OLYMPIC DAM EXPANSION

DRAFT ENVIRONMENTAL IMPACT STATEMENT 2009

APPENDIX S
URANIUM AND RADIATION

bhpbilliton
resourcing the future

ISBN 978-0-9806218-0-8 (set)
ISBN 978-0-9806218-4-6 (appendices)

APPENDIX S

URANIUM AND RADIATION

CONTENTS

Review of the Draft Environmental Impact Statement for the Olympic Dam Development Study

by

Anthony David Wrixon B.Sc., D.Phil., F.Inst.Phys.

Vienna, December 2008

1. INTRODUCTION

I have prepared this report at the request of Arup, who are working under contract to BHP Billiton Olympic Dam Corporation Pty Ltd. to carry out certain consultancy services in connection with the Environmental Impact Statement of the Olympic Dam Expansion. Arup are responsible for some of the infrastructure studies and the Environmental Study component of the Pre-Feasibility Study for the Olympic Dam Development Project. The Core Services of this contract relate to the progression of the Environmental Impact Statement (EIS).

I was specifically requested to undertake a peer review of the methodology used in the estimation of doses in the radiation safety part of the draft EIS.

The contract was in two stages. In the first stage, which was completed in August 2008, detailed comments were provided on drafts of Chapter 22, Appendix S and the Technical Supplement to Appendix S. These were taken into account in the preparation of the following documents which were considered in the second stage:

- Chapter 22 on Health and Safety (RevS. Dec. 08) which contains a section on radiation;
- Appendix S on Uranium and Radiation (14 Nov. 08);
- Technical Supplement to Appendix S (Radiation) of the ODX EIS (latest, Dec. 08); and
- Mine and Plant dose spreadsheets for the current mine and plant for the period 2000-2007.

The focus of the work was on the second and third of the above documents – the Appendix S and its Technical Supplement.

2. BASIS OF THE REVIEW

In undertaking this review, I took account of:

- the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Safety Series No. 115, 1996) and related Safety Standards of the International Atomic Energy Agency;

- the recommendations of the International Commission on Radiological Protection, specifically ICRP Publications 60 and 103; and

- my own personal experience having been involved in radiation protection for more than 35 years.

In addition, I took account of the Code of Practice and Safety Guide on Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

3. FINDINGS

I have thoroughly reviewed the methodology used in the assessment of doses to workers and members of the public from the proposed new facility.

The exposure pathways considered for workers were:

- external gamma radiation;
- inhalation of radon decay products; and
- inhalation of radioactive dusts.

The exposure pathways considered for members of the public were:

- inhalation of radon decay products;
- inhalation of radioactive dusts;
- external gamma radiation from deposited radionuclides and;
- ingestion of water and foodstuffs from deposited radioactive dusts.

I conclude that the overall approach to the assessment of doses from the proposed expansion is acceptable. To the extent that I am able, I have repeated the calculations of doses and can confirm that the assessed doses have been based on cautious assumptions and therefore, if anything, are likely to be overestimates.

17th December 2008

PO Box 515
McLaren Vale
South Australia
Australia 5171

December 16, 2008

Mr. J. Hondros
ARUP

Dear Jim

I have carefully reviewed the radiological parts of Chapter 22 (Health and Safety) and Appendix S (Uranium and Radiation) of your current EIS draft .

I find that Chapter 22 addresses satisfactorily the radiological consequences of the Olympic Dam expansion.

I have examined Appendix S in detail and have confirmed to my satisfaction all of the numerical estimates of doses associated with the expansion.

I am happy therefore to support the dose findings and conclusions of both for the proposed expansion.

Yours sincerely

KH Lokan.

Dr. K. H. Lokan

APPENDIX S1

Introduction to radiation

PREFACE

Many of the concerns regarding the mining and processing of ores containing uranium stem from the fact that uranium is radioactive: that is, it emits radiation. The potential consequences of this include radiation exposure to workers and the public, radioactive material entering the environment and the requirement to manage the resulting radioactive wastes. Summaries of these issues are provided in the Draft EIS and discussed in more detail in this appendix.

This appendix is provided in three parts:

- Part one describes the basic principles of radiation, particularly in relation to mining and mineral processing. Current knowledge on the effects of radiation on health and the principles of radiation protection are also described.
- Part two discusses the predicted radiation doses to workers and the public from the proposed expanded Olympic Dam operation.
- Part three gives outlines of the models used to calculate the predicted doses.

S1 INTRODUCTION TO RADIATION

S1.1 ATOMS, ISOTOPES AND RADIOACTIVE DECAY

All matter is made of atoms. Atoms are made up of protons and neutrons constituting a nucleus, and electrons orbiting around the nucleus. In a normal (un-ionised) atom the number of protons equals the number of electrons, and this number determines the chemical nature of that element (see Figure S1.1)

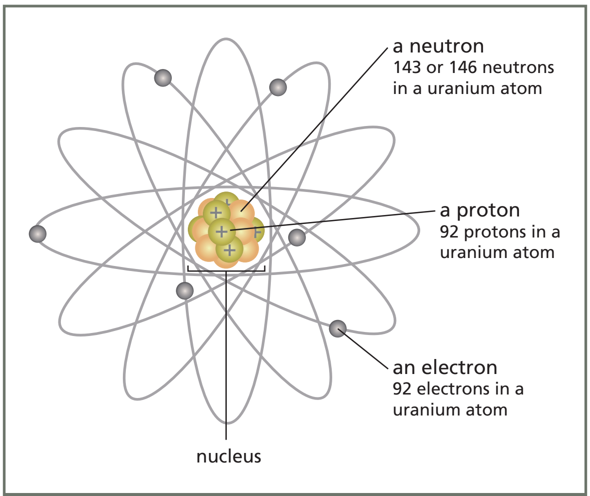


Figure S1.1 A uranium atom

Atoms of the same chemical type can have different numbers of neutrons in their nuclei. These are called isotopes of the element. Some isotopes are unstable, and will spontaneously emit radiation in the form of subatomic particles or electromagnetic energy, and form a lighter nucleus. This process is called radioactivity, and the atoms that undergo it are called radioactive. There are radioactive forms (called radioisotopes or radionuclides) of all elements. For example, lead has 27 different isotopes, of which 23 are radioactive and four are stable (non-radioactive). Most radioisotopes are produced artificially, usually in nuclear reactors, but there are also many naturally occurring radioisotopes. All isotopes of elements heavier than bismuth are radioactive.

Isotopes are written with their chemical symbol and the total number of protons and neutrons in their nucleus (the mass number). Thus the most common isotope of uranium, with 92 protons and 146 neutrons, can be written as ^{238}U or uranium-238.

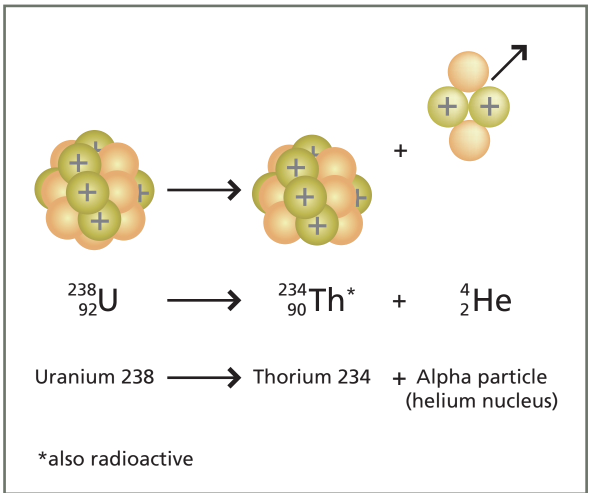


Figure S1.2 Radioactive decay

Different radioactive isotopes emit radiation at different rates. The breakdown (or decay) of radioactive atoms reduces the number remaining, so that the amount of radiation emitted continually reduces (see Figure S1.2). It is convenient to describe the rate of reduction by the 'half-life'. This is the time taken for one half of the radioactive atoms to decay away, and thus also the time for the rate of radiation emission to decrease to one half of its original value. Each radioactive atom has its own half-life, which is fixed, and cannot be changed. Half lives of naturally occurring radioisotopes range from fractions of a second to billions of years. The half life of ^{238}U is 4.5 billion years, one of the longest known.

The decay of a radioisotope with a half-life of 20 days is illustrated in Figure S1.3. An initial 1,000 atoms has been reduced to 500 atoms after 20 days, to 250 atoms after 40 days, and to 125 atoms after 60 days.

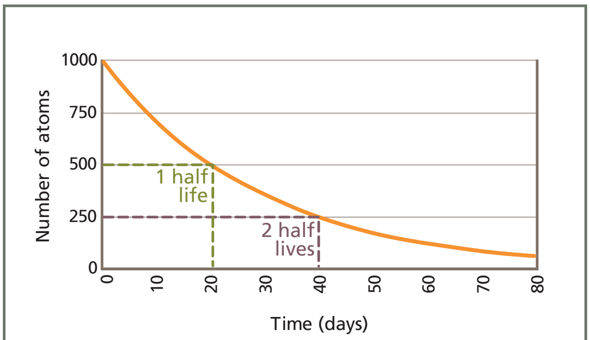


Figure S1.3 Decay of a radioactive isotope with half life of 20 days

When a radioactive atom decays, the new atom formed may itself be radioactive, which might in turn decay to another radioactive atom. For example, in Figure S1.2 above, the ^{234}Th formed from the decay of ^{238}U is also radioactive, and subsequently decays. Such chains of radioactive decay are called 'decay series' or 'decay chains' (see Figure S1.4).

S1.2 URANIUM

Uranium is a naturally occurring heavy metal. It is widespread in Earth's crust, and present in almost all normal soils with an average concentration of about three parts per million (ppm). The best known property of uranium is its radioactivity.

Like all elements, uranium has different isotopes, which are species that have different numbers of neutrons in their nuclei. The most common is uranium-238 (^{238}U) with 92 protons and 146 neutrons, and it makes up more than 99% of natural uranium (by weight). With 92 protons and 143 neutrons, ^{235}U is the next most abundant, with 0.7% by weight.

Uranium mined in Australia is used only in nuclear power reactors (see Section S 1.7). The rare ^{235}U is essential for the operation of such reactors, and the concentration of ^{235}U must usually be increased from 0.7% to about 3% by the process of enrichment before it can be used for that purpose.

The isotopes of the elements formed by the decay of ^{238}U are themselves radioactive, and so form a decay series, ending with the stable (non-radioactive) lead-206. There are 14 radioactive decay products in the series, which is shown in Figure S1.4. Uranium ore contains all of these radioisotopes and they all have different properties. The radiation emitted by all of these needs to be taken into account when considering the radiation exposures that may occur in uranium mining and processing. Uranium-235 and its decay products are also present in the ore, but its relative abundance is so low that they make only a very small contribution to the overall radiation levels.

Type of decay	Nuclide	Half-life
alpha	uranium-238	4.5×10^9 years
beta	thorium-234	24.1 days
beta	protactinium-234	1.17 minutes
alpha	uranium-234	2.4×10^5 years
alpha	thorium-230	7.7×10^4 years
alpha	radium-226	1.6×10^3 years
alpha	radon-222	3.8 days
alpha	polonium-218	3.05 minutes
beta	lead-214	26.8 minutes
beta	bismuth-214	19.9 minutes
alpha	polonium-214	1.64×10^{-4} secs
beta	lead-210	22 years
beta	bismuth-210	5 days
alpha	polonium-210	138 days
	lead-206	stable

adapted from www.uic.com.au

Figure S1.4 Decay of uranium 238

Uranium is extracted from ore by physical and chemical processes. The processes aim to remove only the uranium isotopes, leaving all other radioisotopes in the waste (tailings). As some of these radioisotopes have very long half-lives (^{230}Th half-life is 77,000 years), the tailings will remain radioactive for hundreds of thousands of years, decreasing over time.

S1.3 IONISING RADIATION

The type of radiation emitted by radioactive material, including uranium and its decay products, is called ionising radiation because it is able to ionise material through which it passes. This means that it will produce charged particles called ions as it passes through matter. Ionising radiation is distinguished from non-ionising radiation, which does not have sufficient energy to produce such ions. Examples of non-ionising radiation include microwaves, ultra-violet radiation, infra-red radiation, lasers and radio waves, including those from mobile phones. Non-ionising radiation is entirely different from ionising radiation, arises from different sources, and any health effects it may produce arise from entirely different mechanisms. This appendix is concerned only with ionising radiation, and wherever the term radiation is used, it is referring to ionising radiation.

S1.3.1 Types of radiation

There are three types of radiation emitted by naturally occurring radioisotopes: alpha, beta and gamma radiation (see Figure S1.5, S1.6 and S1.7).

- Alpha radiation consists of streams of alpha particles, which consist of two protons and two neutrons bound together. Alpha particles are relatively heavy and slow moving. Their range in air is only a few centimetres and they are not able to penetrate matter to any significant extent. For example, they cannot penetrate a sheet of paper or the outer (dead) layer of the skin. Inside their range they ionise very heavily (i.e. they produce a dense trail of ionisation) when they pass through matter. To be a health hazard, alpha emitters need to be inside the human body to irradiate sensitive cells.

- Beta radiation consists of high-energy electrons. They have moderate penetration, typically (for ^{238}U decay products) about one metre in air and a few millimetres in water or tissue. Because of their relative short range, most of the ionisation from external beta radiation occurs in the skin cells. However, irradiation of internal cells can occur if the source is within the body.
- Gamma radiation is not a particle but an electromagnetic wave similar to light and X-rays but of much higher energy. Gamma rays are generally able to penetrate up to several centimetres of metal or 10 cm of concrete, and usually pass right through the human body.

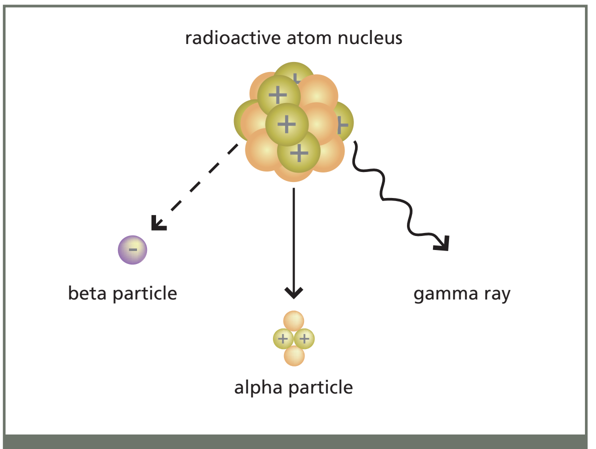


Figure S1.5 Alpha, beta and gamma radiation

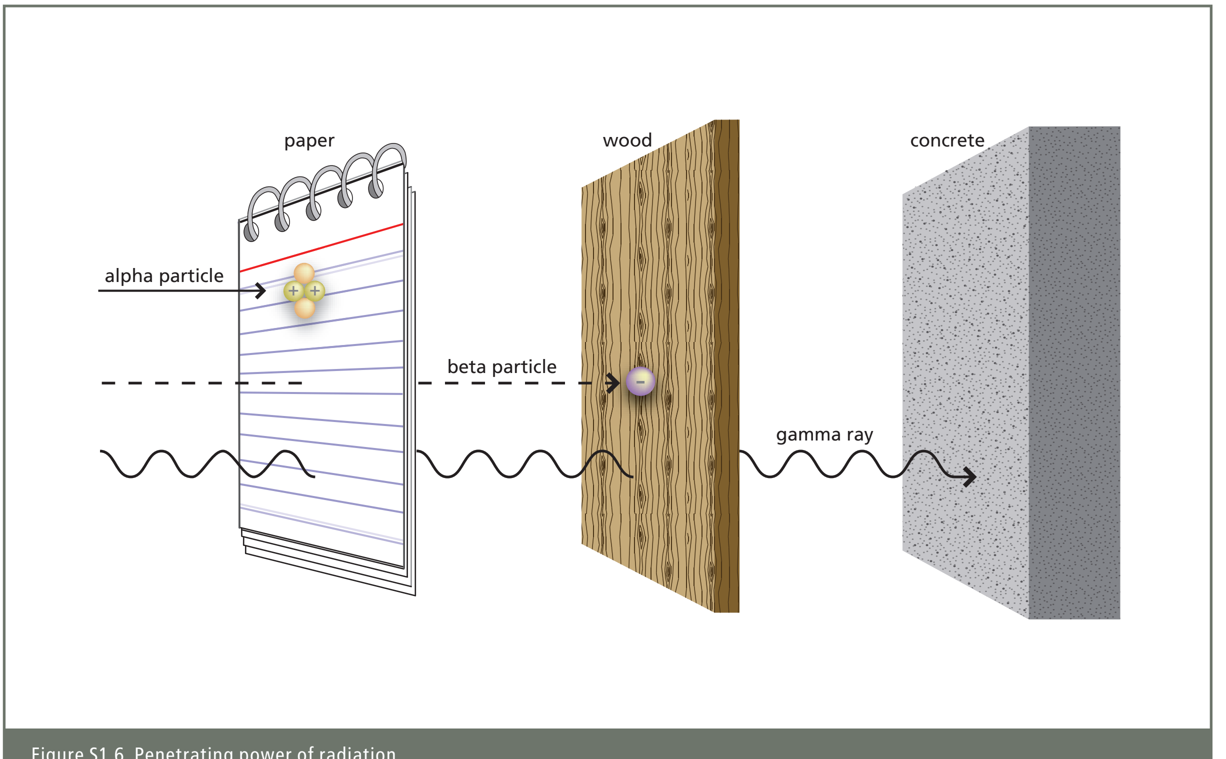


Figure S1.6 Penetrating power of radiation

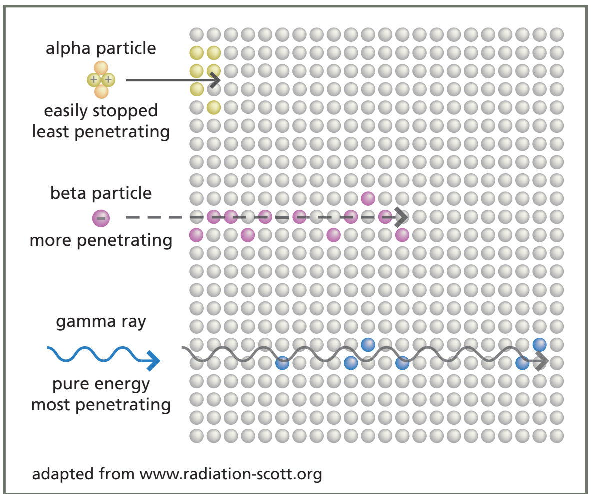


Figure S1.7 Radiation penetration in matter

S1.3.2 Radiation exposure pathways

Radiation exposure can occur only when there is a pathway or exposure route between the radioactive material and the person exposed. There are two general types of exposure: external and internal.

External exposure occurs when the source of radiation is outside the body. Examples include exposure received during a medical X-ray examination, or gamma radiation received by standing near radioactive ore. Because alpha radiation cannot penetrate the skin, it cannot be a source of external radiation. In uranium mining and processing, gamma radiation is the dominant form of external radiation.

Internal exposure arises from radioactive material inside the body. The most common ways that radioactive material enters the body are by inhalation or ingestion (swallowing), with less common ways of entry through wounds and skin absorption. Once inside the body (the lung or the gut), the radioactive material may be absorbed into the bloodstream and transported around the body. Some radionuclides are quickly excreted, but others may be absorbed by various organs and retained for long periods, so that internal exposure can continue long after the initial intake. In contrast, external exposure ceases as soon as the source is removed.

Some of the pathways between the source and the person exposed may be complex. For example, radioactive dust may be deposited on grasses or plants that are then eaten by cows, and the radionuclides may be excreted in milk, which may subsequently be consumed by people.

S1.3.3 Radiation measurement and units

Two types of radiation quantities are used widely in radiation protection. One refers to the amount of 'radioactive material' in a sample. The other refers to the amount of 'radiation' received at a point. They are quite different and there is no simple relationship between them.

Activity

Activity is the measure of the amount of radioactive material. Its unit is the becquerel (Bq), which is defined as the amount of radioactive material that produces one radioactive decay per second. It may be applied to either a single radionuclide, or to a mixture. The activity concentration is the amount of radioactivity in a unit mass (or volume) of material and is measured in becquerels per gram (Bq/g) or per litre (Bq/L).

As an example, the total activity (all ^{238}U series radionuclides) in 1 g of typical Olympic Dam ore is about 80 Bq, of which 6 Bq is from ^{238}U. In comparison, the activity concentration of ^{238}U in normal soil is about 0.03 Bq/g.

Uranium has a number of radiological decay products. In Olympic Dam ore, the decay products are in secular equilibrium with the uranium, that is, the activity of each of the decay products is the same.

Dose

Dose refers to the amount of radiation received at a point or to a person. The main two measures of radiation dose are called *absorbed dose* and *effective dose*.

Absorbed dose refers to the physical amount of ionisation produced in matter by the radiation, as might be directly measured by an instrument such as a Geiger counter. The unit of absorbed dose is the gray (Gy). Absorbed dose may refer to the dose to an object, a person, or parts of a person (organs or tissues).

Effective dose includes factors that take account of the biological effects of radiation on a person. These factors include the type of radiation (alpha, beta or gamma) and the different sensitivities of organs or tissues to radiation. The unit of effective dose is the sievert (Sv). For whole body gamma radiation the absorbed dose (in Gy) equals the effective dose (in Sv).

The effective dose (Sv) gives a measure of the effect (or 'detriment') of radiation on the human body. One mSv has the same detriment no matter if it is, for example, 1 mSv of gamma radiation to the whole body, or 1 mSv to the lung only, or any combination. The limits on dose (to people) that are most relevant in uranium mining are expressed in terms of effective dose, and where the term 'dose' is used alone, 'effective dose' is usually meant. Dose can refer to either internal or external exposure, or a combination of both.

The sievert is quite a large unit of measure, and doses are usually expressed in millisieverts (mSv), thousandths of a sievert. As an example, typical natural background radiation in Australia results in an annual (effective) dose of about two millisieverts (2 mSv).

S1.3.4 Natural background radiation

Radiation is very common in nature and everyone is exposed to natural radiation throughout their life (see Figure S1.8). This radiation comes from the rocks and soil of the earth, the air we breathe, water and food we consume, and from space. Exposure to this radiation is from both external and internal sources.

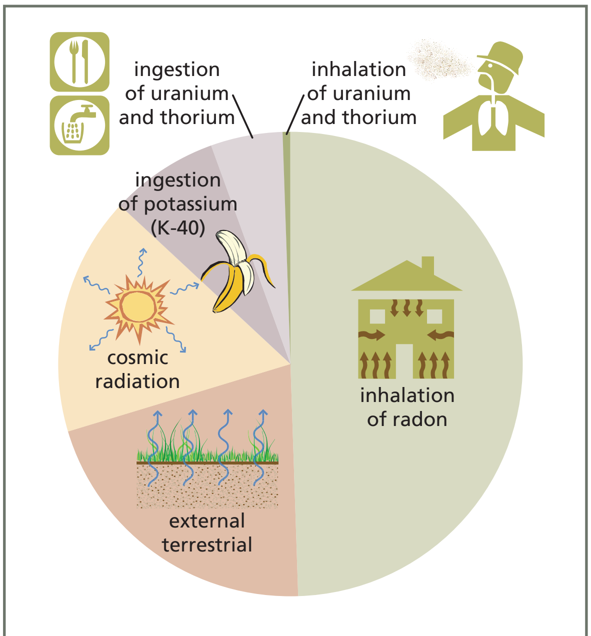


Figure S1.8 Sources of radiation doses

External radiation

The main two sources of external background radiation are cosmic rays and gamma radiation from soil.

Cosmic radiation is a form of ionising radiation that comes from outer space. The atmosphere provides shielding against cosmic rays, and consequently cosmic ray exposure is higher at higher altitudes. Aircrew who regularly fly at high altitudes can receive significant doses of cosmic radiation.

Almost all normal soils naturally contain uranium, thorium and potassium. The average uranium and thorium soil concentrations are approximately 3 ppm and 10 ppm respectively. Both of these have gamma-emitting radionuclides in their decay series, and so contribute to external radiation levels. In addition, one of the isotopes of potassium, K-40, is radioactive, emitting both gamma and beta radiation, and this also contributes to the external dose rate.

In several parts of the world, soils naturally contain much higher concentrations of radionuclides. This is particularly so of thorium, and some parts of Brazil and southern India have quite high natural external dose rates for this reason (UNSCEAR 2000c).

Internal radiation

Naturally occurring radionuclides can enter the human body through inhalation and ingestion.

The largest internal natural background dose generally comes from the inhalation of radon decay products. Radon is a member of the uranium decay series, being formed directly from the decay of radium in the soil. Being a gas, radon can diffuse from the soil and enter the atmosphere, but normal atmospheric mixing keeps concentrations quite low. However, if radon diffuses into an enclosed space, such as a house from the soil below, it may be trapped and build up to high levels. This is particularly so if there are cracks in floors or foundations, allowing easy access for the radon, and where houses are tightly sealed against the cold, thus retaining the radon.

The dose from inhaling radon itself is quite small, but radon decays into radioactive material called radon decay products (formerly known as radon daughters) and if these are inhaled they may lodge in the lung, resulting in quite significant doses. Some houses in North America and Northern Europe have been found with radon decay product concentrations that are higher than would be permitted in modern uranium mines (International Commission on Radiological Protection 1994).

The world average natural background dose from all sources is about 2.4 mSv per year (UNSCEAR 2000c). Doses in Australia are less (2 mSv/y), largely because the dose from radon decay products is much lower because the climate and open-air lifestyle lead to better ventilation of houses, reducing the build-up of radon concentrations (Langroo et al. 1991).

The other main pathway is ingestion, or swallowing of radioactive material that is present in food or drink. Plants will take up a small amount of the radionuclides in the soil in which they grow. These radionuclides may then enter our food chain either directly, by eating the plants, or indirectly, by eating animals that have grazed on them. Similarly, almost all surface and ground waters contain natural radionuclides. Consuming such food or water will result in an internal radiation dose. The largest contribution to internal dose from ingestion is usually from potassium-40 (^{40}K). Potassium is an essential part of the body, and the body will extract its requirements from food. As the body cannot distinguish between the radioactive potassium (^{40}K) and non-radioactive potassium isotopes, the body will always contain some ^{40}K. Other natural radionuclides, including uranium and thorium decay series isotopes, will also be consumed with food and water and hence will be present in the body.

The average contribution of the different components is shown in Figure S1.8 (from UNSCEAR 2000b). As noted above, natural background can vary considerably in different places in the world. While the world average is 2.4 mSv/y, the typical range is quoted as 1–10 mSv/y (UNSCEAR 2000b).

S1.3.5 Enhanced radiation exposure

Some people around the world are regularly exposed to radiation above the natural background levels. Exposure occurs in some occupations (other than in the nuclear industry), from leisure activities (such as flying) and in medical procedures.

Table S1 shows the average annual effective dose from a range of different jobs. Air crews (and passengers) are exposed to higher levels of cosmic radiation than would otherwise be received at ground level.

Table S1 Occupational radiation exposures (UNSCEAR 2000b)

Source/practice	Average annual effective dose (mSv)
Nuclear fuel cycle (including uranium mining)	1.8
Industrial uses of radiation	0.5
Medical uses of radiation	0.3
Air crew	3.0
Mining (other than coal)	2.7
Coal mining	0.7

Another major source of radiation exposure to the general public is medical exposure. Radiation is used extensively for diagnosis and treatment of disease. The average annual radiation dose from diagnostic medical procedures in developed countries is approximately 1.2 mSv/y (UNSCEAR 2000a).

S1.3.6 Health effects of radiation

The health effects of radiation exposure (both internal and external) are well known. At high doses (several sieverts) significant numbers of cells in sensitive organs or tissues may be killed, leading to the breakdown of the organ or tissue, and possibly resulting in death. Other high dose effects include a weakening of the immune system and temporary sterility (in males). The doses required for these effects are similar to those received by Chernobyl fire-fighters. Doses received during uranium mining and milling do not approach these levels (and are generally more than 100 times less) so these high dose effects would not occur.

At lower doses, health effects may arise from cells that are damaged by the radiation but not killed. There are cellular mechanisms capable of repairing this damage and there are other mechanisms that eliminate such damaged cells, but it is possible that damaged cells may develop the ability to proliferate without being subject to the normal controls on cell reproduction. This may be the initiating event for development of a cancer. Development of cancer is a multi-stage process, and some of the stages may take many years to complete, so a cancer would not be expected to appear for many years after initiation. Each cell that is damaged in this way has an extremely small chance of passing through all the different stages, and eventually developing into a cancer.

Alternatively, the damaged cells may be part of the reproductive line (egg cells, sperm or sperm generating cells). Again, repair mechanisms exist and the damaged cells may not survive. However if they do, there is a chance that such damage may be carried over to the next generation and appear as hereditary disorders in the offspring.

Several studies have found an increased risk of cancer among people exposed to moderate doses of radiation. The best known are the studies of the Japanese atomic bomb survivors, who have now been followed for 50 years. These studies have been able to determine the effects of a large range of doses on a large population over a long period (Preston et al. 2007). Other studies have included an international study of radiation workers who were generally exposed to low levels of radiation over a long period (Cardis et al. 2005).

The studies of miners exposed to radon decay products are of particular relevance to uranium mining. Early mines were often poorly ventilated, and as a result miners were often exposed to very high levels of radon decay products. Several groups have been studied, including both non-uranium miners and uranium miners (Lubin et al. 1995).

Both groups of studies show that there is a risk of increased cancer among those exposed to elevated levels of radiation, and that this risk increases as the radiation dose increases. The overall increase is approximately linear; that is, doubling the dose doubles the risk (Brenner et al. 2003).

In general, none of the studies has been able to measure increases in cancer risk from exposures to low doses of radiation (below about 50 mSv). In this range, which includes the annual doses expected to be received by workers at Olympic Dam, any increase in cancer risk has been too low to be detectable. However, it is conservatively assumed that there is an increased risk, and the risk factors derived at higher doses are assumed to apply in this range.

There have also been studies looking for an increased rate of hereditary disorders in the offspring of parents exposed to radiation. No increased risk of hereditary disorders has been found in human studies, including those of the Japanese atomic bomb survivors, but an increase has been found in several animal studies (UNSCEAR 2000a), and it is assumed that there are risks to humans of a similar magnitude to those found in animals. These risks are less than 5% of the cancer risk.

The risks derived from these studies are used in the setting of radiation standards for exposure of workers and the general public.

In standard setting, the International Commission on Radiological Protection (ICRP) states 'it must be presumed that even small radiation doses may produce some deleterious effects' (International Commission on Radiological Protection 1990). This is not to be confused with the often stated 'there is no safe level of radiation', which equates 'safety' with 'no risk at all'. This is not the normal use of the word 'safe'. For example, most people recognise that there is some risk involved in commercial air travel, but still regard it as 'safe', because they consider that the level of risk is so low that it is acceptable. Similarly, exposure to radiation can be considered 'safe' if the resulting risks are low enough to be considered acceptable.

S1.4 RADIATION STANDARDS AND LIMITS

S1.4.1 Sources of standards

The premier international body for radiation protection is the International Commission on Radiological Protection (ICRP). The limits recommended by the ICRP have generally been adopted around the world. The recommended dose limits have changed over time as more information on the health effects of radiation has become available. However there has been only one major change to the recommended limits to workers in the past 50 years, in 1990 (International Commission on Radiological Protection 1990).

The ICRP's most recent recommendations on standards and dose limits were published in 2008 (International Commission on Radiological Protection 2008). These recommendations update the previous recommendations published in 1990 (International Commission on Radiological Protection 1990), and maintain the three key elements of the 'system of dose limitation' (see S1.4.2) and the basic numerical dose limits.

The ICRP recommendations are not of themselves legally binding in Australia, but the Commonwealth, states and territories have adopted them into their own legislation. Currently it is the 1990 recommendations, as set out in ICRP Publication 60 (International Commission on Radiological Protection 1990) that are adopted, but it is expected that the latest recommendations will be adopted where necessary. The Olympic Dam operation is required to comply with the ICRP recommendations under several pieces of South Australian legislation.

S1.4.2 ICRP recommendations

Dose limits form only one part of the ICRP radiation protection system. The three key elements of this system are (International Commission on Radiological Protection 1990):

- Justification – a practice involving exposure to radiation should be adopted only if the benefits of the practice outweigh the risks associated with the radiation exposure.
- Optimisation – radiation doses received should be as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle).
- Limitation – individuals should not receive radiation doses greater than the recommended limits.

Justification

Justification is a necessary prerequisite for any decision regarding radiation exposure. Actions that alter the radiation exposure situation should do more good than harm. This means that by introducing a new radiation source, or a new practice involving radiation, one should achieve an overall societal or individual benefit that is higher than the detriment that the radiation exposure may cause. The benefits and detriments should be considered broadly, and often the radiation detriment will be only a small part of the total.

Optimisation (the ALARA principle)

The ICRP sees the ALARA principle as a central element in radiation protection and, in the hierarchy of radiation protection measures, it ranks ahead of the application of 'dose limits'. The principle requires that every practice involving radiation exposure should be examined along with the potential protection measures. Protection measures that produce a net benefit (i.e. the benefit from reducing the exposure is greater than the cost of implementing that measure) should be implemented. This procedure should be continued until the costs of further reduction measures outweigh the potential benefits of the reduced exposure and radiation protection can then be considered as optimised. The procedure should be implemented at the design stage, and carried on into operation of the practice.

Optimisation may include the use of 'dose constraints' which are upper limits on the predicted doses used in the optimisation process. These are predetermined levels of dose for particular situations, above which it is unlikely that radiation protection is optimised. In the case of members of the public, dose constraints recognise the possibility that individuals may be exposed to radiation originating from more than one operation. In the case of uranium mines in remote locations this is unlikely to be the case. Dose constraints are not prescriptive regulatory limits.

The ALARA principle applies at all levels of exposure: if there are practical, cost-effective measures that can be applied to reduce radiation exposure, then they should be applied even if exposures are already well below the recommended dose limits. Indeed, the ICRP believes that proper application of this principle will generally result in doses that are well below the individual limits, and so those limits will only rarely need to be applied.

Limitation

The effective dose limits recommended by the ICRP which are of most relevance in the mining and mineral processing industries are:

Annual limit to a worker	20 mSv
Annual limit to a member of the public	1 mSv

The doses received may be averaged over five years, but the dose to a worker in any one year must not exceed 50 mSv. Annual doses to members of the public should be allowed to exceed 1 mSv in only 'special circumstances'. In uranium mining and processing, other recommended limits (for the lens of the eye, skin and hands or feet) could be exceeded only in unusual circumstances, which almost certainly would involve effective doses exceeding the above limits.

These limits apply to the total dose received from operational sources including external gamma exposure and inhalation of radon decay products and dusts (with the doses from normal natural background being excluded). There are no exposure limits for the individual dose components. Likewise there are also no specific dose limits set for shorter periods (less than a year). This is because the likely health effects depend only on the total dose accumulated over a long period (possibly decades). In an operational situation, investigation and action levels are set for each pathway at levels that ensure continued exposure will not lead to doses above these long-term limits.

S1.4.3 Radiological protection of the environment

Historically, the risk assessment and management of radionuclides entering or present in the environment has been based principally on human health considerations. The ICRP has stated that the standards of environmental control needed to protect humans to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species.

Recently there has been increasing awareness of the vulnerability of the environment and of the need to be able to demonstrate that it is protected against the effects of industrial pollutants, including radionuclides. The ICRP, in its 2007 Recommendations (International Commission on Radiological Protection 2008) has given more emphasis to the protection of the environment. More detailed advice is given in ICRP Publication 91, 'A framework for assessing the impact of ionising radiation on non-human species' (International Commission on Radiological Protection 2003) which reviews the various methods that have been developed for the assessment of radiological impacts with the objective of identifying and suggesting the best framework. It recommends making an initial assessment using primary (generic) reference organisms for flora and fauna to give an order of magnitude assessment of the probability and severity of likely effects of radiation exposure on the population. Organisms or exposure situations which are not negligible can then be subjected to a more detailed assessment, if necessary using situation or organism specific data. This approach has been adopted by the European Union as part of its ERICA project (see Section S2.5.4) (ERICA Program 2007).

S1.5 LEGISLATION AND REGULATORY REQUIREMENTS

As is discussed in the Draft EIS Chapter 6, Legislative Framework, the radiological aspects of the Olympic Dam expansion are controlled by two sets of legislation:

- *Roxby Downs (Indenture Ratification) Act 1982*, which ratifies the Olympic Dam and Stuart Shelf Indenture
- *Radiation Protection and Control Act 1982* and associated regulations, which requires the operation to hold a licence to mine or mill radioactive ores.

The central requirement for radiological protection under both Acts is compliance with the 'Code of Practice and Safety Guide on Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005)' (the Code) (ARPANSA 2005). This is a requirement under clause 10 of the Indenture and a condition on the licence to mine or mill.

This section sets out the Code's requirements and the way that it is implemented to ensure that workers, members of the public and the environment are protected from the potentially harmful effects of radiation.

S1.5.1 The Code

The Code has three central requirements:

- compliance with the Radiation Protection Standards, set by the ICRP (see Section S1.4.2)
- development of radiation management plans (RMP) and radioactive waste management plans (RWMP) for approval by the regulatory authority
- authorisation from the regulatory authorities before construction or operation of project facilities.

Overall, the RMP and the RWMP and the associated approvals provide the mechanism for the detailed oversight of the operation's radiological aspects by the regulatory authorities.

Radiation management plan

The radiation management plan (RMP) provides for the control of radiation exposure to employees and members of the public arising from the operation. It requires regulatory approval and would be implemented before the operation started.

The RMP is expected to include the following:

- significant exposure sources and pathways
- measures to control radiation exposures, including engineered controls (such as ventilation systems) and administrative measures, such as control of access to potentially high-exposure areas. Other measures include training in the radiological aspects of work, and supervision to ensure that controls are properly used.
- estimates of doses that would arise from the operations
- a radiation monitoring program designed to determine the effectiveness of controls, including monitoring of exposure from all sources (i.e. external gamma, radon decay products and radioactive dusts – see Section S1.6.1), to workers and members of the public
- details on how the RMP would be implemented, including commitments to adequate staffing, equipment and resources
- a quality assurance program, including ongoing assessment, review and revision of the program to ensure continued compliance with the ALARA principle, and updating to incorporate any changes to the operation.

The RMP is expected to demonstrate that the ALARA principle has been properly considered in the development of controls on radiation exposure.

Radioactive waste management plan

The management of wastes, including radioactive wastes, is an integral part of the operation and is addressed from the inception of project planning. A radioactive waste management plan (RWMP) would be developed and implemented to provide for the management of wastes to protect people and the environment from the potential harmful effects of radioactive wastes.

The development of the RWMP and the design of waste management facilities would take into account a number of factors, including:

- the nature of the wastes, including their radionuclide content, and their chemical and physical states
- the particular environment into which the wastes would be discharged or may escape (e.g. climate, topography, hydrology and ecology)
- the pathways by which radionuclides in the wastes may travel through the environment
- estimated concentrations of radioactive contaminants in the environment
- estimated doses to members of the public as a result of the waste management
- the potential for, and consequences of, failure of waste management facilities, and contingency measures to be put in place in such circumstances
- a monitoring program to monitor the system's operations (e.g. quantities of waste stored or discharged) and effects on the environment (e.g. radionuclide concentrations)
- details of the operation of the waste management system, including commitments to provision of adequate staff and resources
- a quality assurance program to ensure that the system is being operated and performs within its design parameters, together with a system of ongoing review and revision.

As in the case of the RMP, the RWMP is expected to demonstrate that the ALARA principle has been properly considered in the development of the waste management system.

S1.5.2 Decommissioning

The RWMP would also address the decommissioning and rehabilitation of the operation, and the long-term management of the wastes. If the operation is expected to have a long lifetime, it may not be practicable to provide full engineering details of the final rehabilitation. As the project progresses, however, and particularly as waste repositories are filled, the decommissioning plans would be finalised, submitted for approval and implemented. Such plans would be reviewed by regulatory authorities for compliance with appropriate criteria, including the objectives of the Code. Decommissioning of facilities would not be implemented until relevant approvals were received.

S1.5.3 Regulatory review

The regulatory authorities are responsible for ensuring that the approved RMP and RWMP are adequate to meet their objectives, and that they are properly implemented. The form in which this is undertaken is determined by those authorities, but it would normally include the requirement for regular reporting on the operation of the plans and the results of monitoring programs, regular inspection and independent monitoring by the authority, auditing of programs and quality assurance systems.

S1.6 RADIATION IN MINING AND PROCESSING

S1.6.1 Sources of exposure

The three principal ways in which radiation exposure can occur in uranium mining and processing are:

- external gamma exposure – gamma rays emitted from uranium ores and concentrates can result in radiation doses to those nearby. The gamma radiation originates mainly from Radium-226 and its immediate decay products
- inhalation of radioactive dusts – dust from uranium ore, concentrates and wastes contain radionuclides. If inhaled, they may be retained in the lungs, or transported by body fluids and deposited in other organs. Subsequent radioactive decay may result in doses to organs. The long-lived alpha emitting radionuclides (^{238}U, ^{234}U, ^{230}Th, ^{226}Ra and ^{210}Po) and the beta emitter ^{210}Pb are the most important for this type of exposure
- inhalation of radon decay products (RnDP) – one of the uranium (^{238}U) decay products is the radioactive gas, radon (^{222}Rn), which can diffuse out of the ore in which it is formed, and into the atmosphere. Inhalation of radon itself does not result in a significant radiation dose, because very little is retained in the lung as it is an inert gas. However, radon decays to short-lived decay products (RnDPs – ^{218}Po, ^{214}Bi, ^{214}Pb and ^{214}Po). These are solids and if they are inhaled they lodge in the lung, and in high concentrations can result in large radiation doses from the alpha particles they emit.

There are two other ways that internal exposure may arise from mining or processing operations:

- ingestion (swallowing) – this may arise in occupational exposure by hand-to-mouth transfer when eating, drinking or smoking with contaminated hands. In the case of environmental exposure it may arise from eating or drinking food or water that has been contaminated with radioactive materials
- wound contamination – radioactive material can enter the body via wounds.

These pathways are minor, and simple measures (e.g. personal hygiene and covering of wounds) can usually reduce them further.

S1.6.2 Methods of control

There are different ways of controlling and reducing external and internal radiation exposure.

External radiation

The main control methods are 'time, distance and shielding'. Reducing the time spent near a source or increasing the distance from that source reduces the exposure. In practice, this means that wherever possible, workplaces should be sited away from radioactive materials, such as ore or concentrates. Using effective shields between the radiation source and the workplace will also reduce exposure. In mining this can be achieved by applying a concrete coating to all surfaces (e.g. shotcreting) or by leaving lower-grade material in front of high-grade ore. Shielding may be provided by heavy machinery and plant and equipment.

Internal exposure

The main control is to reduce the intake of radionuclides. For inhalation, this generally means having fresh air in the workplace and effective ventilation to remove contaminated air quickly. This is particularly important in the case of radon decay products. Good ventilation will reduce the amount of radon in a workplace and also allow less time for the radon decay products to form from radon. Forced ventilation is essential in underground mining, due to enclosed spaces, but natural ventilation is generally sufficient in open-pit operations. Dust control measures such as keeping potential sources (such as ore stockpiles) damp are also important in controlling internal exposures from dusts. In some situations, particularly where the uranium oxide concentrate (UOC) is being handled, enclosed ventilated booths may be used to contain dusts generated. Personal respiratory protection may also be used for added protection or where other methods are not effective. Enclosure systems, such as shed and covered conveyors limit the amount of dust that can escape to the atmosphere. Releases of dusts to the environment may also be controlled, for example by installing dust collection systems on discharge points, in order to reduce doses to members of the public and environmental contamination.

S1.6.3 Radiation monitoring and dose assessment

Monitoring

Radiation monitoring serves two main purposes:

- for the operational control of radiation exposures, by detecting changes in conditions that may lead to exposure, and
- for assessing radiation doses.

There are two general types of monitoring: personal monitoring and area monitoring. Personal monitoring measures the exposure an individual receives, whereas area monitoring measures the radiation levels in an area that people may be working in. Personal monitoring is preferred for estimating doses, but this is not always practicable, and personal monitoring is often not helpful in finding the locations or jobs that are contributing to higher than expected exposures. To determine the exposure of individuals from area monitoring the time spent in that area(s) must be known.

The three components of radiation exposure in the mining and milling of radioactive ores (see Section S1.6.1) are monitored in different ways.

- External gamma radiation can be monitored using personal thermo-luminescent dosimeter (TLD) badges that are worn by the worker for a period (usually one to three months), and then returned to a laboratory for processing. They record the external radiation exposure for the badge (and thus the individual) for the period. Hand-held Geiger counters or similar instruments can be used to perform area surveys for monitoring of workplaces.
- Airborne radioactive dust levels are monitored using a small air sampling pump with a filter that collects the dust. After sampling (preferably for a full shift) the filter can be taken to the laboratory and placed in a detector that counts the alpha activity in the sample. The method can be used for personal or area sampling, but personal sampling is preferable as dust exposures are often quite localised and related to a particular job.
- Radon decay products (RnDP) are usually sampled in a similar way to dusts, but as they have short half-lives the sampling period must be short and they must be counted immediately after sampling (typically three minutes). The technique is not practical for personal sampling, therefore area sampling is generally used. Devices for personal sampling of RnDP decay product concentrations have been developed, and are being assessed for use at Olympic Dam. Individual RnDP exposures can be monitored using personal (passive) radon monitors, but assumptions must be made about the relationship between the radon concentration and that of its decay products.

Similar techniques are used for monitoring radionuclides in the environment, however usually larger samples are taken to allow the lower levels to be detected. Dust is collected on the filter and is then analysed using radiochemical methods. Radon decay products can be monitored using instruments that continuously draw air through a filter, while simultaneously counting the alpha particles emitted from radon decay products collected on the filter. Radionuclide concentrations in food or water, or in environmental samples can be measured using radiochemical methods.

Monitoring program

A monitoring program is an integral part of the radiation management plan for any operation and contains details of the monitoring to be undertaken, the methods of monitoring, where the monitoring will occur and how often. It also includes the methods to be used for dose assessment, including the dose conversion factors to be used. Monitoring results and the assessed doses are properly recorded and programs put in place to implement remedial measures should results higher than pre-defined investigation or action levels be encountered. Appropriate quality assurance programs should be included.

A monitoring program would aim to measure levels across all workplaces but would focus on areas and workgroups where exposures might be higher. Usual practice is for intensive monitoring and individual assessment of dose to be undertaken for those work groups and individuals considered likely to receive more than a quarter of the 20 mSv annual limit (i.e. 5 mSv/y). Doses to those more peripherally exposed to radiation or radioactive materials (including members of the public) are generally assessed on the basis of group averages (ARPANSA 2005). Monitoring to assess doses (or potential doses) to members of the public would also be undertaken. In the uranium mining situation this would include monitoring of airborne concentrations of radioactive dusts or radon decay products. If relevant, waterborne pathways would also be monitored, as well as radionuclide concentrations in food or drinking water that might be affected by the operation. Monitoring of the general environment (flora, fauna, soils, surface and ground water) may also be undertaken.

Dose assessment

Doses from external exposures can generally be derived directly from the results of personal monitoring as described above. However, this is not the case for internal exposures. The monitored results give the concentrations of the radioactive materials in air, and these need to be combined with location, occupancy times and breathing rates to estimate the intake of radionuclides into the body. To calculate the doses that will arise from these intakes, it is necessary to know how the radionuclides are absorbed into the body from the lung or gut, how they will circulate around the body, whether they will concentrate in particular organs, how long they will remain there, and how quickly they are excreted. It is then possible to calculate the dose that will arise from that intake of radioactive material.

Nationally and internationally recommended values of these 'dose conversion factors' (i.e. the dose that will arise from the intake of 1 Bq) for each radionuclide, and for different values of particle size, and solubilities in body fluids (ARPANSA 2005; International Atomic Energy Agency 1996) are then used to convert the calculated intakes to the doses that will be received. Radioactive dust generated in different parts of the operation will generally be composed of different proportions of radionuclides, and hence different factors are used. Similarly, a dose conversion factor is also used to convert radon decay product exposures to dose (ARPANSA 1995, ARPANSA 2005). All methods and data used for dose assessment (including dose conversion factors) for the current operation are approved by the South Australian EPA. Dose conversion factors are given in Attachment 2.

The methods used for assessing the doses of an Olympic Dam underground miner are presented as an example. The gamma exposure is derived from the results of the TLD monitors worn by all underground employees. Badges are changed and sent for readout either monthly (for more highly exposed groups) or quarterly (for most underground employees). Each person's gamma dose is the sum of the doses recorded by that person's monitors for the year (in mSv). Doses from radon decay products are derived from measured mine radon decay product concentrations – approximately 1,400 measurements are made each quarter. These results are combined to provide estimates of the average RnDP concentrations in areas throughout the mine. These averages are then combined with records of the areas where the person worked during the quarter, to derive the exposure (time multiplied by concentration) to radon decay products. A dose conversion factor (approved by the EPA) is then used to convert this exposure into a dose. The dose from inhalation of dusts is estimated in a similar way, using dust concentrations measured using personal sampling (140 per quarter). These results are averaged to provide estimates of the dust exposure to each occupational group. The dose arising from that exposure is obtained by multiplying by the dose conversion factor for ore dust, again as approved by the EPA.

The total dose to each individual is then calculated by adding the doses from the three components; gamma, RnDP and dust obtained by the above procedure.

Similar procedures are used for dose assessment in the plant, the main difference being that different dose conversion factors are used for the different dust exposure situations encountered – for example, uranium product in the calciner and product packing area, and polonium and lead in smelter fumes.

Medical surveillance

The medical examination of all employees is part of BHP Billiton's Fit for Work – Fit for Life program and the examination of all employees who might receive annual doses greater than 5 mSv is a requirement of the Radiation Protection and Control (Ionising Radiation) Regulations 2000. However, as there are no examinations or tests that can determine whether a person is particularly susceptible to the effects of radiation, or provide early warning of cancer (other than standard screening methods as for, say, bowel or cervical cancer), these examinations are limited to general assessments of health. Medical assessments may include such matters as a worker's fitness for wearing respiratory protection, if that is likely to be required.

The results of these examinations, together with radiation dose records, are retained indefinitely. In part they are kept for potential use in future epidemiological studies, although such studies appear to be unlikely to yield useful results for many years because of the long latency period for induction of cancer.

S1.7 NUCLEAR SAFEGUARDS AND SECURITY

Australia's uranium is sold exclusively for use in the civilian nuclear power industry and there is a system of safeguards in place to ensure that it is not diverted for use in nuclear weapons.

Australia's safeguards are based on the system developed by the International Atomic Energy Agency (IAEA) under the Non-Proliferation Treaty, and the strengthened requirements known as 'Additional Protocols'.

This system has three main elements:

- accounting for uranium as it moves through the fuel cycle, to ensure that it is not diverted to nuclear weapons
- physical security of nuclear material
- inspections to verify compliance.

S1.7.1 Accounting

An international accounting system is used to trace the movement of uranium from production to fuel fabrication and its introduction into the nuclear power reactor. The tracking continues when spent fuel is removed from the reactor and is reprocessed into more fuel, or stored and disposed of as waste. The tracking also covers plutonium produced from the uranium in the reactor.

Essentially, this establishes a pool of uranium earmarked for power generation, and material can only be removed from this pool for use in civilian power reactors. All Australian-produced uranium enters this pool.

S1.7.2 Physical security

The requirements set minimum standards for ensuring that nuclear materials (including uranium) are protected from theft or hijacking. These include stringent measures to ensure security during transport, as well as when materials are stored or processed in facilities.

S1.7.3 Inspection and verification

Verification that the safeguards requirements are being properly implemented and complied with is obtained in several ways. These include auditing records of production, transfer and use to ensure that there are no discrepancies, and physical inspection and accounting for nuclear material in facilities. Inspections can include physical inspection, measurements on, for example, amounts of material in storage, or the use of tamper-proof cameras and the like to monitor operations in facilities.

S1.7.4 Australia's safeguards requirements

Australia's requirements for safeguarding nuclear material go beyond those of the International Atomic Energy Agency (IAEA). Australia will sell uranium only to countries with which it has a bilateral safeguards agreement. These are formal agreements with the governments of customer countries that specify the details of how Australian-sourced uranium is to be handled. Australian uranium cannot be exported without a permit, which is granted only if a contract approved by the Australian Government is in place with the customer. Australian uranium cannot be transferred to other countries without the specific agreement of the Australian Government.

APPENDIX S2

Assessment of radiation exposures from the proposed Olympic Dam expansion

S2 ASSESSMENT OF RADIATION EXPOSURES FROM THE PROPOSED OLYMPIC DAM EXPANSION

S2.1 METHODOLOGY

The radiation exposures that are expected to result from the proposed Olympic Dam expansion have been estimated in several ways. Where possible, estimates were made by comparison and extension of the exposures resulting from the current operation, and in some cases other similar operations. Any differences in the expansion that might make significant changes to doses estimated in this way have been taken into account. Some estimates have been based on 'first principles' assessment of the sources or exposure pathways that are expected, while others are derived from computer modelling.

Dose estimates for aspects of the expanded operation have generally been given as an average, and a probable maximum. The latter is meant to represent the maximum average dose that small groups would be likely to receive under normal operating circumstances, and is meant to be approximately equivalent to the 90th percentile dose. Some individuals could receive slightly higher doses in some years.

The radiation exposures resulting from the current operation are measured by an extensive monitoring program. About 1,500 routine radiation measurements are taken each month. Several research projects, involving additional radiation measurements, have also been undertaken by both BHP Billiton and government agencies. The results of the monitoring program are summarised and reported each year in the Olympic Dam Project Radiation Protection Annual Report. Methods and data (including dose conversion factors) that are used in assessing the doses are approved by the South Australian EPA. The results reported below have been taken from the 2001 to 2007 reports.

The uranium content of the ore and other excavated material is important in estimating doses. The following ore grades have been used in this appendix (see Chapter 5, Description of the Proposed Expansion):

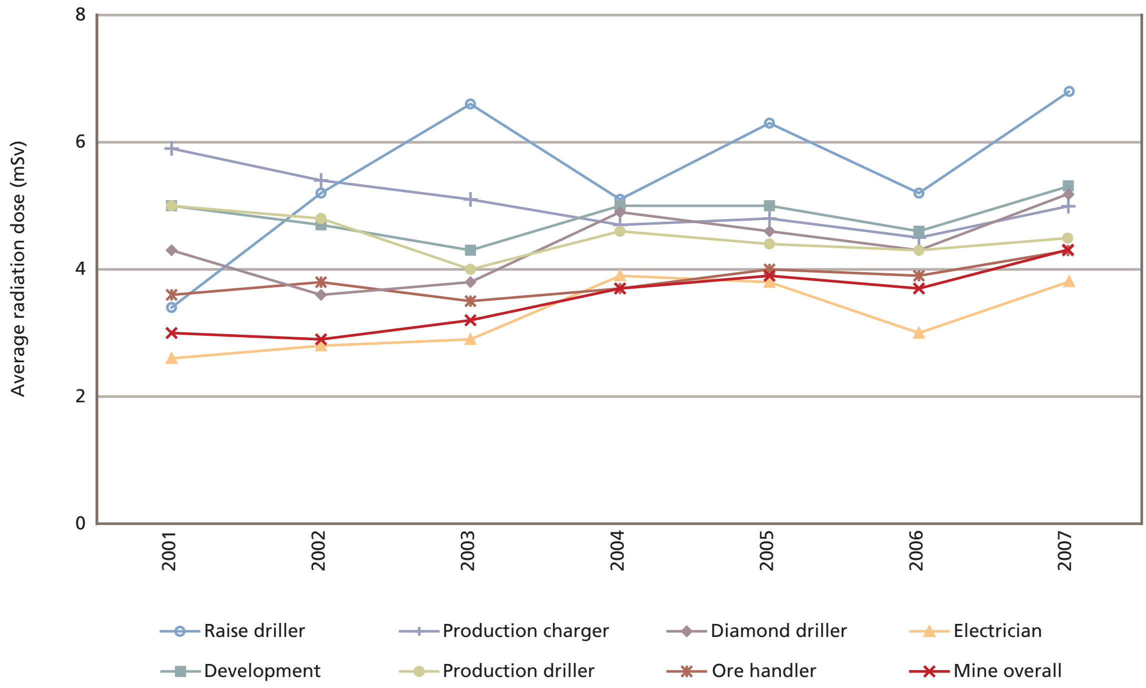
- cover sequence – 5 ppm U
- ore – 500 ppm U
- low grade and unmineralised basement – 70 ppm U
- average of entire pit (40 years) – 100 ppm U
- average of all basement material (including ore) – 200 ppm U
- ore and concentrate in secular equilibrium.

The radioactivity from the ^{235}U chain, which occurs naturally within the ^{238}U chain, is not usually considered as its impact is small (<3%).

S2.2 EXPOSURES IN THE MINE

S2.2.1 Existing (underground) operation

Assessed doses to the main underground workgroups for the period 2001–2007 are shown in Figure S2.1. Doses are for 'full-time designated employees', i.e. those who worked underground for three or more quarters of the year. Note that a number of employees change their jobs during the year. The category recorded is that at the end of the year.



Occupational annual dose limit is 20 mSv

Figure S2.1 Average annual radiation doses for mining

The contribution from each of the dose pathways to the various workgroups is shown in Figure S2.2.

The average dose over the whole period was 3.5mSv. As can be seen from Figure S2.2, the major contributors to total dose were the inhalation of radon decay product and exposure to gamma radiation, each contributing around one half of the total. Inhalation of radioactive dusts contributed on average approximately 5% of the total (0.2 mSv).

There was an overall increase in average dose over the period, mainly due to an increase in radon decay product concentrations, which was slightly mitigated by a small decrease in gamma exposure.

As would be expected, some groups received significantly more than the average but below international limits. These included production drillers and chargers, raise drillers and development miners. Although their doses were higher, the proportion of doses from the various pathways is generally the same as the proportions outlined above (see Figure S2.2).

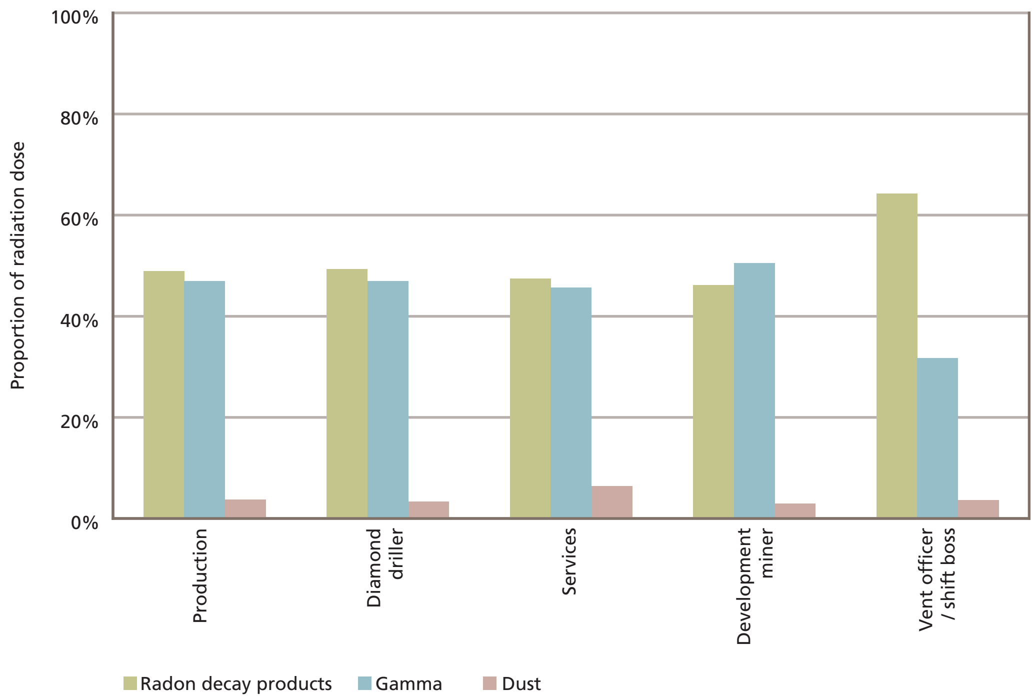


Figure S2.2 Proportion of radiation dose for mining

The most exposed workgroup was raise drillers with an annual average of 5.9 mSv, while the highest annual dose to an individual was 9.9 mSv.

S2.2.2 Predicted exposures – mining

The proposed mining technique for the expansion is an open pit, in contrast to the current underground mining operation. The proposed mining technique is fundamentally different to the existing situation and therefore radiation exposures are expected to be different.

In this section the pathways for exposure from the proposed open pit operations have been identified and potential doses to open pit workers are predicted. These dose predictions have in general been made using one or more of three methods:

- comparison with the existing project
- comparison with other comparable projects
- calculations using models.

Where appropriate, dose conversion factors from the Code (ARPANSA 2005) have been used.

Figure S2.3 demonstrates the exposure pathways for an open pit mine.

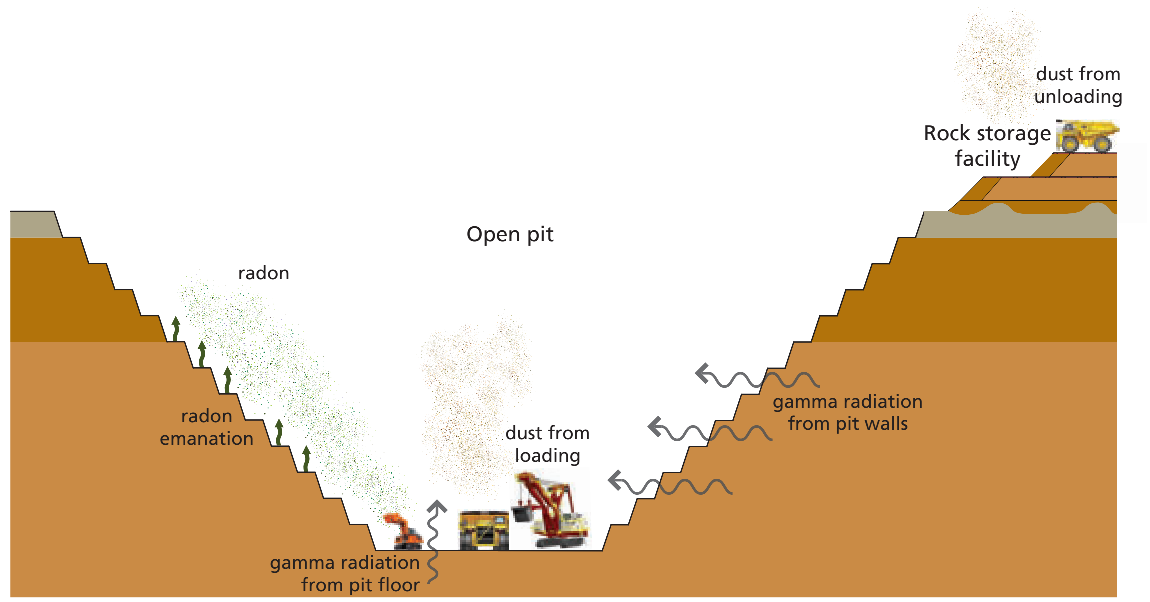


Figure S2.3 Open pit pathways

Gamma exposure

Gamma doses in the open pit have been estimated using theoretical models, the current (underground) mine doses, and comparisons with other open pit uranium mining operations in Australia and overseas.

The gamma dose from an extended (plane) deposit can be calculated using the conversion factor 65 μSv/h/%U (Thomson & Wilson 1980). In the open pit there would be a slight increase over that of an extended plane due to radiation from the walls. However, there would generally be some reduction due to shielding from equipment.

Applying this to the uranium grades for both ore material and excavated material after the cover material is removed (see Section S.2.1) gives annual doses from full-time exposure (2,000 h/y), of about 6.5 mSv and 2.6 mSv respectively.

In practice, it is most unlikely that an individual would work full time on ore, so the value 6.5 mSv/y is likely to represent a significant overestimate. The highest exposure work groups are likely to be the drillers and shot firers. Typically these personnel would spend no more than 60% of their time in one year on ore (when travel time to and from work areas and mining work plans across a whole year are taken into account). This would then give a maximum dose of about 4 mSv/y.

To compare this theoretical calculation with that observed in real situations, a review of doses observed at both current Olympic Dam underground operations and those at the Ranger uranium mine open pit was undertaken.

The gamma doses to open pit workers at Ranger are given in Section S2.2.3. This shows an average worker receives 1 mSv/y gamma dose with a maximum of 4 mSv/y (Energy Resources of Australia 2006). The ore grade of the Ranger pit has an average of 0.26% (2,600 ppm), five times greater than that predicted for the proposed Olympic Dam expansion. As gamma dose is proportional with ore grade, this indicates that the predicted doses (from theoretical calculation) are likely to be considerably overestimated.

The gamma dose to current underground workers is given in Section S2.2.1. This shows the average gamma dose to all workers in the current underground operation was 1.6 mSv. The workgroup receiving the largest gamma dose was that of the production chargers, who receive an average of approximately 3 mSv/y. Gamma doses in an open pit are typically lower than for the corresponding underground operation because contributions to the gamma dose from underground mining can come from material surrounding the miner in the tunnel, whereas in an open pit there would be no material above the miner to contribute to the dose. This again indicates that the predicted doses (from theoretical calculation) are likely to be an overestimate.

Based on this information, the doses to workers in the proposed Olympic Dam open pit from gamma exposure are expected to average less than 2 mSv, ranging up to about 4 mSv.

Radon decay product exposures

Radon decay product exposures are heavily dependent on ventilation. The ventilation conditions in an underground mine are so different from those in an open pit that no useful comparison can be made. However, radon decay product concentrations can be estimated from the rate of release of radon from the ore and waste rock in the open pit, and ventilation rates predicted from atmospheric modelling.

The emanation rate of radon from Olympic Dam ore has been estimated to be 2.5 Bq/m^2/s (Akber et al. 2001) for unbroken *(in situ)* ore, with the emanation rate from low-grade material being reduced proportionately to U grade (Mason et al. 1982; Yu & Cheng 1993). If ore is broken, radon can escape more easily, and the emanation rate is estimated to be five times that of the unbroken.

Open pit ventilation rates have been estimated using a model developed by Thompson (1994), which shows that open pit ventilation is proportional to wind speed. Other studies have shown that in deep open pits, ventilation may be poor, with recirculation of pollutants (Peng & Lu 1995). The radon decay product concentrations in the open pit have been estimated using this model and the radon emanation rate measurements detailed above. Details of this model, along with results, are provided in Section S3.

Two conservative ventilation situations have been considered for the purposes of predicting doses to open pit workers from the inhalation of radon decay products. The first assumes normal ventilation conditions, with low-wind conditions prevailing for the entire year. The second assumes that temperature inversions occur in the pit during still night-time conditions.

The meteorological data at Olympic Dam, summarised in Chapter 13, Greenhouse Gas and Air Quality, and Appendix L, show the long-term average wind speed to be about 3.6 m/s. However, for the purposes of a conservative dose assessment, the low wind speed case of 2 m/s was used in the model to determine the mean radon decay product concentration inside the pit. Even for this low wind scenario, the concentrations are relatively low – about 0.05 μJ/m^3 – resulting in average doses to those working in the pit of about 0.15 mSv/y. This figure has been doubled to 0.3 mSv/y to take account of the potential poorer ventilation in a deep pit (Peng & Lu 1995).

The model was then used to predict the maximum probable radon concentration in the open pit for the second situation, where a temperature inversion forms in the pit in the early evening, trapping the released radon for 12 hours (overnight). The height of the inversion above the pit floor will vary according to the particular conditions. Pacific Air Environment was commissioned for the EIS to undertake modelling of the pit climate. This showed that it may be possible for multiple inversions to occur at heights of from 200 m to 350 m below the (original) ground surface. Because the modelling was limited to a depth of 400 m from the surface, no information on any potential deeper inversions was obtained. A conservative assumption of an inversion 100 m above the base of the pit has been applied (i.e. more than 800 m below the surface). Using these assumptions, the radon decay product concentration is predicted to reach a maximum of 9 μJ/m^3. The subsequent dose from this individual inversion event to a worker who spent an entire 12-hour shift at the base of the pit would be 0.08 mSv.

In order to estimate an annual dose for this second situation, the number of these inversions that would occur in a year needs to be estimated. The frequency of inversions is higher during winter than in other seasons, but the number is not known with any accuracy. For this assessment, the number of inversions was predicted using two methods.

In the first method, the meteorological data, reported in Appendix L, was analysed to produce an atmospheric stability table, based on the Pasquil stability classes. This showed that atmospheric stability class F (low to no wind or stable) occurred on the surface for 26% of nights per year. This is supported by a study that found nocturnal temperature inversions at Olympic Dam occur on 64% of winter nights (or 16% of nights per year) (Leach & Chandler 1992). The result from the first method (26%) was adopted to provide a conservative estimate.

It is expected that the frequency of temperature inversions inside the open pit would be less than that on the surface due to convective mixing caused by the heat given off by heavy equipment, geothermal heat and the differential solar heating of the walls of the pit during the day. However, to ensure a conservative estimate of radon decay product dose during night-time inversions, it was assumed that the frequency of inversions within the pit was the same as that on the surface.

A miner on a rotating shift roster (for example a four-panel roster: four nights every 16 days) would be expected to work on only approximately one quarter of nights. The annual dose from night-time temperature inversion conditions, assumed to occur on 26% of nights, to such an employee would then be 2 mSv.

Thus, the total probable maximum dose to an open pit worker from inhalation of radon decay product would be approximately 2.3 mSv/y (about 0.3 mSv under normal ventilation conditions and 2 mSv from inversion conditions).

The current underground operation would remain in service initially and it is possible that radon from the expanded surface operations would enter the ventilation system of the mine. Using the atmospheric model, the increase in ambient radon concentration at the surface near the mine air intake shafts was estimated to be 100 Bq/m^3 (see Section S3). Assuming that the radon decay products were in equilibrium with radon (worst case), this would be equivalent to an increase of 0.5 μJ/m^3 in mine air. If no other changes were made (for example, to ventilation systems) this would lead to an additional dose to full-time underground miners of 1.4 mSv/y. This figure would be used as a conservative estimate of the increase.

Dust exposures

Doses from other open pit operations around the world were used (see Section S2.2.3) to provide an indication of probable doses from the Olympic Dam expansion open pit. These show that the average dose to open pit workers from the inhalation of dust is between 0.1 and 0.4 mSv/y and maximum doses are 0.9 mSv/y. These are comparable with doses received by current underground workers at Olympic Dam from this exposure pathway (average 0.2 mSv/y and maximum of 0.5 mSv/y).

A dust emission inventory has been generated for the proposed open pit (see Appendix J). Assuming the dust spreads evenly across the entire volume of the pit (i.e. a simplified scenario) the resulting average dust concentration within the proposed open pit would be 0.2 mg/m^3. Assuming all the dust originates from ore material (see Section S2.1), and using the dose conversion factors in the Mining Code (ARPANSA 2005) gives an average annual dose of 0.1 mSv/y.

Data from a total of over 3,000 personal dust samples in NSW open pit coal mines have shown that only 1% of results exceed a concentration of 3 mg/m^3, and all of these were from the 'shot firers' group. This is confirmed by measurements in the existing open pit quarry at Olympic Dam, where the average to quarry operators is 1.3 mg/m^3. The figure of 3 mg/m^3 was used as a conservative figure for dust exposures in the Olympic Dam pit.

As a worst case, if it is assumed that a shot firer worked entirely on ore (see Section S2.1 for uranium grade) for a year and inhaled an average dust concentration of 3 mg/m^3 for that year, then the resulting dust dose would be 1.7 mSv/y. This has been taken as a conservative maximum estimate.

Crushing operations would be conducted at the top of the pit. This operation is considered to be part of 'processing', however, and is discussed in Section S2.3.2.

Estimated total dose to mine workers

The total probable maximum dose to mine workers is thus estimated to be less than 8 mSv/y, consisting of 4 mSv from gamma exposure, 2.3 mSv from inhalation of radon decay products and 1.7 mSv from inhalation of radioactive dusts. The average dose to workers is expected to be considerably less, and somewhat less than the current average for Olympic Dam underground miners (3.5 mSv/y). This dose remains a small fraction of the 20 mSv/y annual worker dose limit (ARPANSA 2005).

S2.2.3 Comparison with other projects

Comparison of the predicted doses for the proposed Olympic Dam expansion with those of other uranium mines was undertaken. Results of this comparison are provided in Table S2, along with the average ore grade of material being mined (Olympic Dam Project 2001–2007; Energy Resources of Australia 2006; Rossing Uranium 2006; Health Canada 2007; Leach et al. 1980; AREVA Resources Canada 2007).

Table S2 Comparison of radiation doses to mine workers at various uranium operations (mSv)

Mine and type of worker	Ore grade ($\%U_3O_8$)	Total dose		Gamma		Radon		Dust	
		Avg	Max	Avg	Max	Avg	Max	Avg	Max
Ranger mine worker	0.29	1.0	4.8	0.5	4.3	0.1	0.4	0.3	0.9
Rössing pit equipment operator	0.035	2.1	n.a.	0.6	n.a.	1.2	n.a.	0.4	n.a.
Rössing pit field staff	0.035	2.5	n.a.	1.0	n.a.	1.1	n.a.	0.4	n.a.
McLean Lake open pit workers	1.6	<1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Canadian surface miners 2004	Various	1.1	<5	n.a.	n.a.	0.3	n.a.	n.a.	n.a.
Nabarlek open pit worker	2	6.6	n.a.	2.3	10	0.3	n.a.	4	n.a.
Olympic Dam underground mine worker	0.07	3.8	10	1.8	4.8	1.8	4.7	0.2	0.5
Estimated (maximum probable) Olympic Dam Expansion open pit worker	0.05	3.5	8	1.4	4	–	2.3	0.1	1.7

n.a. – not available

These results are in broad general agreement. The exception is Nabarlek. Here the ore grade was very much higher than at most of the other operations (approximately 40 times higher than at Olympic Dam), and it operated nearly 30 years ago. In addition, the ore body was completely mined out in one short campaign of approximately 4½ months.

S2.3 EXPOSURE IN THE PROCESSING PLANT

S2.3.1 Current operation

The estimates of doses in most areas of the expanded processing plant were obtained by comparison with current operations. If this was not possible, estimates were made by utilising the atmospheric model, as detailed in Chapter 13, Greenhouse Gas and Air Quality.

The radiation exposures to workers in the processing plant are shown in Figure S2.4. Doses to employees who worked for three or more quarters of the year have been used. As is the case in the mine, workers may change jobs during the year: the category assigned is that held at the end of the year. The contribution of each dose pathway to the various workgroups is shown in Figure S2.5. Doses from inhalation of dusts are determined from the results of personal dust monitoring. Gamma doses are determined from TLD results.

The overall average annual dose is 2.4 mSv. The main exposure pathway is inhalation of dusts (approx 75%), with 20% from gamma exposure and 5% from the inhalation of radon decay products. However, there are wide variations across the plant, particularly between the smelter (average doses up to 5.5 mSv/y, with individual doses to 17.7 mSv) and the remainder of the plant (average doses 1–2 mSv/y, with individual doses to 9.5 mSv). For this reason the estimation of doses to processing plant personnel has been divided into two sections: doses to smelter personnel and doses to hydromet, concentrator and refinery personnel.

The one constant in plant exposures is the low level of radon decay product exposures (see Figure S2.5), where annual doses from this pathway are generally in the range of 0.1–0.2 mSv. This is due to the relatively small sources of radon in the processing plant area compared with the mine and the generally good natural ventilation on the surface.

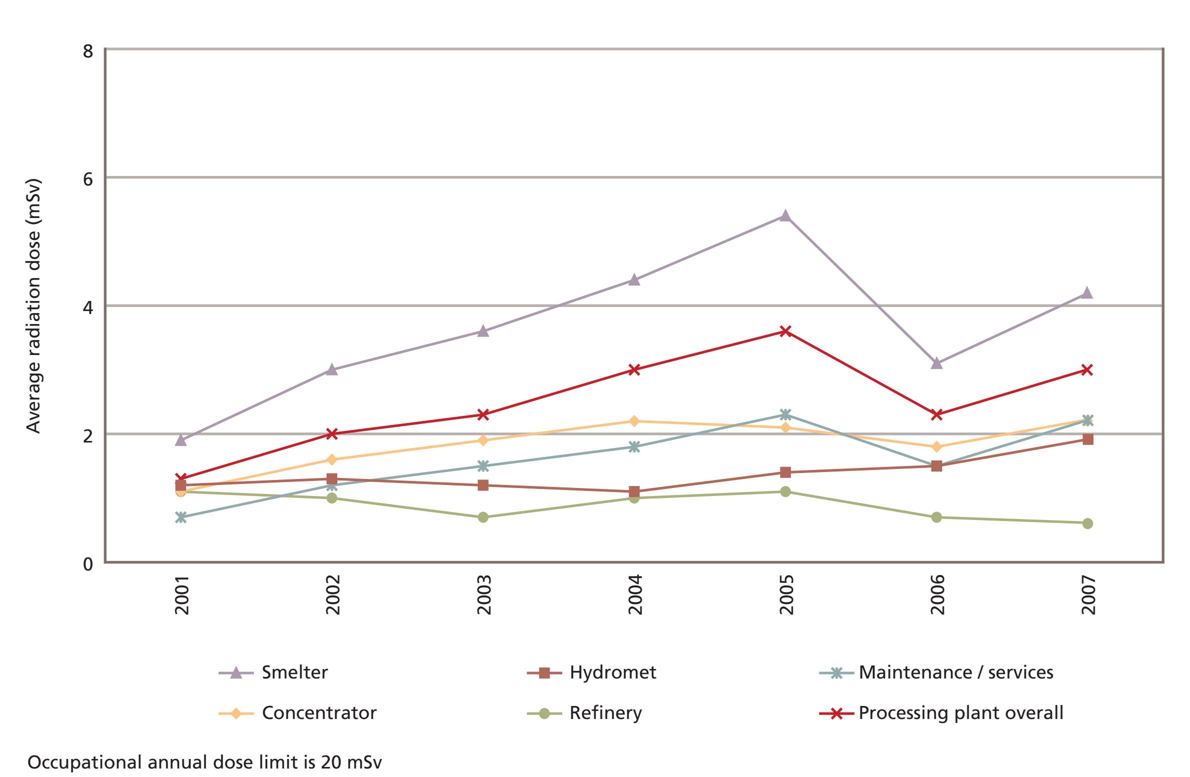


Figure S2.4 Average annual radiation doses for processing

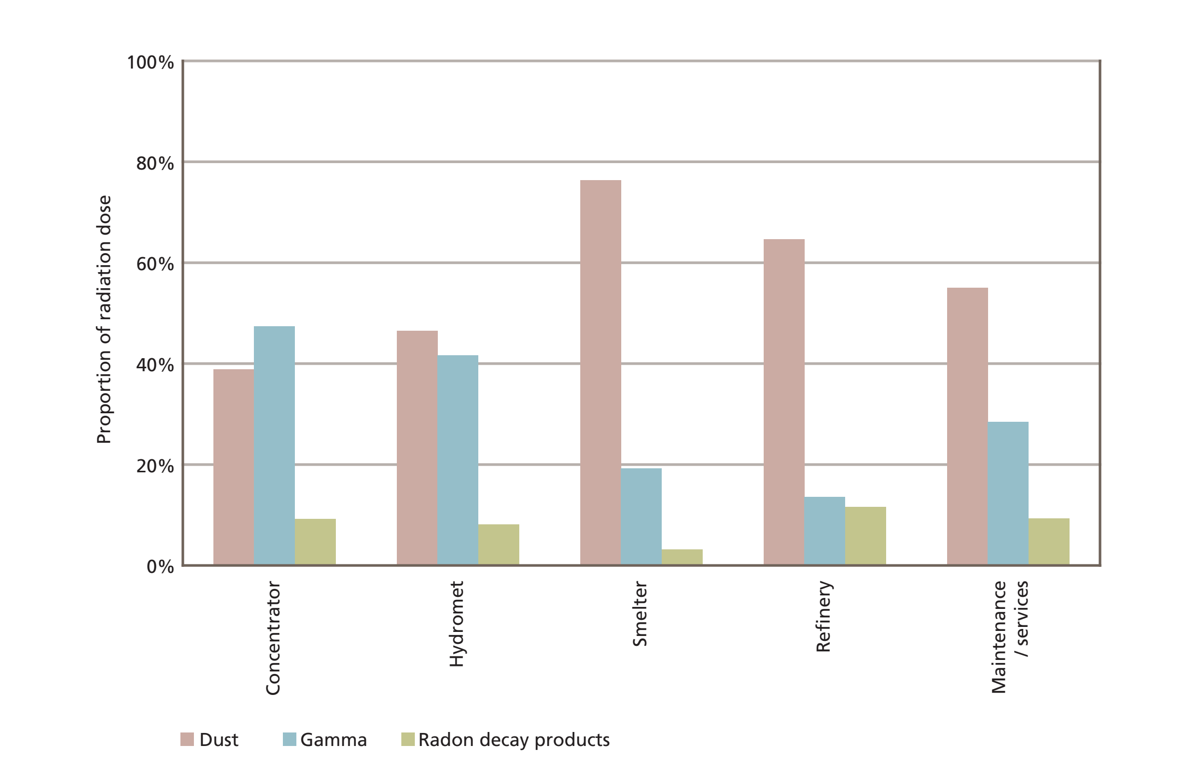


Figure S2.5 Proportion of radiation dose for processing

Doses to smelter personnel

The main source of exposure in the current smelter is the inhalation of polonium-210 (^{210}Po) in fumes from the furnaces, which is mainly released during tapping operations.

^{210}Po is a constituent of the copper concentrate smelter feed (along with the other members of the uranium decay series) and is fed into the flash furnace. Most radionuclides are removed in the smelter slag, but because polonium is volatile it evaporates from the furnace, and enters the smelter off-gas stream. The ^{210}Po condenses and is collected in the smelter gas cleaning circuit, together with a significant amount of dust that is carried over from the smelter. This smelter dust is returned to the smelter as part of the feed in order to recover its residual copper. Thus, the ^{210}Po is returned to the smelter, and completes a circuit: flash furnace – smelter off-gas – dust collection – flash furnace. Without an exit path the ^{210}Po load of the furnace continues to rise and with it the amount released in fumes.

To reduce this build-up of ^{210}Po, a fraction of the smelter dust is removed from the circuit and returned to the leaching circuit, where the ^{210}Po is removed and sent to the tailings retention system. This process stabilises the ^{210}Po concentration; however, it is still at a level that requires extensive occupational hygiene control (mainly in the form of ventilation) to control exposures.

A further complication arises from the presence of lead-210 (^{210}Pb, the immediate precursor of ^{210}Po in the uranium decay series) in the smelter feed. Lead is also volatile (although not to the same extent as polonium) and so it also accumulates in the smelter circuit, but it is more soluble in the smelter slag and some accumulates there. Flash furnace slag is tapped into the electric furnace, where a considerable fraction of its contained copper is recovered. Some copper is retained in the slag, however, and after cooling, this slag ('revert') is crushed and returned to the electric furnace for further copper recovery.

The ^{210}Pb concentration in flash furnace slag is about 10 times the concentration of ^{210}Po. If the return of slag to the flash furnace is delayed, the ^{210}Po content builds up from the decay of its parent ^{210}Pb with a timescale determined by the half-life of ^{210}Po (see Section S1.2 and Figure S1.4). Thus over a period of several months, the ^{210}Po concentration in the slag can increase to the ^{210}Pb levels (that is by a factor of up to 10) and when eventually returned to the furnace, can result in increased ^{210}Po concentrations in air.

From 2001 to 2005, the average annual dose to smelter workers almost trebled (from 1.9 mSv to 5.4 mSv). The 90th percentile dose, which would be more representative of smelter tappers, more than trebled, from 3.9 mSv to 12 mSv (Olympic Dam Project 2001–2007). The most exposed individual's dose rose to 18 mSv. The reasons for this include elements of all three causes:

- the occupational hygiene ventilation system has not been able to operate to specifications
- an increase in production with the installation of a second concentrate burner has led to additional carry-over of dust (and polonium)
- more 'old' slag has been returned to the system.

The doses above are derived from personal sampling of workplace air, and it should be noted that the doses assessed for smelter tappers in particular will be overestimates. During tapping, respiratory protection is mandatory and is worn for protection against sulphur dioxide fumes. This is also effective against ^{210}Po particulates, and so would reduce their dose from this source. This is not considered in the dose assessment procedure, however, because the fraction of exposure that occurs during tapping has not been established and it cannot be assumed that the respirator is worn for the full tapping period. In 2006 the smelter ventilation system was substantially upgraded and the amount of old slag being reprocessed was limited. This has resulted in significant decreases in airborne polonium levels in the smelter, although this is not fully reflected in the 2006 report, as the ventilation improvements were not completed until the middle of the reporting period. A further increase occurred in 2007 as more 'revert' (old slag) was returned to the smelter.

Doses to concentrator, hydromet and refinery personnel

The other areas of the current processing plant have significantly lower doses than the smelter. The largest average dose, about 2 mSv, is in the concentrator. About half of this is from inhalation of ore dust from the stockpiles and ore handling and grinding operations, and half from gamma exposure – mainly from stockpiles. Once ore is in slurry form, dust emission is almost eliminated, and gamma emission is significantly reduced from the absorption of gamma rays by the water of the slurry and the steel of the tank.

For this reason, doses in the hydromet section are also low (about 1.4 mSv/y) and are made up of equal contributions of dust inhalation and gamma exposure. The UOC product roasting and packing area is the one area of the hydromet section which has the potential for significant doses. The concentrated uranium product has a much higher activity per unit weight of material than ore, so quite small masses of airborne uranium can lead to significant doses. Packing is done in a sealed ventilated booth and respiratory protection is worn at all times while inside. With these precautions, average doses have remained consistently low at about 2 mSv/y.

Doses in the refinery are also low and average 0.9 mSv/y, 60% of which is from dust inhalation. The raw material for the refinery is copper anode, which has a very low concentration of radionuclides, and the operations performed do not provide significant pathways for exposure. The one exception is the handling of refinery slimes, and the subsequent extraction of precious metals. Although small in volume, the slimes have significant concentrations of ^{210}Pb and ^{210}Po. Slimes are roasted as part of the precious metals extraction process, and these volatile radionuclides can be liberated as fumes. Significant exposures have occurred in the past (maximum individual dose of 9.5 mSv in 2001) but a complete redesign of the ventilation system in 2002 has reduced doses to about 1 mSv/y.

A maintenance and services workgroup has been identified in the processing plant for dose assessment purposes. These employees generally work throughout the various sections of the plant, and receive doses of about 1–2 mSv/y.

S2.3.2 Predicted exposures – processing plant

The proposed processing plant for the Olympic Dam expansion would be situated south-west of the current facility. The process methods used there would be similar to those used now, so the exposure pathways would be similar; however, the overall size and throughput of the facility would be greater.

It is proposed that the concentrator section would be expanded in order to handle all the ore from the expanded mine (underground and open pit). After concentration, an additional 200,000 tpa of copper concentrate would be smelted, resulting in an expansion of copper output from the current 250,000 tpa to approximately 400,000 tpa. The remaining 1.6 Mt of the concentrate would be exported for smelting overseas.

In general, the processes and equipment to be employed in the proposed expanded plant would be similar to those currently in operation. Consequently, predicted doses are mainly derived from comparison with existing operational doses. Where appropriate, dose conversion factors from the Code (ARPANSA 2005) have been used.

Doses to smelter personnel

The results of monitoring in the existing smelter show that doses are critically dependent on the design, operation and maintenance of the smelter ventilation system. If these aspects are not properly managed, there is the potential for radiation doses to reach unacceptable levels. These requirements are now recognised, and radiation levels have been reduced to those typical of about five years ago.

However, it is proposed that the output of the smelter would be increased by approximately 60%. This would mean that the total radionuclide content of smelter feed, and in particular of ^{210}Po and ^{210}Pb, would also increase by approximately 60%. The appropriate ventilation systems and other radiation protection requirements would be installed around the new facilities required to operate the furnaces at the higher rate (e.g. tap holes, and launders). However, it is expected that there would be more sources of fugitive emissions, and it is likely that general fume concentrations in the smelter would be greater than at present. This means it is likely that the doses to smelter operators would be greater than those that occurred under optimal conditions about five years ago.

Under these circumstances, it is estimated that doses in the smelter would average about 5 mSv/y with a probable maximum of about 9 mSv/y.

Doses to concentrator, hydromet and refinery personnel

Gamma exposures in an expanded plant are not expected to be significantly different from present doses, which average about 0.5–1 mSv/y with a maximum of 2 mSv/y. Dose rates adjacent to large area sources like stockpiles and processing tanks are largely independent of the size of those facilities. These values have been adopted for the expanded plant.

Although radon decay product exposures are low in the current processing plant (about 0.2 mSv/y), the increased radon release from the expanded project is likely to lead to an increased dose from this source. The atmospheric model (see Chapter 13, Greenhouse Gas and Air Quality) was used to give a best estimate concentration in the plant. Details of this modelling are provided in Section S1.

Modelling so close to the source is not as accurate as for regional concentrations, however it does provide an approximate result that can be used for the dose calculation. The results of this modelling show that the average increased radon concentration within the new processing plant would be about 40 Bq/m³ (corresponding to an increased radon decay product concentration of 0.1 µJ/m³) and resulting in an annual dose of 0.3 mSv/y (International Commission on Radiological Protection 1994).

Dust exposures in the open areas of the processing plant are expected to be slightly higher than those of the current operation due to the increase in ambient area dust from open pit operations. The approximate increase in dust concentrations in the vicinity of the new processing plant was predicted using the atmospheric model to be 0.025 mg/m³ total suspended particulates (TSP) (see Chapter 13, Greenhouse Gas and Air Quality). To obtain a conservative maximum dose estimate from dust inhalation it was assumed that all the inhaled material was from ore rather than total excavated material (see Section S2.1). This results in a dose increase of 0.01 mSv/y from the pit dust within the processing plant.

The operations involved in calcining and packaging the uranium product would be similar to those existing, and the facilities would have similar engineering controls and respiratory protection regimes. Therefore, although there would be greater production of uranium concentrate, the doses to these operators are expected to be similar to those currently received. These operators are part of the hydromet work group, whose members receive an average of 1.5 mSv/y and a maximum of 4 mSv/y.

The new ore crushers and associated infrastructure such as ore transfer stations and conveyors would be sited near the open pit rim. Dust suppression and control measures would be employed, but the very large quantities of ore being handled would lead to some occupational dust exposure. Currently at Olympic Dam, the crushing operations are conducted underground and the average dust concentration in the crusher area is less than 1 mg/m³. In comparison, at the Rössing Uranium mine, annual average (respirable) dust concentrations at the fine crushing plant range between 0.9 mg/m³ and 2.8 mg/m³ (Rössing Uranium 2006). A United Kingdom study on surface quarry crushing showed dust concentrations with an arithmetic mean of 2.5 mg/m³ (Creely et al. 2007). With the dust suppression and other control measures planned for the expanded operations, a dust concentration of 2.8 mg/m³ has been taken as a conservative maximum in the vicinity of crushing operations. Full-time (2,000 hrs) exposure to this dust cloud would result in a maximum probable annual dose of 1.6 mSv/y.

Doses in the existing processing plant from expanded operations

The current processing plant will remain operating for some years. Doses to personnel working in this plant are expected to increase with the introduction of new dust and radon source terms from the expanded operations (that is, principally from the open pit and associated facilities). Modelling has been used to predict these increases and the most conservative figures (that is, at year 40) have been used. However, it should be noted that the existing plant may no longer be operating by year 40.

The increased radon concentration in the old processing plant is estimated to be 100 Bq/m³ (equivalent to a RnDP concentration of 0.25 µJ/m³), equating to an annual dose of approximately 0.7 mSv/y. The predicted dust concentration is 0.15 mg/m³ TSP, equating to a conservative estimated increased dose of about 0.08 mSv/y.

Estimated total dose to processing plant workers

Overall, it is expected that doses to workers in the expanded plant would be similar to those currently being received. Other than in the smelter, doses currently average 1.5 mSv/y, ranging up to about 4 mSv (there are some individual higher doses, generally from workers rotating into higher exposure areas like the smelter, but overall the average 90th percentile dose for all areas other than the smelter is 2.5 mSv). There is expected to be some increase in the new plant and old plant from dust and radon sources associated with the pit. These additional doses are expected to be less than 1 mSv/y combined. Additionally, there would be some increases in dose from the addition of crushing operations on the surface. Estimates of annual dust dose for full-time occupancy in the crusher area are less than 1.6 mSv.

Therefore, total annual doses from the expanded concentrator, hydromet and refinery operations are expected to average 3 mSv/y, ranging up to 5 mSv/y. In the smelter, with the increased throughput, and with all planned design controls installed and fully maintained, and including the contributions from the pit, doses are expected to average about 5 mSv/y and to range up to 9 mSv/y.

Doses to administration personnel

A number of people work in the administration area of the current operation, adjacent to the processing plant. Currently this group receives an average dose of approximately 0.5 mSv/y. As noted above, the expanded operation would increase dust and radon concentrations in the existing plant area, leading to increased doses of about 0.7 mSv/y, and thus the total dose is expected to be approximately 1.2 mSv. Although these people are not directly involved in working with radiation, they are still 'workers' and as such, the dose limits for workers (20 mSv/y) is applicable (ARPANSA 2005). As with every other category of worker, the ALARA principle takes precedence over dose limits, and if the doses are not considered to be 'optimised', then consideration of measures to reduce exposure will need to be made. These measures could include relocation of these workers to areas of lower dose.

S2.4 DOSES FROM TRANSPORTATION

S2.4.1 Uranium product transport

In the current operation, uranium oxide (UO) is packed into drums, which are transported in standard sea-containers by road to Port Adelaide. The dose to drivers is estimated from measurements of dose rate made in the cabin before shipment. These average about 1 μSv/h. Therefore, for a driver who makes 100 eight-hour trips (two trips per week) with UO a year, the total dose is estimated to be about 0.8 mSv.

Dose rates at one metre from a container of UO are typically about 10 μSv/h. Bystanders and residents near the transport routes would thus receive very small doses (fractions of a microsievert) as UO containers passed by.

Under accident conditions, it is possible that some exposure to drivers, emergency services crews and bystanders may arise. These exposures would result only if the accident was severe enough to rupture both the shipping container and the drums of UO, releasing the UO, which may then become airborne and be inhaled. Such an accident is very unlikely, and even under such circumstances it is unlikely that significant doses would arise. The UO is a coarse, heavy powder which does not readily become airborne, and the duration of any such exposure would be relatively short, probably much less than an hour. Clean-up workers would be exposed for longer, but would be supplied with appropriate protective equipment, particularly respiratory protection.

From Port Adelaide, some UO is loaded into ships for export, while some is railed to Darwin, and shipped from there. Similar considerations to the above apply to transport by rail, and doses to both train crews and members of the public are expected to be less than those for road transport, because of the generally greater distances between the uranium and the crew or the public.

UO from the proposed expanded operation is expected to be transported in a similar way, with the likely alternative that when the railway to Olympic Dam is completed, UO would be railed to Port Adelaide or direct to Darwin. Doses from the transport of UO from the proposed expansion are thus expected to be similar to those at present.

S2.4.2 Copper concentrate transport

It is proposed that approximately 1.6 Mtpa of copper concentrate produced from the expanded operation would be exported. At present, transport by rail to Darwin is considered the most likely option. Copper concentrate is expected to contain radionuclides approximately equivalent to ore of about 1,000 to 2,000 ppm uranium. The concentrate would thus be considered radioactive for the purpose of transport (ARPANSA 2008; International Atomic Energy Agency 2005). It is expected that the concentrate would be transported either in purpose-built railway wagons, fitted with lids to prevent the escape of dust, or in standard shipping containers.

Using the conversion factors in (Thomson & Wilson 1980), the dose rate 1 m from such a wagon is estimated to be approximately 10 μSv/h. This is expected to be an overestimate as it assumes that the wagon is infinitely large. Using a more reasonable estimate for the size of a wagon reduces this estimate by approximately a factor of 3. A conservative gamma dose rate of 5 μSv/h at 1 m is assumed. The dose rate would be further reduced at greater distances.

Although the exposure time for train shipment to Darwin would be considerably longer than for transport to Adelaide, as discussed above, the much greater separation of train crews from the load than is the case for the drivers of trucks would lead to a significant reduction in dose rate in the crew's compartment. Therefore doses to crews of trains transporting copper concentrate are expected to be similar to those for transport of UO. For members of the public, doses are expected to be very small because of the generally large separation between occupied areas and the railway track.

S2.5 RADIATION IN THE ENVIRONMENT

S2.5.1 Exposure pathways

There are two main pathways by which radioactive materials can enter the general environment from an operational area: airborne and waterborne (see Figure S2.6). These are both internal pathways. Gamma external exposure from ore stockpiles, tailings and other facilities are expected to be negligible outside the special mining lease area due to the distances involved.

Waterborne pathways

In the arid environment at Olympic Dam, waterborne pathways are either non-existent or insignificant.

The general area is divided into small, disconnected catchments with no surface drainage lines. If any significant run-off occurs, the water collects in local depressions from which it either evaporates or infiltrates into the ground.

The groundwater does not reach the surface in the area and is very saline. It therefore cannot be consumed without treatment, and any such treatment (e.g. reverse osmosis) would remove radionuclides as well as other dissolved elements. The consumption of contaminated groundwater thus does not constitute a pathway for human or environmental exposure.

Airborne pathways

Potential airborne pathways include both the inhalation of radon decay products and the inhalation of radioactive dusts.

The results of an extensive program for monitoring radiation in the environment at the current Olympic Dam operation, including continuous monitoring of radon decay products at five locations and dust concentrations at three locations, have been used to estimate the doses to members of the public at Roxby Downs and Olympic Village from current operations. The project-related doses are estimated to be less than 25 μSv/y, with approximately 20 μSv/y from inhalation of radon decay products and <5 μSv/y from inhalation of dust (Crouch et al. 2005).

There are possible indirect airborne pathways such as eating home grown vegetables affected by dust fallout, drinking rainwater from roofs that may also collect dust, and of gamma exposure from dust fallout in occupied areas, but these are expected to be low. Dose assessment to members of the public via the ingestion pathway can be seen in Section S2.5.3.

Monitoring

An environmental radiation monitoring program would be developed and implemented for the proposed expanded operation. This program would be developed in conjunction with appropriate regulatory authorities, and submitted for approval. For the reasons outlined above, it would be expected to focus on monitoring of airborne concentrations of dust and radon decay products, but would also include some monitoring of other parameters, including groundwater.

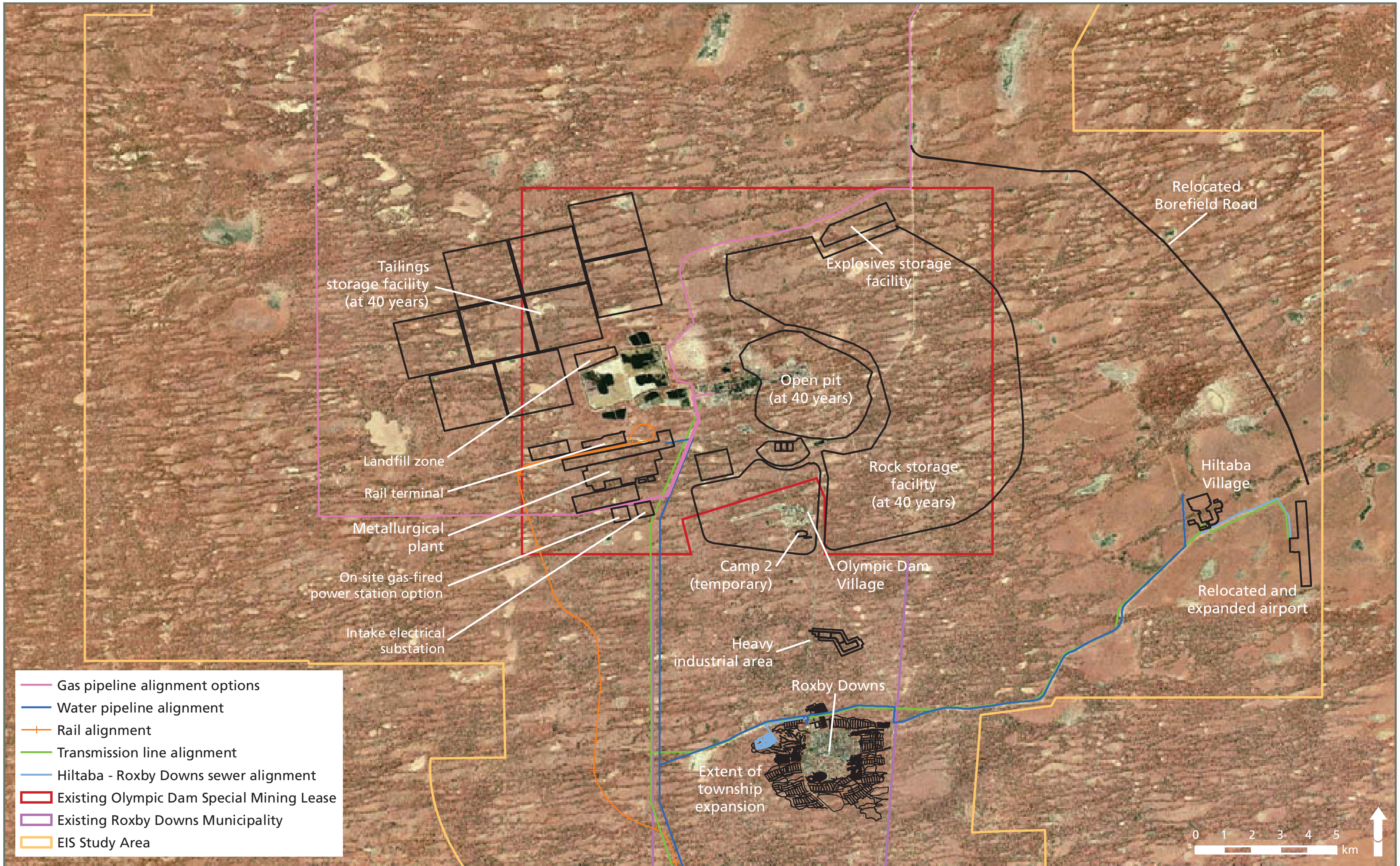


Figure S2.6 Residential locations

S2.5.2 Doses to members of the public

There are three main 'members of the public' groups that may be exposed (see Figure S2.6):

- residents of Roxby Downs Municipality
- off-shift workers and members of the public at Olympic Village (which because of its proximity to proposed operational areas would be expected to be decommissioned soon after the expanded project commenced)
- off-shift workers and members of the public at Hiltaba Village

In addition, it is possible that Indigenous traditional owners may enter the Special Mining Lease and surrounding areas, and may consume 'bush food' while there. Such visits would be transitory, and entry into operational areas (including waste management areas) would be restricted for safety and security reasons.

An atmospheric dispersion model has been developed to predict concentrations of radon and dust at these locations from the expanded operations. The model was developed using the most conservative meteorological conditions that would yield maximum concentrations at the three potential exposure sites. Further details of the atmospheric model are provided in Section S3 and Chapter 13, Greenhouse Gas and Air Quality.

Doses from radon decay products

Results of the radon modelling are provided in Figure S2.7. It shows the estimated mean annual radon concentration at each of the main areas occupied by members of the public. The resulting dose to a resident inhaling this concentration for a whole year was calculated using the dose conversion factors from UNSCEAR (2000a) for indoor and outdoor exposure and can be seen in Table S3.

A dominant source of radon is the rock storage facility (RSF) (see source terms in Section S3). The modelling assumed that the RSF was left uncovered for the assumed operational period (40 years). If the RSF were to be progressively covered with inert material, the radon production from this source and the resulting dose to members of the public would be reduced proportionally.

Table S3 Estimated radon decay product dose to members of the public

Location	Radon concentration (Bq/m^3)	Estimated dose to members of the public (µSv/y)		
		Indoor	Outdoor	Total (rounded)
Roxby Downs	3.4	86	32	120
Olympic Village	30	760	290	1,000
Hiltaba Village	3.3	83	31	120

Doses from dust inhalation

The air dispersion model described in Chapter 13, Greenhouse Gas and Air Quality provided an estimate of total suspended particulate (TSP) concentration at each area occupied by members of the public. A figure showing the TSP contours is given in Chapter 13, Greenhouse Gas and Air Quality. These mean annual dust concentrations were used to estimate the dose to a representative individual at each location. The assumptions made in this dose assessment were: an average uranium grade for all excavated material (see Section S2.1), uranium in equilibrium with its decay products and ICRP recommended breathing rates and dose conversion factors (International Commission on Radiological Protection 1996) for adults and children aged one and 10 years (see Table S4).

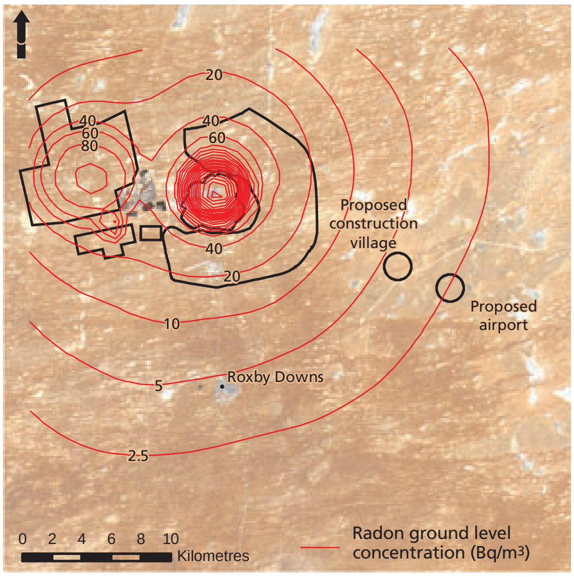


Figure S2.7 Estimated radon ground level concentration

Table S4 Estimated dust dose to members of the public

Location	Dust concentration ($\mu g/m^3$)	Estimated dust doses to members of the public (μSv/y)		
		1 year old	10 year old	Adult
Roxby Downs	15	2	3	3
Olympic Village	50	6	9	11
Hiltaba Village	15	2	3	3

S2.5.3 Estimated total dose to members of the public

A dose of approximately 1,000 μSv (1mSv) is estimated for Olympic Village. Because of its proximity to operations, however, it is expected that no members of the public would be residing at this site after production commenced. At year 40, the current Olympic Village site would be covered by the RSF.

The estimated total dose to a member of the public living at either Roxby Downs municipality or Hiltaba Village as a result of this project is 130 μSv/y (0.13 mSv/y), comprising 120 μSv from radon decay product exposure and 3 μSv from inhalation of radioactive dusts.

There is little information on the radionuclide content of 'bush foods' in the Olympic Dam area. Doses have been estimated for Indigenous people living in the Alligator Rivers region of the Northern Territory, where there are a number of poorly rehabilitated uranium mining and processing sites, including accessible areas for exposed wastes, and bush food is relatively plentiful. The estimate was based on occupancy of the area of about nine months of the year, with approximately 50% of food consumed being 'bush food'. The estimated dose resulting from such occupancy was approximately 300 μSv/y (Böllhofer et al. 2002). Because people travelling through the Olympic Dam area would be expected to spend less than two weeks per year in the area, and because of the relative scarcity of bush food, the dose from such short-term occupancy would be less than 10 μSv/y.

Using standard ICRP dosimetric modelling, relevant standards and natural background levels, the doses from locally grown and consumed beef can be determined. Based on environmental sampling at Olympic Dam, conservative estimates of doses from the regular consumption of beef from the local areas are between 0.02 and 0.04 mSv/yr (for both children and adults). A most conservative case for ingestion dose from home grown vegetables and drinking water from rain tanks for the public in Roxby Downs is estimated to be 0.01 mSv/y.

S2.5.4 Radiation in the non-human environment

ICRP has developed its approach to the assessment of impact to non-human species (see Section S1.4.3). The European Commission has developed an assessment tool called ERICA (Environmental Risk from Ionising Contaminants: Assessment and Management) to provide an integrated approach to the assessment and management of environmental risks from ionising radiation, along with software and databases to assist with assessments (ERICA Program 2007).

The assessment is structured in three tiers.

- Tier one is a simple assessment of the worst-case situation for all radionuclides and organisms, in which all situations where there is a potential risk are identified.
- Tier two is a more detailed risk assessment undertaken only on those situations that were identified as having a potential risk in tier one. This assessment is undertaken using best estimate values and yields a low, moderate or high-risk result.
- Tier three is a detailed, site specific, radiological assessment of any high-risk situations that are identified by the tier two assessment.

ERICA assessment results

The ERICA tool was used to assess the potential radiological risk to the terrestrial environment (non-human biota) surrounding the Olympic Dam expansion area.

A tier one assessment is undertaken initially. This is designed to be simple and conservative, requiring a minimum of input data and enabling the exemption of the situation from further evaluation, provided the assessment meets a predefined screening criterion. The default screening criterion in the ERICA integrated approach is an incremental dose rate of 10 µGy/h to be used for all ecosystems and organisms. This value was derived from a species sensitivity distribution analysis performed on chronic exposure data and is supported by other methods for determining predicted zero effect values. This default value was used for the Olympic Dam expansion assessment. The screening dose rate is used to calculate environmental media concentration limits (EMCLs) for all reference organism/radionuclide combinations. The tool compares the input media concentrations with the most restrictive EMCLs for each radionuclide and determines a risk quotient (RQ). If the RQ is less than one, the tool suggests no further assessment; if greater than one, the assessment should continue.

As detailed in Section S2.5.1, the critical pathway for transport of radionuclides into the environment is by air. Unlike the assessment of dose to humans, where radon inhalation is significant, the major pathway for ecological exposure results from long-term dust deposition.

The air dispersion model (see Chapter 13, Greenhouse Gas and Air Quality) was used to determine the dust deposition immediately outside operational areas. This showed a maximum of about 25 $g/m^2/y$ inside the lease boundary, falling to below 6 $g/m^2/y$ outside the lease boundaries. Over time the deposited dust would mix with the underlying soil. The depth of this mixing would vary with the soil type. Typically, surface soil sampling is undertaken in the top 200 mm and is thought to give an average representation. The area surrounding the Olympic Dam expansion area has sand dunes, swale and clay pans. Mixing within the dunes is likely to far exceed 200 mm, however little to no mixing is likely to occur in the swale or claypan. For the purposes of modelling, it was assumed that over the 40 years of deposition, the dust would mix uniformly into the top 10 mm of soil. Using the uranium grade for all excavated material (see Section S2.1), the increase in uranium concentration after 40 years of operations is estimated to be 6 ppm U in the highest deposition areas. Note that the average uranium concentration in soils is about 3 ppm, but concentrations three times higher are also commonly found in normal soils (UNSCEAR 2000b).

This maximum predicted soil concentration was used in the tier one assessment, yielding a risk quotient of less then one (negligible risk) for all but two radionuclides, Radium-226 in detritivorous invertebrates and Polonium-210 in mammals (rats and deer). For the purposes of this assessment, small mammals were considered to be equivalent to rats and kangaroos equivalent to deer.

A tier two assessment was then conducted for these radionuclides and reference animals. Again the maximum predicted soil concentration was used and the most conservative position was selected. The resultant risk quotient for this assessment was less than one for each radionuclide and reference animal, indicating that there is negligible risk and that a detailed tier three assessment was not required.

The results of this assessment indicate that the radiological risk to non-human biota as a result of dust deposition from the proposed Olympic Dam expansion over a 40-year mine life is negligible.

APPENDIX S3

Attachments

S3 ATTACHMENTS

S3.1 RADON MODELLING

S3.1.1 Source terms

Radon emissions from the pit, stockpiles and tailings were determined from radon emanation terms and the areas of the emitting sources (Akber et al. 2001; Sonter 1987). The emanation rates used are shown in Table S5.

Table S5 Radon emanation rates

Material	Emanation rate ($Bq/m^2/s$)
Ore (*in situ* – 500 ppm)	2.5
Rock (*in situ*)	2.5 x (U/500) [1]
Broken ore material	5 x unbroken
Tailings	0.5

[1] U = uranium content (ppm)

The radon emission from the underground workings was estimated from the measured current emission, with a 10% increase to allow for additional workings. The radon release from processing was estimated by assuming that all contained radon in the ore was released in processing. The resulting source terms used for modelling are shown in Table S6.

Table S6 Radon source terms for the expanded operation

Radon source	Emission rate (MBq/s)
Underground exhaust air	3.33
Open pit emanation	8.6
Processing ore stockpile	0.44
ROM ore stockpile	0.83
Rock storage facility	82.5
Concentrators	0.91
Tailings storage facilities	13.9

It will be noted that the major source is the rock storage. For the purposes of modelling it was assumed that there was no particular segregation of rock types. However, it is proposed that rock will be deposited so that active rock (containing higher uranium concentrations) would be progressively covered with low-grade material during deposition. This would substantially reduce the radon emission.

S3.1.2 In-pit model

The model used for normal ventilation is based on the following expression for open pit ventilation:

$T = 33.8\,(V/U_rLW)[0.7\cos(\theta) + 0.3]$ (Thompson 1994)

where T is the residence time, V is the pit volume, U_r the wind velocity, L and W are the pit length and width, and θ is the angle of the wind to the pit long axis. This model was applied for wind speeds from 0.1 m/s to 10 m/s. The radon decay product concentrations were estimated from the worst-case assumption that they were in equilibrium with radon.

The low-ventilation model assumed that an inversion formed 100 m above the base of the pit (assumed to be entirely ore) which trapped all radon produced, and remained in place for 12 hours. Radon decay products were assumed to be in equilibrium with radon. Under these conditions, the radon decay product concentration was estimated to reach 6 $\mu J/m^3$ after 12 hours. The average concentration over the period of inversion was 3 $\mu J/m^3$.

S3.1.3 Environmental model

The atmospheric dispersion model described in Chapter 13, Greenhouse Gas and Air Quality, was used, with the source terms shown above. Again, it was assumed that the radon decay products were in equilibrium with radon, which gives a worst-case estimate. The estimated annual average ground-level concentrations are provided in Table S7 and Figure S2.7.

Table S7 Ground-level radon concentrations at Roxby Downs, Hiltaba Village and Olympic Village

Pollutant	Averaging period	Roxby Downs	Hiltaba Village	Olympic Village
Radon	Annual (Bq/m^3)	3.37	3.26	30

S3.2 DOSE CONVERSION FACTORS

S3.2.1 Occupational exposure

Dust

The following are the dose conversion factors approved by the regulatory authority for use in deriving doses from monitored dust concentrations in the existing operation. They are based on the measured or inferred radionuclide contents of the various dusts, and particle size expressed as activity median aerodynamic diameter (AMAD). 'αdps' means the activity concentration of long-lived alpha emitting radionuclides in the relevant dust cloud.

Ore dust:	7.2 μSv/αdps
Product dust:	7.9 μSv/αdps
Smelter dust:	6.3 μSv/αdps
Refinery dust:	4.5 μSv/αdps

These dose conversion factors were also used as appropriate in estimating doses from the proposed expanded operation.

Radon decay products

The approved dose conversion factor for the existing operation is 1.4 mSv.m^3/mJ.h. This factor was used for estimation of doses in the proposed expanded operation (open pit), with the assumption that RnDPs are in equilibrium with the parent radon.

S3.2.2 Environmental exposure

Dust

The dose conversion factor used for environmental dust exposure was 51 μSv/Bq. This was derived from the dose conversion factors for relevant individual radionuclides in International Atomic Energy Agency 1996, using a 1 μm particle size (AMAD) and using the 'S' lung absorption class. The activity used with this dose conversion factor is the parent ^{238}U activity.

Radon decay products

The dose conversion factor for environmental exposure recommended by UNSCEAR (9 nSv/(Bq.h.m^{-3}) together with the recommended factors for equilibrium factor for indoors and outdoors (0.4 and 0.6 respectively) and indoor and outdoor occupancy (7,000 hours and 1,760 hours respectively) were used to estimate doses. The activity used with this dose conversion factor is the activity of radon (^{222}Rn). (UNSCEAR 2000 Annex B, para 153)

S3.3 WORKED EXAMPLE OF DOSE CALCULATION

The method for dose assessment is detailed and an indicative worked example is provided for a worker in the underground mine at Olympic Dam. The steps are outlined in the first column of Table S8 and an example calculation is provided in the adjacent column. The steps are adapted from (Olympic Dam Project 2001–2007).

The example is a truck driver in the underground mine at Olympic Dam.

Table S8 Worked example of employee dose calculation

Steps in Determining Occupational Radiation Dose		Example Calculation
Gamma radiation		
1	Miners are issued with a TLD badge for a period of one month or three months, depending upon their work group.	The truck driver will receive and wear his badge for one month.
2	At the end of the wearing period, the badges are collected and sent to the ARPANSA analysis laboratories in Melbourne and results are reported back to Olympic Dam.	The estimated dose from exposure to gamma radiation is 200 µSv for the month.
3	Where a badge may have been lost, the work group average is allocated.	For the truck drivers, the average of all truck driver results can be calculated by adding all the results and dividing by the number of truck drivers.
4	Where exposure levels are known to be low (though monitoring), TLD badges may be given only to a representative group of workers.	For example, for mine office staff, an average would be calculated based on random sampling.
Exposure to long lived radionuclides in dust		
1	Airborne dust sampling of workgroups is used as the basis for dose assessment. Workers are asked to wear a dust sampling pump on their persons for a shift. For workers who are not mobile (for example drillers), a dust pump is placed within their workplace.	Typical workgroups in the mine include truck drivers, loader operators, drillers and production crews.
2	Dust samples are analysed giving an average dust concentration (in Bq/m^3) of long lived alpha radiation in airborne dust for the wearer or location.	The long lived alpha emitter levels in dust for a particular truck driver for a shift might be 0.05 Bq/m^3. (Note that dust samples are also used for regular dust monitoring and control).
3	Average dust levels are determined for workgroups.	During a week, 25 samples might be taken on truck drivers, giving an average long lived alpha emitter level in dust for truck drivers of 0.05 Bq/m^3, for example.
4	The time that the individual spent working in that workgroup is determined from employee time sheets.	This information is obtained from workers' time cards. Workers are required to provide as much detail on locations and occupation as possible on their time cards.
5	By multiplying the time spent in the concentration, you get the exposure levels (usually in Bq.h/m^3).	If an individual was a truck driver for 170 hours in a month, then the total exposure would be 8.5 Bq.h/m^3 (of long lived alpha radiation).
6	To convert the exposure to a dose, you need to know the type of dust and its particle size. Additional monitoring at Olympic Dam provides this information. Once you know the type of dust, you can then convert the exposure to a dose using a dose conversion factor (these can be seen in Attachment S3).	The dust conversion factor for ore (see section 3.2.1) is 7.2 µSv per alpha disintegration per second. The calculation is: 7.2 x 8.5 = 60 µSv for the month.
Exposure to radon decay products (RDP)		
1	Exposure to RDP is assessed using the results from the approved radiation monitoring program.	Unlike dust monitoring, RDP monitoring is location based, that is, radiation technicians go to a workplace or location and sample the air and analyse the result immediately.
2	The mine is considered to have a number of 'ventilation districts'. RDP levels are determined for these districts based on routine monitoring, giving area averages in micro Joules per cubic metre (µJ/m^3).	The average of 10 RDP measurements for a week in a production heading might be 1.2 µJ/m^3. Over the next three weeks of the month, concentration averages might be 0.9, 1.4 and 0.5.
3	The time that workers spend in these districts is determined through their time sheets which is combined with the RDP concentrations to give a RDP exposure.	The truck driver might work 40 hours per week all month in this production heading, so the exposure would be 40 x 1.2 + 40 x 0.9 + 40 x 1.4 + 40 x 0.5, giving a total exposure for the month of 160 µJh/m^3.
4	The ICRP recommended factor that converts RDP exposure to effective dose is used.	The dose conversion factor for RDP is 1.4 mSv.m^3/mJ.h, (which is the same as 1.4 µSv.m^3/µJ.h). Therefore, the calculation is 1.4 x 160, giving 224 µSv for the month.
Calculating total dose		
1	The doses from each of the exposure pathways are added together to provide a total dose equivalent in µSv.	Gamma dose = 200 µSv Dust dose = 60 µSv RDP dose = 224 µSv Total dose = 484 µSv This is rounded up to 500 µSv for the month.

S4 REFERENCES

Akber, R, Jeffries, C & Dhamasiri, J 2001, *Rn-222 emission due to mining and milling activities at WMC Olympic Dam Operations*, Western Mining Corporation, Olympic Dam, SA.

AREVA Resources Canada 2008, *2007 Annual Review*. AREVA Resources Canada, Saskatoon.

ARPANSA 1995, *Recommendations for Limiting Exposure to Ionizing Radiation, Radiation Protection Series*, vol. 1, Australian Radiation Protection and Nuclear Safety Agency 2002, Yallambie, Victoria.

ARPANSA 2005, 'Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing', *Radiation Protection Series*, vol. 9, Australian Radiation Protection and Nuclear Safety Agency, Yallambie, Victoria.

ARPANSA 2008, *Safety Guide, Safe Transport of Radioactive Material*, Australian Radiation Protection and Nuclear Safety Agency, Yallambie, Victoria.

BHP Billiton 2008, E*nvironmental Management and Monitoring Report 1 July 2007 – 30 July 2008*, Report no. ODENV 41, BHP Billiton, Olympic Dam.

Bollhöfer, A, Ryan, B, Pfitzner, K, Martin, P & Iles, M 2002, 'A radiation dose estimate for visitors of the South Alligator River Valley, Australia, from remnants of uranium mining and milling activities', *Uranium Mining and Hydrogeology III*, eds BJ Merkel, B Planer-Friedrich & C Wolkersdorfer, Technical University, Bergakademie Freiberg, pp. 931–940.

Brenner, DJ, Doll, R, Goodhead, DT, Hall, EJ, Land, CE, Little, JB, Lubin, JH, Preston, DL, Preston, RJ, Puskin, JS, Ron, E, Sachs, RK, Samet, JM, Setlow, RB & Zaider, M 2003, 'Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know', *Proceedings of the National Academy of Science*, vol. 100, no. 24, pp. 13,761–13,766.

Cardis, E, Vrijheid, M, Blettner, M, Gilbert, E, Hakama, M, Hill, C, Howe, G, Kaldor, J, Muirhead, CR, Schubauer-Berigan, M, Yoshimura, T, Bermann, F, Cowper, G, Fix, J, Hacker, C, Heinmiller, B, Marshall, M, Thierry-Chef, I, Utterback, D, Ahn, Y-O, Amoros, E, Ashmore, P, Auvinen, A, Bae, J-M, Bernar Solano, J, Biau, A, Combalot, E, Deboodt, P, Diez Sacristan, A, Eklof, M, Engels, H, Engholm, G, Gulis, G, Habib, R, Holan, K, Hyvonen, H, Kerekes, A, Kurtinaitis, J, Malker, H, Martuzzi, M, Mastauskas, A, Monnet, A, Moser, M, Pearce, MS, Richardson, DB, Rodriguez-Artalejo, F, Rogel, A, Tardy, H, Telle-Lamberton, M, Turai, I, Usel, M & Veress, K 2005, 'Risk of cancer after low doses of ionizing radiation: retrospective cohort study in 15 countries', *British Medical Journal,* vol. 331, p. 77–82.

Creely, KS, Van Tongeren, M, While, D, Soutar, AJ, Tickner, J, Agostini, M, De Vocht, F, Kronhout, H, Graham, M, Bolton, A, Cowie, H, & Cherrie JW 2006, *Trends in Inhalation Exposure – mid 1980s till present, HSE Research Report 460*. HSE Books, Sudbury, UK.

Crouch, P, Green, S & Worby, M 2005, 'Radiation Doses to Members of the Public from the Olympic Dam Operation'*, Radiation Protection In Australasia*, vol. 22, no. 1, p. 4.

Energy Resources of Australia 2006, *Radiation Protection and Atmospheric Monitoring Program – Report for the year ending 31 December 2005,* Energy Resources of Australia, Darwin.

ERICA Program 2007, *Protection of the environment from ionising radiation in a regulatory context (EC Euratom 6th Framework programme: Contract No. FP6-036425)*, European Commission Euratom Supply Agency, Lancaster, UK.

Health Canada 2007, *2006 Report on Occupational Radiation Exposures in Canada*, Health Canada, Ottawa.

International Atomic Energy Agency 1996, 'International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources', *Basic Safety Standards*, IAEA, Vienna.

International Atomic Energy Agency 2005, *Regulations for the Safe Transport of Radioactive Material*. IAEA Safety Series, vol. TR-1, IAEA, Vienna.

International Commission on Radiological Protection 1990, '1990 Recommendations of the International Commission on Radiological Protection - ICRP Publication 60', *Annals of the ICRP,* vol. 21, no. 1–3, p. 1.

S2.2.2 Predicted exposures – mining

The proposed mining technique for the expansion is an open pit, in contrast to the current underground mining operation. The proposed mining technique is fundamentally different to the existing situation and therefore radiation exposures are expected to be different.

In this section the pathways for exposure from the proposed open pit operations have been identified and potential doses to open pit workers are predicted. These dose predictions have in general been made using one or more of three methods:

- comparison with the existing project
- comparison with other comparable projects
- calculations using models.

Where appropriate, dose conversion factors from the Code (ARPANSA 2005) have been used.

Figure S2.3 demonstrates the exposure pathways for an open pit mine.

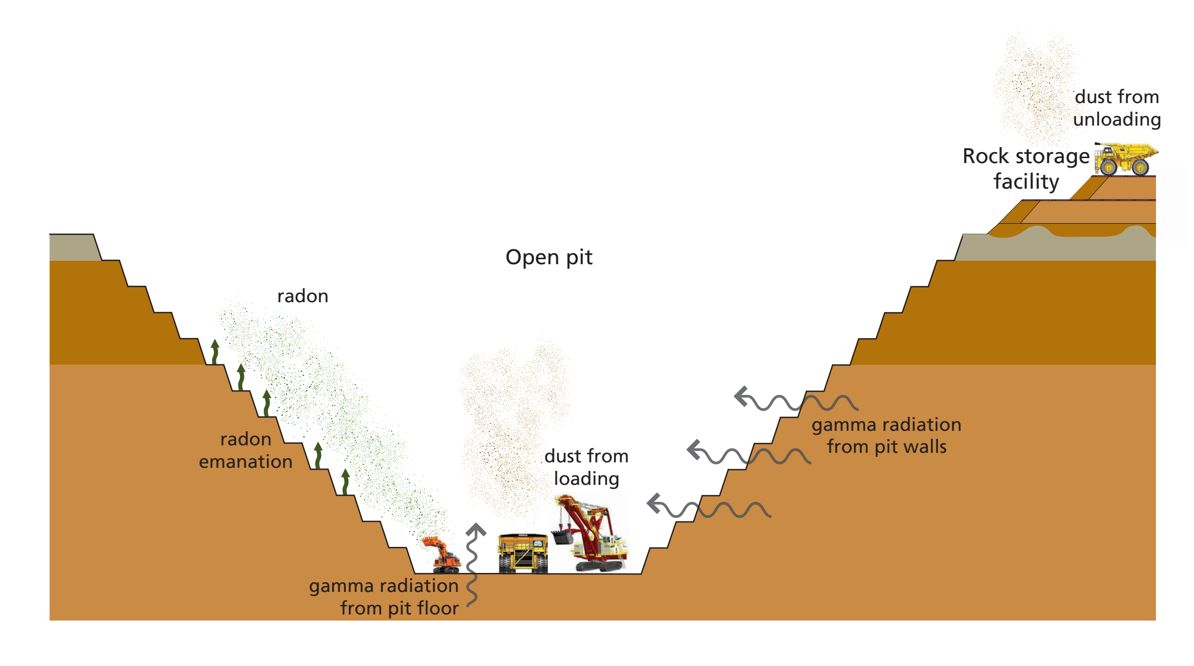


Figure S2.3 Open pit pathways

Gamma exposure

Gamma doses in the open pit have been estimated using theoretical models, the current (underground) mine doses, and comparisons with other open pit uranium mining operations in Australia and overseas.

The gamma dose from an extended (plane) deposit can be calculated using the conversion factor 65 μSv/h/%U (Thomson & Wilson 1980). In the open pit there would be a slight increase over that of an extended plane due to radiation from the walls. However, there would generally be some reduction due to shielding from equipment.

Applying this to the uranium grades for both ore material and excavated material after the cover material is removed (see Section S.2.1) gives annual doses from full-time exposure (2,000 h/y), of about 6.5 mSv and 2.6 mSv respectively.

In practice, it is most unlikely that an individual would work full time on ore, so the value 6.5 mSv/y is likely to represent a significant overestimate. The highest exposure work groups are likely to be the drillers and shot firers. Typically these personnel would spend no more than 60% of their time in one year on ore (when travel time to and from work areas and mining work plans across a whole year are taken into account). This would then give a maximum dose of about 4 mSv/y.

To compare this theoretical calculation with that observed in real situations, a review of doses observed at both current Olympic Dam underground operations and those at the Ranger uranium mine open pit was undertaken.