Submission No. 32

Australian Government

Australian Radiation Protection and Nuclear Safety Agency

HOUSE OF REPRESENTATIVES STANDING COMMITTEE ON INDUSTRY AND RESOURCES

CASE STUDY: THE STRATEGIC IMPORTANCE OF AUSTRALIA'S URANIUM RESOURCES

SUBMISSION BY THE CEO OF THE AUSTRALIAN RADIATION PROTECTION AND NUCLEAR SAFETY AGENCY

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1. INTRODUCTION

This submission provides information of relevance to term of reference (d) of the case study and to several matters on which members of the Committee have indicated they would also welcome advice (letter of 18 March from Committee Secretary to CEO of ARPANSA).

The submission first describes the relevant provisions of the *Australian Radiation Protection and Nuclear Safety Act 1998* (the ARPANS Act). Sections of the submission then cover:

- The existing and developing framework in Australia for radiation protection and radioactive waste management in the mining and processing of uranium ores and in transport
- Health effects of ionizing radiation and standards for control of exposure
- Radiation doses to workers as a result of uranium mining and milling in Australia
- The security categorisation of radioactive materials.

An appendix to the submission discusses the radiation doses to the public and workers from the entire nuclear fuel cycle.

2. PROVISIONS OF THE ARPANS ACT

The Act establishes the office of CEO of ARPANSA. Section 15 of the Act states the functions of the CEO. Those relevant to the case study being undertaken by the Committee are:

(a) to *promote uniformity* of radiation protection and nuclear safety policy and practices across jurisdictions of the Commonwealth, the States and the Territories;
(b) to *provide advice* on radiation protection, nuclear safety and related issues;
(c) to *undertake research* in relation to radiation protection, nuclear safety and medical exposures to radiation;
(d) to *provide services* relating to radiation protection, nuclear safety and medical exposures to radiation.

The Act also establishes the CEO as the regulator of: the construction and operation of nuclear installations or prescribed radiation facilities; or dealings with radiation sources; by 'controlled persons'. A 'controlled person' is a Commonwealth entity (Commonwealth Department, agency or body corporate or Commonwealth controlled company) or a Commonwealth contractor.

Therefore, ARPANSA[1] does not have a direct role in regulation for radiation protection of current uranium mining in Australia. Through the CEO's function of promoting national uniformity, however, it plays a major part in establishing the national framework for radiation protection applying, inter alia, to uranium mining and milling. Its advisory, research and service provisions roles are also relevant.

The CEO of ARPANSA has issued a facility licence to Parks Australia North, a Commonwealth entity, to undertake certain works in regard to the stabilisation of tailings from a legacy uranium mine situated in the Kakadu Park.

The Act also establishes the Radiation Health and Safety Advisory Council and the Radiation Health Committee.

The Radiation Health and Safety Advisory Council has the functions of identifying emerging issues and matters of major concern to the community and advising the CEO on them. Specifically, it has the function of advising the CEO on the adoption of recommendations, policies, codes and standards in relation to radiation protection and nuclear safety.

The functions of the Radiation Health Committee are:

(a) to advise the CEO and the Council on matters relating to radiation protection;
(b) to develop policies and to prepare draft publications for the promotion of uniform national standards of radiation protection;
(c) to formulate draft national policies, codes and standards in relation to radiation protection for consideration by the Commonwealth, States and Territories;
(d) from time to time to review national policies, codes and standards in relation to radiation protection to ensure that they continue to substantially reflect world best practice;
(e) to consult publicly in the development and review of policies, codes and standards in relation to radiation protection.

The members of the Radiation Health Committee are: the CEO of ARPANSA; a 'radiation control officer' from each State and Territory; a representative of the Nuclear Safety Committee (also established under the Act); a person to represent the interest of the general public; up to 2 other members.

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[1] In the remainder of the submission, ARPANSA is used to mean the CEO and the APS employees engaged to assist the CEO, together constituting a statutory agency for the purposes of the *Public Service Act 1999*.

3. NATIONAL REGULATORY FRAMEWORK

Codes and Standards

Regulation for radiation protection and of radioactive waste management of the mining and milling of uranium takes place primarily through State/Territory legislation. Radiation protection provisions are principally based upon several national codes of practice and standards, which in turn draw upon international guidance.

The current codes and standards dealing directly with the mining and milling of radioactive ores are:

- *Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (1987)*
- *Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (1982)*

These Codes were developed through arrangements under the *Environment Protection (Nuclear Codes) Act* 1978. This Act was repealed at the time the ARPANS Act came into effect.

The mining *Nuclear Codes* specified the responsibilities of owners, operators and managers for radiation protection of employees and members of the public, and for the management of radioactive waste, respectively. Further detail on the technical requirements for the application of these Codes was provided through guidelines.

The fundamental regulatory limits in radiation protection are the 'dose limits'. These are the radiation doses that must not be exceeded for an individual worker or for a member of the public. Importantly, the dose limits defined in the above mining *Nuclear Codes* have now been superseded by those established by the *Recommendations for limiting exposure to ionizing radiation* and the *National standard for limiting occupational exposure to ionizing radiation* (1995) first published by the National Health and Medical Research Council and the National Occupational Health and Safety Commission. This document was re-published by ARPANSA in 2002 as part of the Radiation Protection Series[2].

The basis for the system of radiation protection and the dose limits established by the *Recommendations* and *Standard* are described in Section 4 of this submission.

The process of revising and updating the mining *Nuclear Codes* is being completed through the Radiation Health Committee. A draft of a single Code of Practice *Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* has been developed and been the subject of a period of public comment and discussion at a recent national conference (April 2005) on radiation protection in mining and minerals processing. The Code of Practice is accompanied by a Safety

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[2] The Radiation Protection Series includes all radiation protections Codes of Practice, Safety Guides and Recommendations that have been prepared or revised since the formation of ARPANSA in 1999.

Guide, which offers best-practice advice on the requirements of the Code. It is hoped that the Code and Safety Guide will be adopted and published by the end of 2005.

The Codes have been revised as there have been major changes in recent years in radiation protection and waste management philosophies and standards. The International Commission on Radiological Protection (ICRP) released revised recommendations in 1991 and subsequent guidance on a number of relevant matters. The International Atomic Energy Agency (IAEA) published the Basic Safety Standards in 1996.[3] There has also been an emerging recognition in radiation protection of the employer's "duty of care" and ultimate ownership of occupational risks, while working in cooperation with the employees and the regulator, rather than within a prescriptive enforcement regime. There have also been developments in international guidance in radioactive waste management since the publication of the Waste Code.

Transport of Radioactive Material

The transport of radioactive materials, including uranium, is dealt with through the *Code of Practice for the Safety Transport of Radioactive Material* (Radiation Protection Series No 2, ARPANSA, 2001). This Code of Practice, which effectively adopts the international transport requirements published by the International Atomic Energy Agency, also replaced an earlier Code made under the *Environment Protection (Nuclear Codes) Act 1978.*

The *Code* is mentioned in the ARPANS Regulations (Regulation 62A) which requires that the practices and procedures described in the mentioned Codes must, to the extent that they are relevant, be followed by controlled persons. The Code is also mentioned as a statutory licence condition in Regulation 48. Thus, relevant Commonwealth activities are effectively regulated under the provisions of the *Code.*

State and Territory jurisdictions have adopted the *Code*, with the current exception of Victoria which is moving to adopt the *Code.*

For the transport of radioactive material by air and sea, the IAEA transport regulations become law due to Australia's ratification of the Chicago and SOLAS Conventions respectively, which both contain annexes relating to the safe transport of dangerous goods, of which radioactive materials are one class.

To put it at its simplest, the *Code* first establishes some general provisions about a radiation protection program, emergency response, quality assurance, compliance assurance and allows for special arrangements. It describes some basic requirements for packages in which radioactive materials may be transported. It then specifies a number of package types of varying degrees of robustness and sets out the limits for the activity and activity concentration of the different radionuclides and forms of material that might be contained within such a package. The description is complicated because of the differing package types and because 'the package' includes the packaging and the form of the radioactive contents. Controls on the

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[3] These international changes are reflected in RPS 1 *Recommendations for limiting exposure to ionizing radiation* and the *National standard for limiting occupational exposure to ionizing radiation*

design and use of the package, and its required strength, increase as the hazardous nature of its radioactive contents increases.

The categories of packaging used to transport radioactive material include:

- 'Industrial Packages' of Types 1,2 and 3. These are typically used to transport low specific activity radioactive material such as ores containing uranium, or low activity solids. 'Yellowcake' would normally be transported in an Industrial Package Type 2 or 3;
- Type A Packages typically used for the transport of medical isotopes
- Type B Packages used for the transport of higher activity radioactive material
- Type C Package used for the transport of large amounts of radioactive material, including fissile material, by air.

Packaging toughness is measured by its ability to withstand various conditions of transport – these are routine conditions (incident free); normal conditions (minor mishaps); and accident conditions. For Industrial Packages Type 2 and Type 3, and for Type A packages, the package is required to maintain its integrity under normal (ie minor incidents) conditions of transport. Industrial packages are typically used in Australia to transport natural uranium ores and concentrates.

For Type B and Type C Packages, the package is designed and tested for routine, normal and accident conditions of transport. Such packages are typically used in Australia to transport fresh and spent nuclear fuel, and a range of radioactive sources used by industry, science and research organisations

After the package, the next level of safety derives from active controls. These include: labeling; marking and placarding; loading, stowage, storage and segregation provisions; quality and compliance assurance inspections. Active safety also includes such things as approval of the package design by a competent authority.

Within the *Code*, there are defined roles for the *competent authority*, effectively the radiation regulator for the transport. ARPANSA is listed as the Commonwealth competent authority, with State/Territory regulators playing that role within their jurisdictions.

National Directory for Radiation Protection

The purpose of the *National Directory for Radiation Protection* is to provide an agreed overall framework for radiation safety, including both ionizing and non-ionizing radiation, together with clear regulatory statements to be adopted by the Commonwealth, States and Territories. The Australian Health Ministers' Conference (AHMC) endorsed the development of the *National Directory for Radiation Protection* in August 1999 as the means of achieving uniformity in radiation protection practices between jurisdictions. In particular, the Conference agreed that the *National Directory* would be prepared by the Radiation Health Committee for approval by the Conference, via a process for issues resolution which included meeting the Council of Australian Governments' (COAG) requirements for national standard setting. There would be full consultation with stakeholders in the development of the Directory.

The AHMC agreed that upon consideration and approval of the provisions of the Directory, the regulatory elements of the Directory shall be adopted in each jurisdiction as soon as possible, using existing Commonwealth/State/Territory regulatory frameworks. Ministers recognised that as a variety of agencies have a legislated responsibility for aspects of radiation safety (eg mines, occupational health and safety and transport agencies in many jurisdictions), these other agencies were to be involved actively in measures to progress national uniformity, including the development of the Directory.

The first edition of the Directory was approved by Ministers in July 2004, subject to finalisation of some regulatory impact analysis. The first edition is not applied to the mining and minerals processing industries, for reasons that include the fact that the new mining Code was not completed.

It is hoped that the second edition of the Directory, planned for completion in 2006, will incorporate the new mining Code and deal with other matters relevant to including mining and minerals processing within its coverage.

4. HEALTH EFFECTS OF IONIZING RADIATION AND STANDARDS FOR CONTROL OF EXPOSURE[4]

It is well known that high doses of ionizing radiation can cause harm, but there is continuing scientific uncertainty about effects at low doses. At levels of dose routinely encountered by members of the public and most present-day radiation workers, there is little or no epidemiological evidence of health effects. Radiation protection standards recognize that it is not possible to eliminate all radiation exposure, but they do provide for a system of control to avoid unnecessary exposure and to keep doses in the low dose range.

Extreme doses of radiation to the whole body (around 10 sievert[5] and above), received in a short period, cause so much damage to internal organs and tissues of the body that vital systems cease to function and death may result within days or weeks. Very high doses (between about 1 sievert and 10 sievert), received in a short period, kill large numbers of cells, which can impair the function of vital organs and systems. Acute health effects, such as nausea, vomiting, skin and deep tissue burns, and impairment of the body's ability to fight infection may result within hours, days or weeks. The extent of the damage increases with dose. However, 'deterministic' effects such as these are not observed at doses below certain thresholds. By limiting doses to levels below the thresholds, deterministic effects can be prevented entirely.

Doses below the thresholds for deterministic effects may cause cellular damage, but this does not necessarily lead to harm to the individual: the effects are probabilistic or 'stochastic' in nature. It is known that doses above about 100 millisievert, received in

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[4] This section of the submission is drawn from an agreed 'health effects' annex included in RPS publications.

[5] The sievert (Sv) is a unit of measurement of radiation dose (see ARPANSA's *Recommendations for limiting exposure to ionizing radiation (2002)*).

a short period, lead to an increased risk of developing cancer later in life. There is good epidemiological evidence – especially from studies of the survivors of the atomic bombings – that, for several types of cancer, the risk increases roughly linearly with dose, and that the risk factor averaged over all ages and cancer types is about 1 in 100 for every 100 millisievert of dose (i.e. 1 in 10 000 per millisievert).

At doses below about 100 millisievert, the evidence of harm is not clear-cut. While some studies indicate evidence of radiation-induced effects, epidemiological research has been unable to establish unequivocally that there are effects of statistical significance at doses below a few tens of millisieverts. Nevertheless, given that no threshold for stochastic effects has been demonstrated, and in order to be cautious in establishing health standards, the proportionality between risk and dose observed at higher doses is presumed to continue through all lower levels of dose to zero. This is called the linear, no-threshold (LNT) hypothesis and it is made for radiation protection purposes only.

There is evidence that a dose accumulated over a long period carries less risk than the same dose received over a short period. Except for accidents and medical exposures, doses are not normally received over short periods, so that it is appropriate in determining standards for the control of exposure to use a risk factor that takes this into account. While not well quantified, a reduction of the high-dose risk factor by a factor of two has been adopted internationally, so that for radiation protection purposes the risk of radiation-induced fatal cancer (the risk factor) is taken to be about 1 in 20 000 per millisievert of dose for the population as a whole.[6]

If the LNT hypothesis is correct, any dose carries some risk. Therefore, measures for control of exposure for stochastic effects seek to avoid all reasonably avoidable risk. This is called optimizing protection. However, risk in this sense may often be assessed in terms of risk to a population, and may not ensure sufficient protection of the individual. Consequently, the optimization approach is underpinned by applying dose limits that restrict the risk to individuals to an acceptable level. The fundamental regulatory philosophy is expressed in three principles, based on the recommendations of the International Commission on Radiological Protection (ICRP), which may be summarized as follows:

> *Justification*: human activities that cause exposure to radiation may be permitted only if they do more good than harm;
>
> *Optimization of protection*: exposure to radiation from justified activities should be kept as low as reasonably achievable, social and economic factors being taken into account; and
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> *Limitation of individual dose*: doses must not exceed the prescribed dose limits.

Determining what is an acceptable risk for regulatory purposes is a complex value judgement. The ICRP reviewed a number of factors in developing its

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[6] This risk is usually expressed as 5% per sievert. It is noteworthy that recent data gathered by the ICRP would put the risk calculated on the same basis as 4.4% per sievert.

recommendations, which have in general been internationally endorsed, including by the World Health Organization, the International Labour Organisation and the International Atomic Energy Agency. The Radiation Health Committee has recommended that the international standards be adopted in Australia. The recommended dose limits are summarized as follows:

Limit on effective dose[7]

	For occupational exposure	For members of the public
To limit individual risk	20 mSv per year, averaged over 5 years	1 mSv in a year

In most situations, the requirements for limiting individual risk ensure that doses are below deterministic thresholds, but for cases where this does not apply, the recommended limits are as follows:

Annual limit on equivalent dose[8]

	For occupational exposure	For members of the public
To prevent deterministic effects		
in the lens of the eye	150 mSv	15 mSv
in the skin	500 mSv	50 mSv
in the hands and feet	500 mSv	–

In the case of occupational exposure during pregnancy, the general principle is that the embryo or fetus should be afforded the same level of protection as is required for a member of the public. For medical workers, the ICRP recommends that there should be a reasonable assurance that fetal dose can be kept below 1 mGy[9] during the course of the pregnancy. This guidance may be generalised to cover all occupationally exposed pregnant workers by keeping the fetal dose below 1 mSv. A full explanation of radiation protection principles and of the recommended standards for Australia is given in ARPANSA/NOHSC Radiation Protection Series No. 1: *Recommendations for limiting exposure to ionizing radiation (1995)* and *National standard for limiting occupational exposure to ionizing radiation (both republished 2002).*

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[7] for details, see ARPANSA's *Recommendations for limiting exposure to ionizing radiation (2002)*

[8] for details, see ARPANSA's *Recommendations for limiting exposure to ionizing radiation (2002)*

[9] The gray (Gy) is a unit of radiation dose. For X-rays and gamma radiation, it is essentially equivalent to the sievert.

5. OCCUPATIONAL RADIATION DOSES FROM URANIUM PRODUCTION IN AUSTRALIA

The mining and milling of uranium ores can lead to external and internal exposure of workers. External exposure is a result of exposure to gamma rays from the radionuclides in the ore as it is mined or processed. Internal exposure arises from the inhalation of radon gas and its decay products and of radionuclides in ore dust. The extent of internal exposure will depend on the ore grade, the airborne concentrations of radioactive particles (which will vary with the type of mining operation and the ventilation) and the particle size distribution. The total internal exposure is generally of greater importance in underground mines than in open-pit mines.

Australian data reported to the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for 1991-1994 and reported in UNSCEAR's 2000 report to the UN General Assembly, show the average annual effective dose to measurably exposed workers from uranium mining was 1.43 mSv down from 4.11 mSv reported for 1985-1999. The average reported worldwide for 1990-1994 was 5.39 mSv.

ARPANSA's Personal Radiation Monitoring Service (PRMS) has published the annual photon (ie external) doses monitored by the PRMS during 2004 for uranium mining[10]:

Occupational Classification	Quartile Doses (μSv)			Max Dose (μSv)	Average Dose (μSv)	No of Wearers
	Q1	median	Q3			
Uranium mining						
Mine workers	260	900	1710	7770	1125	583
Mill workers		740	1780	2950	977	49
Miscellaneous		60	310	2600	302	89

These results show that most workers are receiving external doses below about 2 mSv with a maximum dose of 7.8 mSv for miners and 2.9 mSv for mill workers.

An earlier Parliamentary inquiry into uranium mining (Senate Select Committee on Uranium and Milling, May 1997) recommended, inter alia, that there be established a national radiation dose register for occupationally exposed persons. ARPANSA's predecessor organisation, the Australian Radiation Laboratory and then ARPANSA took some steps to attempt to progress such a register. The matter was discussed by the Radiation Health Committee in 2003 and the Committee did not then support the development of such a register but agreed with the collection and supply of data to UNSCEAR. The Committee's view was formed on the basis that the level of doses being received and likely to be received in Australia, together with the number of exposed workers, meant that there was no value in a register from the point of view of any study of health effects.

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[10] The PRMS does not supply monitoring to all current Australian uranium mines.

6. SECURITY CATEGORISATION OF RADIOACTIVE MATERIALS

There have long been specific requirements for the physical protection of nuclear materials (eg *INFCIRC 225/Rev.4./Corr*) so as to prevent the acquisition of nuclear material for nuclear weapons purposes. The enforcement of these requirements is undertaken under the *Nuclear Non-Proliferation (Safeguards) Act 1987* by the Australian Safeguards and Non-Proliferation Office.

Following the attacks of 11 September 2001, however, the possible use of nuclear and radioactive material by those with malicious intent (such as in a Radioactive Dispersal Device (RDD)) has been discussed.

The IAEA has undertaken such a generic risk assessment to define a security categorisation of radioactive sources based upon the activity of the source compared with the activity of a 'dangerous' source.

For a source to be a 'dangerous source', the activity of the source must be such so as to result in serious radiation doses. The categorisation includes five categories – from Category 1 where the source has an activity of more than a thousand times the activity of a 'dangerous' source through to Category 5 where the source is less than a tenth of the level of a 'dangerous' source.

For uranium, the available data on the forms most commonly used and transported in Australia, that is natural uranium ores and concentrates, as well as depleted uranium often used for radiation shielding purposes, the low specific activity of the material means that should this material be dispersed in an RDD, some 10mg of powdered material would need to be inhaled to obtain a dose equal to the dose from a Category 5 source.

Given the standard breathing rate of a person, this would entail remaining in a dense cloud of dust (made from the uniformly dispersed low specific activity uranium) under stable weather conditions for 30 minutes. This is highly unlikely as most persons coughing reaction to such a thick dust cloud would mean they would exit the area.

As a consequence of this assessment, it is considered that the use of natural uranium, such as is processed and transported by the uranium mining industry, would not present any hazard to persons or the environment if used by terrorists with malicious intent. However, there could be psychological and social consequences of such an action, and this needs to be taken into consideration by any response agencies.

APPENDIX

RADIATION DOSES FROM THE NUCLEAR FUEL CYCLE

The Nuclear Fuel Cycle

At the end of 1997 there were 437 operating nuclear power plants in 31 countries with an installed capacity of 352 gigawatt (GW), producing a total of 254 gigawatt years (GWa) of energy representing 17% of the global electricity production. There are several well defined stages in the nuclear fuel cycle that may give rise to exposure of workers and the public to ionizing radiation sources. In a recent report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000 Report to the General Assembly) a review was made of the world wide doses from nuclear power production. The estimates of dose were made for the period of the mid 1990s.

For convenience when making dose estimates UNSCEAR divided the nuclear fuel cycle into the following stages:
- Uranium Mining and Milling
- Uranium Enrichment
- Fuel Fabrication
- Reactor Operation
- Fuel Reprocessing
- Waste Management

Exposures and releases were modelled for each stage and estimates of dose made for the public and for workers. In order to assess the overall impact on nuclear power production the collective dose to the critical group was estimated and expressed in units of manSievert. Collective doses were then normalised per unit energy produced so that the impact of the various stages of production could be compared irrespective on annual fluctuations in production at each stage.

Public Doses

Uranium mining and milling

Uranium mining is usually performed in underground mines or in open-cut pits. Other production comes from in-situ leaching and as a by-product from other mineral processing. Milling operations involve the processing of ore up to the production of uranium in a partially refined form known as yellowcake. Offsite exposures from mining and milling operations are mainly due to releases of radon gas (^{222}Rn) which is one of the decay products of uranium. This occurs both during mining operations and from waste residues called tailings where the long lived radionuclides ^{226}Ra and ^{230}Th (half lives of 1,600 years and 80,000 years respectively) generate radon gas. Radon itself has a half life of 3.82 days and once released may be dispersed a considerable distance off site. UNSCEAR assessed doses locally and regionally and also for global dispersion. Because of the long half lives of the radionuclides generating radon it was assumed that the release from stabilised tailings remained unchanged for 10,000 years.

The collective effective dose per unit energy generated was estimated to be 0.19 manSievert $(GWa)^{-1}$ during operation of the mine and mill; and 7.5 manSievert $(GWa)^{-1}$ for an assumed 10,000 year period of constant, continued release from residual tailings piles. These doses relate to the situation that existed in the mid 1990s from operating mines and old mines that have been closed down. Some older mines were located close to population areas and tailings residues were not conditioned in accordance with practices that are commonly implemented today to reduce radon emissions. These mines contribute significantly to the collective dose. In a recent study site-specific data relating to currently operating mills in four countries (Australia, Canada, Namibia and Niger) were used. This study used a more detailed dispersion model than UNSCEAR and local and regional population densities applicable to the mines in question were much lower than those assumed by UNSCEAR, which take into account high population densities reported in areas surrounding mills in China. The tailings management practices employed at mines today are more rigorous than have been applied historically and soil covers to reduce radon emissions are more substantial than employed in the past. The result of all this is that for currently-operating mines the collective dose from radon emissions is five times lower at 1.4 manSievert $(GWa)^{-1}$. This value would be more representative of new and future mines operated in accordance with current international practice.

Uranium enrichment and fuel fabrication

Several types of reactors require that uranium be enriched in the fissile isotope ^{235}U to an enrichment of 2 - 5%. This is needed for light-water moderated and cooled reactors and for advanced gas-cooled and graphite moderated reactors. Enrichment is not needed for gas-cooled, graphite moderated reactors or for heavy -water cooled and moderated reactors. Uranium from milling operations (yellowcake) is converted to uranium hexafluoride for enrichment and then into uranium dioxide which is sintered and clad in zirconium alloy and stainless steel to make fuel elements.

The release of radioactive materials from conversion, enrichment and fuel fabrication plants are generally small and consist mainly of uranium series isotopes. The normalised collective effective doses form these operations was estimated to be 0.003 manSievert $(GWa)^{-1}$ and this arises mostly from the inhalation pathway.

Reactor operation

Calculated exposures for a reference reactor are used by UNSCEAR to provide a generalised measure of reactor operating experience and serve as a standardised parameter for analysing long term trends in the practice. The model for the reference reactor uses derived average releases of radionuclides and takes into account geographical location, the release point, the distribution of population, food production and consumption habits, and environmental pathways for released radionuclides.

Radioactive materials are released from reactors during routine operations as airborne and liquid effluents. Airborne effluents include noble gases, tritium, ^{131}I and airborne particulates and liquid effluents include tritium and other radionuclides. Averaged normalised releases were estimated for each reactor type for each of the above categories of releases. The normalised collective dose for all reactors, weighted by the relative energy production for each reactor type was estimated to be 0.43 manSievert (GWa)$^{-1}$ for 1994. This showed a slight downward trend with time from previous estimates corresponding to a downward trend in releases per unit energy production.

Although Pressurised Water Reactors produce nearly two third of electricity production they contribute only 13% of the dose, producing only 0.09 manSievert (GWa)$^{-1}$. By comparison Heavy Water Reactors and Gas Cooled Reactors produce more than twenty times that dose and Boiling Water Reactors and Light-Water Cooled, Graphite Moderated Reactors about seven times (Figure 1).

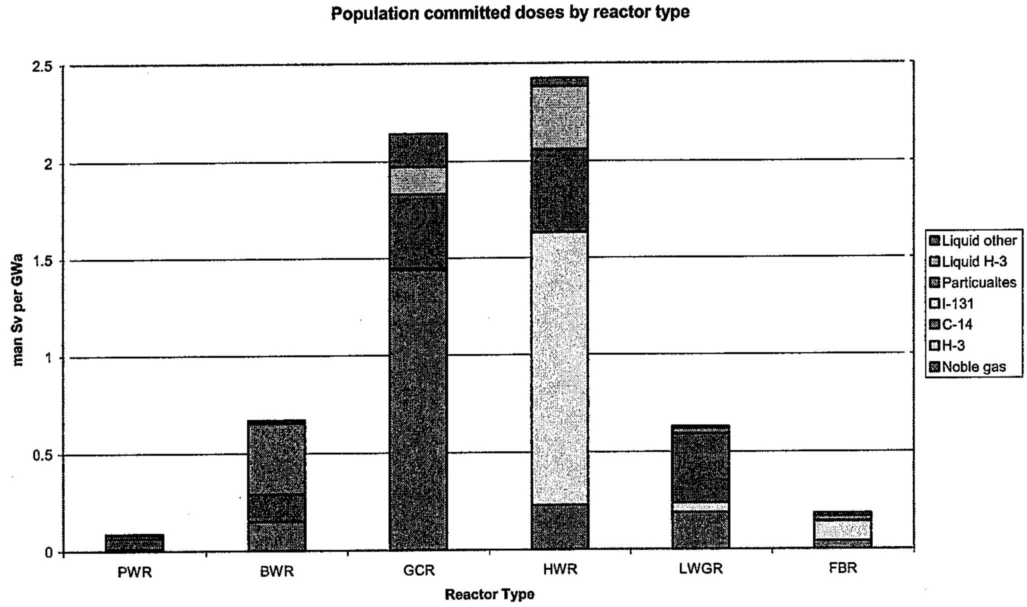

Figure 1

Fuel reprocessing

The purpose of reprocessing spent fuel from reactor operations is to recover fissile uranium and plutonium for reuse in reactors. At present most spent fuel from reactors is retained in interim stores on-site and only a small amount submitted for reprocessing. Large quantities of radioactive materials are contained in spent fuel and in the process these are released from their contained state and put into solution. The potential for release of radioactive material in waste discharges is greater for this part of the fuel cycle than for other stages. Routine releases have historically been as discharges to the sea however releases have been substantially reduced in recent years. For local and regional releases the collective dose was estimated to be 0.13 manSievert (GWa)$^{-1}$.

Some radionuclides that are released as a result of reprocessing are sufficiently long-lived and easily dispersed as to give rise to global doses over many years. Nuclides such as ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I with half lives of 12.26 years, 5730 years, 10.7 years and 16 million years respectively are of particular interest. There are large uncertainties in estimating doses over long periods of time due to problems of predicting environmental pathways, population distributions, dietary habits and climate change etc. In some cases integration of doses over ten of thousands of years or even millions of years could occur, however in the UNSCEAR assessment the global dose commitments were truncated at 10,000 years. For globally dispersed radionuclides ^{14}C becomes the dominating term and using the above assumptions the committed dose from this source was estimated to be 40 manSievert GWa^{-1}.

The above estimate for globally dispersed ^{14}C assumes that the practice of nuclear power production continues at the present rate (250 GW) for 10,000 years. In any year the annual dose to an individual would be $1\mu Sva^{-1}$, assuming the population of the world stabilises at 10 billion people. If it is assumed that the current practice of nuclear power generation is truncated after 100 or 200 years the individual annual doses would fall to 0.11μSv and 0.16μSv respectively as the build up of anthropogenic ^{14}C in the biosphere would be substantially less.

Radioactive waste management, storage and disposal

Low level and intermediate wastes are generated at various stages during the nuclear fuel cycle which are usually disposed of by shallow burial in trenches or in concrete lined structures. The collective dose from this source is estimated to be 0.5 manSv $(GWa)^{-1}$. The long term disposal of high level waste is not yet common practice and the radiological impact of such a repository has to rely on modelling of the behaviour of waste packages and the migration of released radionuclides near the site and at greater distances over long periods of time. Such assessments have been performed in formulating design criteria for hypothetical repositories and this data could be used to estimate potential doses from this pathway. The estimated collective dose from this part of the process was estimated at 0.05 manSievert $(GWa)^{-1}$. Transport of radioactive materials occurs at various stages of the nuclear fuel cycle and the this contribution is conservatively estimated to be 0.1 manSievert $(GWa)^{-1}$. To date very little decommissioning has taken place, however some experience with decommissioning nuclear facilities is accumulating and this information indicates that the exposure of the public from this pathway will be very small.

Summary of dose estimates to the public

The local and regional collective doses from the nuclear fuel cycle are estimated to be 0.9 manSievert $(GWa)^{-1}$ with the largest part of this dose received within a few years of release. This dose comes mainly from reactor and mining operations with largest doses coming from the continued use of some older style reactors. For modern Pressurised Water Reactors doses are about one fifth of those reported.

Comparing releases in the 1990s to those of the1970s there has been a substantial reduction in emissions from reactors and reprocessing facilities by up to an order of magnitude. Doses estimates from the emission of globally dispersed radionuclides has also halved in that time.

The radionuclide that dominates the globally dispersed wastes is ^{14}C both from reactor operations and from reprocessing. This is due to its long half life and the fact that it becomes part of the carbon cycle through the dispersion of carbon dioxide in the atmosphere. The collective dose from this pathway has been assessed at 40 manSievert $(GWa)^{-1}$ by integrating the effects over the global population for many generations. Actual doses to individuals in any one year are very small and less than a thousandth of the dose from natural radiation sources. There is currently much debate regarding the significance of aggregating small doses over large numbers of people over many years (that is over many generations) and assigning the aggregated dose to individuals in one year where as the risk to any individual is trivial.

After ^{14}C the next largest contributor to the collective dose is from radon emanation from uranium mine tailings. The estimate made is for the situation in the mid 1990s and includes many abandoned mines from the last fifty years where management of tailings was not as effective is common practice today. In some countries, particularly China, some of old tailings repositories are close to large population areas and this contributes to the collective dose. Reviews of practices at current mine sites show that good tailings management and more substantial tailings covers combined with the remote location of many of the large producers would reduce this contribution from 7.5 manSievert $(GWa)^{-1}$ to 1.4 manSievert $(GWa)^{-1}$.

Table 1
Public Doses from Nuclear Power Production - (1995 - 1997)

Practice	Public (manSv GWa^{-1})	
	Regional Component	Global Component
Mining	0.19	
Milling	0.008	
Mine and Mill Tailings	0.04	7.5
Fuel Fabrication	0.003	
Reactor Operation	0.44	0.5
Reprocessing		
- Solid Waste	0.13	0.05
- Globally dispersed		40
Transportation	0.1	
Total	0.92	48

Occupational Exposures

Uranium mining and milling

As part of its survey of occupational radiation exposures UNSCEAR looked at doses to workers in the nuclear fuel cycle and reported doses for the following categories of workers: uranium mining, uranium milling, uranium enrichment, fuel fabrication, reactor operations, fuel reprocessing, waste handling and disposal, and research and development activities associated with the nuclear fuel cycle.

The mining and milling of uranium ores can lead to both internal and external exposures of workers. Internal exposures arise mainly from the inhalation of radon gas and it decay products and of radionuclides in ore dust. In recent years many of the older and smaller mines have ceased operations and production is now mainly from larger more recent mines. With this development there has been a reduction in the doses to workers over the last 20 years falling by a factor of three in that time to 1.7 manSievert $(GWa)^{-1}$.

Enrichment and fuel production

Uranium enrichment and fuel fabrication are an important part of the nuclear fuel cycle but not one that results in large doses to workers. The radioactive material handled in these operations is uranium without most of the decay products. As such external radiation is very low and the main pathway for exposure is from internal contamination. These operations take place in highly sophisticated plants that are designed to remove this hazard and not surprisingly doses at this stage of the cycle are small. In addition there are relatively few workers engaged in these operations. The combined collective dose from enrichment and fabrication is estimated to be 0.12 manSievert $(GWa)^{-1}$.

Reactor operations

Doses from reactor operations vary significantly for different types of reactors. There are five different types of reactors currently used for the large scale production of electrical energy and Table 2 (Figure 2) shows the variation in worker dose for each reactor type.

Table 2
Collective effective dose to workers per unit energy produced by reactor type

Reactor Type	Dose manSv GWa^{-1}
Pressurised Water Reactors (PWR)	2.8
Boiling Water Reactors (BWR)	4.8
Heavy Water Reactors (HWR)	3.0
Light-Water Cooled Graphite Moderated Reactors (LWGR)	20.3
Gas Cooled Reactors (GCR)	2.0
Normalised Total	3.9

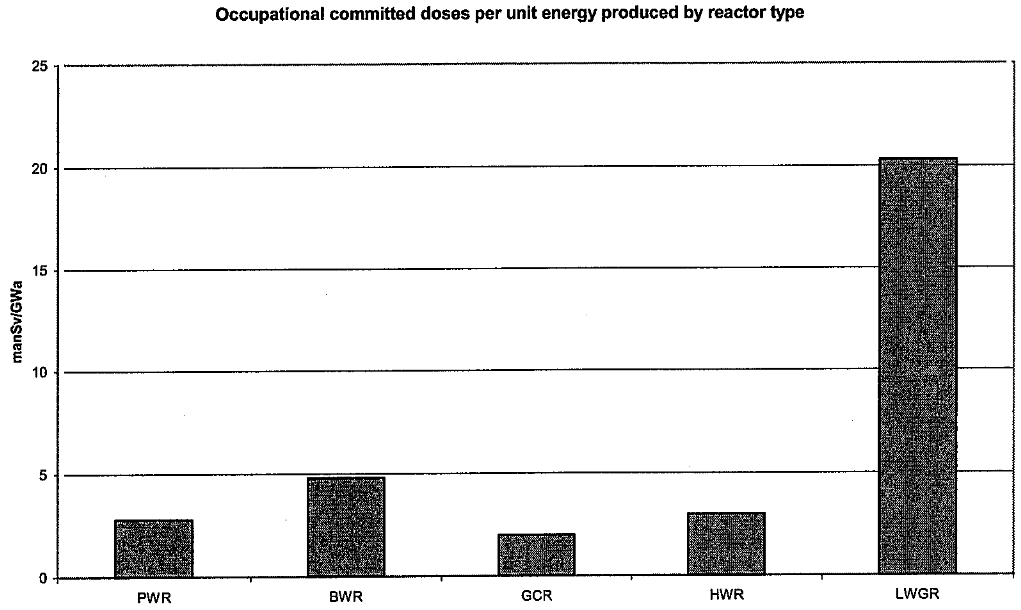

Figure 2

The normalised collective effective dose to workers per unit energy production was estimated to be 3.9 manSievert $(GWa)^{-1}$ in 1994 and this has fallen by about a factor of three over the previous 20 years. The annual effective dose to monitored workers averaged over all reactors fell from 4.1mSv to 1.4mSv in the same period. In 1994 the annual effective dose to monitored workers who received a measurable exposure was 2.7mSv. This downward annual trend is evident for each reactor type except for LWGC reactors. Of the estimated 800,000 workers estimated to work in the nuclear fuel cycle by far the largest number, 530,000, work in reactor operations.

Reprocessing and waste management

Fuel reprocessing usually involves dissolution of spent fuel in acid baths and chemical separation of uranium and plutonium from fission products. This usually occurs several years after spent fuel has been stored to allow for decay of short lived fission products. High activities of radionuclides are still present during reprocessing requiring remote handling and heavy shielding to protect workers. There are few commercial-scale reprocessing operations and many plants are small or experimental in nature and very few radioactive wastes from the nuclear fuel cycle have been mover to final repositories. Consequently the data available on occupational dose is limited. There has been a general reduction in worker doses in all countries over time and the average annual effective dose to monitored workers was estimated to be1.5mSv in 1994. It was estimated that 45,000 workers were engaged in these activities worldwide and that the collective dose per unit energy production from this source was 3 manSievert $(GWa)^{-1}$.

Nuclear fuel cycle research

Considerable research and development into the various phases of the nuclear fuel cycle are continually taking place. Although data are difficult to obtain due to the wide variety of programs approximately 120,000 workers were estimated to be engaged in these activities in the mid 1990s. The annual average effective dose to these workers was estimated at 0.8mSv in 1994 which like other practices show a general fall over the previous 20 years and more stringent radiation protection practices have been adopted. The collective dose from these operations was estimated to be 1 manSievert(GWa)$^{-1}$.

Table 3
Occupational Exposures from Nuclear Power Production (1990- 1994)

Category	No of workers (x1000)	Average Dose (mSv)	Collective dose (manSv/GWa)
Uranium Mining	69	4.5	1.7
Uranium Milling	6	3.3	0.11
Uranium Enrichment	13	0.12	0.02
Fuel Fabrication	21	1.03	0.10
Reactor Operations	530	1.4	3.9
Fuel Reprocessing	45	1.5	3.0
Research	120	0.8	1.0
Total	800	1.75	9.8

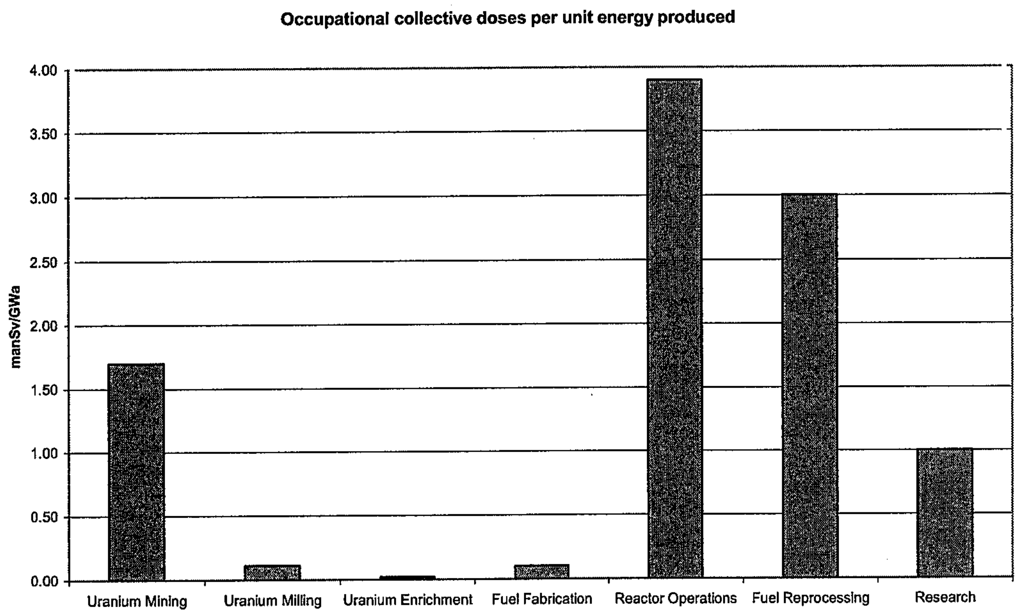

Figure 3

Summary

The overall radiological impact of nuclear power production was estimated by UNSCEAR for the mid 1990s. Taking into consideration all stages of the nuclear from mining to waste disposal the impact was assessed to be 49 man Sv (GWa)$^{-1}$ for public exposures and 10 manSievert (GWa)$^{-1}$ for occupational exposures making a total of 59 manSievert GWa^{-1}. Using currently accepted risk factors for ionizing radiation exposure this would equate to approximately three additional fatal cancers per year for each GWa of electrical energy produced.

The collective dose for the public is due mainly to reprocessing (^{14}C releases), uranium mining (radon releases) and reactor operations and reflects practices in the mid 1990s which included a number of older type reactors and abandoned mine tailings.

The largest contribution to the dose (40 manSievert $(GWa)^{-1}$) comes from the global dispersion of ^{14}C and its subsequent incorporation into the biosphere. Inherent in the assumptions associated with this estimation is that the current practice of nuclear continues for 10,000 years. If, as seems more realistic, the current practice of nuclear power production only continues for 100 years the collective dose per unit energy production in the hundredth year would then be less than 5 manSievert $(GWa)^{-1}$and the individual dose in that year would be less than 0.2μSv per caput.

Radon exposures from uranium tailings are the next most significant component but doses from this source have been significantly reduced at modern large scale mines compared to past practices. Collective doses from globally dispersed radon for modern mines are estimated to be 1.4 manSievert $(GWa)^{-1}$ compared to the estimate of 7.5 $(GWa)^{-1}$ estimated for the mid 1990s.

There are significant differences in public and occupational exposures from different reactor types. The total collective dose, weighted for production by reactor type in the mid 1990s, for both public and occupational exposures was estimated to be 4.4manSvGWa^{-1} whereas Pressurised Water Reactors gave the least dose of any type of reactor at 2.9manSievert $(GWa)^{-1}$.

From the data presented it is possible to estimate the future impact of nuclear power production for a Pressurised Water Reactor using uranium from a current uranium mine operating to international best practice. In this situation the contribution from mining and reactor operations would fall from 14manSievert $(GWa)^{-1}$ to 7manSievert $(GWa)^{-1}$. The overall effect of nuclear power production including fuel reprocessing would then be approximately 12manSv $(GWa)^{-1}$ in the hundredth 100 years of practice. This would result in less than one additional fatal cancer from radiological exposures based on current risk factors. This would equate to an effective dose of approximately 0.3μSv per caput, or less than one thousandth of the dose received due to naturally occurring radionuclides.