Radiation exposure in the transport of heavy mineral sands

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Contents

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The subject of the study was the mineral sands industry in Australia. Heavy minerals (zircon, rutile, ilmenite, leucoxene, and monazite) are mined and processed in all States of Australia (except Tasmania). The transport of minerals is a significant component of the 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 the pipe 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 2mm) and then – 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 processing 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, typical titanium content ~60%,
- Ilmenite = 4.5-5.0, typical titanium content ~30%
- Zircon = 4.6-4.7, zirconium silicate

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

As a rule, the elements of the Th^{232} and U^{238} decay chains are present in the minerals in the state of secular equilibrium. Typical content of radioactivity in different products 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 route 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

Note: monazite concentrate that is classified as 'radioactive' for the purposes of transport was not included in this study.

Table 2 – Average activity concentrations in material 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

In accordance with the ARPANSA Code of Practice for the Safe Transport of Radioactive Material [1] that adopts International Atomic Energy Agency Transport Safety Regulations [2]:

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;

Therefore, transport safety regulations do not apply to all materials listed in Table 1, due to the '10-times' factor provided specifically for 'natural' materials.

The main purpose of this study was to determine if the exemption of the transport of material in bulk in mineral sands industry is justified and if the 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 to be studied 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 with the help of portable radiation monitor and electronic dosimeters / TLD badges, and airborne radioactivity with the help of personal and positional dust samples), 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.

All together the radiation exposure has been obtained for sixteen 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 tailings return 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; also assessment of radiation exposures for wharf workers;
d) Transport of final product to a customer overseas, three routes – sea.

The study was carried for the transport of minerals at and between mining and processing sites of BeMax Resources, Iluka Resources and TiWest Joint Venture 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).

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

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 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

HMC is transported within site B, on 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 font 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 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 (36 readings) = 1.18 – 2.43 μSv/h (average of 1.77 μSv/h).
Inside the cabin of the loader in the HMC stockpile area (7 readings) = 0.94 – 1.69 μSv/h (average of 1.23 μSv/h).

Three drivers were monitored for approximately six hours:
Gamma radiation readings from a loaded truck in the background area (away from the HMC stockpile):
Level inside truck cabins (6 readings) = 0.20 – 0.29 μSv/h (average of 0.24 μSv/h);
Outside truck, 1 metre distance (8 readings) = 0.24 – 0.41 μSv/h (average of 0.33 μSv/h);
Outside truck, 0.1 metre distance (15 readings) = 1.08 – 2.23 μSv/h (average of 1.62 μSv/h).

These three drivers were provided with electronic dosimeters for the duration of the 6-hour monitoring period and the readings were between 0.9 and 2.3 μSv (the average was 1.7 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.

Three 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 – 0.017 Bq/m^3 (average of 0.011 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

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 assist 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, also 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

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 five hours (two – carrying tailings from site C to site B, and two – carrying HMC from site B to site C). Typically, only one third 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.

Three drivers were monitored for the duration of four hours (one round trip):
Two drivers were provided with electronic dosimeters for the duration of the 5-hour round trip and the readings were 1.2 and 1.7 μSv (the average was 1.5 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.
Three personal dust monitors were also provided and the results were as follows: dust concentration = 0.22 – 0.51 mg/m^3, dust activity = 0.036 – 0.057 Bq/m^3 (average of 0.047 Bq/m^3);

Route 5

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.

Eight personal dust monitors were also provided and the results were as follows:
Truck drivers (five samples): dust concentration = 0.01 – 0.20 mg/m^3, dust activity = 0.004 – 0.006 Bq/m^3 (average of 0.005 Bq/m^3);
Loader operators (three samples): dust concentration = 0.03 – 0.37 mg/m^3, dust activity = 0.004 – 0.009 Bq/m^3 (average of 0.006 Bq/m^3).

Route 6

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

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 (14 readings) = 0.07 – 0.13 μSv/h (average of 0.11 μSv/h);

HMC stockpile area (10 readings) = 0.91 – 2.03 μSv/h (average of 1.62 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 also 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).

<u>Route 8</u>

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 the reading was 0.5 μSv.
Six personal dust monitors were also 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 for the last 2 years (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

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 (28 readings) = 0.07 – 0.14 μSv/h (average of 0.10 μSv/h);
HMC stockpile area (12 readings) = 0.60 – 1.42 μSv/h (average of 1.08 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 occasionally tailings with concentrations in order of 5-7 Bq/g are also returned to the mine site.

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 in the last 24 months (33 samples) were as follows: dust concentration = 0.04 – 1.18 mg/m^3, dust activity = 0.004 – 0.029 Bq/m^3 (average of 0.012 Bq/m^3).

A special situation exist due to the fact that 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). The results of the monitoring of two loader operators indicate that their quarterly exposure to the external gamma radiation varies between 0.13 and 1.04 mSv (four results), being on average 0.61 mSv/quarter. Registered annual exposures (4 results) are between 1.77 and 2.83 mSv/year, being on average 2.32 mSv/year. Until further investigations into these exposures are completed, the company was advised to either adjust the working hours and locations for these workers or consider training truck drivers as loader operators as well.

Route 10

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 all 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

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.

Eight personal dust samples were taken and the results were as follows:
Truck carrying ilmenite: dust concentration = 0.22 – 0.41 mg/m^3, dust activity = 0.007 – 0.010 Bq/m^3 (average of 0.009 Bq/m^3); truck carrying zircon: dust concentration = 0.17 – 0.45 mg/m^3, dust activity = 0.009 – 0.015 Bq/m^3 (average of 0.012 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 in the last three years were in the range 0.18 – 0.43 μSv/hour, with an average of 0.26 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. The results at this wharf in the last three years (8 samples) were as follows: 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 (5 samples):
Dust concentration = 0.41 – 1.26 mg/m^3, dust activity = 0.009 – 0.039 Bq/m^3 (average of 0.019 Bq/m^3), personal electronic dosimeter (2 readings, 6 hours) – 0.7 and 0.7 μSv (background = 0.5 μSv).
Ship operator – zircon (4 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 (1 sample): dust concentration = 0.28 mg/m^3, dust activity = 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

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

Measurements were taken from two 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 = 0.08 – 0.14 mg/m^3, dust activity = 0.005 – 0.012 Bq/m^3 (average of 0.009 Bq/m^3); personal electronic dosimeter (2 readings, 4 hours) – 0.5 and 0.8 μSv, average = 0.6 μSv (background = 0.4 μSv).

Route 13

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

Measurements were taken from two 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 = 0.14 – 1.124 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 in the last three years were in the range 0.07 – 1.08 μSv/h, with an average of 0.24 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 in the last three years (15 samples) were 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

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

Route 14

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,
Owners 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 – 0 μSv,
Galley, poop deck – 70 μSv,
Engine control room – 70 μSv,
Forecastle store – 70 μSv,
Average = 67 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 all these activities are carried out by the wharf employees.

Route 15

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 extremely 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 – 0 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 – 0 μSv,
Forecastle store – 0 μSv,
Galley – 80 μSv,
Engine control room – 80 μSv,
Average = 51 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 all these activities are carried out by the wharf employees.

Route 16

Ilmenite and synthetic rutile is transported from the wharf associated with the sites 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 – 0 and 70 μSv,
Average = 58 μSv.
Other areas of the ship:
Captain's office – 70 μSv,
Ship's office – 0 μSv,
Chief officer's cabin – 0 μSv,
Galley – 0 μSv,
Crew mess room – 0 μSv,
Seaman's cabin – 0 μSv,
Bosun's store – 0 μSv,
Engine control room – 70 μSv,
Average = 18 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 all these activities are carried out by the wharf employees.

2.5. Additional monitoring data and remarks

Additional data for routes 14-16

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).

Radon and thoron

It is not a current practice in the mineral sands industry to sample for radon (Rn^{222}) and thoron (Rn^{220}), due to the comparatively low uranium content in mineral sands and very short half-life of thoron. Eight ten-minute samples were taken at one wharf (both in the storage shed and between storage sheds) and the activity on all filters analysed 7 to 15 hours after sampling (using the 'Rock method', [3]) was, in all cases, less than minimum detection limit of the equipment in use.

It is possible to supplement this study by placing long-term radon/thoron monitors in different locations where mineral sands are stored but prior to this an investigation of reliability of such equipment (there are several suppliers) should be carried out.

Shipping of minerals in containers

In the course of this study it was considered impracticable to monitor the shipment of mineral sands in containers 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.

It is, however, possible to supplement this study with the results of monitoring of two of three container shipments.

2.6. 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,
- Exploranium 'Indentifier' 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 properly calibrated equipment.
- Canary II Model 4080 portable electronic dosimeters, calibrated by the Radiation Health Branch of the WA Department of Health,
- 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.

  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.
- 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 Am^{241} calibration sources calibrated by the Radiation Health Branch of the WA Department of Health.

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 2.6 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 2.6 above. The dose conversion factors (mSv/Bq) that were used in dose assessments were derived from ICRP-68 [6] and ICRP-72 [7] 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 Consumer and Employment Protection of Western Australia, Resources Safety, May 2008) [8] and are detailed below:

Table 3 – 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 & synth.rutile	15:1	0.0073
F/14	zircon	1:1.25	0.0044
C,D/15	ilmenite & synth.rutile	15:1	0.0073
E/16	ilmenite & synth.rutile	25:1	0.0075

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. Where it was worn, the assessment of the efficiency of a site's respiratory protection program was beyond the scope of this study.
4. 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.

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 $\times$ 0.5 h + (0.14 – 0.11) μSv/h $\times$ 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 $\times$ 100 shifts = 40 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.007 $Bq/m^3 \times 1.2\ m^3/h \times$ 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 $\times$ 0.0067 mSv/Bq = 67 μSv.

Therefore, the highest possible exposure of a driver on this route is <u>107 μSv/year</u>, 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: (1.23 – 0.12) μSv/h $\times$ 2 h + (0.24 – 0.12) μSv/h $\times$ 4 hr = 2.6 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 2.6 μSv $\times$ 100 shifts = 260 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.011 $Bq/m^3 \times 1.2\ m^3/h \times$ 1200 h = 15.8 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: 15.8 Bq $\times$ 0.0068 mSv/Bq = 107 μSv.

Therefore, the highest possible exposure of a driver on this route is <u>367 μSv/year</u>, and the highest hourly exposure is 306 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 (using the breathing rate of 1.2 m^3/h):
Locomotive operator – 0.009 $Bq/m^3 \times 1.2\ m^3/h \times 350\ h = 3.8\ Bq$,
Operator involved in HMC loading – 0.032 $Bq/m^3 \times 1.2\ m^3/h \times 350\ h = 13.4\ Bq$,
Operator involved in HMC unloading – 0.042 $Bq/m^3 \times 1.2\ m^3/h \times 350\ h = 17.6\ Bq$.

Using the dose conversion factor from Table 2 (0.0068 mSv/Bq), the highest annual internal radiation exposures of workers on this route are:
Locomotive operator – 3.8 Bq $\times$ 0.0068 mSv/Bq = 26 μSv,
Operator involved in HMC loading – 13.4 Bq $\times$ 0.0068 mSv/Bq = 91 μSv,
Operator involved in HMC unloading – 17.6 Bq $\times$ 0.0068 mSv/Bq = 120 μSv.

Therefore, the highest possible exposure of a 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 1.0 μSv during the 5-hour sampling period (0.20 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 $\times$ 500 h = 100 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.047 $Bq/m^3 \times 1.2\ m^3/h \times 500\ h = 28.2\ Bq$.
Using the dose conversion factor from Table 2 (0.0069 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is: 28.2 Bq $\times$ 0.0069 mSv/Bq = 194 μSv.

Therefore, the highest possible exposure of a driver on this route is 294 μSv/year, and the highest hourly exposure is 588 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
1.0 μSv during the 6-hour sampling period for loader operators (0.17 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 $\times$ 2000 h = 140 μSv, and for the loader operator 0.17 μSv/h $\times$ 900 h = 153 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.005 Bq/m^3 $\times$ 1.2 m^3/h $\times$ 2000 h = 12.0 Bq for truck drivers, and
0.006 Bq/m^3 $\times$ 1.2 m^3/h $\times$ 900 h = 6.5 Bq for loader operators.
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 12.0 Bq $\times$ 0.0067 mSv/Bq = 80 μSv, and the same for the loader operator 6.5 Bq $\times$ 0.0067 mSv/Bq = 44 μSv.

Therefore, the highest possible exposure of a driver on this route is <u>220 μSv/year</u> (197 μSv/year for a loader operator); and the highest hourly exposures are 110 nSv/hr for truck driver and 219 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 $\times$ 100 h + 0.41 μSv/h $\times$ 100 hr + 0.03 μSv/h $\times$ 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 (using the breathing rate of 1.2 m^3/h):
0.009 Bq/m^3 $\times$ 1.2 m^3/h $\times$ 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 $\times$ 0.0068 mSv/Bq = 73 μSv.

Therefore, the highest possible exposure of a driver on this route is <u>151 μSv/year</u>; 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 (using the 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.

Therefore, the highest possible exposure of a driver on this route is <u>604 μSv/year</u> (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 (using the 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 2 (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.

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.

As described in part 2.2, a special situation exist due to the fact that specifically designated loader operators on the mine site typically spent most of their working day in the 'supervised radiation area' where the HMC is stored, or in its immediate vicinity. Other duties of these operators include re-handling of the material in the HMC storage area and handling the tailings returned to the mine site. 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). The results of the monitoring of two loader operators indicate that their quarterly exposure to the external gamma radiation varies between 0.13 and 1.04 mSv (four results), being on average 0.61 mSv/quarter. Registered annual exposures (4 results) are between 1.77 and 2.83 mSv/year, being on average 2.32 mSv/year.
It is not known at the moment which percentage of working time of these operators is dedicated to the loading of trucks with HMC, and which – to site duties that are not associated with HMC/tailings transport. Therefore, purely 'transport exposure' cannot be accurately quantified and included into the summary in part 3.8. Until further investigations into these exposures are completed, the company was advised to either adjust the working hours and locations for these workers or consider training truck drivers as loader operators as well.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
$0.012\ Bq/m^3 \times 1.2\ m^3/h \times 1400\ h = 20.2\ Bq$.
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 $20.2\ Bq \times 0.0067\ mSv/Bq = 135\ \mu Sv$.

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).

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 $\times$ 500 h = 10 μSv and 0.04 μSv/h $\times$ 500 h = 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):
0.009 $Bq/m^3 \times$ 1.2 $m^3/h \times$ 500 h = 5.4 Bq (ilmenite), and
0.012 $Bq/m^3 \times$ 1.2 $m^3/h \times$ 1200 h = 7.2 Bq (zircon).
Using the dose conversion factor from Table 2 (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 $\times$ 0.0075 mSv/Bq = 40 μSv (ilmenite), and 7.2 Bq $\times$ 0.0044 mSv/Bq = 32 μSv (zircon).

Therefore, the highest possible exposure of a driver on this route is 52 μSv/year; and the highest hourly exposures for drivers are 100 nSv/h (ilmenite) and 104 nSv/h (zircon).

Route 11 – wharf operators

External radiation exposure was measured with electronic dosimeters and was on average:
0.2 μSv during the 6-hour sampling period for operator loading ship with ilmenite (0.03 μSv/h),
0.4 μSv during 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 $\times$ 500 h + 0.11 μSv/h $\times$ 400 h = 59 μSv (ilmenite), and
0.07 μSv/h $\times$ 500 h + 0.11 μSv/h $\times$ 400 h = 79 μSv (zircon)

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.019 $Bq/m^3 \times$ 1.2 $m^3/h \times$ 500 h + 0.0006 $Bq/m^3 \times$ 1.2 $m^3/h \times$ 400 h = 11.7 Bq (ilmenite), and
0.017 $Bq/m^3 \times$ 1.2 $m^3/h \times$ 500 h + 0.0006 $Bq/m^3 \times$ 1.2 $m^3/h \times$ 400 h = 10.5 Bq (zircon).
Using the dose conversion factor from Table 2 (0.0075 mSv/Bq – ilmenite, 0.0044 mSv/Bq - zircon), the highest annual internal radiation exposure of a wharf operator is:
11.7 Bq $\times$ 0.0075 mSv/Bq = 88 μSv (ilmenite), and 10.5 Bq $\times$ 0.0044 mSv/Bq = 46 μSv (zircon).

Therefore, the highest possible exposure of a wharf operator is 147 μSv/year; and the highest hourly exposures are 163 nSv/h (ilmenite) and 139 nSv/h (zircon).

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 $\times$ 600 h = 30 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.009 Bq/m^3 $\times$ 1.2 m^3/h $\times$ 600 h = 6.5 Bq.
Using the dose conversion factor from Table 2 (0.0044 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is:
6.5 Bq $\times$ 0.0044 mSv/Bq = 29 μSv.

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 $\times$ 500 h = 10 μSv.

Internal radiation exposure:
The intake of radioactivity per year is estimated as follows (using the breathing rate of 1.2 m^3/h):
0.010 Bq/m^3 $\times$ 1.2 m^3/h $\times$ 500 h = 6.0 Bq.
Using the dose conversion factor from Table 2 (0.0073 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is:
6.0 Bq $\times$ 0.0073 mSv/Bq = 44 μSv.

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 $\times$ 1000 h = 130 μSv.

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

Therefore, the highest possible exposure of a wharf operator is 134 μSv/year; and the highest hourly exposures are 134 nSv/h (ilmenite) and 132 nSv/h (zircon).

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 67 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.

Route 15

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 51 μSv in 500 hours (0.10 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:
0.10 μSv/h $\times$ 1200 h = 120 μSv.

Internal radiation exposure needs 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 two 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 2 (0.0073 mSv/Bq), the highest annual internal radiation exposure of a driver on this route is:
0.2 Bq $\times$ 0.0073 mSv/Bq = 2 μSv.

Therefore, highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be 122 μSv/year; and the highest hourly exposure is 102 nSv/h.

Route 16

External radiation exposure of ship's crew was measured with TLD badges and is estimated at 18 μSv in 400 hours (0.05 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:
$0.05\ \mu Sv/h \times 1200\ h = 60\ \mu Sv$.

Internal radiation exposure needs 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 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 2 (0.0075 mSv/Bq), the highest annual internal radiation exposure is:
$0.2\ Bq \times 0.0075\ mSv/Bq = 2\ \mu Sv$.

Therefore, highest possible exposure of a member of the crew of the ship carrying ilmenite and/or synthetic rutile will be <u>62 μSv/year</u>; and the highest hourly exposure is 52 nSv/h.

The exposure of workers carrying out the unloading of the ship can also be assessed. In one of the overseas ports 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:
$0.42\ \mu Sv/hr \times 8\ hr \times 6 = 20\ \mu Sv$

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):
$0.012\ Bq/m^3 \times 1.2\ m^3/h \times 48\ h = 0.7\ Bq$.
Using the dose conversion factor from Table 2 (0.0075 mSv/Bq), the highest annual internal radiation exposure is:
$0.7\ Bq \times 0.0075\ mSv/Bq = 5\ \mu Sv$.
Therefore, highest possible exposure of a worker at the wharf unloading ilmenite and/or synthetic rutile will be <u>25 μSv/year</u>; and the highest hourly exposure is 52 nSv/hr.

3.6. Exposures during emergency situations such as transport accidents and spillages

In the case of a transport accident it is not believed likely that any employee 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 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 can be registered from the HMC] minus 0.10 μSv/h [average natural background value].
The result (5.0 μSv/h) is multiplied by: 2 [an additional 'safety margin' factor – to account for any increases in gamma-radiation levels that may not have been taken into account at this time], and further multiplied by 12 hours = 120 μSv.

When similar calculations are performed for the typical concentrates and products transported in the mineral sands industry and without the safety factor, the values of this exposure would be:
HMC – between 10 and 36 μSv, with an average of 20 μSv;
Zircon – between 10 and 25 μSv, with an average of 17 μSv;
Ilmenite and/or synthetic rutile – between 5 and 15 μSv, with an average of 10 μSv.

It is not believed that the internal radiation exposure to the HMC or other mineral sands dust will be a significant 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.

The total radiation exposure of the worker involved in the clean up of an accidental spillage of the concentrate would be 21 μSv, zircon – 18 μSv, ilmenite and/or synthetic rutile – 11 μSv. In the hypothetical 'worst case' the exposure of the worker would not exceed 124 μSv.

3.7. Potential exposures of the members of the general public

The members of the general public can only be exposed to radiation in the case of the road transport.
As the assessment in the part 3.5 above clearly shows, in the case of traffic accident that involves collision between the truck carrying 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.

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 will be in order of 10-15 minutes.

The worst-case scenario of public exposure can be assessed as follows:
1 hour-long exposure, 45 minutes at the distance of 1 metre from the truck and 15 minutes leaning on the truck or being in the vicinity of 10-20 cm from it; three times per year:
$[0.5\ \mu Sv/h \times 0.75\ h + 2.0\ \mu Sv/h \times 0.25\ h] \times 3 = \underline{2.6\ \mu Sv}$.

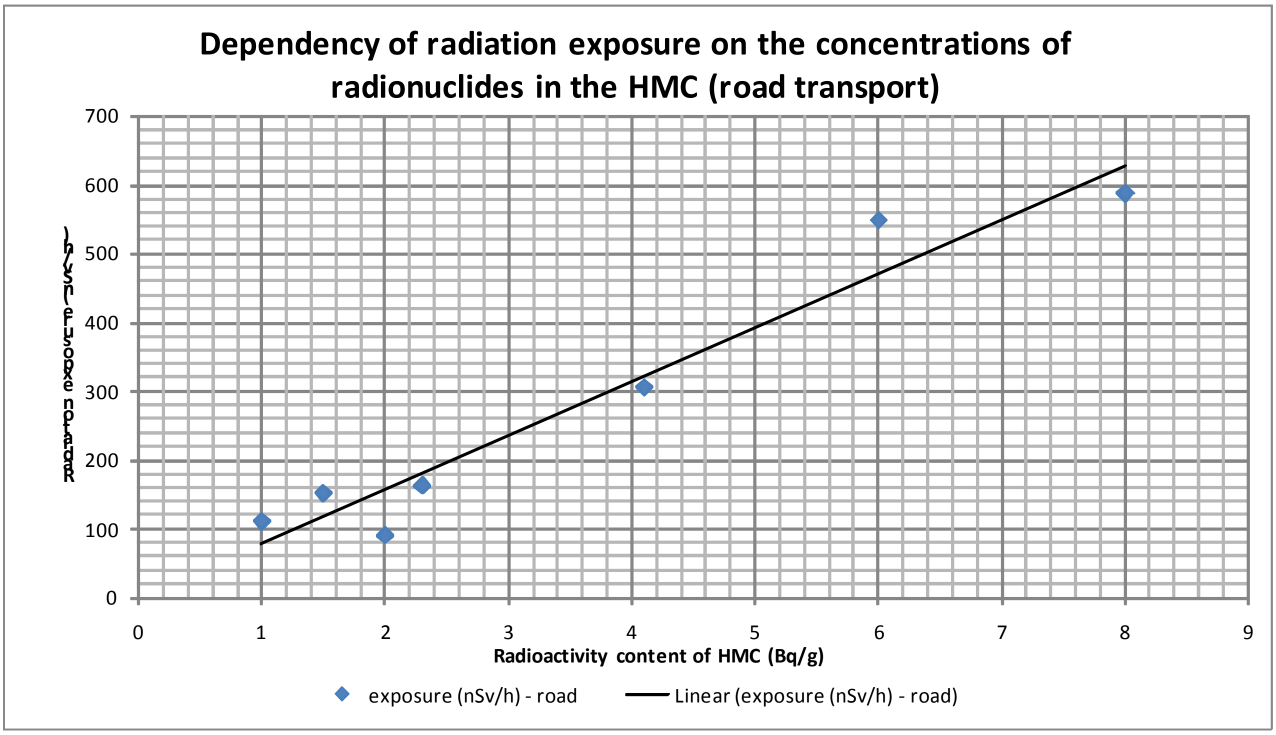
3.8. Summary

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

Table 4 – 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	367	306
3	HMC – rail	4.3	229	423
4	HMC tailings – road	8.0	294	588
5	HMC – road	1.0	220 (driver)	110 (driver)
			197 (loader)	219 (loader)
6	HMC – road	1.5	151	151
7	HMC – road, tails return	3.9/8.0 ~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	52 (driver)	104 (driver)
			125 (wharf)	139 (wharf)
11	Ilmenite / synthetic rutile – road	1.8	50 (driver)	100 (driver)
			147 (wharf)	163 (wharf)
12	Zircon – road	3.8	59	98
13	Ilmenite / synthetic rutile – road	1.0	54 (driver)	108 (driver)
			134 (wharf)	134 (wharf)
14	Zircon – marine	3.8	168	140
15	Ilmenite / Synthetic rutile – marine	1.8	122	102
16	Ilmenite / Synthetic rutile – marine	1.1	62	52

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 Road Transport, with data for rail and marine transport added

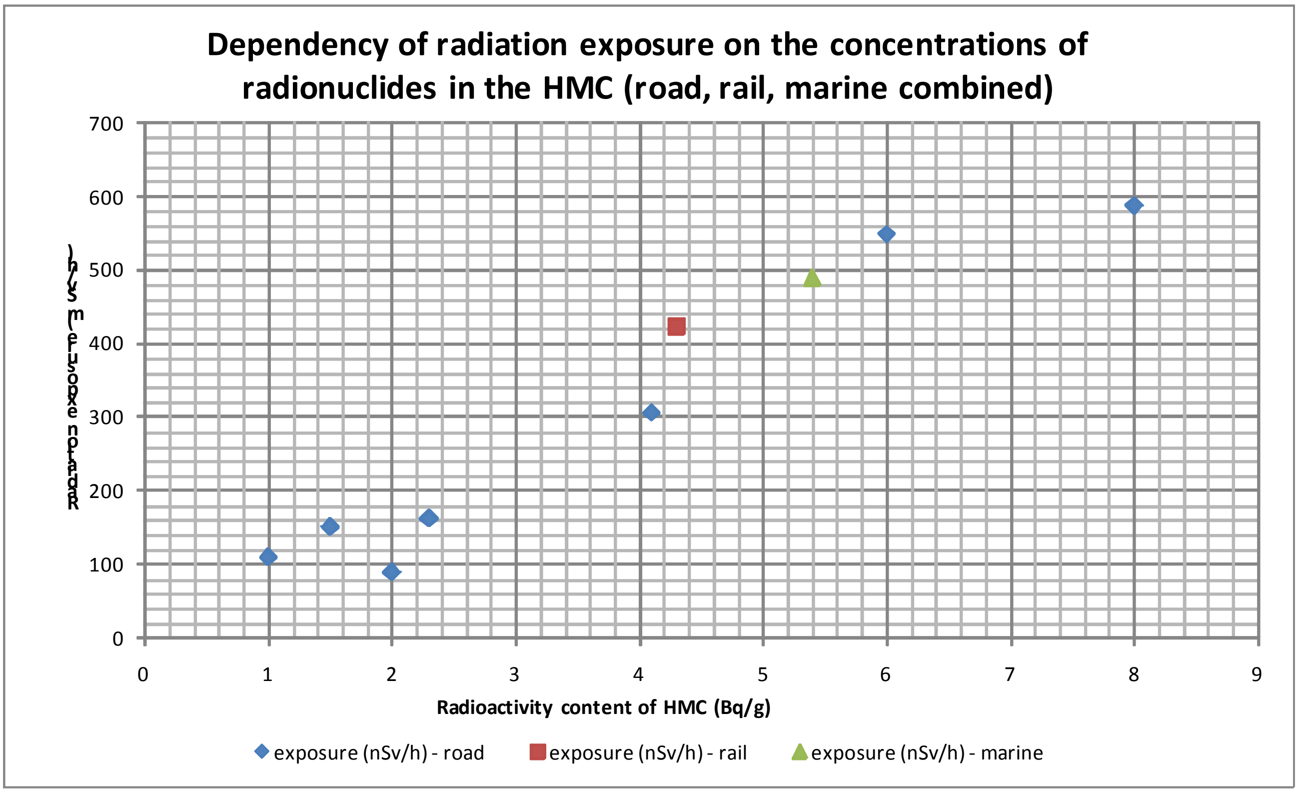
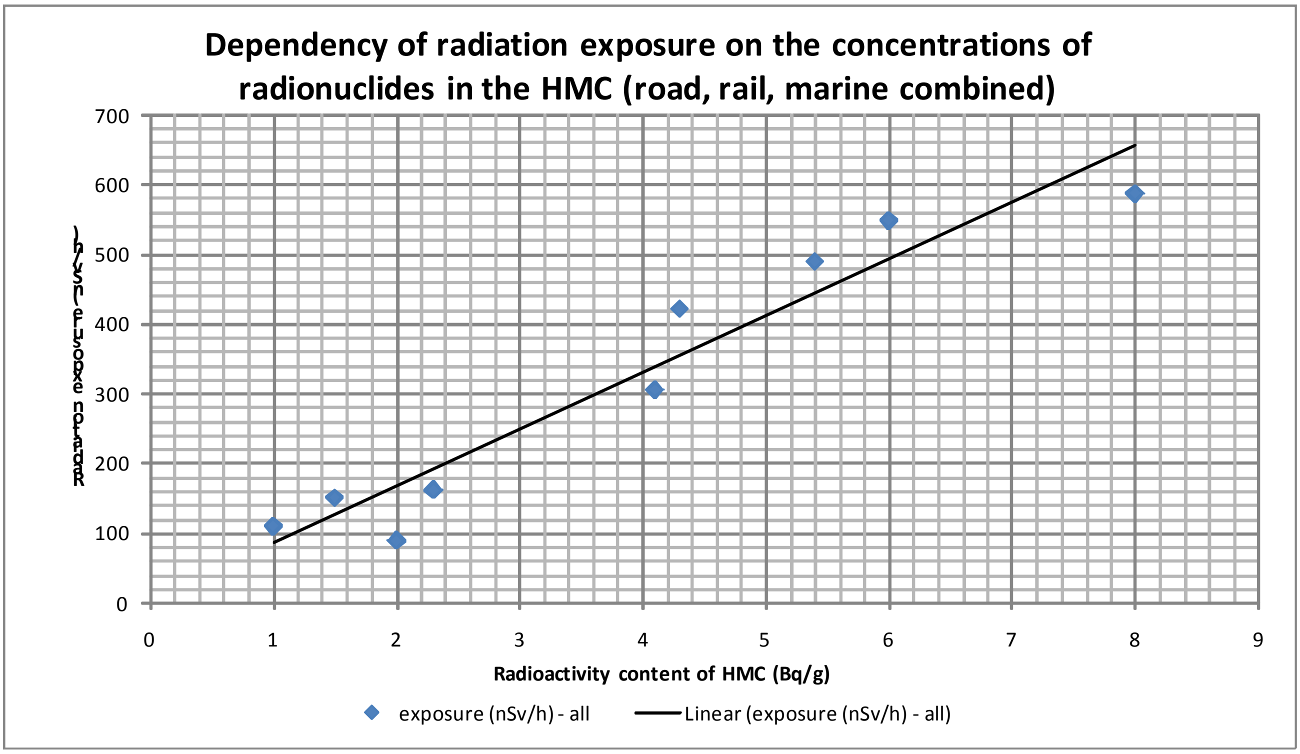


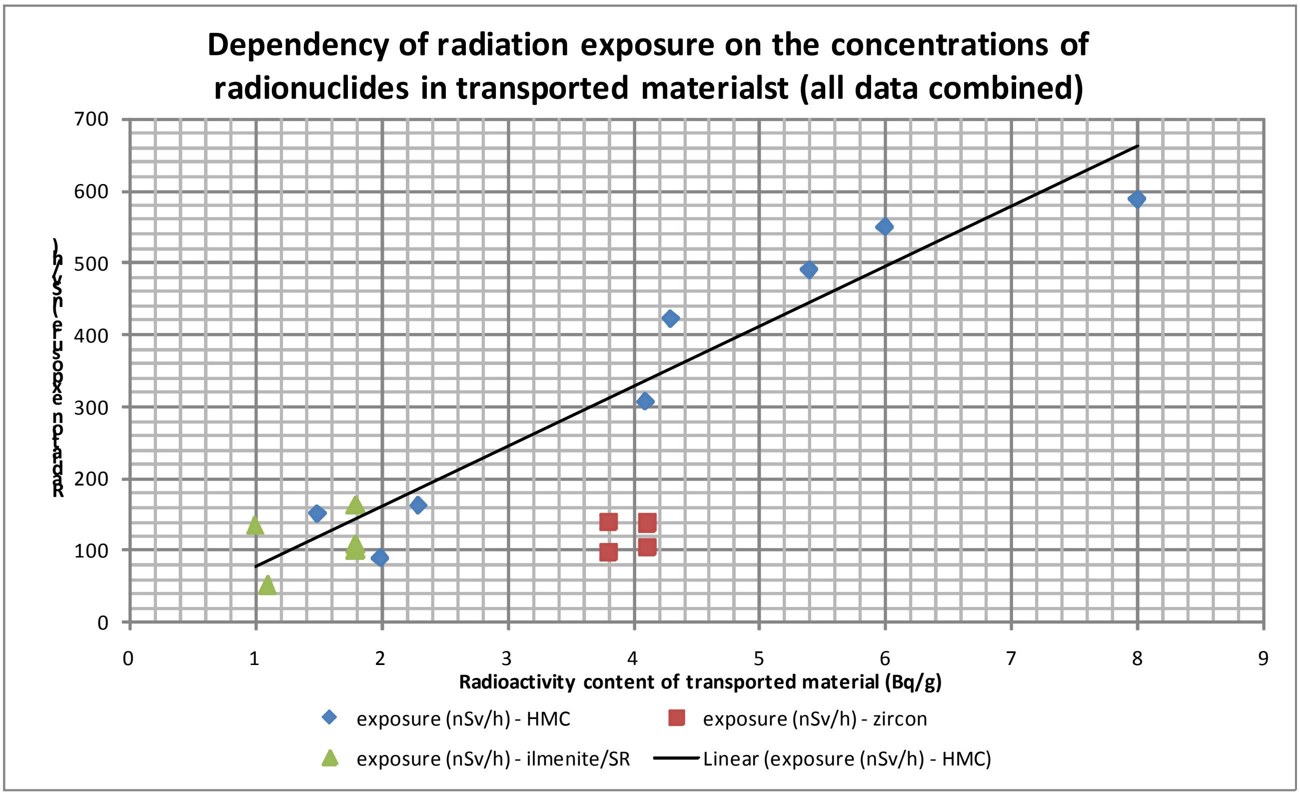
Chart 3 – HMC Road Transport – combined data



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. Due to the comparatively low thorium and uranium concentrations in these materials, only a slight variety in these concentrations in titanium minerals (ilmenite and synthetic rutile), and almost no variations in zircon it is difficult to quantify the dependency between radioactivity concentrations and radiation exposure of workers involved in the transport of these minerals.

As shown on the chart 4 below, whilst the exposure factor appears to follow the trend observed for the HMC in the case of titanium minerals (ilmenite and synthetic rutile) – this is not the case 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, appear to be:

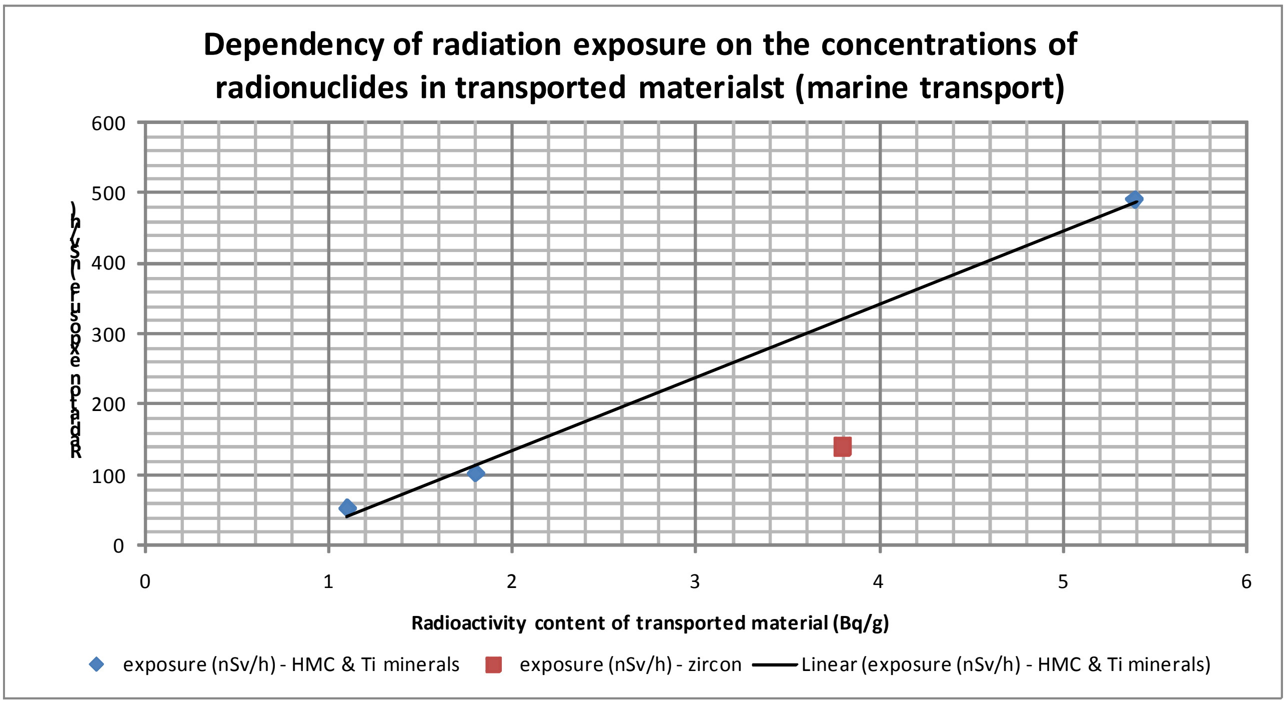
1. Different weight ratios of Th:U in these materials and associated dose conversion factors for the exposure to airborne dust.

Heavy mineral concentrate, Th:U = 6:1 – 9:1, dose conversion factors = 0.0065 – 0.0069 mSv/Bq;
Ilmenite, synthetic rutile, Th:U = 15:1 – 25:1, dose conversion factors = 0.0073 – 0.0075 mSv/Bq;
Zircon, Th:U = 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 activity concentration, and 65% of radiation exposure from HMC dust of the same activity concentration.

2. Different gamma-radiation exposure levels 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:
HMC = 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 Th^{232} series is approximately 30% higher than for U^{238} series (UNSCEAR, [9]) 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 – Marine transport - all monitoring data combined



4. Conclusions

- The highest annual radiation exposure of a worker involved in the transport of mineral sands in Australia is 604 μSv. This value may theoretically increase to 728 μSv/year in a very unlikely case of an accident that would have occurred under worst-case circumstances.
- 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 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 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.
- As the results of the study indicate, this factor may possibly be increased to 15 (in this case the highest possible annual radiation exposure is still expected to be below 1 mSv/year – the limit of exposure for the members of the general public). However, this recommendation would only be valid if the results of this study are supported by the measurement data for radon (Rn^{222}) and thoron (Rn^{220}) concentrations in relevant workplaces and the detailed additional monitoring of transport workers, including at least four more marine shipments of minerals (two of which would need to be container shipments).

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