summary of potential exposures of workers involved in the transport of mineral sands products is provided in the following table and on associated charts.

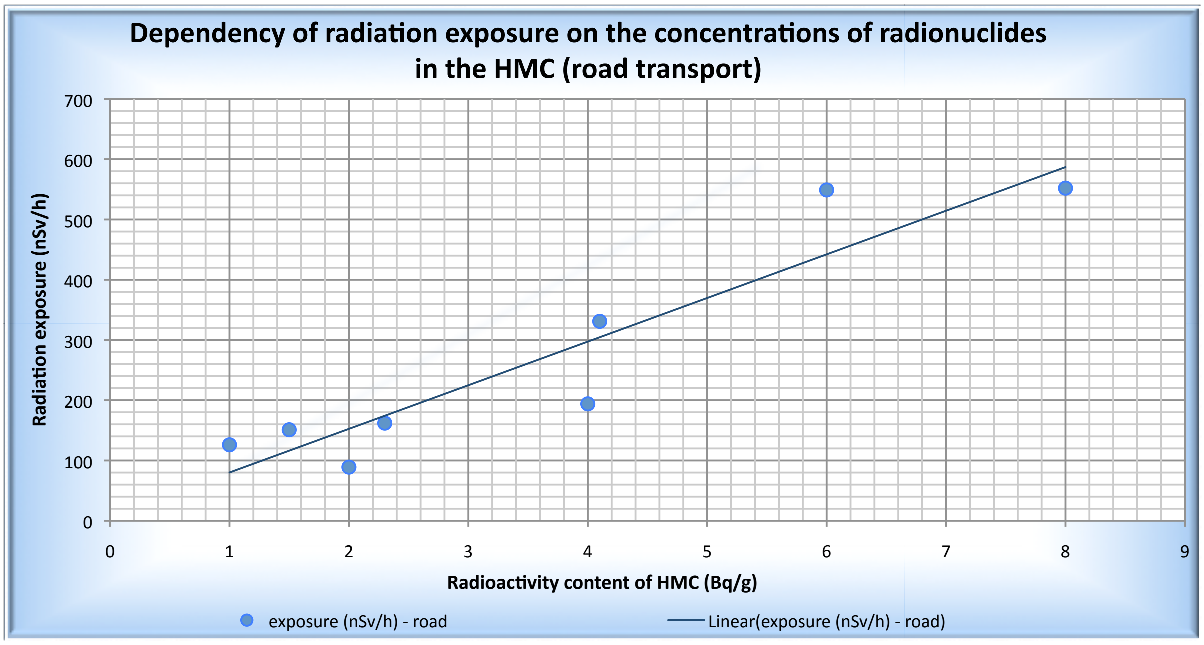
Table 8 – Summary of the results of the study

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)	126 (driver)
			210 (loader)	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)	194 (driver)
			426 (loader)	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)	114 (driver)
			442 (wharf)	214 (wharf)
11*	Ilmenite / synthetic rutile – road	1.8	69 (driver)	138 (driver)
			442 (wharf)	228 (wharf)
12*	Zircon – road	3.8	59	98
13*	Ilmenite / synthetic rutile – road	1.0	54 (driver)	108 (driver)
			371 (wharf)	279 (wharf)
14#	Zircon – marine	3.8	168	140
15#	Ilmenite / Synthetic rutile – sea	1.8	134	112
16#	Ilmenite / Synthetic rutile – sea	1.1	25	52
17*	Synthetic rutile – sea	1.2	74	62
18*	Zircon – sea	3.9	134	111
19*	Synthetic rutile – sea	1.4	86	72
Additional assessments				
A	Zircon – containers	3.9	48 (driver)	40 (driver)
			162 (freight)	135 (freight)
B	Thorium mineral – containers	4.7	132 (driver)	110 (driver)
			221 (freight)	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

** – New and/or more accurate data available in the current version of the report, in comparison with the 2008 report to ARPANSA [1]*

 # - ARPANSA data [1]

Chart 1 – HMC road transport



It appears that when two values obtained for the HMC rail and marine transport are added to this chart, they are following the same dependency, as detailed on charts 2 and 3 below.

Chart 2 – HMC transport, with data for rail and marine transport added

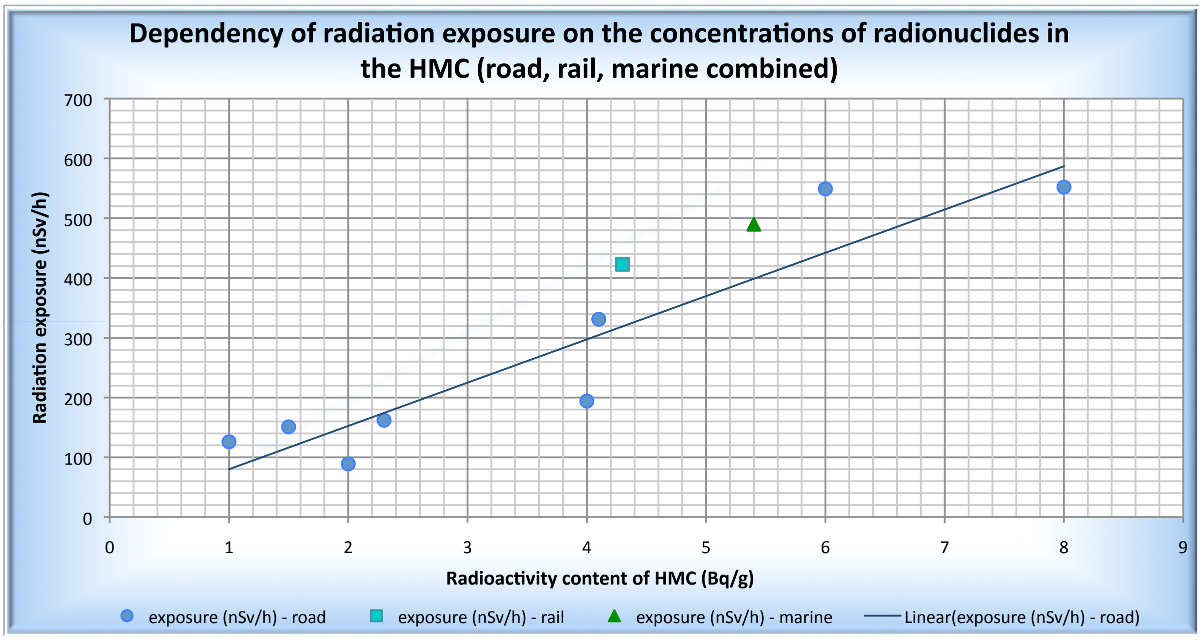
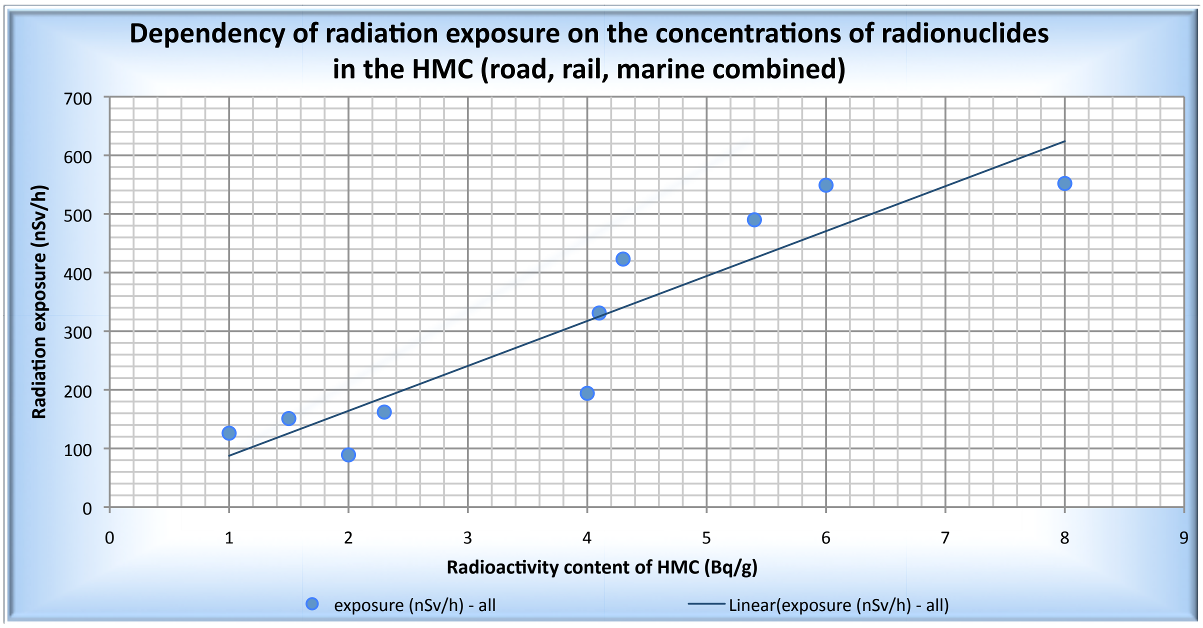


Chart 3 – HMC Transport – combined data

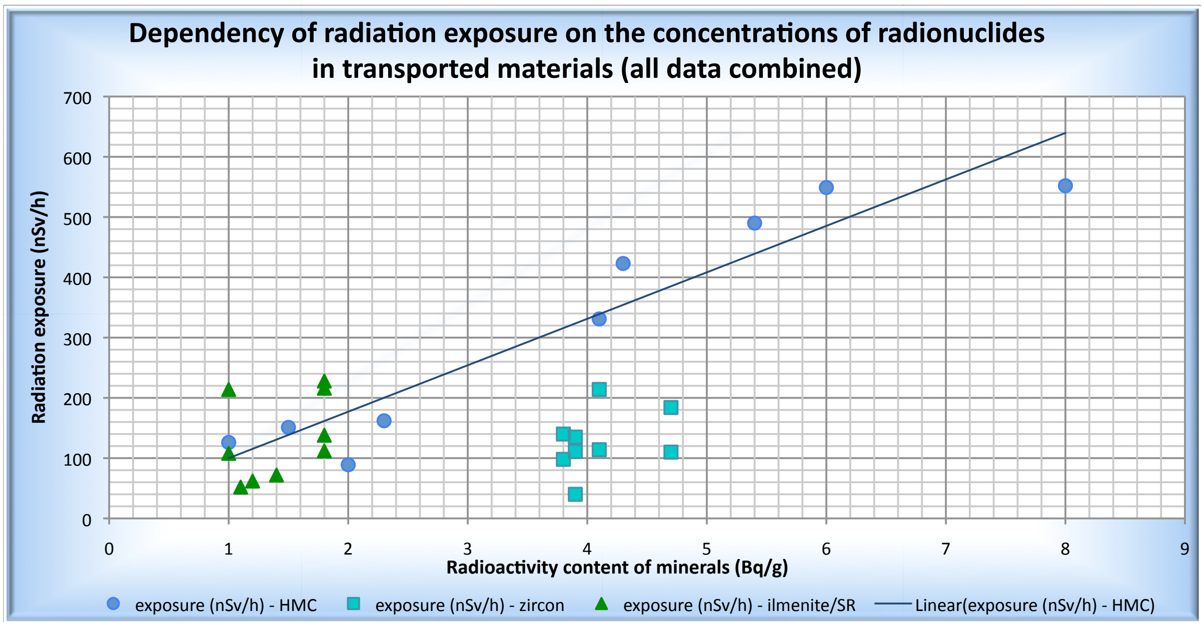


The situation becomes unclear when the data obtained for the transport of products such as ilmenite, synthetic rutile and zircon is added to this chart. It is difficult to quantify the dependency between radioactivity concentrations and radiation exposure of workers involved in the transport of these minerals, due to:

- Comparatively low thorium and uranium concentrations in these materials,
- Only a slight variation in these concentrations in titanium minerals (ilmenite and synthetic rutile), and
- Almost no variations in these concentrations in zircon.

As shown on the chart 4 below, the exposure factor appears to follow the trend observed for the HMC in the case of titanium minerals (ilmenite and synthetic rutile) – but this not in the cases when zircon is transported.

Chart 4 – 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:

1. Different typical weight ratios of Th:U in these materials and associated dose conversion factors for the exposure to airborne dust:
   - Heavy mineral concentrate, Th:U ratio = 6:1 – 9:1, dose conversion factors = 0.0065 – 0.0069 mSv/Bq;
   - Ilmenite, synthetic rutile, Th:U ratio = 15:1 – 25:1, dose conversion factors = 0.0073 – 0.0075 mSv/Bq;
   - Zircon, Th:U ratio = 1:1.25, dose conversion factor = 0.0044 mSv/Bq.

   Effectively, radiation exposure to zircon dust would result in about 60% of radiation exposure received from ilmenite/synthetic rutile dust of the same specific activity concentration, and 65% of radiation exposure from HMC dust of the same specific activity concentration.

2. In the case of transport of synthetic rutile, possible exposure of workers due to the inhalation of thoron also needs to be considered and may contribute to the overall exposure level.

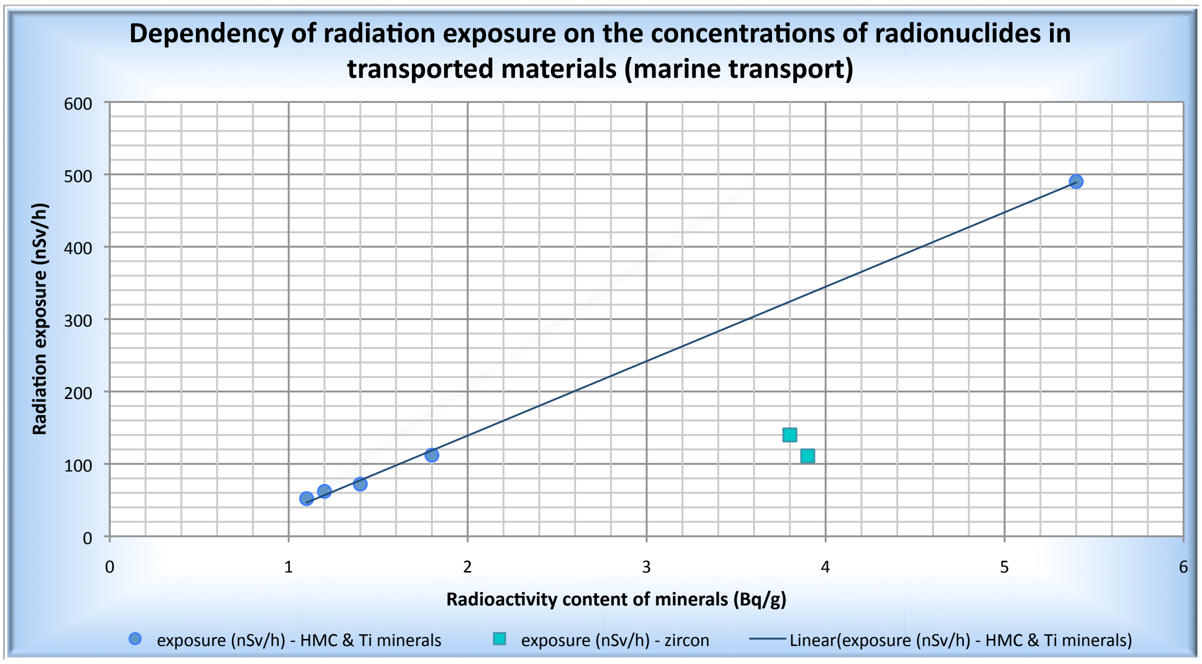
3. Higher gamma-radiation exposure levels are expected from a ‘combined’ Bq/g value of HMC, ilmenite and synthetic rutile (predominantly thorium) and zircon (typically more uranium than thorium).

The Th:U "Bq/g" ratios are typically:

- Heavy mineral concentrate = 2:1 – 3:1;
- Ilmenite, synthetic rutile = 5:1 – 8:1;
- Zircon = 1:4.

It is known that the typical dose coefficient (μSv/h per Bq/g) for ^{232}Th series is approximately 30% higher than for ^{238}U series (UNSCEAR, [11]) and this fact may be an explanation of the fact that the 'transport exposure factor' (in nSv/h) is lower for zircon even in the case of marine bulk shipments of minerals, where the exposure to the airborne dust is not considered to be a significant contributor to the overall level of radiation exposure (Chart 5 below).

Chart 5 – Marine transport - all monitoring data combined



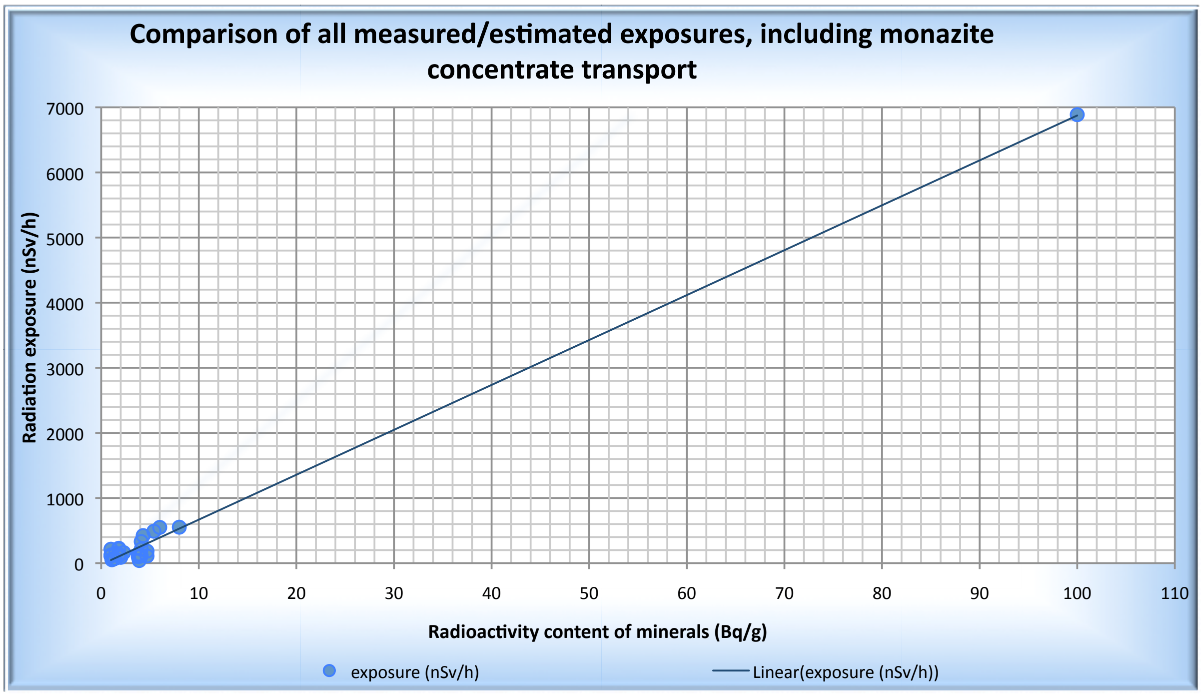
4. An assessment of the '10 times' exclusion factor provided in Transport Safety Regulations for 'natural' material

An important part of the project was an approximate estimation of radiation exposures received in the process of transport of concentrates of the mineral monazite. Monazite is also a heavy mineral sand and is currently sold in the form of concentrate (together with other mineral sands), with an average specific activity ranging typically between 90 and 110 Bq/g.

All transport is undertaken in accordance with Transport Safety Regulations, therefore a company intending to carry out a monazite concentrate shipment is required to submit a relevant radiation management plan to the State Authorities in Western Australia, and the shipment is only allowed to proceed when the statutory approval is obtained.

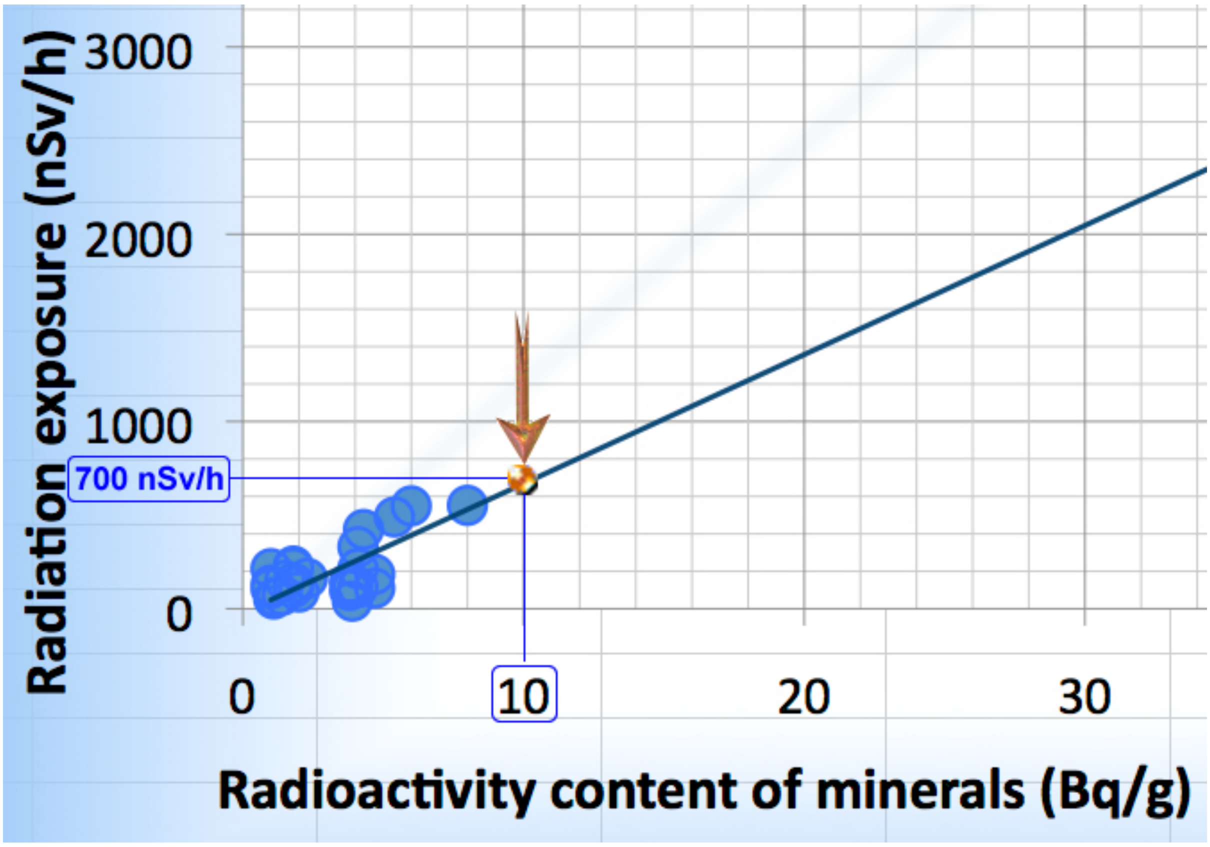
The exposure levels vary, but for the purposes of an approximate estimation, the results of all monitoring undertaken are plotted on the Chart 6 below, together with an overall average value obtained for the transport of monazite concentrate:

Chart 6 – all monitoring data combined (monazite concentrate data added)



It is estimated that a worker typically will not be involved in the transport of materials in the minerals industry for more than 1200 – 1400 hours in a year. Therefore, to ensure that the overall exposure of this worker does not exceed 1 mSv/year, his hourly exposure level should not be above 715 nSv/h (for 1400 hours). A closer examination of the Chart 6, presented on the Figure 2 below provides information on the applicability of the 'exclusion factor of 10' for the mineral sands industry products and concentrates:

Figure 2 – A 'close-up' view of the Chart 6



It is, therefore, clear that the factor of 10 appears to be entirely appropriate for the transport of heavy mineral sands.

5. Conclusions

- The highest annual radiation exposure of a worker involved in the transport of naturally occurring radioactive materials (NORM) in heavy mineral sands industry in Australia is 739 μSv.

- The highest 'per hour' values were registered for loader operators inside the sheds at different wharves. It has been established that additional attention may need to be given to monitoring of radon, thoron and their progeny concentrations during handling and storage of heavy mineral sands. 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 exposure to 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 typical level of radiation exposure, which was normalised to a value expressed in nSv/h.

- 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 specific activity concentrations.

- 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 last conclusion in the 2008 report to ARPANSA [1] was that 'exclusion' factor of 10 for the concentrations of radionuclides in natural materials in the Transport Safety Regulations may possibly be increased to 15 and that additional data is needed to confirm this suggestion. In the course of additional studies it has been established that the use of the factor of 10 is entirely appropriate and should be maintained, but this value cannot be increased to 15.

- The typically expected exposure levels were derived from charts 4 and 6 and are summarised in Table 9. It is suggested that this information can be used in the predictions 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.

Table 9 – 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 ±10%)	
1	100
2	180
3	260
4	330
5	410
6	490
7	560
8	640
9	720
Typical zircon (expected variance of ±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 ±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 [12] and potential problems and their solutions in international transport and trade in NORM [13, 14], this report complements previous papers by providing data on *practical* measurements and assessment of *actual* radiation exposures in the transport of NORM.

6. Acknowledgements

The initial stage of this research was undertaken for the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), which provided funding for the first part of the study (transport of heavy minerals concentrate between mine sites and from mine sites to processing plants in Australia).

The second part of the study (transport of materials from processing plants to ports and to customers overseas) was jointly sponsored by BeMax Resources Limited (now Cristal), Iluka Resources Limited, TiWest Joint Venture (now Tronox) and Calytrix Consulting Pty Ltd.

After the publication of the first version of the report additional monitoring was undertaken at several mining and processing sites, including radon and thoron monitoring; and four more shipments of mineral products overseas were also monitored. The third part of the study was jointly sponsored by BeMax Resources Limited (now Cristal Mining), Doral Mineral Sands Limited, Iluka Resources Limited, TiWest Joint Venture (now Tronox) and Calytrix Consulting Pty Ltd, and the final part was carried out exclusively by Calytrix Consulting Pty Ltd.

The successful conclusion of the research was only possible due to the cooperation of *over seventy different organisations* and advice and understanding of their employees:

Australia:

- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)
- Australian Customs
- Basin Sands Logistics
- BeMax Resources Limited (now Cristal Mining)
- Brambles Limited
- Bunbury Port Authority
- Doral Fused Materials
- Doral Mineral Sands
- Fremantle Port Authority
- Geraldton Port Authority
- Giacci Bros Pty Ltd
- Iluka Resources Limited
- Kalari Transport Services
- Kellogg Brown and Root Pty Ltd
- Monson Agencies Australia Pty Ltd
- MPL Laboratories
- Perth International Airport

- Piacentini & Son Pty Ltd
- Portland Port Authority
- Qantas Airways
- TiWest Joint Venture (now Tronox)
- WestNet Rail

<u>China:</u>

- Cathay Pacific Airways
- Customs of the People’s Republic of China
- Gaoqi International Airport (Xiamen)
- Hong Kong International Airport
- Hong Kong Customs
- King Far East Shipping Company Limited
- Minelco Aisa Pacific Limited (Hong Kong)
- Oceanic Shipping Limited (Hong Kong)
- Quarantine Inspection Bureau
- Radiation Health Unit (Hong Kong)
- Xiamen Airlines
- Xiamen Port Authority

<u>Japan:</u>

- Aisan Shosen Kaisha Limited
- All Nippon Airways
- Austbulk
- Bay Tower Hotel (Osaka)
- Haneda Airport (Tokyo)
- Himeji Port Authority
- ISK
- Japan Customs
- Japan Railways Group
- Kansai International Airport
- Ministry of Economy, Trade and Industry
- Mitsui & Co Limited
- National Institute of Radiological Sciences
- Nippon Steel Logistics
- Osaka Port Authority
- Rasa Corporation
- Sojitz Corporation
- Tayca Corporation
- Yokkaichi Port Authority

Malaysia:

- Kuala Lumpur International Airport
- Malaysia Airlines
- Malaysia Customs

Singapore:

- Changi International Airport
- Jurong Port Authority
- Singapore Airlines
- Singapore Customs
- Singapore Port Authority

South Africa:

- Richards Bay Minerals

International:

- MV *Dolfijngracht*
- MV *Donaugracht*
- MV *Lupinus*
- MV *Oneida Princess*
- MV *Pacific Grace*
- MV *Portland*
- MV *Sir Henry*
- MV *Spring Accord*
- International Atomic Energy Agency (IAEA)

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APPENDICES

Appendix 1 – Potential exposures of the members of the general public

The members of the general public could be exposed to radiation only in the case of the road transport.

As the assessment in the part 3.8 of the report clearly shows, in the case of a traffic accident that involves collision between the truck carrying heavy mineral concentrate (HMC) or other mineral sand and a spillage of the material, it is very unlikely that any member of the public will be exposed to more than 10-20 μSv; even if the member of the public is an emergency services worker attending the scene of an accident.

In the worst case scenario the gamma radiation level close to the truck is expected to be in order of 4 μSv/h. The levels at a distance of 1 metre from the truck loaded with HMC are typically in the range between 0.25 and 0.33 μSv/h (in cases of the transport of tailings back to a mine site this level may increase to 0.4 – 0.5 μSv/h). Typically, at a distance of 3 – 4 metres from the loaded truck the levels of gamma-radiation are indistinguishable from the natural background.

Due to this fact and a very short time of potential exposure, it is very unlikely that motorists following or overtaking the truck will receive any measurable dose of radiation.

The only potential exposure may arise if a member of the public parks his/her vehicle close to a loaded truck at a petrol station or at a rest spot on the highway. The typical time of exposure for a member of the public would be in order of 10-15 minutes.

The worst-case scenario of public exposure can be assessed using the following assumptions: 1 hour-long exposure, 45 minutes at the distance of 1 meter from the truck and 15 minutes leaning on the truck or being in the vicinity of 10-20 cm from it; four times per year:

$$[0.5\ \mu\text{Sv/h} \times 0.75\ \text{h} + 4.0\ \mu\text{Sv/h} \times 0.25\ \text{h}] \times 4 = \underline{5.5\ \mu\text{Sv/year}}.$$

It is, therefore, clear that the transport of mineral sands industry products and concentrates does not pose a hazard for members of the general public.

A special case is the transport of monazite concentrate, which is classified as radioactive material and is, therefore, transported in accordance with Transport Safety Regulations.

As pointed out in part 3.8 of the report, the potential 12-hour exposure in the case of traffic accident would be in order of 550 μSv/year.

The exposures in the course of normal conditions of transport are expected to be significantly lower, as shown in assessments below. Please note that these assessments are based on the worst case scenario where the concentrate is transported over a period of one month (instead of typical 'transport project' with a duration of 4 to 5 days).

There are several potential scenarios of radiation exposure of the members of the general public; all of them are due to the possible exposure to gamma-radiation, as the mineral is fully enclosed inside the truck trailers. The time estimates for the scenarios below are provided on the monthly basis.

1. Member of the public following the truck

It is assumed that a member of the public follows the truck daily on the way to work (30 working days) for 20 minutes each day and overtaking the truck each time (0.5 minutes). Total exposure time equates to 10 hours at a distance of ~40 meters (using the 3-second rule for 'following' distance) and 0.25 hours at a distance of 2 meters.

2. Members of the public driving alongside truck

A member of the public may drive alongside the truck when it enters the city traffic in the built-up area. The exposure time is conservatively estimated at 2 hours at a distance of 2 meters.

3. Member of the public alongside container truck (stationary)

Members of the public may potentially be exposed alongside the truck for short periods of time at petrol stations and rest stops. The annual exposure time is conservatively estimated at 2 hours at 1 meter and 4 hours at 4 meters.

4. Public in suburban and rural areas

Road trucks move through rural areas where members of the public may be exposed at varying degrees. It is unlikely that any dwellings are closer than 10 meters from roads. Members of the public residing at these locations would be exposed to approximately 10 trucks a day for about 10 seconds, over a period of 30 days. The total exposure time is estimated at about 45 minutes. Due to the lower speeds of the truck, the same scenario for the suburban areas would result in the exposure for approximately 1.5 hours.

The equation described in part 3.7 of the report can be used to estimate the gamma-radiation dose rate levels from two trailers with mineral at various distances with the following parameters:

$$\text{Dose Rate}_{(d)} = \text{Dose Rate}_{(surface)} \times [1 - d/(d^2 + A \times B/3.14)^{0.5}]$$

d – distance to the source,
A – height = 2 meters,
B – width = 30 meters,
$\text{Dose Rate}_{(surface)} = 40\ \mu\text{Sv/h}$.

The possible exposure time over a year would vary depending on the mineral being transported. It could be conservatively assumed that shipments of heavy mineral concentrate occur throughout the year (not more than 300 days/year), most minerals for export are transported in ‘campaigns’ (not more than 120 days/year), monazite concentrate is transported occasionally (not more than 30 days/year). The results of the modelling are summarised in the table below.

Scenario	Distance (m)	Exposure (hours)	Dose rate (μSv/h)	Exposure (mSv)
Rutile, ilmenite, synthetic rutile				
1	40	40	0.0	0.001
	2	1	0.6	
2	2	8	0.6	0.005
3	1	8	0.8	0.011
	4	16	0.3	
4	10	3	0.0	0.000
		6	0.0	0.000
Zircon				
1	40	40	0.0	0.001
	2	1	1.1	
2	2	8	1.1	0.009
3	1	8	1.6	0.022
	4	16	0.6	
4	10	3	0.0	0.000
		6	0.0	0.000
Heavy mineral concentrate (HMC)				
1	40	100	0.0	0.006
	2	2.5	2.3	
2	2	20	2.3	0.046
3	1	20	3.1	0.114
	4	40	1.3	
4	10	7.5	0.3	0.002
		15	0.3	0.005

Scenario	Distance (m)	Exposure (hours)	Dose rate (μSv/h)	Exposure (mSv)
Monazite concentrate				
1	40	10	0.24	0.008
	2	0.25	23.4	
2	2	2	23.4	0.093
3	1	2	31.1	0.114
	4	4	13.0	
4	10	0.75	3.4	0.003
		1.5	3.4	0.005

Taking into account the fact that the assessments above are very conservative, it can be concluded that no member of the public will be exposed to a dose of radiation that is more than 10% of the annual exposure limit of 1 mSv during the transport of any heavy mineral sand (including monazite concentrate), under normal conditions, and in most cases this exposure will be unmeasurable.

Appendix 2 – Discharge (unloading) of the ship in an overseas port

The following is a brief description of the monitoring of the discharge (unloading) of the ship with mineral sand in one of the overseas ports. It is believed that the photos below are representative and provide sufficient information on the current practices that are considered satisfactory from the radiation protection point of view.

1. **View of the port**

2. **Ship in the port**

3. Preparation for unloading

4. TLD badge in the ship's office

5. TLD badge in the galley

6. A worker in the cargo hold; commencement of unloading process

7. Ship’s discharge (unloading) process

8. Ship’s discharge (unloading) – video still captures

Appendix 3 – Surface dose monitoring system for trucks

As described in part 2.2 (route 9), at the site H some tailings are returned back from the plant to the mine site for disposal. Typical radioactivity content of these tailings is less than 1 Bq/g of Th and U, but relatively often the tailings with concentrations in order of 5-9 Bq/g are also returned to the mine site.

Due to the fact that the gamma radiation levels from the trucks carrying this type of material may be comparatively high, the company has introduced a comprehensive system of monitoring to ensure that no trucks exhibiting surface gamma radiation levels in excess of 5 μSv/h are allowed to leave site.

Therefore, regardless of the radioactivity concentration in the mineral, all material is transported to the mine site as 'excepted package', in accordance with paragraph 516 of the International Transport Safety Regulations:

516. The radiation level *at any point on the external surface of an* excepted package *shall not exceed 5 μSv/h.*

It is believed that this system can serve as an example of appropriate monitoring and management of bulk mineral shipments by road – particularly in cases where it is known that concentrations of radionuclides in the material are in the range between 1 and 8-9 Bq/g, but it is not practicable to determine the exact values for each shipment.

The brief description of the system is as follows (illustrations are provided on the following pages):

1. Mineral is loaded from a storage bin into truck trailers. The potential generation of dust is minimised by the fact that rubber "socks" are used to ensure that the mineral is discharged into the trailer at the distance that is as short as practicable. It should be noted that, as a rule, this system is not required when material is transported in the moist form – as is often the case in the transport of heavy mineral concentrate (HMC) from mine sites to processing plants;
2. When the loading is completed – it is the duty of the driver to undertake three surface measurements of the radiation level (as per §516 of the Regulations [2]);
3. All readings are entered into the log book (together with the day, time of the day, number of the truck and an approximate percentage of the truck's capacity taken by the given load), and the truck leaves site on the route to the mine site;
4. In a rare case when at least one reading exceeds 5 μSv/h, the truck is not leaving site, the material is instead unloaded in a specifically designated area for further processing and/or blending;
5. A properly calibrated and maintained radiation monitor is provided and all drivers are regularly trained in its correct use. Site Radiation Safety Officer inspects the

monitor and the log book typically every 2-3 days – to ensure that the equipment operates correctly and the log book is being maintained.

Illustrations

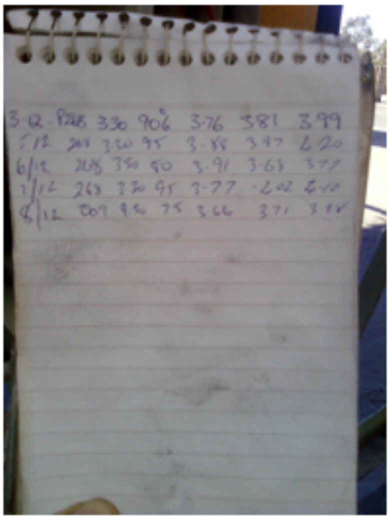
1. Loading of heavy mineral concentrate (HMC) at a mine site – no dust

2. **Typical truck that is used to transport HMC from the mining site to the processing site and to transport tailings back to the mining site**

3. **Location of the radiation monitor – storage cabinet located next to the mineral storage bins**

4. Inside the storage cabinet and the type of monitor used

5. Log book pages



Appendix 4 – Additional illustrations

Possibilities of mineral loss during the transport through spillage

Truck loading

Ship loading – poorly maintained loading conveyor

Ship loading – spillages

Unloading of the ship

Sea barrier from natural granite and gamma radiation level