AUSTRALIA

Technical Memorandum 20

Radiation exposure of members of the public resulting from operation of the Ranger Uranium mine

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Supervising Scientist for
the Alligator Rivers Region

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RADIATION EXPOSURE OF MEMBERS OF THE PUBLIC RESULTING FROM OPERATION OF THE RANGER URANIUM MINE

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Australian Government Publishing Service

Canberra 1987

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P.O. Box 387, Bondi Junction
N.S.W. 2022, Australia

December 1987

ISSN 0810-9532
ISBN 0644 01368 0

This Technical Memorandum was prepared by:

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Printed in Australia by Finepress Offset Printing Pty. Ltd., Sydney, NSW 2212

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ABSTRACT

Johnston, A. (1987). Radiation exposure of members of the public resulting from operation of the Ranger uranium mine. Technical Memorandum 20, Supervising Scientist for the Alligators Rivers Region.*

The climatic, aquatic and demographic features of the Alligator Rivers Region that are relevant to the assessment of radiation exposure to the public resulting from operation of the Ranger uranium mine are described. The specific locations or activities at the mine site that act as sources for the transport of radionuclides into the environment are identified, and the steps taken to minimise such transport are summarised. Critical groups for the two principal transport pathways, atmospheric and surface water transport, are identified.

Data on atmospheric transport of radon and long-lived nuclides in dust are reviewed. The current best estimate of the annual effective dose equivalent to a member of the critical group is 0.1 mSv per year. Of this total, 30% arises from radon daughter exposure, and 70% from inhalation of long-lived nuclides in dust.

Modelling of the radiation exposure resulting from release of radionuclides into surface waters is described. The estimate of annual effective dose equivalent received by members of the critical group via the surface water pathway is 0.003 mSv per year for current operations.

Thus, for current operation of the Ranger mine and mill, radiation exposure via the atmospheric pathway dominates. The critical group's exposure is estimated to be one tenth of the maximum recommended by the International Committee on Radiation Protection.

*This article will appear, in an abbreviated form, under the title 'Site-specific Dose Assessments - Australia' in the monograph 'Environmental Behaviour of Radium' to be published by the International Atomic Energy Agency, Vienna.

1 INTRODUCTION

Four major uranium ore deposits have been identified within that area of Australia's Northern Territory known as the Alligator Rivers Region; Ranger, Nabarlek, Jabiluka, and Koongarra (Fig. 1). Current production is restricted to the two mine/mill developments operated by Ranger Uranium Mines (~ 3000 tU/y) and Queensland Mines (~ 1300 tU/y) located at Jabiru and Nabarlek respectively. The site specific dose assessment described here has been developed for the Ranger mine because it is the larger operation, it will continue for a long production period, and it is close to a larger centre of population than the Nabarlek mine. An unusual feature of the assessment is that it relates to a mining development in a region where Aboriginal people still have, to a certain extent, a traditional hunter-gatherer lifestyle.

Control of uranium mining at Ranger is exercised through a complicated network of interlocking legislation of both the Northern Territory and of the Commonwealth of Australia. These institutional arrangements recognise the regulatory responsibilities of the Northern Territory as a self-governing territory, as well as the responsibilities for control over national park interests, Aboriginal interests, and the more general controls in relation to uranium mining and export all of which are exercised by the Commonwealth. Thus, regulation of uranium mining at Ranger is carried out by the Northern Territory Government under the *Uranium Mining Environmental Control Act* 1979, whilst co-ordination of the Commonwealth and Northern Territory interests is conducted by the Co-ordinating Committee for the Alligator Rivers Region which was set up under Commonwealth legislation by the *Environment Protection (Alligator Rivers Region) Act* 1978. The Co-ordinating Committee is chaired by the Supervising Scientist for the Alligator Rivers Region, a statutory officer appointed by the Commonwealth under the same act and who exercises a supervisory, co-ordinating and research role.

In 1975 the Ranger development was the subject of a public environmental inquiry (Fox et al. 1976, 1977). Most of the recommendations stemming from this inquiry relating to the regulation, design and conduct of the Ranger operation were accepted by both governments and the recommended environmental constraints were included in the UMEC act in the form of a series of environmental requirements. The institutional arrangements and the environmental constraints themselves have led to a very strict regime of environmental control under which uranium mining at Ranger is carried out, a regime which encompasses research, monitoring, review, and approval.

2 SITE DESCRIPTION

2.1 Climate

The Alligator Rivers Region is located in the tropical monsoonal belt of Australia which is characterised by contrasting Wet (December-March) and Dry (April-November) seasons. Average annual rainfall is about 1560 mm and the annual evaporation is about 1950 mm. Although there is a net average evaporation capacity available for water management purposes, it is not very large.

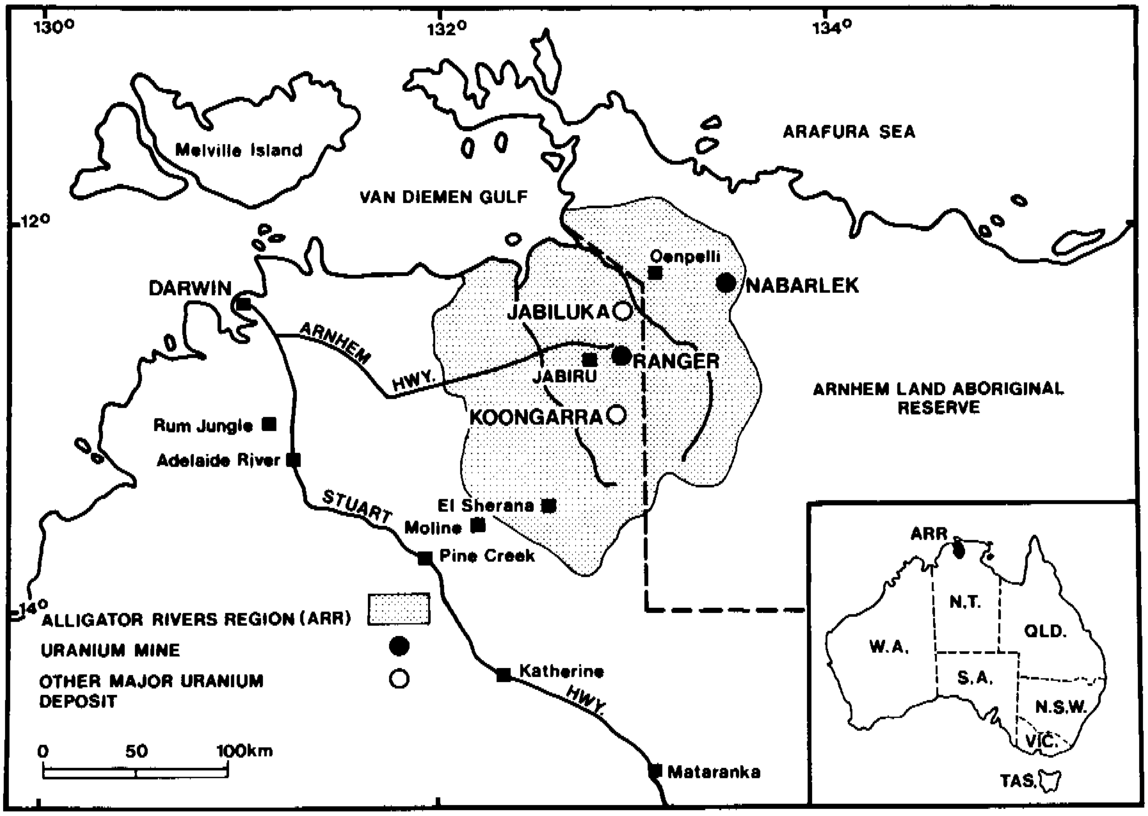

Figure 1. Location of uranium deposits in the Alligator Rivers Region of the Northern Territory, Australia

2.2 Surface waters

The Ranger mine is close to Magela Creek, a watercourse whose associated system drains a catchment of 1500 km^2, of which approximately 600 km^2 lies upstream of the minesite. The creek flows seasonally and during the Wet season flow can exceed 1000 m^3/s during periods of cyclonic depression.

Some 12 km downstream from Ranger the Magela Creek enters a floodplain system; in average years the inundated area is about 200 km^2. The flood plain drains into the East Alligator River during the Wet season but drainage ceases during July when the flood plain becomes an isolated freshwater lagoon for the duration of the Dry season. By the end of the Dry season, evaporation reduces water cover to a few isolated water holes or billabongs. The flood plain is part of Kakadu National Park which has been entered on the World Heritage List. It is partly for this reason, and partly because the Region is occupied by Aboriginal people living, to some extent, on a diet of traditional bush foods, that the regulatory regime under which mining is conducted is subject to such strict controls.

During the Wet season surface waters of the region are of high purity. Suspended sediments are low (~ 10 mg/L) as are total dissolved solids (~ 5 mg/L). Both Ca and Mg have concentrations of about 0.5 mg/L whereas those of heavy metals are usually less than 2 μg/L. Radionuclides of the natural uranium and thorium series are present in concentrations of about 5 mBq/L. The waters are slightly acidic (pH range ~ 4.5-6.5) with poor buffering capacity, usually containing > 5 mg/L of total organic carbon.

Metals in creek water are approximately equally divided between the particulate fraction (> 0.45 μm) and the filterable fraction; the filterable fraction is predominantly complexed or colloidal.

2.3 Demography

Demographic information on the region has been summarised by the Ranger mining company (Koperski 1986) for the purposes of estimating radiation exposure. About 1600 people live permanently in the vicinity of the Ranger mine. The main township of Jabiru is located 9 km west of the mine and mill and has a population of ~1300 including the Aboriginal settlement at Manaburduma Camp (Fig. 2). The temporary township of Jabiru East, about 3.5 km NW of Ranger and within the Ranger project area, was set up during the construction phase of the mine/mill and still supports a population of about 280 and is the site of scientific laboratories and light industrial activities. A settlement at Mudginberri Station and a nearby Aboriginal camp, located on Magela Creek and 12 km NNW of Ranger, has a population of about 80.

The indigenous Aboriginal population is essentially permanent, although there is always a small number of transient Aboriginal visitors at each camp from outside the immediate area of Ranger. It is estimated that fewer than 10% of the non-Aboriginal population remain for longer than four years.

2.4 Mine and mill

The relatively shallow formation of the No. 1 orebody at Ranger (Fig. 3) has led to exploitation by conventional spiral road open-cut mining. The mine pit has a surface area of about 52 ha and will ultimately reach a depth of 175 m below the surface. The resource is estimated at 53 000 tonnes of U_3O_8 at a mean grade of 0.3%.

The mill uses a conventional sulphuric acid leach and counter-current decantation to separate leach liquors from tailings, which are neutralised with lime before being impounded in an earth/rock-fill ring dyke structure. Uranium is recovered from the pregnant liquors by solvent extraction, precipitated as ammonium diuranate and calcined to a product assaying over 95% U_3O_8. (Baily 1984)

For atmospheric transport of radon and long-lived nuclides in dust, the principal potential sources of radionuclides are the mining pit, ore stockpiles, waste rock dump, primary crusher, calciner and the tailings dam. Dust suppression and minimisation of radon emanation are achieved in the pit, on the stockpiles and on the waste rock dump by conventional water-spraying techniques. Dust concentrations in the vicinity of the crusher are controlled by the use of water sprays and wet impingement dust collectors. The stacks which ventilate the calciner and product areas are fitted with wet scrubber systems to minimise the discharge of uranium to the atmosphere. The regulatory limit on such emissions is 1.5 kg of uranium per day but actual discharges are much less than this. Emissions from both stacks are monitored on a monthly basis using isokinetic samp-

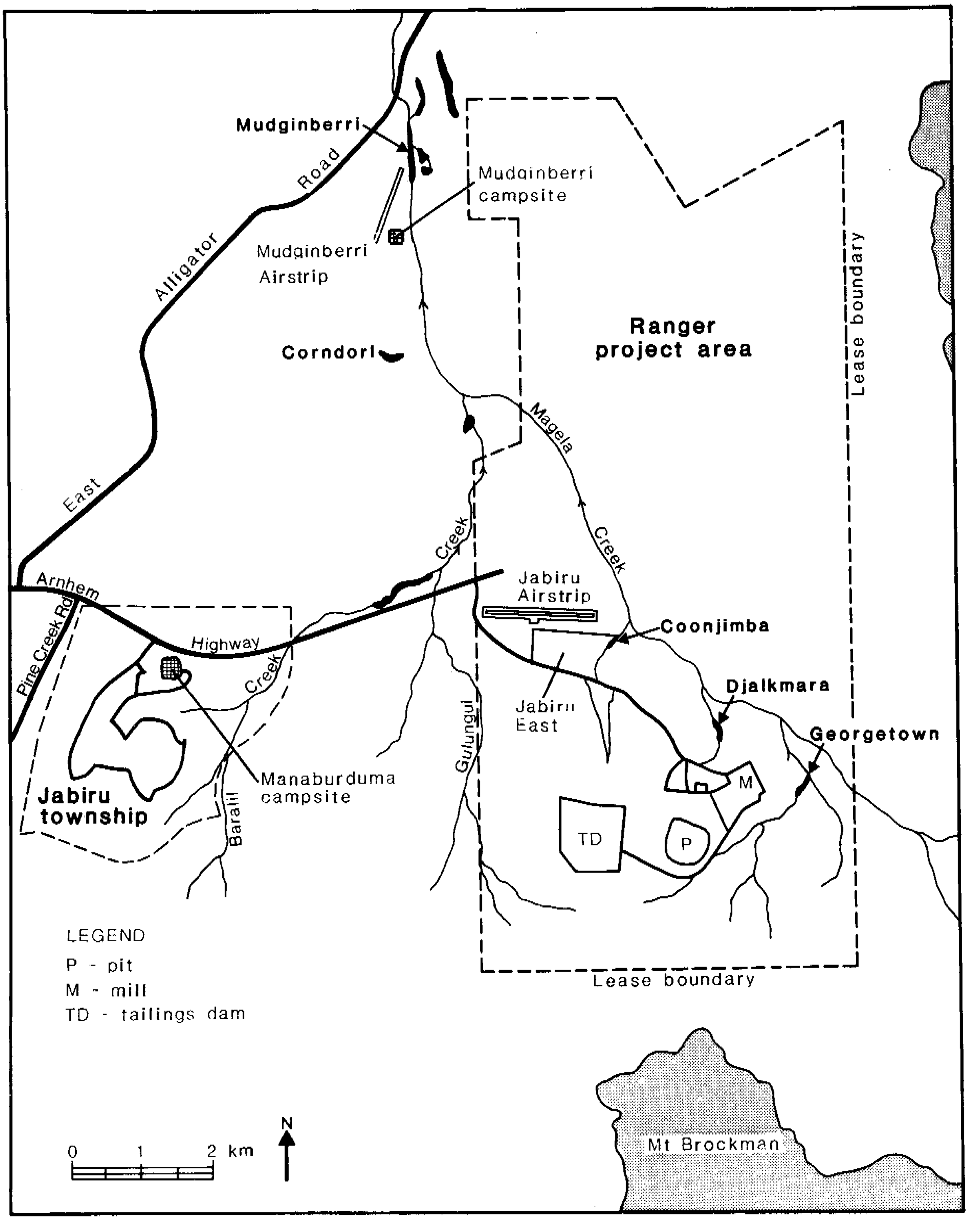

Figure 2. Location of the main centres of population at Jabiru, Jabiru East, and Mudginberri with respect to the Ranger mine site

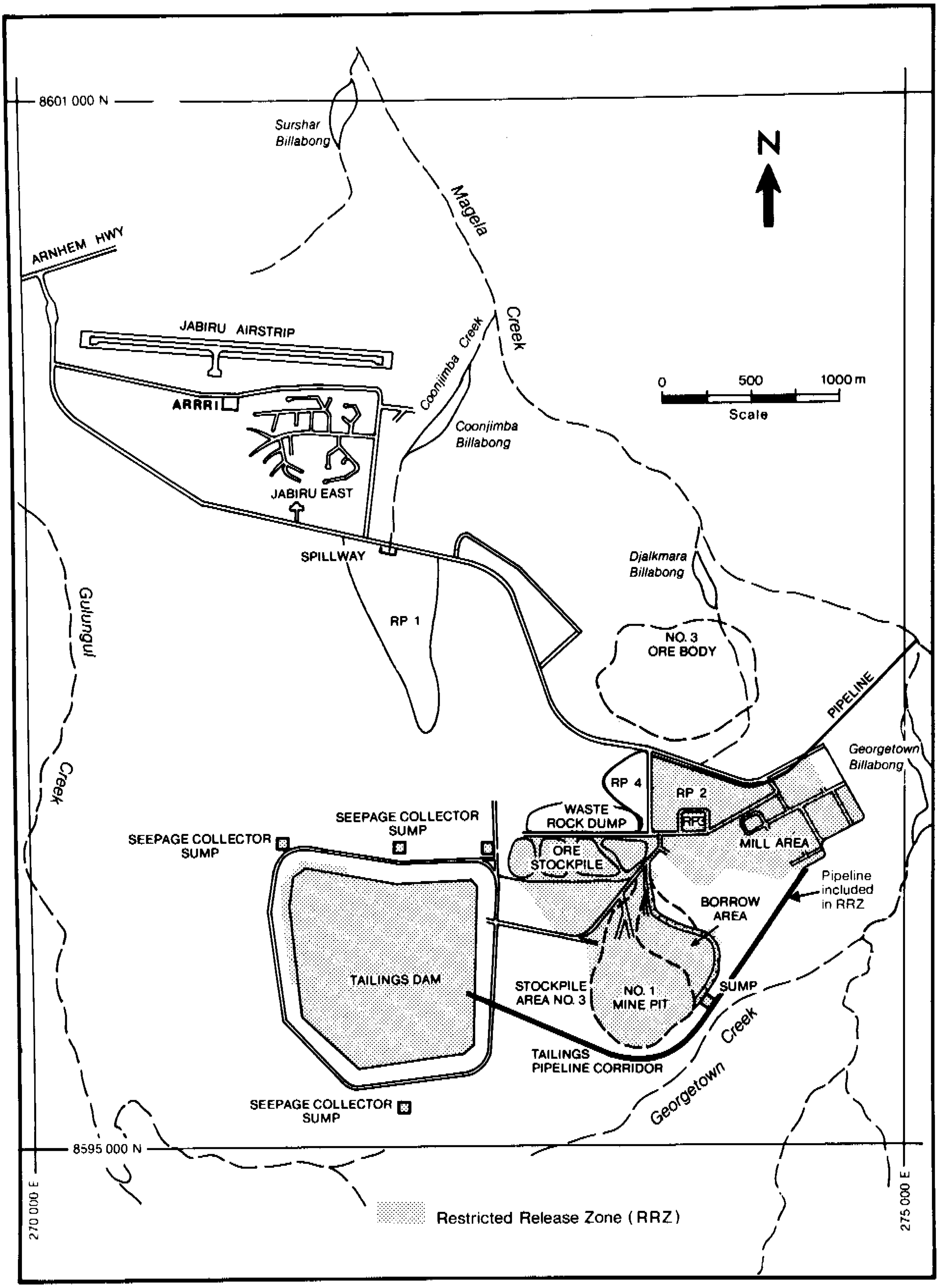

Figure 3. Ranger mine site

ling techniques to demonstrate compliance with this limit. At the tailings dam, both radon emission and dust suppression are currently controlled by the maintenance of a water cover over the tailings, although a change to sub-aerial tailings deposition has been proposed by the company.

Strict control is exercised over the water management system at Ranger. A restricted release zone (RRZ) has been defined to include all areas within the project area in which significant mineralisation occurs (uranium concentration > 0.02%). It includes the tailings dam, the mine pit, ore stockpiles, the mill and retention ponds 2 and 3 (RP2 and RP3) (Fig. 3). RP2 contains relatively clean plant run-off waters and also receives water from other catchments, including the pit and stockpiles, either by direct run-off or by pumping. RP3 receives water from a small catchment including the primary crusher area and adjacent stockpiles. All water entering the RRZ from rainfall, seepage, and groundwater bores is retained within the project area and may only be discharged with the prior permission of the supervising authority. In addition, no process water may be transferred from the mill/tailings circuit to retention ponds other than the tailings dam. During the first six years of mining, permission to discharge RRZ waters to Magela Creek has not been granted even though this restriction has caused interruptions to mining. Authorisation has been given for the discharge of some RRZ water by land irrigation during the Dry season: this authorisation excludes process water and tailings water.

Areas in which no significant mineralisation occurs are not included within the RRZ. Thus, runoff from the waste rock dump (which is collected in RP4) and from the outer slopes of the tailings dam (most of which is collected in RP1) may be discharged to Magela Creek. The discharge of RP4 water by pipeline to Magela Creek is authorised during the Wet season subject to legislated water quality standards and hydrological constraints. RP1 currently discharges each Wet season via a weir outlet structure and this mode of discharge will be permitted to continue provided legislated water quality standards are satisfied. If the trend of observed contaminant concentrations is such that a violation of these standards is predicted, an alternative water management system for RP1 will be required. Such a system might include pumping of the initial Wet season flush to the RRZ or the discharge of water directly to Magela Creek under controlled conditions. Alternatively, future improvements in the modelling of exposure of the critical group may allow a relaxation of the water quality standards.

Shallow groundwater is collected around the periphery of the tailings dam by a seepage collector system which discharges into four sumps positioned around the dam. This system is believed to be effective in intercepting about 70% of the seepage through the wall of the tailings dam. Water collected in this way is returned to the dam. Seepage through the floor of the tailings dam to deeper aquifers is not intercepted by the seepage collector system. Water quality is monitored in RP1 which is down-gradient of the tailings dam and which is expected to show the first effects of seepage. Results of this monitoring program show an increase in sulphate concentrations in recent years, probably due to seepage, but no increase in radionuclide concentrations. These results are consistent with the expected retardation of radionuclide transport with respect to that of more mobile ions.

3 TRANSPORT PATHWAYS AND CRITICAL GROUPS

The principal pathways by which the public can be exposed to radiation resulting from the current mining and milling operations at Ranger are:

- atmospheric transport of radon/radon daughters and dust containing the long-lived nuclides of the uranium series; and
- surface water transport of the long-lived nuclides contained in water discharged from the mine.

Other pathways, which may be of significance in the future, are not considered here because their current impact is negligible and their future impact is subject to regulatory decisions yet to be made. These include groundwater transport and external radiation from the rehabilitated site.

The two principal pathways give rise to two distinct potential critical groups. From the point of view of atmospheric transport the critical group has been identified as that group of inhabitants of Jabiru East who spend a significant fraction of the day outdoors and whose homes are not air-conditioned. Although all permanent houses have air-conditioning units, these units are frequently not in use in the evenings, particularly during the Dry season when it is cooler and when the prevailing wind is from the direction of the mine-site.

Release of radionuclides into the surface waters of Magela Creek does not give rise to enhanced concentrations in drinking water for the non-Aboriginal population of the region, since the local potable supply is derived from groundwater bores. The major effect of such releases would be increased concentrations of nuclides in aquatic flora and fauna through bioaccumulation processes. The group most at risk would be those people who derive a significant proportion of their food from a traditional diet based on hunting and fishing in the Magela system downstream from Ranger. The critical group has, therefore, been identified as the Aboriginal people living at Mudginberri Station.

4 DOSE ESTIMATES FOR ATMOSPHERIC TRANSPORT

4.1 Radon daughters

Estimates of predicted radon concentrations in the vicinity of Ranger (Clark 1977) were based on calculations of radon emission rates from the pit, stockpiles, crusher, mill and tailings dam for hypothetical mining conditions corresponding to production rates of 3000 tonne/year (the current rate) and 6000 tonne/year (the anticipated rate in 1990). Estimates of near-ground level radon concentrations at distant sites were made using a Gaussian plume dispersion model which incorporated the results of a two-year program of meteorological measurements. The annual average radon concentration at Jabiru East (for the current production rate) predicted by these calculations was 2 Bq/m^3. Table 1 lists the corresponding radon daughter concentration (in mWL) for an equilibrium factor of 0.3 and the estimate of annual effective dose equivalent for a member of the critical group resulting from this radon daughter concentration. An occupancy factor of 100% is assumed (since indoor and outdoor radon daughter levels in the housing at Jabiru East are unlikely to differ) with a conversion factor of 8.5 mSv effective dose equivalent per WLM exposure. A less conservative but possibly more realistic conversion factor of 5.5 mSv per WLM could be justified (NEA 1983).

Since the start of mining, Ranger has carried out a comprehensive monitoring program for radionuclides in the environment, including radon and radon daughters in Jabiru East. Koperski (1986) has performed an analysis of the radon daughter data to determine whether or not a statistically significant difference exists between the data set corresponding to those days on which the wind was blowing from the mine-site and the set corresponding to those days on which the wind was in the opposite direction. From this analysis he derived an estimate of the annual average radon daughter concentration in Jabiru East arising from the mining operation. This value is given in Table 1 together with the corresponding estimate of the annual effective dose equivalent. The statistical uncertainty in these results is estimated to be about 60%. The experimental result is in reasonable agreement with the theoretical prediction and both are significantly below the current ICRP recommended limit of 1 mSv per year for total exposure of a member of the public.

A detailed research program has recently been initiated which includes meso-scale meteorological measurement and modelling, with model verification by radon and radon daughter monitoring. This program is considered necessary because Clark's predictions for average radon concentrations in the nearby populated areas, 2 Bq/m^3, are very much lower than those observed in the routine monitoring program conducted by the company, about 100 Bq/m^3. Although these high concentrations do not appear to be mine related, their origin will only be established through measurements of correlations between radon concentrations and meteorological variables such as wind velocity. This program should enable a considerable improvement to be made in the estimates of radiation dose arising from radon daughter exposure.

4.2 Long-lived radionuclides in dust

Initial estimates of the radiation dose received by members of the public due to the presence of uranium in dust transported from the Ranger mine were made by Clark (1977) in a manner similar to that described above for radon daughters. The source inventory used in that work distinguished between those sources in which radioactive equilibrium could be assumed (pit, crusher, stockpiles) and those in which uranium would be enriched (calciner). The annual average concentration of each of ^{234}U and ^{238}U in the air near ground-level in Jabiru East was predicted by this analysis to be about 0.1 mBq/m^3 (Table 1).

Concentrations of the other nuclides were not calculated specifically by Clark (1977) but an estimate of these has been obtained by subtracting from the source inventory that fraction which was attributed to the calciner. The latter represented approximately 70% of the total. The resulting estimate for the annual average concentration of each of the long-lived daughters of the uranium series in the air at Jabiru East is given in Table 1.

The values of committed effective dose equivalent corresponding to these concentrations were obtained using the expression:

$$H = 8760vf \sum_i Q_i C_i$$

where v is the breathing rate per hour, f is a correction factor related to organ size, Q_i is the concentration of the ith nuclide in air, and C_i is the conversion factor between inhaled activity and effective dose

Table 1. Estimates of dose to members of the critical group, at Jabiru East, resulting from atmospheric transport of radionuclides from the Ranger mine and mill

(A) Radon daughters

Source	Concentration (mWL)	Annual dose[a] (mSv/y)
Clark 1977	0.16	0.08
Koperski 1986	0.06	0.03

(B) Long-lived radionuclides in dust

Source	Radionuclide	Concentration (mBq/m^3)	Annual dose[a] (mSv/y)	Total (mSv/y)
Clark 1977	^{238}U, ^{234}U	0.1	0.08	
	Others[b]	0.03	0.03	0.11
Koperski 1986	^{238}U, ^{234}U	0.12	0.09	
	Others[b]	0.17	0.17	0.26
Pettersson et al. 1986	^{238}U, ^{234}U	0.04	0.03	
	Others[b]	0.04	0.04	0.07

[a] Effective dose equivalent
[b] Each of the remaining nuclides of the uranium series, with the exception of radon and its short-lived daughters.

equivalent for that nuclide. The latter were taken from ICRP (1979). The values for breathing rate ($v = 0.6\ m^3/h$) and the protection factor ($f = 2$) corresponding to a juvenile member of the critical group were assumed, since these yield a slightly higher dose estimate than that obtained using the adult values. The predictions of annual effective dose equivalent obtained by using Clark's (1977) concentrations of radionuclides in dust are given in Table 1.

In a manner similar to that outlined above for radon daughters, Koperski (1986) has analysed the data obtained by Ranger using high volume air samplers to obtain an estimate of the radiation dose arising from long-lived nuclides in dust. Concentrations of the nuclides ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po were measured. The uranium concentrations listed in Table 1 were attributed to the mining operation. The concentration listed for the other nuclides of the uranium series is the average of the results obtained for ^{230}Th, ^{226}Ra and ^{210}Po. Concentrations of ^{210}Pb were found to be, on average, a factor of three higher than those of ^{210}Po; however subsequent work (Pettersson et al. 1987) has shown that such elevated concentrations also occur in rainwater but that they are independent of distance from the mine site. Also given in the Table are the values of the annual effective dose equivalent corresponding to continuous exposure at these concentrations. Statistical uncertainties are estimated to be about 50%. The total dose attributed by Koperski (1986) to nuclides in dust is 25% of the dose limit for members of the public recommended by ICRP.

Caution should, however, be exercised in the interpretation of these data. Reliable meteorological data were not available for the periods covered by the reported measurements. Measurements were identified as upwind or downwind on the basis of the prevailing wind direction on a seasonal basis only. Since the maximum duration of a sampling period was one week and at most two samples were collected during any single season (Wet or Dry), the use of the prevailing wind direction is of questionable validity. In addition, the air concentrations of radionuclides observed in Jabiru township were similar to those obtained in Jabiru East which is much closer to the mine site. For these reasons, the deduced effects may not be mine-related but may simply reflect the variations in the concentrations of radionuclides in the soils of the region.

Because of the apparent significance of this pathway, a more detailed research program was commenced (Pettersson et al. 1987) to discriminate more clearly between background concentrations and those which are attributable to the mining operation. In this project, the variation in the long-term average concentrations of atmospheric radionuclides is being measured as a function of distance from the mine site using passive air sampling techniques. Normalisation of the results is obtained by comparison with concentrations measured using high volume air samplers. Preliminary results, using normalisation of gross alpha concentrations only, are given in Table 1. These data indicate that the total dose rate (0.07 mSv/y) is lower than the previous experimental estimate by a factor of four. The statistical error in the dose rate is estimated to be about 50%.

In summary, the current best estimate of the annual effective dose equivalent to the critical group arising from atmospheric transport is about 0.10 mSv per year. Of this total, 30% arises from radon daughter exposure and 70% arises from long-lived radionuclides in dust.

5 DOSE ESTIMATES FOR SURFACE WATER TRANSPORT

5.1 Diet of the critical group

The group of people theoretically most at risk from a surface water release of radionuclides has been identified as the Aboriginal community living at Mudginberri Station. The composition of their diet, which is made up partly of traditional foods and partly of shop-bought items, has proved difficult to establish with any certainty, principally because of the reluctance of the Aboriginal people to become involved in an intrusive quantitative investigation into the details of their dietary intake.

A diet applicable to the critical group has been estimated by:

- using an average annual food intake corresponding to that observed for Aboriginals from the Arnhem Land region, namely 430 kg per annum (Meehan 1977; McArthur 1960);
- deducing the percentage contribution of each of the components to the total traditional diet from studies carried out by Ranger staff (Bywater, private communication; Koperski 1986); and

- estimating the shop-bought contribution to the total diet from the records of the company which delivers stores to the Mudginberri community.

The annual consumption of each of the major components in the diet deduced by this procedure is listed in Table 2. The surface water component of drinking water has been assumed to be 600 L/y though this is likely to be conservative because, although water intake is expected to be high for Aboriginal people in this region, the source of most drinking water at their permanent campsites is, in fact, groundwater bores.

Uncertainties in these figures are, in some cases, large but the most significant component in terms of radionuclide intake is, without doubt, the freshwater mussel *Velesunio angasi*. Other attempts to estimate the consumption of this component (from private discussions with Aboriginal people and social workers, by counting shells in contemporary middens found near local waterbodies, etc.) have led to figures similar to that shown in Table 2. Also, estimates of the extent of foraging required to maintain an intake of 4 kg/y by each of the 50 individuals in the critical group indicate that it would be difficult to exceed this consumption rate.

5.2 Dispersion model for surface water transport

In order to calculate the intake of radionuclides based upon the above annual diet of Aboriginal people, it is necessary to calculate the increment in the annual average concentration of radionuclides in the water (C_w) and sediment (C_s) of the Magela system resulting from the release of a total quantity (Q_i) of any isotope during a short period of the Wet season. A dispersion model has been developed (Johnston & Murray, unpublished data) which includes:

Table 2. Diet of the critical group for surface water transport of radionuclides discharged from the Ranger mine site

Diet component	Annual consumption (kg)
Buffalo	220
Magpie goose	15
File snake	3
Freshwater mussel	4
Turtle	1.5
Fish	38
Goanna	3
Water lily	3
Shop-bought	140
TOTAL	430
Surface water	600 L/y

- initial rapid dilution with creek water;
- transport, including deposition and absorption, in the creek region;
- dilution on the flood plain; and
- the annual cycle on the flood plain, including deposition and absorption, drainage to the sea during the Wet season, evapo-concentration during the Dry season and possible resuspension during the early part of the subsequent Wet season.

The available data on natural transport processes were used, where possible, to determine the parameters of the model. Wherever such data were not available conservative assumptions were made.

The results of the modelling process are expressed in the form:

$$C_w = k_w Q_i$$

$$C_s = k_s Q_i$$

where k_w = 1.7E-12 (Bq/L)/Bq and k_s = 3.0E-11 (Bq/kg)/Bq. Research projects are currently underway (Johnston et al. 1987*a*) to obtain more precise information on these transport processes.

5.3 Bioaccumulation of radionuclides in diet components

Concentration factors relating concentrations in the water column or sediment to those in aquatic or terrestrial animals and plants were used to represent bioaccumulation processes. Initially, these were derived from the literature and from previous work in the region (Davy & Conway 1974), but for some of the most significant food items (freshwater mussels, fish and water lilies) further experimental work (Johnston et al. 1984, 1985*a*, 1987*b*) has led to locally derived concentration factors. This work is continuing. The concentration factors are listed in Table 3.

Table 3. Concentration factors* for radionuclides of the uranium series

Diet component	^{238}U, ^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	Medium
Buffalo	4E-3	6E-5	6E-3	5E-3	2E-2	Sediment
Magpie Goose	50	20	60	20	620	Water
File snake	24	110	50	95	340	Water
Freshwater mussel	100	500	19000	5100	10000	Water
Turtle	100	500	210	50	100	Water
Fish	140	230	370	150	680	Water
Goanna	140	230	200	150	680	Water
Water lily	1900	140	230	150	720	Water

*Units: $(Bq/kg)_{food}/(Bq/litre)_{water}$ for water medium

$(Bq/kg)_{food}/(Bq/kg)_{sediment}$ for sediment medium

The use of equilibrium (steady-state) concentration factors is only a first approximation to a correct description of bioaccumulation processes and their use can, in some cases, lead to significant errors in the estimated radiation exposure. For this reason the approach that has been used in the Alligator Rivers Region was as follows:

- initial estimates of concentration factors derived from the general literature were used to rank the diet components in order of significance with respect to radiation exposure of the public resulting from release of water from the Ranger site;
- site-specific concentration factors for the most significant diet components were measured using local species in the local aquatic system; and
- detailed laboratory and field studies were undertaken to develop an understanding of the mechanisms responsible for uptake of radionuclides in the most significant components of the diet of the critical group.

The detailed studies have shown that the assumptions inherent in the simplified concentration factor model of bioaccumulation (i.e. steady-state concentration ratios between compartments with linear kinetics and constant transfer coefficients) are invalid in some cases. For example, the rate of uptake of radium in freshwater mussels is dependent on the calcium and magnesium concentrations in the host water (Jeffree & Simpson 1986) and the half-life for loss of radium is very long, about five years (Johnston et al. 1985*b*). Similarly, radium accumulation in water lilies arises partly via the plant-water interface and partly via the plant-sediment interface and the dependence of uptake on other variables (e.g. calcium concentrations in the host medium) is different for each part of the plant at different times of the growing season (Twining 1985, 1986).

Nevertheless, the simple model of bioaccumulation has been retained in this assessment because:

- all the non-linear and non-steady-state effects observed so far are such that the use of concentration factors yields a conservative estimate of radiation exposure; and
- the resulting estimate of committed effective dose equivalent is small; about 0.3% of the ICRP limit for public exposure.

In these circumstances, a more rigorous and complicated assessment would not be justified.

5.4 Dose estimate for current operations at Ranger

As stated in Section 2.4, no discharge of water from the RRZ at Ranger has taken place during the first six years of operation; the only water discharged to Magela Creek has originated as runoff from the waste rock dump and from the outer slopes of the tailings dam and the undisturbed catchment of RP1. The total load of each of the long-lived isotopes of the uranium series released in this way during 1985 is listed in Table 4. To estimate exposures associated with mining operations to date, these loads are taken to be typical of the annual discharges under current operation of the Ranger water management system.

Table 4. Estimates of dose to members of the critical group, at Mudginberri, resulting from surface water transport of radionuclides from the Ranger mine and mill

Radionuclide	Annual load (Bq)	Annual intake (Bq)	Conversion factor[a] (Bq/mSv)	Dose[b] (μSv)
^{238}U	3.0×10^7	0.65	2000[c]	0.33
^{234}U	3.0×10^7	0.65	1800[c]	0.37
^{230}Th	3.4×10^6	0.08	4000	0.02
^{226}Ra	1.6×10^7	2.5	2000	1.25
^{210}Pb	4.3×10^6	0.21	400	0.53
^{210}Po	5.1×10^6	0.70	1000	0.70
			TOTAL	3.2

[a] Conversion factors (Bq/mSv) = Allowable intake/1 mSv
= 0.01 x Stochastic Worker ALI

[b] Committed effective dose equivalent for one year's discharge

[c] For uranium, gut transfer factor of 0.2 assumed (see text)

The annual intake, I_i, of each element i by a member of the critical group has been calculated using the above results for concentrations in water and sediment, combined with the dietary and concentration factor data. Thus:

$$I_i = (k_w \sum_j m_j T_{ji} + k_s \sum_r m_r T_{ri}) \cdot Q_i$$

where the sum over j includes aquatic foods j of mass m_j consumed per annum, and the sum over r includes terrestrial foods r of mass m_r. The factors T_{ji} and T_{ri} are the corresponding concentration factors. The resulting estimates of annual intake of each nuclide for current operations are given in Table 4.

Two methods were used to estimate factors which convert intake of radionuculdes to dose for members of the public; these were based, firstly, on values of the Annual Limit on Intake (ALI) for radiation workers for stochastic effects (ICRP 1979) and, secondly, on estimates of doses resulting from the intake of radioncludes by members of the public (Greenhalgh et al. 1985). There are infants and children in the group of people identified as being most at risk from discharges of effluent into surface waters. Infants would not consume the diet given in Table 2; this is the estimated diet of an adult. However, the diet of 10-year-old children has been assumed to be similar to that of an adult. Hence, because of the smaller organs of a child, the most restrictive case in estimating conversion factors is that of the 10-year-old child.

Following the recommendatons of IAEA (IAEA 1982), a factor of 1/50 has been applied to the ALI to take into account the difference in dose limits (1 mSv/year for the public, 50 mSv/year for radiation workers) and an additional factor of 1/2 has been applied to take into account the mass of organs averaged over a lifetime. The resulting values of allowable intake per milliSievert were taken as conversion factors (Table 4). (The uranium values have been further reduced by the use of a conservative gut transfer factor of 0.2, this value being suggested by ICRP as being more appropriate for environmental forms of uranium than the value of 0.05 used in the derivation of the ALI).

Estimates of conversion factors were also made using the calculations of absorbed dose integrated over a lifetime following ingestion of each radionuclide by a 10-year-old child (Greenhalgh et al. 1985). In all cases the conversion factors obtained by this method were greater than or equal to those based on the ALI; the maximum discrepancy was 45%. The more conservative values given by one hundredth of the ALI were used in dose estimation.

The estimated dose received by members of the critical group has been calculated for each radionuclide (Table 4); the total dose, 0.003 mSv, is significantly less than the current limit of 1 mSv recommended by ICRP. A detailed sensitivity analysis has been carried out to estimate the probable error in the dose calculated using the above dose assessment model for surface water transport; both statistical and systematic errors in the variables of the model were taken into account. Although the number of variables is large, the calculated dose is dominated by a few variables, notably the weights of mussels and fish consumed by members of the critical group and the concentration factor for radium in mussels. This analysis shows that the dose is unlikely to be underestimated by more than a factor of two.

The ICRP system of dose limitation is based upon regulation of the incremental dose from controlled exposures without taking into account the natural background (except perhaps in exceptional circumstances). It is of interest to compare the incremental dose to the local Aboriginal population arising from current water management practice at Ranger with that arising from the intake of radionuclides in their traditional diet due to the natural occurrence of uranium series radionuclides in Magela Creek. Annual natural loads of radionuclides in Magela Creek have been estimated from the annual average concentrations of each nuclide in creek water (Johnston et al. 1985*c*) and the average total discharge of the creek at Jabiru (4.5×10^8 m^3). The results for the total load of each isotope and the corresponding estimate of annual effective dose equivalent for members of the critical group are given in Table 5. The estimate of total dose rate is about 0.85 mSv per year. Thus the incremental dose arising from current discharges of water from the Ranger site is about 0.4% of the dose arising from the natural occurrence of uranium series radionuclides in creek water.

6 CONCLUSION

The development of uranium mining in the Alligator Rivers Region of Australia's Northern Territory has been subject to a very strict regime of environmental control. In particular, during the first six years of operation of the Ranger mine and mill at Jabiru, the only water discharged from the mine site has been rainfall runoff from the waste rock dump and from the outer slopes of the tailings dam. Authorisation for the discharge of water from the restricted release zone has not been given, even though this has led to significant interruption of the mining operation.

Table 5. Estimates of dose to members of the critical group, at Mudginberri, arising from the natural loads of uranium series radionuclides in Magela Creek

Radionuclide	Natural annual load (Bq)		Natural dose rate[a] (μSv/y)
^{283}U	1.1×10^9		12
^{234}U	1.1×10^9		14
^{230}Th	2.0×10^9		12
^{226}Ra	2.6×10^9		205
^{210}Pb	2.3×10^9		280
^{210}Po	2.4×10^9		330
		TOTAL	853

[a] Effective dose equivalent

As a result, radiation exposure of members of the public via the surface water pathway has been very small. The estimated value of the annual effective dose equivalent for an average member of the critical group for this pathway is 0.003 mSv per annum. Thus, under the current management system, radiation exposure via the atmospheric pathway dominates, and the critical group's exposure is estimated at 0.1 mSv per annum. Seventy percent of this total arises from the transport of long-lived radionuclides in dust. The dominance of the atmospheric pathway could change if the release of RRZ waters is authorised.

The author would like to thank the staff of the Australian Atomic Energy Commission and of the Alligator Rivers Region Research Institute for helpful discussions on this topic, and also for the use of data prior to publication.

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