Chapter 2. SOURCES OF RADIATION EXPOSURE - AN OVERVIEW

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ABSTRACT

Sources of radiation exposure are reviewed from the perspective of mining and milling of radioactive ores in Australia. The major sources of occupational and public exposure are identified and described, and exposures from mining and milling operations are discussed in the context of natural radiation sources and other sources arising from human activities.

INTRODUCTION

Most radiation exposure of humans comes from natural sources. About 80% of the world average of the effective dose equivalents (see Chapter 1) received by individual people arises from natural radiation, with a further 15-20% coming from medical exposures*. Exposures resulting from human activities, such as mining and milling of radioactive ores, nuclear power generation, fallout from nuclear weapons testing and non-medical use of radioisotopes and X-rays, add less than 1% to the total (Figure 1).

However, the potential for high individual doses is greatest in those industries in which radioactive materials are processed or handled or in which radiation generating equipment is used. Radiation protection practice is guided by the International Commission on Radiological Protection (ICRP). In general, the ICRP recommendations are endorsed in Australia by the National Health and Medical Research Council (NHMRC, 1981), and taken up in various Codes of Practice, in particular the 'Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1987)' (DASETT, 1987). The ICRP's basic philosophy is to keep all exposures 'as low as reasonably achievable, economic and social factors being taken into account' - the ALARA principle - and to keep the dose equivalents to individuals below recommended limits (see Chapter 11). Those responsible for mining and milling of radioactive ores in Australia are required to manage the radioactive materials and sources under their control such that the objectives of the Code (or equivalent State or Territory legislation) are met. This requires a clear identification of the sources of radiation and the pathways for human exposure.

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* Most of the figures quoted in this Chapter are taken from or based on the 'Report of the United Nations Scientific Committee on the Effects of Atomic Radiation' (UNSCEAR, 1982). This Report should be consulted for more detailed information on this topic and for references to original information in the literature. A revised UNSCEAR Report was published in 1988

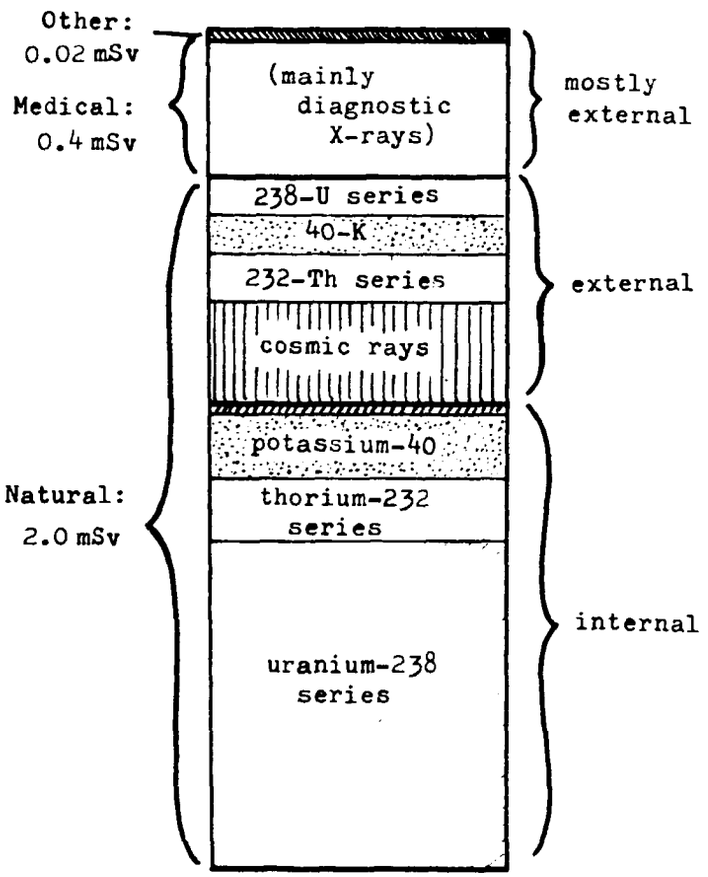

Figure 1. Estimated magnitudes of world average exposures of individuals (Source: UNSCEAR 1982). Note that the exposure from natural sources was revised upwards to 2.4 mSv in the 1988 UNSCEAR Report.

NATURAL SOURCES

Natural sources arise both from the terrestrial environment (radioactive elements in the Earth's crust and atmosphere) and the extra-terrestrial environment (cosmic rays). The latter irradiate the human body from the outside, while terrestrial radionuclides can be taken into the body by ingestion or inhalation to irradiate internal organs and tissues, as well as being sources of external radiation. Cosmogenic radionuclides, those created by the impact of cosmic rays on atoms in the atmosphere, contribute very little to overall exposure; most of the terrestrial exposure comes from primordial radionuclides, those that have been present in the Earth's crust since its formation. The estimated average annual exposures from natural sources are summarised in Table 1.

Table 1. Estimated annual effective dose equivalents from natural sources of radiation

Source	Annual effective dose equivalent (mSv)		
	External irradiation	Internal irradiation	Total
Cosmic rays			
Ionising component	0.30		0.30
Neutron component	0.055		0.055
Cosmogenic radionuclides		0.015	0.015
Primordial radionuclides			
Potassium-40	0.15	0.18	0.33
Rubidium-87		0.006	0.006
Uranium-238 series	0.10	1.24	1.34
Thorium-232 series	0.16	0.18	0.34
TOTAL	0.8	1.6	2.4

Source: UNSCEAR 1988. Note that these figures are revised from those in the 1982 UNSCEAR Report.

Nearly half of the total of 2.4 mSv annual effective dose equivalent comes from the inhalation of radon daughters, while about one sixth each is contributed by cosmic rays, potassium-40, and thorium-232 series radionuclides. The global average of 2.4 mSv per year from natural sources is a useful benchmark with which to compare additional doses received from other sources.

Cosmic rays

The cosmic ray component of natural radiation is fairly constant at the Earth's surface, but it does vary with altitude and, to a lesser extent, with latitude. On entering the atmosphere, the highly energetic primary cosmic rays (mainly protons and alpha particles) collide with the nuclei of atoms in the air, generating a range of collision products and losing large quantities of energy which materialises in the form of pions, gamma rays and electron-

positron pairs. Secondary cosmic rays (mainly protons, neutrons and pions) rapidly lose energy through multiple collisions with air molecules, and few reach the Earth's surface; but pions decay to muons (a kind of 'heavy electron') which reach the Earth at a rate of about one per square centimetre per minute. Muons also decay, into electrons. The major part of the cosmic ray exposure comes from muon collision electrons (electrons knocked out of their parent atoms by muons) and the electrons produced by muon decay. The global average effective dose equivalent from this source is estimated to be 0.3 mSv per person per year (Table 1).

Terrestrial radionuclides

The radionuclides potassium-40, uranium-238 and thorium-232 all have half-lives comparable with the age of the Earth ($\geq 10^9$ years) and they are distributed throughout the Earth's crust. Their concentrations vary from place to place, and in some areas the external exposure rate may be up to ten times the world average for this source, but these regions of high dose rate are estimated to contribute less than 10% to the global collective dose. Some typical concentrations in soil are given in Table 2, and some of the many exposure pathways from soil and rock to people are illustrated in Figure 2.

Table 2. Average activity concentrations of the major terrestrial radionuclides in soil, and corresponding absorbed dose rates in air 1m above the ground

Radionuclide or series	Average conc. in soil ($Bq\ kg^{-1}$)	Dose rate per unit conc. ($Gy\ h^{-1}/Bq\ kg^{-1}$)	Absorbed dose rate at 1m ($Gy\ h^{-1}$)
Potassium-40	370	4.3×10^{-11}	1.6×10^{-8}
Uranium-238	25	4.3×10^{-10}	1.1×10^{-8}
Thorium-232	25	6.6×10^{-10}	1.7×10^{-8}

Source: UNSCEAR 1982

The major exposure pathway is through inhalation of radon daughters resulting from the decay of radon gas. Radon is a chemically inert element and it can migrate to the atmosphere through the pore spaces in the medium in

which it is produced from its parent radium (see Table 2 and Figure 14, Chapter 1). Radon itself delivers a relatively small dose, but its daughter products include short-lived alpha-particle emitting radionuclides which can irradiate lung tissues (see Chapter 8).

For people not occupationally exposed to sources of uranium series radionuclides, most radon daughter exposure, about 90%, occurs indoors. Exposure rates indoors are typically higher than outdoors, and it is estimated that people spend about 80% of their time indoors. Most indoor radon emanates from the ground beneath the building and from building materials, although some gets in from the outside air and some is also dissolved in water supplies and released indoors. Daughters of both radon isotopes, ^{222}Rn and ^{220}Rn, contribute to the total exposure, but the thoron (^{220}Rn: see Table 4 and Figure 15, Chapter 1) component is only about one fifth of the ^{222}Rn exposure.

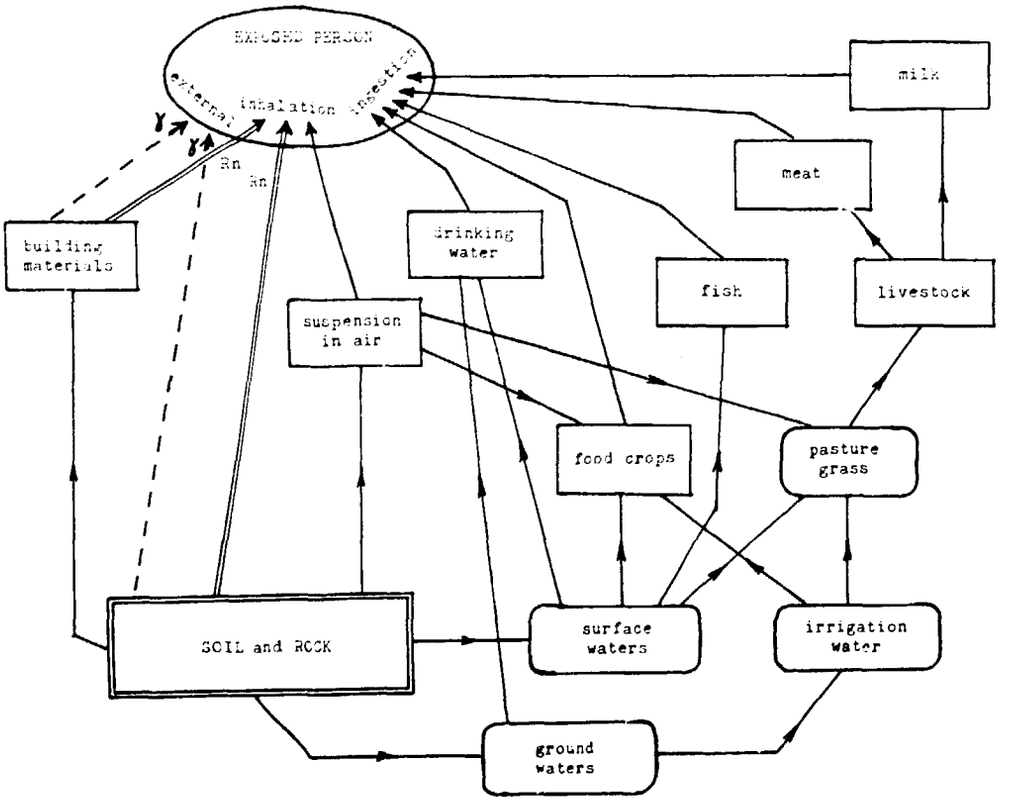

Figure 2. Some of the major exposure pathways for terrestrial radionuclides.

The magnitude of exposure rates in dwellings has been fully appreciated only in the last few years, and several studies, both overseas and in Australia, have been undertaken to establish more accurately the typical concentrations of radon and radon daughters indoors. Estimated global average equilibrium equivalent (see Chapter 1) concentrations of radon daughters are given in Table 3, together with corresponding estimated doses.

Table 3. Estimated equilibrium equivalent concentrations of radon and consequent average annual effective dose equivalents from inhalation of radon daughters.

		Equilibrium conc. ($Bq\ m^{-3}$)		Annual effective dose equiv. (mSv)	
		^{222}Rn	^{220}Rn	^{222}Rn	^{220}Rn
Indoors	Mean	15	0.7	0.9	0.2
	Range	5-60		0.3-3.7	
Outdoors	Mean	1.8	0.2	0.06	0.02
	Range	0.1-10		0.003-0.3	

Source: UNSCEAR 1982

A significant exposure pathway occurs through ingestion of potassium-40, which is present in stable potassium at about 0.01% by mass. Potassium is ubiquitous in nature, forming about 2% of the Earth's crust, and it is essential to human metabolism, forming about 0.2% of body mass. The modelling of intake by the ICRP using Reference Man (see Chapter 8), assumes a daily intake of 3.3g of potassium in food and fluids - corresponding to about 85 Bq of potassium-40 per day. The average annual effective dose equivalent from this source is estimated as 0.18 mSv.

Terrestrial radionuclides also contribute to external exposure through irradiation of the body by gamma rays. As for internal exposure, the major part of the dose is delivered indoors. Brick or concrete buildings typically provide good shielding against gamma radiation incident from outside, so that

indoor doses arise predominantly from the building materials. Average dose rates are estimated to be 20% higher than outdoors. The average annual effective dose equivalent due to external radiation from terrestrial radionuclides is about 0.35 mSv.

SOURCES ARISING INDIRECTLY FROM HUMAN ACTIVITY

There are some circumstances in which exposure to natural radiation is enhanced by human activity or technological development. Examples are: travelling by air, living in the neighbourhood of a coal-fired power station, and using phosphate fertiliser or building materials containing phosphogypsum.

Coal contains trace quantities of natural radionuclides. When burned, some of the combustion products, in particular the fly ash, may be carried through plant emission stacks to the atmosphere. Exposure can then occur either through inhalation of the dispersed aerosol or through ingestion of food affected by the deposition of radionuclides on edible crops or pasture grass. The global collective effective dose equivalent commitment (CEDEC: see Chapter 1) from this source is estimated as about 2000 person-sievert per year - which corresponds on average to less than 10^{-3} mSv individual effective dose equivalent per year.

Phosphate rock is a major source of phosphate fertilisers. It contains trace amounts of natural radionuclides which can find their way through the food chain. A major by-product of the processing of phosphate rock is phosphogypsum, which has been much used in building materials, such as plaster-board. The concentration of radionuclides in phosphogypsum is quite high (up to 1500 Bq kg^{-1} of radium-226, for example), and this pathway, via indoor irradiation and inhalation of radon daughters, is estimated to lead to a collective dose many times larger than that attributed to the use of phosphate fertilisers.

Exposure to cosmic radiation is enhanced by air travel. Absorbed dose rates at the cruising altitudes of jet aircraft may be 50 times greater than at ground level. A flight from Sydney to London could add about 50 μSv to a passenger's effective dose equivalent. This pathway is estimated to contribute about 2000 person-sievert per year to the global CEDEC - less than 10^{-3} mSv individual effective dose equivalent per year.

In total, the average collective dose arising from the sources described here is very much smaller than that received from natural sources, as outlined in the previous section.

SOURCES ARISING FROM HUMAN ACTIVITIES DIRECTLY ASSOCIATED WITH THE EXPLOITATION OF RADIOACTIVE MATERIALS OR RADIATION

Radiation and radioactive materials are exploited in many fields, such as: nuclear power, radiography, radiotherapy, radioactive tracers, smoke detectors, radioluminous products, anti-static devices and cardiac pacemakers. Each of these sources contributes in different measure towards the total human collective dose, though the largest by far is due to medical uses of radiation.

Medical sources

Most medical exposure arises from diagnostic radiography. Although radiotherapy administers very large individual doses, only a few people are so exposed, and the consequent collective dose is only a small fraction of that received by the very large number of people who undergo diagnostic radiography at much lower individual doses. Many reviewers of this field have expressed the view that there is a great potential for reduction of the collective dose which arises from medical exposure, through improved procedures and equipment, or by using alternative techniques, such as ultrasound. In total, the average dose due to medical exposures is believed to be about 20% of the average dose from natural sources, that is about 0.4 mSv per year.

Nuclear fuel cycle

Recent estimates of the world's energy production suggest that nuclear power contributes about 15% of the world's electrical power generation, through about 350 reactors in 26 countries, with a further 180 reactors under construction. Projections to the year 2000 suggest that about one quarter of the world's electricity needs will then be met by nuclear power.

The generation of nuclear power involves many steps in handling and processing radioactive materials, and at each stage some release to the environment may occur. Mining and milling operations are discussed in a later section; other processes include chemical treatment of the uranium mill product, enrichment of the uranium-235 component, fabrication of fuel elements, production of power in nuclear reactors, disposal or reprocessing of spent fuel rods, and management of wastes arising from the industry. The

contribution to the global average collective effective dose equivalent commitment from these sources is of the order of 10^3 person-sievert per year, with about half coming from reactor release of carbon-14 to the atmosphere. This is equivalent to an individual average annual effective dose equivalent of about 10^{-4} mSv, predicted to rise to about 10^{-3} mSv by the end of the century.

Fallout from nuclear weapons testing

Through the 1950's and early 1960's atomic weapons were frequently tested in the atmosphere, causing a world-wide dissemination of radioactive fallout. The most significant radionuclides remaining are carbon-14, caesium-137 and strontium-90. The collective effective dose equivalent commitment (over thousands of years) from intake of fallout radionuclides is estimated to be 3×10^7 person-sievert, implying an individual annual effective dose equivalent of $\sim 10^{-2}$ mSv, which is gradually decreasing over the years. In Australia, there are potential sources of exposure at abandoned nuclear weapons test sites, but the contribution to global collective dose is minute.

Occupational exposures

There are several groups of workers who are occupationally exposed to radiation, such as: uranium miners, mineral sands miners, nuclear power plant workers, industrial radiographers, medical radiographers and nurses in nuclear medicine wards. There is a very wide variation of doses received both between groups and within job categories. Some doses are extremely high - usually these are the consequence of an accident involving radioactive sources or radiation sources. The irregularity in doses makes it difficult to estimate meaningful averages for occupational exposure, but for those workers directly involved with radiation sources or radioactive materials the average annual effective dose equivalent is believed to be a few mSv.

In the case of workers in the nuclear industry, most exposures come from reactor operation and fuel reprocessing, with less than 5% of the total estimated collective occupational dose arising from mining and milling operations. Past experience suggests that occupational doses received by nuclear industry workers are distributed approximately log-normally*, with very few doses exceeding 50 mSv per year.

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* A variable X is said to be distributed log-normally if the values of $y = \ln X$ are distributed normally, that is they form a normal, or Gaussian, distribution.

SOURCES OF EXPOSURE ARISING FROM THE MINING AND MILLING OF RADIOACTIVE ORES

Uranium mining

Australia produces about 4000 tonnes of uranium oxide per year at a value of about $300M (1987) on the export market. There is one active above-ground mine and one underground mine. Two mills are in production, with a third currently being commissioned, almost coincidentally with the imminent decommissioning of one of the existing mills. There are many sites of

Figure 3. Major sites of active and proposed uranium mines.

economically recoverable ore (Figure 3) estimated at over 500,000 tonnes, but further development in the industry is unlikely in the near future, while market conditions and Government policy are unfavourable.

Both types of mining lead to radiation exposure. The three major exposure pathways are external irradiation from the ore, inhalation of radon daughters, and inhalation of radioactive dusts. The relative magnitudes of these components vary between mines and from place to place within a mine site.

Above-ground, or open-cut, mining involves explosive blasting of a mineralised rock deposit to release the ore, collection of broken rock by scoop or front-end loader, and transport to the mill stockpile by truck. Removal of the ore proceeds bench by bench as the pit grows (Figure 4). The latter operations may be carried out from within air-conditioned cabins, which reduce concentrations of radon daughters and dust, and which afford some shielding from external radiation. However, some of the drilling operations, placement of charges and other mine activities require occupation of the mine pit for extended periods, and for those workers absorbed doses may be high and radon daughter exposures may be substantial, although radon daughter concentrations at Australian open-cut mines have been found to be quite low (Leach et al 1980).

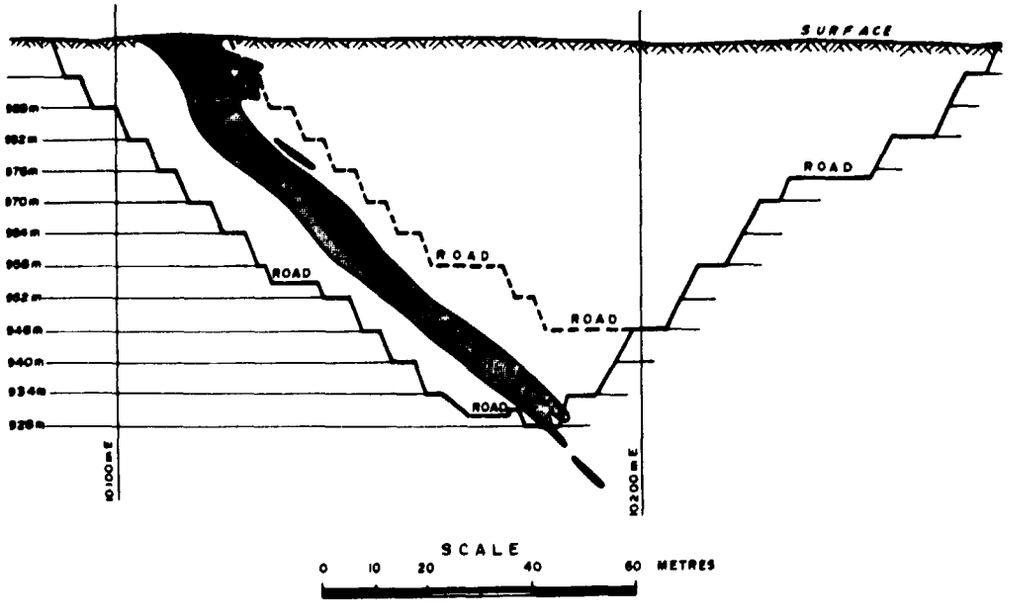
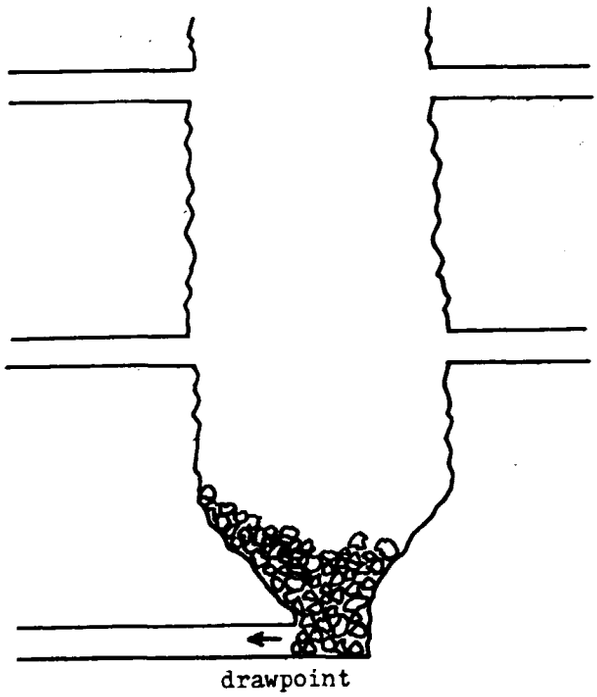
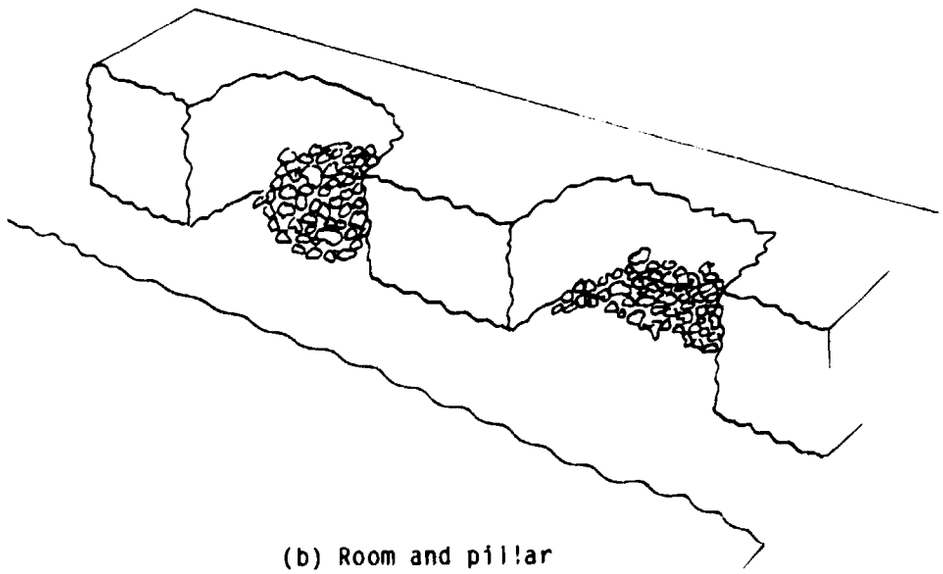


Figure 4. Cross section through open-cut uranium mine.

In underground mines, both radon daughter concentrations and absorbed dose rates have the potential to be high, depending on the ore grade being mined. Again, those workers occupying air-conditioned cabins on drilling machines and earth-moving vehicles are afforded some protection from radiation. Adequate ventilation of the mine is required to ensure acceptably low concentrations of radon daughters (see Chapter 14), and occupancy may need to be restricted in areas of high ore grade to limit absorbed doses. Ventilation design and performance is a key concern of the Radiation Safety Officer at an underground mine (Sonter, 1987). Dust inhalation may be significant following blasting, at ore collection points and near ore crushing stations (Figure 5).



(a) Open stoping



(b) Room and pillar

Figure 5. Underground mining methods.

Most uranium mills use an acid leach process similar to that illustrated in Figure 6. The ore is crushed wet to a slurry and passed to leaching tanks. Acid leaching takes about 24 hours, then the uranium-bearing solution (pregnant liquor) is separated from the solid tailings by counter-current decantation and passed to a solvent extraction process. The uranium is transferred from the loaded solvent to an ammonium sulphate solution from which it is precipitated as ammonium diuranate by addition of ammonia. The diuranate is then dried and calcined (roasted in a furnace) to drive off the ammonia, leaving a uranium oxide product containing in excess of 90% U_3O_8. Apart from the initial crushing stage, all subsequent processing up to the calciner involves wet chemistry in sealed vessels or water-covered tanks. Consequently, there is very little release of dust or radon in the mill. A potential for dust raising occurs at the calcining stage and in product packing, but these operations are normally controlled remotely or automated, requiring very little human occupancy of those areas. As most of the gamma flux from the ore comes from radon daughters, once the tailings have been separated from the process stream, absorbed dose rates in the latter stages of the mill are moderate. Average annual effective dose equivalents at one Australian mill have been estimated at between 1 mSv for office workers, storemen, etc and 15 mSv for mill operators and maintenance staff, with up to 26 mSv being received by a small group of sample preparers (Marshman, 1983).

An alternative extraction method is based on leaching with sodium carbonate, but handling of ore and intermediate products would be similar to the acid leach process, as would radiation exposure conditions. In-situ leaching has been proposed for one Australian site (Honeymoon) and, while this raises environmental issues related to the possible release of radionuclides into ground waters, the milling side of the process would be similar to that described above.

Associated with a mine and mill complex are various other sources of exposure, including stockpiles, waste rock piles and tailings disposal areas. All are potential sources of radon and radon daughters, and those that are left after decommissioning of the mill - waste rock and tailings - create a source of potential long-term exposure of members of the public from radon daughters and surface-water or ground-water pathways (see Chapter 9). During operation, the major pathway for public exposure from a mine and mill having an effective water-management program is likely to be radon daughter inhalation arising from the atmospheric dispersal of radon from the large areas of exposed ore, waste rock and tailings.

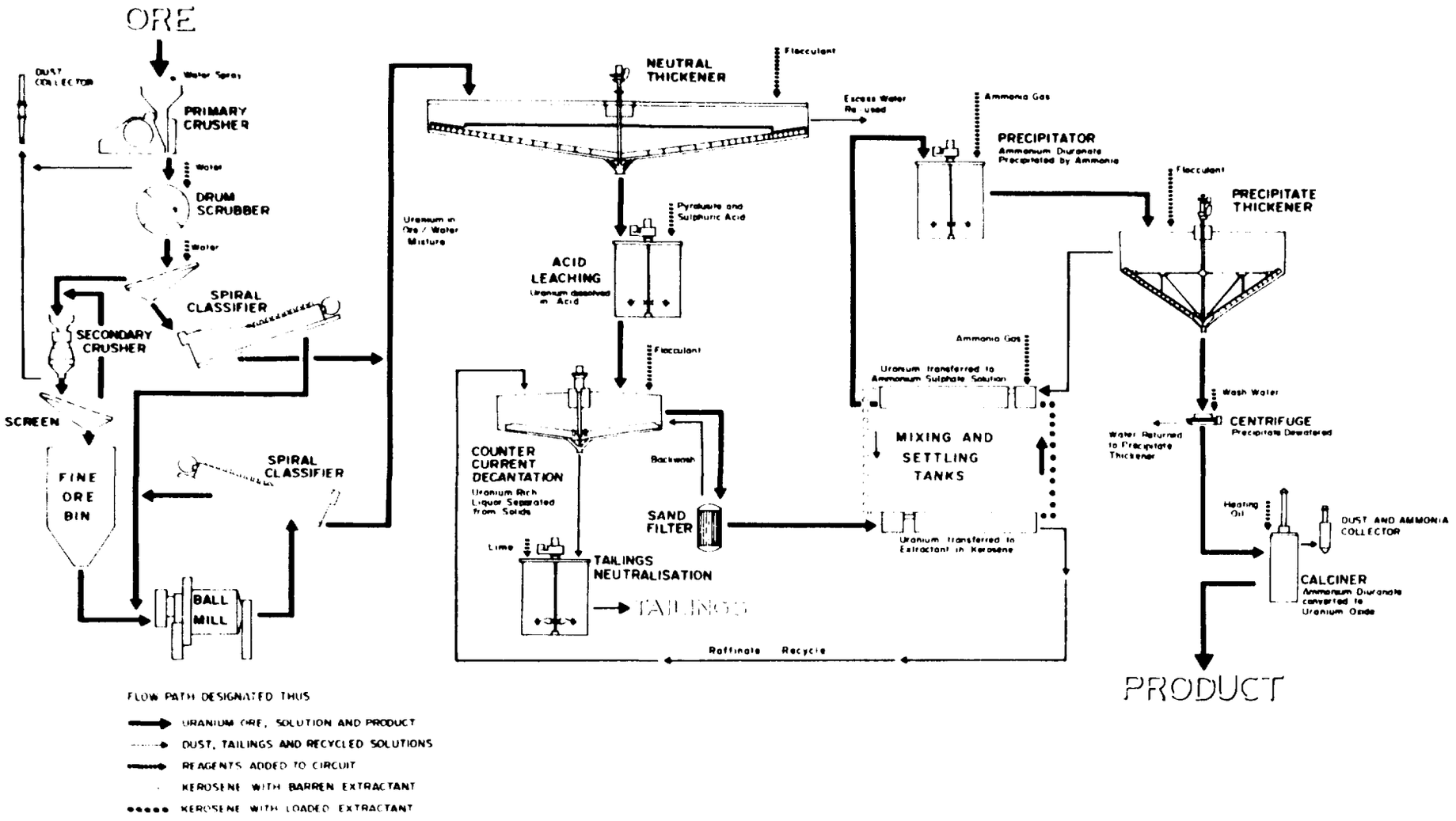


Figure 6. Outline of typical uranium extraction process.

Mineral sandmining

Australia is a major producer and exporter of minerals derived from sandmining operations on the West and East coasts (Figure 7). The most significant minerals are ilmenite, rutile, zircon and monazite (Table 4).

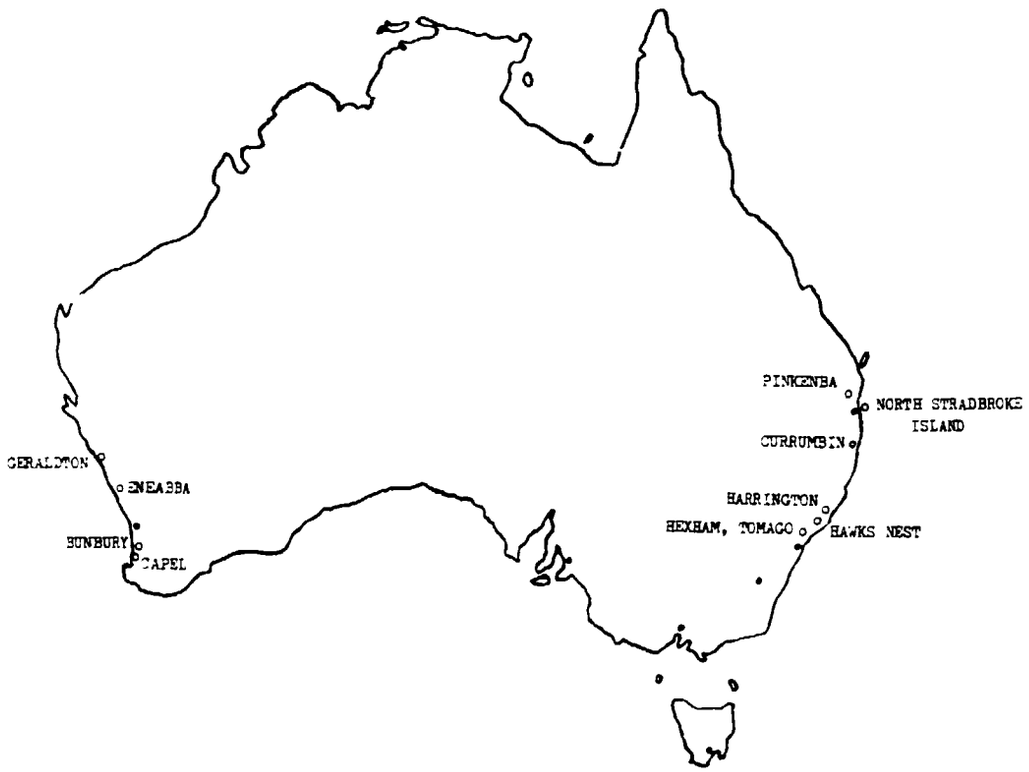


Figure 7. Sites of mineral sands mining and processing.

Table 4. Australian mineral sands production

Mineral	Economic reserves		Annual production		
	(thousand tonnes)	% of world resources	(thousand tonnes)	% of world production	value ($)
Ilmenite	40,000	5	1,200	19	41M
Rutile	8,000	6	190	47	51M
Zircon	11,500	26	440	61	55M
Monazite	217	3	18	60	7.6M

Total export earnings: $160 million per year (1984).

All of these minerals contain small impurities of thorium and uranium series radionuclides, the most active by far being monazite which contains 6-7% thorium-232. Monazite is mined mainly for its content of rare-earth elements, including lanthanum, cerium, neodymium, gadolinium, dysprosium, yttrium and europium, used in various applications in the electronics, metallurgy, ceramics and chemical industries. However, the rare-earths are not, at present, extracted in Australia, and the monazite is exported as a radioactive mineral product.

The minerals occur naturally as small grains in beach sand. Mine sites on the West coast lie on pre-historic beach sands, several kilometres from the present coastline, and mining is typically by scraper or bucket wheel. On the East coast, mine sites are near the coastline or on offshore islands and some of the mining is by underwater dredge. A primary concentration process at the mine site removes much of the silica sand by wet gravity separation (Figure 8). There is little of radiological significance to this point in the process, as the concentration of radionuclides in the ore as mined is very low.

The primary concentrate, which typically may contain about 1% monazite, is transported to a secondary separation plant, which is often remote from the mine site. It is at the secondary, or dry, separation stage that radiation exposures become significant, principally from inhalation of radioactive dust and external irradiation by gamma rays.

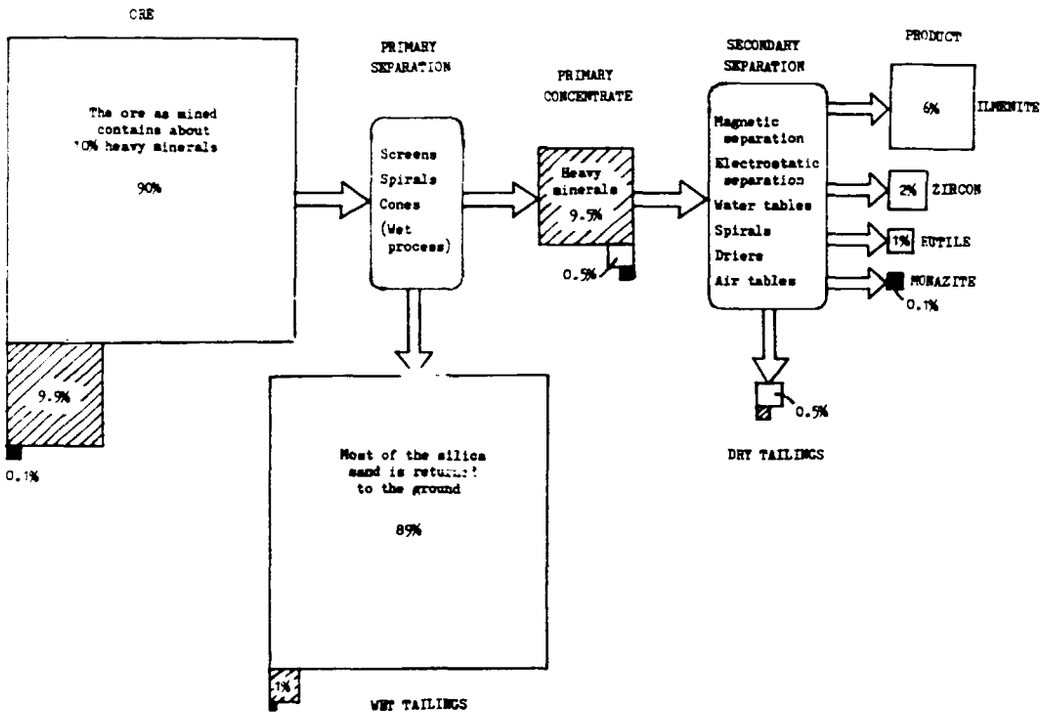


Figure 8. Outline of mineral sands processing.

Separation of the primary concentrate into the various mineral products exploits differences in their densities and electrical and magnetic properties (Figure 9). Differences in electrical conductivity permit some minerals to be separated in high electric fields - rutile is more conducting than zircon and monazite, for example (Figure 10a). Differences in magnetic susceptibility allow the more magnetic minerals - for example, ilmenite - to be separated from the less magnetic (Figure 10b). Differences in density allow both wet and dry gravity separation (Figure 10c).

All of these proceses, apart from wet gravity separation, require a very dry process material for efficient separation. The feed to the separation equipment is in a spatially dilute form to allow each grain to feel the effect of the applied electric, magnetic or gravitational field. As the efficiency of any one separation stage is rather poor, many stages are required and multiple passes of product streams may be necessary to reach an acceptable purity of mineral product. A consequence of the machine handling of hundreds of tonnes a day of such material is that copious dusts are raised, which may be inhaled by plant workers.

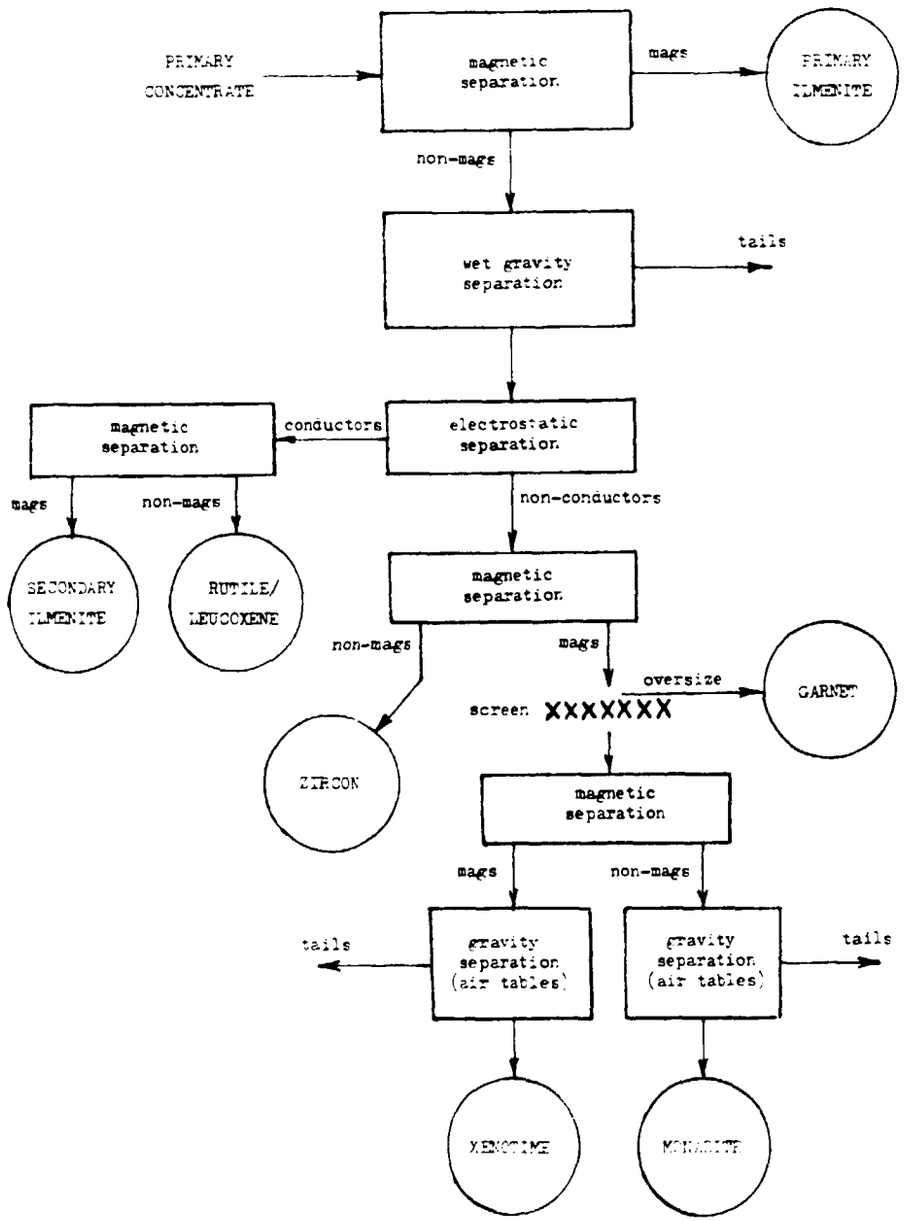
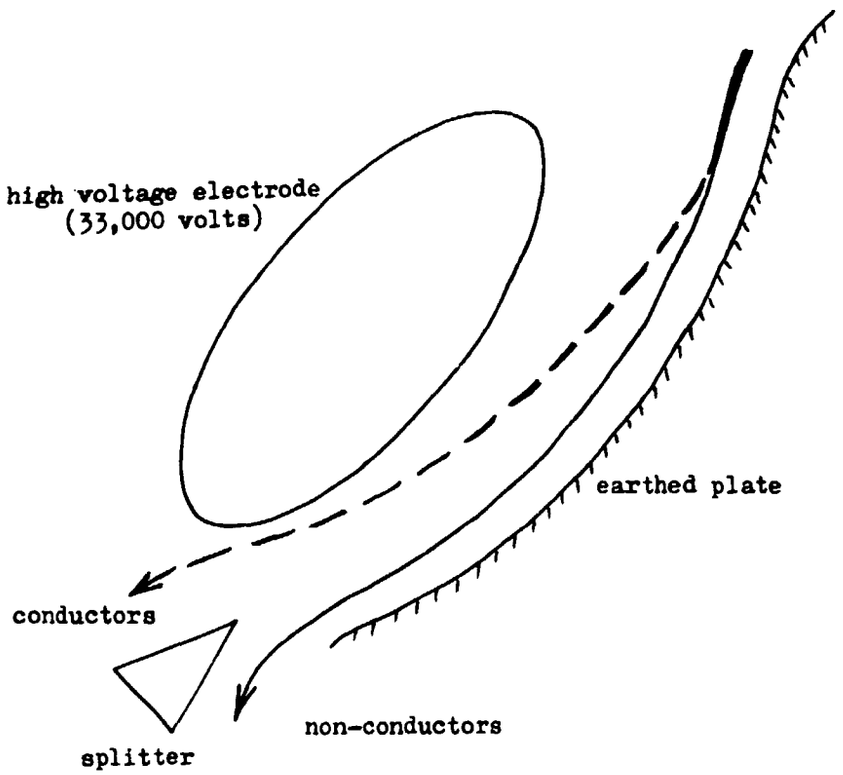


Figure 9. Secondary separation of mineral sands (schematic illustration)

(a) ELECTROSTATIC SEPARATOR



(b) CROSS BELT MAGNETIC SEPARATOR

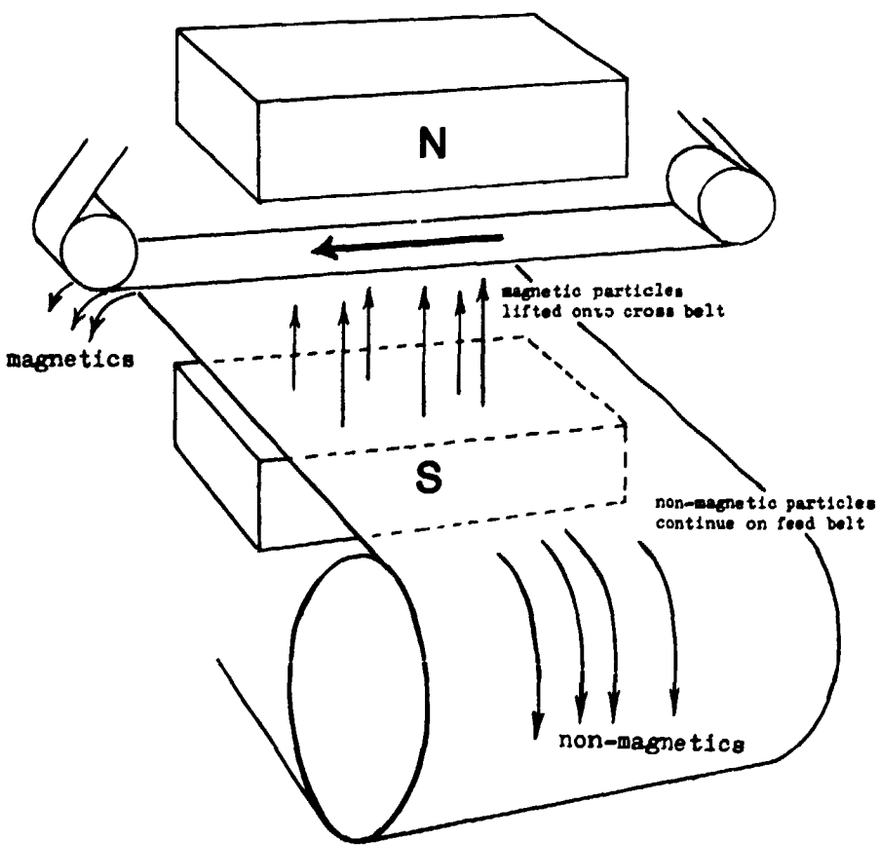


Figure 10. Mineral sands separation techniques

(c) AIR TABLE SEPARATOR

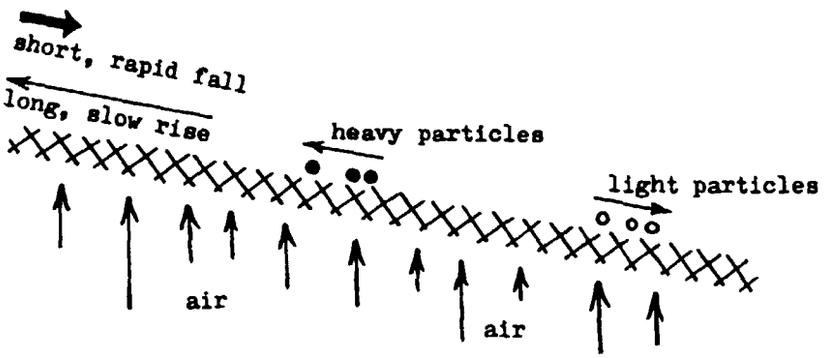


Figure 10. (cont.)

Radionuclide concentrations in airborne dust near monazite processing streams are high (Mason et al 1984) and they are typically quite significant throughout the dry separation plant. In addition, absorbed dose rates near monazite bagging and storage areas are high (Figure 9). Thus special precautions are required in those areas, such as restricted occupancy, ventilation control or wearing of dust masks. Thoron and radon concentrations are quite low. It is this occupational exposure that is of prime concern radiologically.

Public exposures could arise from the dispersal of material off site. Tailings from a mineral sands operation are normally of little radiological consequence, as most of the activity has been removed with the monazite and zircon. The small quantities of active tailings from the latter stages of separation can be effectively disposed by dilution with primary tailings. A possible pathway for public exposure is through windblown material from dry stockpiles of active mineral. The major pathway in the past has been due to improper use of mineral sands products and tailings. There have been many instances of active tailings being used for domestic or commercial landfill - some of these have subsequently required remedial action. Also, until recently, an active garnet product derived from mineral sands processing has been used as a sandblasting grit (Wallace and Leach 1987). Neither of these pathways should occur in the future if relevant State regulations are observed.

SUMMARY

The mining and milling of uranium ore and processing of mineral sands creates several sources of exposure of people employed in those industries and, in some cases, of members of the public. Properly identified, monitored and assessed, the pathways for human exposure can be controlled to limit the doses received to acceptable levels.

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