AAEC/E272

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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

PROCEEDINGS OF THE AAEC SYMPOSIUM ON ENVIRONMENTAL AND RADIOLOGICAL SAFETY ASPECTS OF THE MINING AND PROCESSING OF URANIUM

LUCAS HEIGHTS, 9 - 10 DECEMBER 1971

April 1973

ISBN 0 642 99554 0

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PAPER I

REVIEW OF WORLD TRENDS IN THE URANIUM INDUSTRY

(A SUMMARY)

by

R. K. WARNER

Chief, Nuclear Technology Division, AAEC

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KEYWORDS

The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA–INIS–12 (INIS: Manual for Indexing) and IAEA–INIS–13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

Paper I	AUSTRALIA; AVAILABILITY; ELECTRIC POWER; GEOLOGIC DEPOSITS; MARKET; NUCLEAR INDUSTRY; URANIUM
Paper II	CONTROL; DOSE LIMITS; ENVIRONMENT; HUMAN POPULATIONS; MAN; MINING; RADIATION DOSES; RADIATION PROTECTION; RADIOACTIVE WASTE DISPOSAL; RADIOACTIVITY; SAFETY; URANIUM
Paper III	CONTAMINATION; LEACHING; MINING; ORE PROCESSING; POLLUTION; RADIOACTIVE WASTES; URANIUM; URANIUM ORES
Paper IV	CLIMATES; CONTAMINATION; DRINKING WATER; ENVIRONMENT; FOOD; MINING; NORTHERN TERRITORY; ORE PROCESSING; PLANNING; POLLUTION; RADIOACTIVE WASTES; RADIOACTIVITY; URANIUM ORES
Paper V	CONTAMINATION; CONTROL; LAND POLLUTION; LEACHING; MANAGEMENT; MINING; ORE PROCESSING; PLANNING; URANIUM; URANIUM ORES; WASTE DISPOSAL; WATER POLLUTION
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Paper IX	BIOLOGICAL RADIATION EFFECTS; CARCINOGENS; CONTROL; DAUGHTER PRODUCTS; LUNGS; MAN; MAXIMUM PERMISSIBLE CONCENTRATION; MAXIMUM PERMISSIBLE LEVEL; MINING NEOPLASMS; RADIATION DOSES; RADON; URANIUM
Paper X	DAUGHTER PRODUCTS; DOSIMETRY; GAMMA RADIATION; INHALATION; MINING; RADIATION DOSES; RADIATION HAZARDS; RADIATION PROTECTION; RADON; URANIUM; URANIUM ORES; WHOLE-BODY IRRADIATION
Paper XI	DAUGHTER PRODUCTS; GAMMA RADIATION; INGESTION; INHALATION; MINING; PERSONNEL DOSIMETRY; RADIATION MONITORING; RADIATION PROTECTION; RADON; SURFACE CONTAMINATION; URANIUM; URANIUM ORES; WHOLE-BODY IRRADIATION
Paper XII	CONTROL; DAUGHTER PRODUCTS; DOSE RATES; MINING; RADIATION DOSES; RADIATION HAZARDS; RADIATION MONITORING; RADIATION PROTECTION; RADON; URANIUM; URANIUM ORES; VENTILATION

National Library of Australia card number and ISBN 0 642 99554 0

FOREWORD

These Proceedings contain papers presented at a two-day Symposium on Environmental and Radiological Safety Aspects of the Mining and Processing of Uranium held at the Research Establishment of the Australian Atomic Energy Commission on December 9 and 10, 1971. The Symposium was organised by the Commission at short notice at the request of industrial organisations interested in the mining and processing of uranium ore.

The prime purpose of the Symposium was an educational one, to draw attention to the problems associated with the protection of man and the environment in the vicinity of uranium mining projects and to collect together relevant information for future reference. The demand for copies of the papers has been such that the Commission has decided to issue the papers presented by Commission staff in one volume of Proceedings. The demand is an indication of the interest which industrial organisations and government departments showed in the material presented, and of the future importance of uranium resources and processing to Australia.

The Commission has a charter under the Atomic Energy Act to be a centre of knowledge and expertise on atomic energy matters. Its involvement with others in base-line environmental studies in the Northern Territory has been directed towards the development of criteria relating to control of pollution in mine-site environments within certain defined discharge limits.

There is appreciable expertise available within the Commission on protection of the environment and on the protection of man in the presence of potential radioactive and chemical pollutants. The Commission can provide assistance and guidance in such fields and welcomes contacts with other organisations. We hope that industry and government departments will find further opportunities for exchanges of views and information.

J. L. SYMONDS
ACTING DIRECTOR

1. SUMMARY

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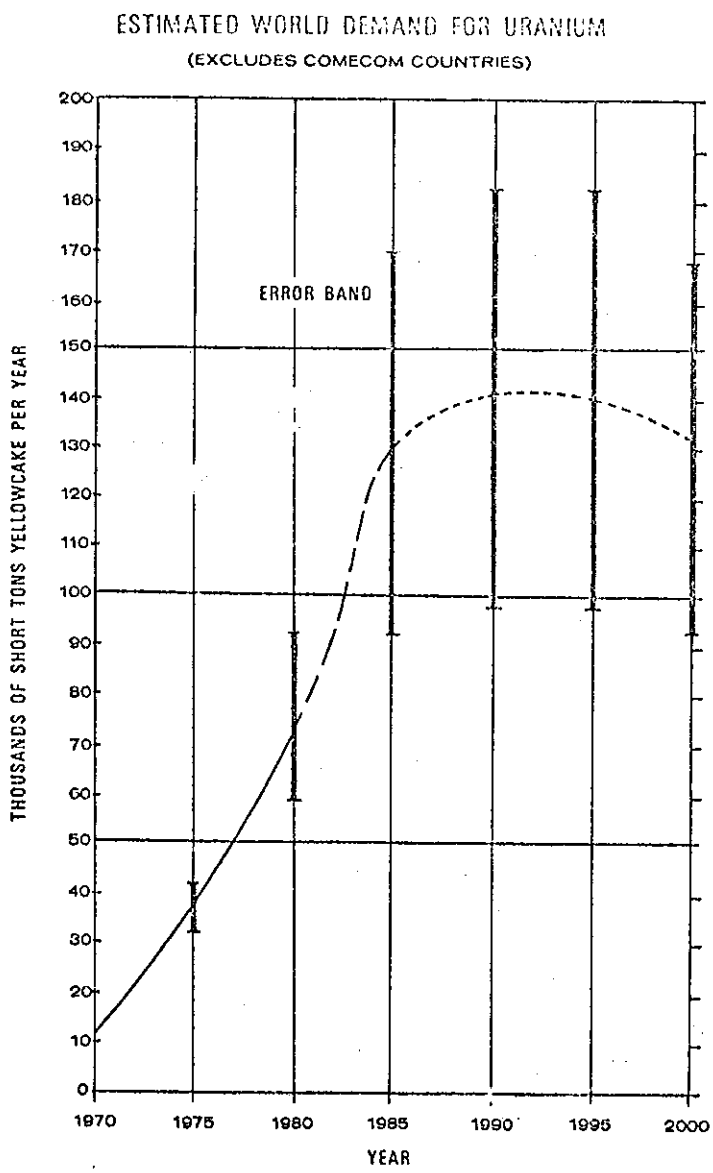

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PAPER II

PHILOSOPHY OF ENVIRONMENTAL PROTECTION AND CONTROL

by

G. M. WATSON

Chief, Health and Safety Division, AAEC

1. THE NATURE OF THE PROBLEM

There are really two problems which should be identified here; protection of the environment as such, and protection of man in that environment. This introduction will deal primarily with the second of these, the protection of man, since for him there are acceptable limits of radiological exposure from which we can logically derive operational limits for the release of radioactive materials from mines or nuclear plant. Mines, especially, are also apt to produce chemical pollutants. It is probably also legitimate to treat the risks to man from metallic or other chemical pollutants in much the same way as radioactivity although, for the most part, the available data will not allow us to relate exposure to risk in the same way as with radiation. The published limits for chemical pollutants are usually taken as thresholds below which no effects are seen, although it is doubtful if this can always be supported.

It is certainly the case that the environment of civilisation is gradually accumulating various man-made contaminants some of which are carcinogens, and whose effects may be additive among themselves and with radiation. An assumption that is generally reasonable is that, if man is adequately protected from environmental radiation injury, so will be the plant and animal species in the area. This assumption is clearly not valid for chemical pollutants.

To deal properly with the first problem, protection of the environment as such, is less simple than looking after the immediate welfare of man. We do not have a set of prescribed values, corresponding to the dose limits for man, which would allow us to say this natural feature is untouchable, or that one can be put at risk. We do not think this is an insoluble problem; a mine operator can put a cost figure on the measures he is required to undertake in order to meet the demands of conservation; equally it should be possible for the conservtionist to evaluate the worth of what he wants to conserve. If he does this he is on stronger ground in demanding that operators spend money on conservation. I do not intend to enter here into the details of how this might be done, since it is merely one aspect of a broad concept of land use, but it is a legitimate subject for discussion and must concern many participants.

2. BACKGROUND RADIATION

The effects of man-made or man-released radiation should always be assessed within the perspective afforded by the existence of a ubiquitous natural background radiation. This arises from cosmic radiation which is altitude and latitude dependent, from terrestrial gamma radiation which varies with soil or rock type, and from naturally radioactive constituents of the body, in particular potassium-40. The total average background radiation to which an

individual is subject is in the region of 120 millirem per year but in many centres it will be twice this figure, or more, without any harmful effect being manifest. So one can say categorically that exposures of 100 millirem or so per year above the 'normal' background can be regarded as trivial.

3. CRITERIA FOR THE RELEASE OF RADIOACTIVITY

The last paragraph indicated that some degree of radiation exposure to man can be regarded as trivial. It is implicit in our thinking that some larger amount is too much and it is necessary to decide what is a proper upper limit for individuals, occupationally exposed, or as members of the public without control over their exposure. It is possible to extend this question to ask what is the proper upper limit for the mean exposure of a population; should it be less than that derived from the sum of allowed individual doses?

These questions have engendered a good deal of public controversy, but governments of all hues and their specialist advisers have generally gone along with the recommendations of the International Commission on Radiological Protection for both occupational and involuntary exposure. For environmental purposes the relevant recommendation is that the dose limit for the gonads, bone marrow and whole body, for a member of the public shall be 0.5 rem in a year. In this country this is spelt out with varying degrees of clarity in State regulations and explicitness in a publication of the National Health and Medical Research Council. From this datum it is possible to derive limits for the release of radioactivity to the environment.

4. CALCULATIONS OF ALLOWABLE RELEASES

In nuclear operations of most kinds, and this certainly includes mining and milling it is not practicable to confine radiation and radioactivity absolutely. There will usually be many and complex pathways by which released radionuclides will ultimately cause radiation exposure to man. In the ideal situation it would be possible to make a complete inventory of the distribution and fate of released radionuclides; in practice this is not necessary, since in any given situation it will be possible to identify certain nuclides and pathways as being more important than others. These are then designated as 'critical' pathways and will provide the limitations on discharges to the environment. Within these pathways may be found one or more groups of people whose habits or characteristics in some respect, age, location, eating habits, for example, will cause them to be regarded as critical groups. Their behaviour will then provide the limits of discharge.

In any real situation it will usually be wise to adopt a pragmatic

approach as well as the analytical one. That is, after releases, set conservatively, have begun, the components of the environment will be sampled and a factual basis supplied where possible to the analysis.

The pathways by which released radioactive materials can find their way to man can be complex. For example iodine or strontium radioisotopes may be deposited on grass, the grass eaten by cows, and the radioisotopes finally ingested in the milk by children. Marine dispersion may be still more complicated. Released radioactive metals may be taken up in succession by phytoplankton, molluscs or crustaceans, small fish and larger predatory fish before being ingested by man. At each stage there may be a concentration factor and in some instances this can be very high; for example oysters will concentrate zinc from sea-water by a factor of 10^4 or more.

It may be of interest to cite examples of significant pathways. Here at Lucas Heights we discharge small amounts of radioactivity, according to an agreed formula, into the Woronora estuary. The conceivable exposure pathways are:

- Eating of oysters farmed in the water below the liquid effluent discharge point.
- Sunbathing on beaches which may be contaminated.
- The possibility of grains of contaminated sand entering the body through minor injuries.

Here the problem is trivial since the monthly discharges amount only to a few millicuries of hard β-emitters and trifling amounts of tritium and α-emitters. At the Windscale Works in the United Kingdom, where nuclear fuels are processed, the problem is of an altogether different order of magnitude. Here it was found that the concentration of ruthenium radionuclides into an edible seaweed which, in that part of the world, is made into a form of bread, was critical for the assessment of hazard to the public. That is, consumers of seaweed come nearer to receiving the permissible radiation dose than do beach users and fish eaters.

The ICRP does not define limits of radioactivity for the various foodstuffs which enter into these calculations. It does provide tables of the maximum possible concentrations allowable in drinking water for persons occupationally exposed. These concentrations would give the 'standard' man, who consumes 2.2 litres of water daily, a body burden of the nuclide in question just sufficient to irradiate the most sensitive organ to the allowable limit. Dividing the listed concentration by 30 gives the figure appropriate to the general public. Since the concentrations are given as $\mu Ci/cm^3$, multiplication

by 2,200 gives the allowable daily intake for each radionuclide. From this derived limit it is possible, if the pathway, eating habits, concentration factors and dilution factors are well-enough known, to quantify allowable releases for each radionuclide. Since the effects of ingested radionuclides are additive, any discharge authorisation must allow for their summation in the calculations. Similar arguments can be applied to atmospheric dispersion.

5. ENVIRONMENTAL CONTROL

Pre-operational investigations have several objectives:

- To obtain sufficient information on what are the critical radionuclides, pathways and population groups, to allow at least a provisional evaluation of what discharges are allowable. In some cases it may be better to postulate a hypothetical critical group with extreme characteristics, which will be the 'worst case', as a basis for initial formulation. Observation will then allow refinement.
- To provide information on pre-operational levels of radiation and radioactivity. These will not affect the conduct of operations but will facilitate the interpretation of later results.
- The conduct of experiments to obtain unknowns, e.g. concentration and dilution factors and, for chemical contaminants, allowable concentrations for local habitats.
- Post-operation environmental surveys are necessary to:
  Provide evidence that the assumptions underlying discharge formulations are valid or conservative.
  Provide sufficient random sampling to ensure that unrecognised pathways of exposure do not exist.
  Provide the data necessary to meet the needs of good public relations.

The work required under the first two headings is self-limiting and, providing there are no major changes in plant operation, should reduce with time. It is important to review the monitoring programme from time to time, not only because it might have been wrong in the first place but because review when operations are stablised may allow substantial reductions in the scale of monitoring programmes. In installations where processes and waste releases are closely monitored, environmental monitoring may become unnecessary, but the nature of maining operations is such that continued monitoring is likely to be necessary.

6. CONCLUSION

In summary, the philosophy of radiological environmental control is to restrict exposure of the public to ICRP-originating limits for individual

members of the public. The ICRP also provides for a limitation on genetic dose to the population (not dealt with by the N.H. and M.R.C) but this is unlikely to have relevance, in the present context, for many years if at all. It is also a sine qua non that doses are kept as low as possible, but the definition of 'possible' is rather subjective.

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PAPER III

SOURCES OF POLLUTION IN URANIUM MINING AND PROCESSING ACTIVITIES

(A SUMMARY)

by

R. K. WARNER

Chief, Nuclear Technology Division, AAEC

1. SUMMARY

The possible sources of pollution in the mining and processing of uranium ores are as follows:

(i) Natural weathering and leaching of ore from costeans and other works during exploration.

(ii) Leaching from overburden, below-ore-grade material and ore stockpiles; contamination of surface and underground water entering the mining operations; radon emission from the mine; radiation from ore stockpiles.

(iii) Radon and daughter products emitted during crushing and grinding (silica also of concern).

(iv) Solid tailings produced after leaching and decantation to recover uranium; tailings present the greatest problem encountered in pollution control since they contain residual uranium, essentially all of the radium in the ore, and other radioactive daughter products, as well as possibly deleterious minerals and residual leaching agents; effective and permanent containment of solid tailings is mandatory.

(v) Liquid effluents arising from purification of the uranium solution; quantity and type depends on process used; radium and daughter products and soluble chemical reagents will be present; solvent extraction will also give rise to soluble and entrained solvent and extraction agents; recycle and/or treatment before discharge required.

(vi) Chemical liquors arising from final precipitation of uranium (ammonium sulphate solution if ammonia used in this step).

(vii) Dust arising from calcining and packaging of yellowcake product.

Each of the above is discussed briefly, with particular emphasis being given to the effects of (i), (ii), (iv) - (vi) in operations carried out in a high rainfall area such as the Alligator River Uranium Province in the Northern Territory.

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PAPER IV

ENVIRONMENTAL STUDIES FOR URANIUM PROVINCES – AIMS AND METHODS

by

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Head, Health Physics Research Section, AAEC

1. INTRODUCTION

The present-day concern for the environment reflects a view that if degradation is not minimised, man's future existence is in doubt. In this context, new activities should be embarked upon only if the benefits outweigh the costs. In this cost-benefit analysis, environmental diversity, conservation of resources, etc, would be tangible cost factors.

In this broad context of land usage the input data needed to resolve questions related to the development of the uranium extractive industry could include consideration of the world demand for uranium and Australia's share of the market, the free market price and the economic break-even grade, the magnitude of Australia's reserves (proved and potential) their locations and the uniqueness of the locations, the world tourist industry, in-vogue recreational habits and Australia's potential attractions, and Australia's balance of payments.

Armed with these data and predictions, decisions could be taken on what deposits can be developed and when development should commence, and on which deposits cannot be developed while the predictions remain true.

Many of the above criteria are closely related to national goals. Our environmental studies relate to only one aspect of this broad issue; by pointing to design criteria for mine development that directly affect the cost of production, we influence the economic break-even grade. The extent of this influence depends on the environmental characteristics of the area containing the deposit.

Much of this paper concerns the Northern Territory uranium province. We do not have great knowledge of this area but it is intended to investigate it in the coming year. By describing what I consider should be done and why it should be done, the meaning of design criteria should become clear.

2. DESIGN CRITERIA

Technology can always be used to reduce environmental deterioration due to exploitation of a particular resource. The relevant design criteria can be phrased in terms of seasonal or monthly allowable discharge limits. They must take into account all potential pollutants and be related to the environment in which the discharge may occur. Thus they are not guide-lines for the industry as a whole. There would be specific requirements for specific deposits.

In principle the criteria are not geared to the practicalities of mining and processing but rather to certain subjective appraisals of the mine environment. In practice each plant site and mine development proposal would

have separately determined design criteria. Of course if there is no practical way to meet the criteria, then the deposit becomes uneconomic.

3. POTENTIAL POLLUTANTS

The source and nature of potential pollutants have been described in an earlier paper. They were seen to be of four general classes; heavy metal, chemical, radioactivity and suspended solids.

Sources of heavy metal contamination are mine drainage, seepage from overburden, tailing dumps and ore storage areas, and the liquid effluent from the treatment plant. Fish communities are the most likely to be sensitive to heavy metal toxicity, especially that of copper and lead.

The nature of the chemical pollutants, including changes in acidity, will depend on the method of leaching. This will normally involve either sulphuric acid or alkaline sodium carbonate leachants.

The radiologically significant isotopes in the uranium series are uranium-238, radium-226, lead-210 and polonium-210. It should be noted that uranium ores are generally not in extreme disequilibrium so ore containing a metric ton of uranium will contain 0.3 Ci of each of these isotopes. Only the uranium radioactivity will be extracted during ore processing.

Suspended solids relate mainly to soil erosion from the camp site and the overburden dumps. They are pollutants in the sense that they can cause deterioration of the environment by altering the flow of water-courses etc.

Table 1 summarises the waste arisings from a 3,000 tonne U_3O_8/annum plant. These figures are extrapolations of published data on the Rum Jungle and South Alligator Creek plants (Bellingham 1961; Allman, Harris and Bayly 1962) and take no credit for economies of scale. For calculational purposes it has been assumed that the ore grade is 6 lb/ton (throughput, 3,000 tons of ore per day), that the deposit is below the water table (mine seepage: 10 million gallons of water per day) and that this seepage is in partition equilibrium with the mineralisation (i.e. water from a costean is representative of mine seepage water).

Where appropriate, Table 1 also lists current World Health Organisation (WHO) requirements on clean water. In the main, these limits are based on standards for human drinking water. Most of our programme would be concerned with determining which of these, if any, are too restrictive and which, if any, are not restrictive enough for the particular environment in which the discharges will occur. The programme would also determine the effective dilution or concentration factor applicable from the point of discharge to the most sensitive habitat.

4. GENERAL APPROACH

Having defined the aims and the nature of the problem, it becomes simple to set out the general approach to be adopted. It is:

(i) Evaluate the environmental characteristics of the area.

(ii) Determine the ecological significance of the range of habitats likely to be influenced by mining operations and their relative sensitivities to the range of potential pollutants.

(iii) Measure the tolerance of significant habitats to possible heavy metal, chemical or radiological pollution.

(iv) Investigate the significance of potential radioactive or chemical pollutants with emphasis on items of food or food processing and possible exposure routes to man, both in relation to food collection by aborigines and present water usage and in relation to the development of mining towns.

There is also a public relations aspect to the study since it would assemble documentary and photographic evidence of the state of the local environment before the commencement of mining operations.

5. PRELIMINARY ASSESSMENT - N.T. URANIUM PROVINCE

5.1 Characteristics of the Environment

The drastic change in climate encountered in the Northern Territory is a large factor in the ecology of the area. Plant species must be able to tolerate waterlogged conditions during the monsoons as well as the dry conditions which follow. On the black soil plains surrounding the estuaries, reeds flourish in the low lands and then die as the plains dry out, leaving the area barren.

The black soil plain areas are of immense importance to magpie geese; the reeds growing through the floodwaters provide their breeding grounds and the wild rice, that grows as the water recedes, provides food for their young. Conservation of the black soil plains is a pre-requisite to the survival of this species.

Further upstream where freshwater systems prevail, zones of vegetation can be clearly seen when the floodwaters recede. Away from the stream there is first a sedge meadow, then a strip of paperbarks on the bank followed by a zone which includes Pandanus and Eugenia sp. (native apples). Beyond this is a small grassy plain which gives way to a Eucalyptus woodland as the ground rises.

Two main types of billabong are seen; Type 1 which has a substrate of fine particle black clay and gradually sloping sides (e.g. Jabiru waterhole);

and Type 2 which has a sandy bottom, steep sides and is usually larger.

Type 1 develops sedge meadows on the margins as the water dries out and the water becomes turbid and warmer. As evaporation continues during the dry season, ionic heavy metals become concentrated, temperatures increase and dissolved oxygen levels decrease rapidly, and bottom muds become anaerobic. These anaerobic conditions are believed to be responsible for a chemically induced precipitation of uranium and could explain the existence of swamp anomalies on the Koongarra leases and the high uranium content of bottom muds in other billabong systems (see Table 2).

Commonly a dense layer of microscopic algae forms on the top in the warmer areas at temperatures from 32°C - 37°C. At the end of the dry season fish kills are often observed. All the factors just mentioned could be implicated and it is possible that metabolites from the floating algae could be toxic.

Type 2 billabongs are seen closer to the escarpment and may be replenished by underground water. At the end of the dry season they are clearer and cooler and present a more moderate environment. Barramundi spawn in the open seas and migrate to the fresh water river/billabong system as juveniles during the next wet. They may remain in the billabongs for many years. Thus for the billabong systems, the toxic effect of heavy metals on fish egg hatchability is less important than if we were, for example, dealing with salmon. However catfish, mudfish etc., do spawn in the billabongs and these species will need to be considered.

One of the most noticeable changes during the wet season is the growth of grass to a height of 6' - 8' over most of the area. During the dry season this becomes flammable and in the past was burnt by aborigines to assist hunting. More recently prospecting companies have burnt this grass to gain access to the area. Extensive burning may bring about large changes in a plant population if the species are not specialised to deal with it so that a study of the past practice of the aborigines should be made to determine what does constitute a 'natural' environment.

5.2 Critical Habitats

5.2.1 Black soil plains

A possible environmental limitation on the discharge of mill effluent into the S. Alligator River and Nourlangie/'Sawcut' Creek waterways during the wet season relates to the black soil plains.

The assumed problem associated with these plains is:

(i) During the wet, the flood waters, which would carry discharged sulphate etc., do not flow into Van Diemen Gulf but simply spread out over the subcoastal plains.

(ii) From year to year, while the total acreage flooded will vary somewhat, the main variable is simply depth of flooding.

(iii) At the end of the wet, the water levels drop, mainly as a result of solar evaporation.

(iv) Any contained sulphate would be deposited on the plains and this process would repeat itself each year during the life of the mining operation.

(v) Allowable sulphate discharges would then have to be such that integration over, say, a 40 year period would remain within an acceptable limit with respect to, for example, the continued growth of wild rice.

In attempting to evaluate the significance of this potential hazard we are faced immediately with an almost complete lack of basic data, e.g. rainfall records, depth of flooding and areas involved and the nature of the floodwater (i.e. of river origin or mainly rainwater) and we cannot feel hopeful that this situation can be improved within the time available.

The only alternative to a conservative calculation based on the above hypothesis is somehow to work back by making geochemical studies on cores taken from the black soil plains.

If we assume:

- that because the plains are still subcoastal, the annual sediment deposition is small,
- the dissolution of uranium into the run-off of the headwaters for the river systems would be diffusion limited and independent of the total rainfall,
- the organic sediment deposited on the plains is directly related to the rate of rainfall and approximately related to the total rainfall,
- the N.T.A. sampling programme will lead to a reasonable estimate of the total uranium entering the plains system during the 71/72 wet, and
- all uranium in the non-flowing floodwater is precipitated as a result of anaerobic conditions,

then a geochemical dating seems feasible. Firstly, the specific activity as a function of core depth should inversely correlate with the Darwin rainfall data. Secondly, the specific activity integrated over each annual sediment

layer would lead to a similar total quantity of uranium. Thirdly, the annual uranium deposition rate leads to a direct estimate of the percentage of uranium entering the system that is deposited on the surface. The situation for contained sulphate etc., could be no worse than this.

Investigations should be made of these assumptions and the feasibility of the approach with the first 10 feet or so of core samples obtained from a black soil location that has hopefully, not been disturbed by buffalo. In the first instance, the vertical distribution of uranium could be measured with the dielectric foil technique. The tolerance of rice etc., to potential pollutants could be evaluated as in Section 5.3.

5.2.2 Billabong system

To maintain existing fish communities, the concentration of heavy metals in the billabong system will need to be below tolerance levels by the end of the dry season. During the dry, the level of contaminants will increase as a result of solar evaporation. A conservative assumption for this concentrating mechanism is that it is numerically equal to the ratio of the volume of the billabong system at the end of the wet to that at the end of the dry. This could be evaluated quite simply by spot tritiated water dilution experiments.

More realistically, some water is drunk by stock and seepage will either add to or subtract from the total volume. These factors can also be evaluated with a tritium tracer but the solution is a little more complex. A free surface of tritiated water will change in tritium content by two mechanisms. Firstly, evaporation enriches the remaining water in tritium because HTO has a higher water vapour pressure than H_2O and secondly, by exchange of water vapour from the air (which has effectively no tritium) with the free water surface. This leads to a reduction in tritium content. Crude approximations for these two correction factors can be obtained by using semi-empirical relationships that involve a knowledge of water surface temperatures, air temperature and humidities and wind velocity. Selected billabong systems should be investigated with this technique. Again, tolerance levels for fish to the potential pollutants will need to be determined.

5.3 Tolerance Levels

Tolerance levels are those levels of pollutants in which an organism can survive rather than flourish. For fish it has been suggested that the permissible concentrations of toxic substances in effluent waters be 1/10 of the median tolerance level (TL_m). TL_m is the concentration at which half of the test animals survive. However, if the toxicity/concentration relationship follows the general equation $C^nT = k$ (C = concentration of toxic

substance, T = median survival time and n and k are constants), then for a value of n = 1, a 1/10 reduction will give a tenfold increase in survival while for n = 3 a similar reduction will increase survival a thousand times.

This means that the toxicity of each pollutant must be well known before permissible discharge levels can be set.

When doing experiments to determine these figures it is also necessary to use water and test animals from the rivers which will receive the effluents. Local variables which may be unsuspected (e.g. natural toxic substances and local speciation in test animals) are then taken into consideration.

Thus to set meaningful criteria for discharges it is necessary to have a field station to investigate the lethality of as many expected pollutants as possible on a number of aquatic species.

Synergistic effects where toxic substances operate in combination with high water temperature and low dissolved oxygen should also be investigated, bearing in mind that the dry season will be the most severe time for most billabong species.

Tolerance levels for some of the heavy metals likely to be encountered in the uranium province are shown in Table 3. These figures are presented as a guide only since they pertain to temperate zone fish.

The determination of tolerance levels for other critical habitats, e.g. sedge meadows, will require field experiments based on agricultural plot methods, using polluting substances made to approach predicted wastes from mining operations. That substance would include clay flocculents containing SO_4^{2-}, heavy metals and soluents.

5.4 Radiological and Chemical Purity Aspects

Existing or potential exposure routes in the Northern Territory uranium province relate to:

- drinking water supplies,
- aquatic food production,
- grazing by livestock,
- food gathering by aborigines,
- supplies of process water for local slaughter yards, and
- irrigation.

5.4.1 Drinking water supplies

The International Commission on Radiological Protection (ICRP) has made recommendations on acceptable levels for radioactive contaminants in drinking water for the general public, e.g. radium-226, 10 pCi/ℓ; natural uranium, 20,000 pCi/ℓ; lead-210, 100 pCi/ℓ; polonium-210, 700 pCi/ℓ. WHO recommendations

on chemical purity are given in Table 1.

It is only in exceptional circumstances (e.g. natural spring waters containing much dissolved radon gas) that the levels of lead-210 or polonium-210 will substantially exceed that of radium-226. Thus a specific analysis for radium-226 in drinking water will generally suffice. Table 4 summarises values that have been found for water samples from the area.

5.4.2 Aquatic food production

To meet biological needs, all organisms concentrate certain elements from their diet. The factor that relates the concentration of a particular element in the organism to that in the surrounding medium is called the biological concentration factor (CF). Experimentally determined CF values for radium-226, copper and lead in freshwater mussels, catfish and barramundi are given in Table 5. For edible organisms, the allowable limit of radioactivity can be derived from the ICRP recommendations on drinking water:

$$(\text{mpc})_{\text{food}} = (\text{mpc})_{\text{water}} \frac{2200}{x} ,$$

where x is the assumed consumption (in gal/d) and 2200 (mℓ) is the daily water intake assumed by the ICRP in deriving their recommendations. The same simplification may not apply to chemical contaminants because of possible acute effects.

For any uranium province it is expected that there would be sufficient radium-226 occurring naturally in the waterways for appropriate concentration factors to be determined from samples collected in the field. Note that if CF > 2200/x then food consumption is more limiting on contaminant level than is the drinking of the water.

5.4.3 Grazing by livestock

To expound on an exposure route associated with livestock grazing, much needs to be known; degree and extent of grazing, partition coefficients for water → soil → grass → animal, biological concentration factors and so on. Initially it is being assumed that this whole relationship can be expressed simply by the ratio between the radioactive and chemical level of buffalo meat and those of the water in its wallow. Preliminary results for Oenpelli and Mudginbarry buffalo are shown in Table 6.

5.4.4 Food gathering

The wide range of native foods that are gathered by aborigines is indicated in Table 7. Not all of these are in the category of delicacies and only those marked with an asterisk are believed, at the moment, to be

important. Of these, only water lilies, mussels and native fruits (apples, plums and pandanus nuts) have been widely sampled. Preliminary results for these items are given in Table 8.

5.4.5 Process water in slaughter yards

The washing down of freshly slaughtered beef leads to much evaporation and, presumably, concentration of any contaminants in the water. Although yet to be estimated by experiment or calculation, it is not expected that this mechanism will numerically exceed the related biological concentration factor. However, for sulphates and copper, the limiting factor could be an aesthetic one (discolouring of fat) rather than health. This will need to be investigated.

5.4.6 Irrigation

As for the case of grazing animals, much basic data is needed to evaluate an exposure route associated with crop irrigation. An indication of the relative importance of the various metabolic pathways may be obtained from the results of fall-out cesium-137 cycling in paddy rice (Myttenaere, Bourdeau and Masset 1969). It was found that the rice absorbed a factor of 30-100 more of the radiocesium present in the irrigated water than of that previously fixed by soil. Further, the plant roots are relatively much more contaminated from activity in the soil than from the water, whereas the reverse is true for the edible parts.

Table 9 summarises some of the findings. Of perhaps greatest significance to us is the finding that cultivation in nutrient solutions provides a reasonable approximation to the more elaborate paddy cultivation experiments.

6. TENTATIVE CONCLUSIONS

6.1 Radiological

- Depending on assumed consumption, the eating of barramundi would be more limiting on allowable radium-226 levels than would be the drinking of water.
- Radium-226 and U do not move in parallel and the levels of one is not representative of the other.
- Mussels appear to concentrate Ra in the flesh to about the same level irrespective of the Ra level in the water, i.e. CF inversely correlates with radium-226 levels in the water (cf oysters for Cu and zinc-65)
- Mussels do not concentrate U as much as they do Ra.

From results to date, the native living off the land is no more at risk than a person on a more European diet.

6.2 Chemical Purity

- Buffalo kidneys and geese concentrate U, Cu, Pb. These species graze extensively on sedge meadow and the water weeds of these areas significantly concentrate U, Cu, Pb and Co.

6.3 Geochemical

- Pandanus concentrate Cu and Pb.
- Salmon gum green leaves are high in U, Cu, Pb and Co.

7. REFERENCES

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TABLE 1 (a)

ANNUAL WASTE ARISING FROM A HYPOTHETICAL URANIUM MINING/MILLING OPERATION PRODUCING 3×10^6 kg U_3O_8 PER YEAR FROM ORE OF 6 lb/TON USING SOLVENT EXTRACTION ON A SULPHURIC ACID LEACHANT AT AN OVERALL EFFICIENCY OF 85%

Nature of waste	Annual arisings
Uranium - in tailings	3.8×10^5 kg
Uranium - in raffinate	4.5×10^3 "
Uranium - in mine seepage	1.5×10^3 "
Radium - in tailings	730 Ci
Radium - in mine seepage	20 Ci
Sulphuric acid - as sulphates	7.4×10^7 kg
Amine or similar solvent	1.2×10^4 "
Long chained alcohol	2.1×10^5 "
Kerosene	1.8×10^5 "
Sodium Chloride	4.5×10^6 "
Copper - from mine seepage	7.2×10^2 "
Lead - " " "	2.3×10^3 "

TABLE 1 (b)

WORLD HEALTH ORGANIZATION STANDARD FOR POTABLE WATER

(all values in ppm)

Constituent	Criterion	
Lead	0.1	mpc
Arsenic	0.2	
Chromium	0.05	
	Permissible	Excessive
Iron	0.3	1.0
Manganese	0.1	0.5
Copper	1.0	1.5
Zinc	5.0	15
Magnesium	50	150
Sulphate	200	400
Chloride	200	600

TABLE 1 (c)

ANALYSIS OF WATER SAMPLES

(units are ppm)

Station*	Cu	Pb	Co	U x 10^3
KN1	0.007	< 0.03	0.01	6.4
KN2	0.013	0.03	0.006	1.0
KN3	0.02	< 0.03	0.025	1.8
KN4	0.008	0.03	< 0.005	1.0
R1	0.012	< 0.03	0.015	1.0
R2	0.035	< 0.03	0.055	1.6
R4	0.025	< 0.03	0.055	1.0
R5	0.015	0.03	0.045	1.2
R6	0.007	0.03	0.02	0.8
R7	0.008	< 0.03	< 0.005	< 0.08
R10	0.045	0.07	0.10	2.2
R11	0.008	< 0.03	0.03	0.6
Ranger Anomaly	0.16	0.5	0.08	336
Oenpelli Red Lily Lagoon	0.008	< 0.03	0.008	11.6
NQ1	0.006	< 0.03	< 0.005	1.4
NQ2	0.07	0.06	0.13	96
NQ3	0.005	< 0.03	< 0.005	1.4
NQ5	0.007	< 0.03	< 0.005	< 0.08
NQ6	0.025	< 0.03	< 0.025	0.6

*See Appendix A

TABLE 1 (d)

FILTERED WATER SAMPLES

Station*	Cu	Pb	Co	U x 10^3
KN1	< 0.03	< 0.3	< 0.05	2.5
KN2	"	"	"	2.4
KN3	"	"	"	32
KN4	0.04	"	"	0.7
R1	< 0.03	"	"	1.6
R2	"	"	"	6.6
R4	"	"	"	2.0
R5	"	"	"	3.4
R6	"	"	"	1.5
R7	"	"	"	0.6
R10	"	"	"	1.7
R11	"	"	"	0.06
Ranger Costean	"	0.7	"	120
Oenpelli Red Lily	"	< 0.3	"	2.8
NQ1	"	"	"	0.1
NQ2	"	"	"	0.06
NQ3	"	"	"	0.06
NQ5	"	"	"	0.06
NQ6	"	"	"	0.06

*See Appendix A

TABLE 2

ANALYSIS FOR SOIL AND BILLABONG BOTTOM SEDIMENTS

(for chemical analysis, units are μg/g ash; for ^{210}Pb, units are pCi/g fresh weight)

Station*	^{210}Po	U	Cu	Pb	Co	$\frac{\text{Ash}}{\text{Dry Wt.}}$ %
KN1	0.36	0.1	0.42	0.7	0.3	99.5
KN3	3.65	3.6	9.9	8.3	7.9	79.3
KN4	1.36	1.4	1.0	1.7	1.5	94.5
KN5 - Near surface	2.26	2.6	3.0	6.5	8.5	96.8
KN5 - 1 ft	1.50	1.2	1.1	3.5	7.7	95.7
KN6 - Near surface	2.24	7.3	3.4	8.6	1.0	93.6
KN6 - 1 ft	1.84	4.1	3.4	5.7	5.9	99.2
KN7 - surface	52.2	5.8	2.2	2.0	1.0	96.6
KN7 - 1 ft	5.66	0.6	0.6	< 0.5	< 0.1	99.5
KN8	2.33	1.2	1.1	2.4	1.2	98.5
NQ1		1.2	1.8	2.1	1.6	95.4
NQ3		3.7	1.7	3.0	1.8	98.6
NQ5		0.8	2.1	3.0	2.1	96.8
NQ6		1.4	3.7	5.9	6.6	94.0
R1		4.6	9.2	5.0	8.7	86.1
R2		3.8	5.2	3.5	4.3	95.5
R4		3.8	14.0	23.0	13.0	81.3
R5		0.4	0.9	4.0	1.7	97.3
R6		1.5	4.3	4.6	2.7	90.8
R7		0.1	0.43	0.7	0.15	99.6
R10		1.8	2.3	4.0	2.9	96.5
R11		5.0	4.3	8.7	4.6	85.7
Oenpelli Red Lily Lagoon		1.3	2.0	7.2	5.1	94.0

*See Appendix A

TABLE 3

96 h TL_m FOR TEMPERATE ZONE FISHES

Metal	Form	Minnow		Bluegill		Stickleback
		Soft	Hard	Soft	Hard	Soft
U	$UO_2SO_4 3H_2O$	2.8	138			
U	$UO_2(NO_3)_2 6H_2O$	3.1				
V	$VO\ SO_4$	4.8	30	6	55	
V	VO_5	13	55			
Sb	$SbCl_3$	9	17			
Cd	$CdCl_2$	0.9	5			
Ni	$NiCl_2$	4	24			
Ni	$Ni\ (NO_3)_2$					1.5
Pb	$Pb\ Cl_2$	2.4	75			
Pb	$Pb\ (NO_3)_2$					0.3
Cu	$Cu\ SO_4$	0.05	1.4	0.2	10	
Cu	$Cu\ (NO_3)_2$					0.06
Mn	$Mn\ (NO_3)_2$					100
Co	$Co\ (NO_3)_2$					20
Zn	$Zn\ SO_4$					0.7
Hg	$Hg\ Cl_2$					0.2

TABLE 4

RADIUM-226 LEVELS IN WATER SAMPLES FROM THE NORTHERN TERRITORY URANIUM PROVINCE

Station*	General Location	^{226}Ra (pCi/ℓ)	
-	Ranger Costean	1194.4	
R1	Corndorl	2.3	
R2	George Town	8.45	
R10	W branch Magela Ck.	4.54	
R11	Jabiru	2.32	
-	Ranger bore water	3.7	4.44
	- sediment	0.74	
NQ1	Nabarlek billabong	0.49	
NQ4	Drinking water supply	1.68	17.2
	- sediment	15.5	
NQ3	Downstream of NQ4	0.29	
Q1	Oenpelli - Red Lily	0.37	
KN4	Sawcut Ck. escarpment	1.52	
KN1	Nourlangi billabong	1.02	

* See Appendix A

TABLE 5

CONCENTRATION FACTORS FOR AQUATIC ORGANISMS

$$CF = \left(\frac{\text{concentration in organism}}{\text{concentration in water}}\right)$$

Organism	Station*	U		Cu		Pb		Co		Ra	
		CF	Concn. µg/g Fresh Weight	CF	Concn. µg/g Fresh Weight	CF	Concn. µg/g Fresh Weight	CF	Concn. µg/g Fresh Weight	CF	concn. µg/g Fresh Weight
Mussel Flesh	NQ1	1000	0.1							6,000	3.9
	NQ5		0.3							-	-
	R2	33	0.23		1.2		1.8		0.6	230	1.9
	KN1	10	0.03							1,400	1.5
	KN4	10	0.01							1,800	2.7
	Oenpelli	200	0.62		1.6		1.8		1.0	12,000	4.2
Barramundi - flesh	Oenpelli	60	0.16		0.3		< 0.4		< 0.3	70	0.025
- gut	Oenpelli	1	0.002								
Catfish - flesh	R2	~ 1	< 0.001		0.5		0.5		0.2	4	0.04
- gut	R2	10	0.04		2.1		0.67		0.4		

* See Appendix A

TABLE 6

APPARENT* CONCENTRATION FACTORS (ACF) FOR URANIUM

RADIUM, LEAD AND COPPER IN GRAZING ANIMALS

Element	Species	Location	Concentration (ppm)		ACF
			natural	water	
Uranium	Buffalo	Mudginbarry	0.002	0.001	~ 2
"	"	Oenpelli	0.015	0.0116	~ 1
"	" (liver)	"	0.002	"	~ 0.2
"	" (kidney)	"	0.032	"	~ 0.3
"	Magpie goose	Noranda	0.044	0.0064	~ 7
			$\times 10^{-6}$	$\times 10^{-6}$	
Radium	Buffalo	Mudginbarry	0.006	0.0023	~ 3
"	"	Oenpelli	0.004	0.00037	~ 10
"	Magpie goose	Noranda	0.008	0.0015	~ 5
Copper	Buffalo	Mudginbarry	0.24	0.012	~ 20
"	"	Oenpelli	0.08	0.008	~ 10
"	" (liver)	"	0.33	"	~ 40
"	" (kidney)	"	1.25	"	~ 160
"	Barramundi	"	0.35	"	~ 50
"	Magpie goose	Noranda	1.02	0.007	~ 150
Lead	Buffalo	Mudginbarry	0.2	< 0.03	> 7
"	"	Oenpelli	< 0.15	< 0.03	
"	" (liver)	"	< 0.16	"	
"	" (kidney)	"	0.22	"	> 7
"	Magpie goose	Noranda	< 0.64	"	

* See text for qualification

TABLE 7

NATIVE FOODS GATHERED BY ABORIGINES

Vegetable	Water lily rhizomes grass roots yams
Fruit	Grape figs (plums ?) red love apples
Animal	wallabies[x], bandicoots, lizards[x], water snakes, long necked tortoises[x], geese[x], duck, emu, jungle fowl, fish[x]

[x] regarded as significant food sources

TABLE 8

ELEMENTS CONTAINED IN BIOLOGICAL SAMPLES

(μg or pCi per gram Fresh Weight)

Sample	Sample Code	U	Cu	Pb	Co
Apple Flesh	NO 3-4	0.015			
	R3	0.031			
	R10	0.026			
	KN4	0.019	0.23	< 0.3	0.09
Apple Seed	NQ 3-4	0.006			
	R3	0.01			
	R10	0.006			
	KN4	0.004			
Plums	NQ 3-4	0.014			
	R9	0.006			
	KN1	0.008			
	KN4	0.01			
Pandanus	NQ 3-4	0.01	2.1	0.25	0.19
	R3	0.01	2.8	0.33	0.17
	R7	0.011	2.2	0.37	0.18
	R10	0.006	2.9	0.18	0.14
	KN1	0.005	2.6	0.22	0.16
	KN4	0.06	1.3	0.4	0.4
Gooseberry	KN1	0.003			
	KN4	0.015			
Waterweed	R1	0.39	2.6	2.0	1.2
	R11	0.51	2.5	1.2	1.4
Waterlily	NQ1	0.07	0.3	0.53	0.4
	NQ4	0.02	0.5	0.2	0.2
Woody Fruit	K8	0.005	0.6	0.4	0.2
Plum Leaves	NQNA5	0.33			
Salmon Gum Leaves	NQNA5	3.7	2.4	1.0	10.0

TABLE 9

CONCENTRATION FACTORS BETWEEN PLANTS AND WATER (^{137}Cs)

AND BETWEEN PLANTS AND SOIL (^{134}Cs)

Plant Part	CF_1 Plant/Water*	CF_2 Plant/Soil**	$\frac{CF_1}{CF_2}$	CF in nutrient solution
Roots	63	0.572	110	225
Leafy shoots	111	0.052	2,135	55
Panicle minus grains	70	0.019	3,684	-
Hull	45	0.010	4,500	94
Caryopsis	20	0.005	4,000	32

* $\frac{\text{Activity lg dry matter}}{\text{Activity of lcc irrigation water}}$ ** $\frac{\text{Activity lg dry matter}}{\text{Activity of lg dry soil}}$

APPENDIX A

Approximate locations of sampling points:

Station	Area	Map Series	Map Reference
NQ1	2 miles S of Nabarlek - billabong west of Cooper Ck.	-	-
NQ2	West branch Cooper Ck	QM Annual Report	12.5 cm (X) 7 cm (Y)
NQ3	" " " "	"	9 x 3.3
NQ4	" " " "	"	3.5 x 0
NQ5	Cooper Ck billabong due N of Nimbuwah	-	GS 821001
NQ6	Unnamed tributary of Cooper Ck	SD53-1	68/43.5
R1	Corndorl	R621/1	70/03
R2	Georgetown	"	75/97
R3	Unnamed	"	69/00
R4	Numerous waterholes	"	67/99
R5	Unnamed	"	66/03
R6	E branch Magela Ck - billabong	-	133°/12°40'
R7	- creek		"
R8		R621/1	82/92
R9	W branch Magela Ck		133°/12°47'
R10	" " " "		133°/12°49'
KN1	Nourlangi billabong	R621/11	59/77
KN2	" "	"	60/76
KN3	" "	"	61/77
KN4	Sawcut Ck	"	75/72
KN5		"	73/73
KN6		"	71/74
KN7	Swamp anomaly	"	71/78

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ENVIRONMENTAL AND RADIOLOGICAL SAFETY ASPECTS OF THE MINING AND PROCESSING OF URANIUM

LUCAS HEIGHTS, 9 – 10 DECEMBER 1971

PAPER V

METHODS OF CONTROL OF POTENTIAL POLLUTANTS

(A SUMMARY)

by

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1. INTRODUCTION

The potential sources of pollution in uranium mining and processing activities have been discussed by Dr. R.K. Warner. The most important potential sources of pollution to waterways, fauna and flora are the mine waters, heaps of overburden and marginal ore, stockpiles, tailings areas, and the large volumes of raffinates. These sources can contain concentrations of uranium ranging from ppm (mine-waters, overburden) to 5-20 lb/t (stockpiles), together with radium, thorium, other heavy metals, and sulphates, etc. The raffinates may also contain organic materials, e.g. amines, which even in trace amounts are highly toxic to fauna.

The leaching of heaps of material, and the breaching of dams, may be serious problems in the Northern Territory in which there is a monsoon season, and a far higher rainfall than in the uranium mining and milling areas in North America and several other countries, e.g. 65 inches instead of < 10 inches.

Methods of control are briefly examined under two main headings in Tables 1 and 2.

TABLE 1

INITIAL DESIGN, ENGINEERING AND MINE MANAGEMENT

. Aim for total containment of solids and closely-regulated release of liquid and gaseous effluents.
. Selection of sites for tailings dams and ponds.
. Design and management of overburden and bogum heaps for controlled leaching to enable uranium and/or heavy metals to be recovered profitably and pollution minimised, e.g. sealed base pads, collection of run-off.
. Design and management of stockpiles to prevent leaching and minimise loss and pollution, e.g. sealed tops and possible pads.
. Dust control in crushing, grinding and packaging.
. Surface stabilisation of tailing dams and old ponds with neutral materials and vegetation.
. Design and management of monitoring procedures.
. Restriction of access to tailings ponds and ore storage areas.

TABLE 2

FLOWSHEET DESIGN AND MANAGEMENT OF CHEMICAL OPERATIONS

- Selection of acid or alkaline leaching circuit
- Selection of ion-exchange or solvent-extraction.
- Maximum recycle of process wastes.
- Utilisation of mine-waters for washing and dilution.
- Limitation of solvent losses in soluble and entrained forms.
- Neutralisation of acid effluents and decontamination before settling in ponds.
- Efficient scrubbing of gaseous effluent and dusts.

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PAPER VI

INTRODUCTION TO RADIOLOGICAL SAFETY

by

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1. IONISATION

If one or more of the orbital electrons of a neutral atom are forcibly removed from their orbits, whilst the nucleus is unaffected, the resultant atom is no longer electrically neutral but has a net positive electric charge the size of which depends on the number of electrons lost. The resultant charged atom is called an ion, and in this particular instance it is a positive ion. The free electron and the positively charged atom are known as an ion pair. The orbital electrons which have been removed may remain free for a period of time, but will usually attach themselves to other atoms forming atoms with extra orbital electrons. In this case the resultant atoms are negative ions. Ionisation is thus defined as the result of a process whereby an electrically neutral atom acquires either a positive or negative net charge. The radiations given off when radioactive atoms disintegrate are capable of interacting with the atoms of materials through which they pass and in doing so they produce ionisation in the material.

2. RADIOACTIVITY

Certain combinations of neutrons and protons in nuclei of atoms are stable and other combinations are unstable. An unstable nucleus attempts to achieve stability by changing its ratio of neutrons and protons by means of spontaneous disintegration or decay (i.e. is radioactive).

The three main types of radiation given off by the disintegration of radioactive atoms are alpha particles, beta particles and gamma rays. The energies of these ionising radiations are usually expressed in units of millions of electron volts (MeV). (One electron volt (eV) is the energy acquired by an electron after being accelerated through a potential difference of one volt.)

Alpha (α) particles are identical with helium nuclei (having two protons, each carrying a unit positive charge, and two neutrons) and are usually emitted by heavy radioactive atoms, such as uranium and radium. Their initial speed of emission from the nucleus of a disintegrating radioactive atom is of the order of 10,000 miles per second, but they quickly dissipate their energy by colliding with the atoms of the material through which they travel causing ionisation to take place. Their specific ionisation in air ranges from 10,000 to 70,000 ion pairs per cm and over its complete path length an energetic alpha particle produces about 250,000

ion pairs. An alpha particle has a range of a few cm in air and about 50 microns in soft tissue. Most naturally occurring alpha particles are not able to penetrate the outer layer of human skin.

Beta (β) particles are high speed electrons ejected from the nuclei of radioactive atoms when a neutron is converted into a proton in the nucleus. The maximum speed of emission of a beta particle may be very nearly equal to the velocity of light (186,000 miles per second). A beta particle has a greater penetrating ability than an alpha particle of the same energy, but will be stopped by a few millimetres of aluminium, a centimetre or so of human tissue or a few metres of air. The specific ionisation in air of beta particles ranges from 60 to 7,000 ion pairs per cm.

Gamma (γ) rays are electromagnetic radiations originating from the nucleus, similar to energetic X-rays. They travel at the speed of light, have a high penetrating power and can travel through several hundred metres of air or many centimetres of dense materials such as rock or lead in which they are absorbed exponentially.

3. RADIOACTIVE DECAY PHENOMENA

Each radioactive nuclide has its own unique characteristic pattern of disintegration and the 'vital statistics' of decay are:

- type of ionising radiation(s) emitted;
- energy of emitted radiation(s);
- rate of decay (typified by the radioactive half-life or the disintegration constant).

All nuclei of a given nuclide seeking stability by radioactive decay do so in a specific manner. Thus radon-220 decays by emitting an alpha particle which may be accompanied by a gamma photon; this is the only mode of decay available to a radon-220 nucleus. Other radioactive nuclides may decay with branching and then a choice of decay modes exists.

The disintegrations of radionuclides are spontaneous and random but occur with a regularity characteristic of each particular species. Thus a given radium-226 nucleus may disintegrate immediately or wait some years before emitting an alpha particle; the only certain prediction that may be made is that half of all the radium-226 nuclei present in a sample will disintegrate within a period of 1620 years. This period of time is called the radioactive half-life of radium-226.

In some cases a given species of radionuclide decays directly to a stable nuclide (e.g. radioactive phosphorus-32 decays by beta emission to stable sulphur-32. In other cases decay yields a daughter which is radioactive giving rise to a radioactive family or series (e.g. the uranium series starting with uranium-238 and ending ultimately with stable lead-206). In such a series, alpha emission decreases the atomic number by two and beta emission increases the atomic number by one. The paper 'Engineers guide to the elementary behaviour of radon daughters' (Evans 1969), gives some detailed information for radioactive decay of single radionuclides and radioactive families.

Table 1 gives details of half-lives, types of radiation and energies for each nuclide in the uranium (4n + 2) series (US Department of Health, Education and Welfare 1970).

4. THE HAZARDS OF IONISING RADIATIONS

Ionising radiations may be harmful if excessive amounts are received by living organisms. Since none of the human senses will give warning of the presence of ionising radiations it is necessary to detect them by devices which measure the ionisation they produce. Such devices include geiger counters, ionisation chambers, scintillation counters, photographic films, thermoluminescent dosemeters etc.

When ionising radiation strikes the human body it will penetrate to a depth which depends on the type and energy of the radiation. Inside the body, part or all of the incident radiation will be absorbed, producing ionisation and excitation of atoms and molecules. The living cells of which the body is composed will be affected when energy arising from the resulting ionisation caused by the radiation, is absorbed in the complex structure of the cells. Molecular ions will be produced which can interfere with the natural chemical reactions in the cells and may give rise to harmful biological effects. Within certain limits the damage thus caused may be repaired by the body so that there is no apparent effect, but if excessive amounts of radiation are received, then some harm may result.

Ionising radiation can cause two main biological effects which are known as somatic effects and genetic effects. Somatic effects may be simply described as those effects which give rise to injuries to the cells concerned with maintenance of body functions of the individual

who receives the ionising radiation, e.g. cells in the blood and bone marrow. Genetic effects may be described as those effects which give rise to damage in the sex cells which transmit hereditary characteristics to the unborn children of the individual who receives the ionising radiation. Ionising radiations can give rise to either external or internal radiation exposure according to whether the source of the radiation is inside or outside the body of the person receiving the radiation.

5. RADIOLOGICAL UNITS

The amount or quantity of ionising radiation to which a person, or sample of material, is exposed is designated the radiation exposure. The consequence of this exposure is designated the radiation dose. The consequence may be defined in various ways e.g. in physical terms such as the energy absorption per unit mass of irradiated material or in biological terms such as the risk of adverse effect to the health of a person exposed to the radiation.

If the type, number, energy and direction of the ionising particles or photons are known, then the radiation exposure may be specified exactly, but it will give no direct indication of the resultant radiation dose. As electromagnetic radiation (X- or gamma rays) passes through air the interactions which take place produce electrons, which then lose energy by creating ion pairs. The exposure is measured by collecting these ion pairs, thus the exposure concept is based on the ability of photons to produce ionisation. The unit of exposure is the roentgen, one definition of which is as follows:

> "One roentgen is an exposure of X- or gamma radiation such that the associated corpuscular emission per 0.001293 grams of air (1 cm^3 of air at NTP) produces, in air, ions carrying 1 esu of quantity of electricity of either sign."

The 'associated corpuscular emission' refers to the secondary electrons (and positrons, if present) produced by the electromagnetic radiation. The phrase "ions carrying one esu of quantity of electricity of either sign" corresponds to the production of 2.08×10^9 ion pairs.

An exposure of one roentgen is equivalent to an energy absorption by air of 87.7 ergs per gram and by soft tissue of 98 ergs per gram.

Radiation damage by ionising radiation in tissue depends on the absorption of energy from the radiation and is proportional to the concentration of absorbed energy. Hence the unit of absorbed dose is expressed in terms of energy absorbed per unit mass of irradiated material. The unit of absorbed dose is the rad and is equal to an energy adsorption of 100 ergs per gram. The rad is applicable to all types of ionising radiation and any type of matter.

For equal absorbed doses of different types of ionising radiation the resultant biological effects may vary. Thus for radiological protection purposes there is need for a quantity that expresses, on a common scale for all ionising radiations, the radiation dose equivalent incurred by exposed persons (i.e. the biological effect of radiation in tissue does not depend solely on the average amount of energy absorbed per gram of tissue but must also take account of how this energy absorption is distributed throughout the tissue). The absorbed dose (in rads) is therefore multiplied by an appropriate factor (quality factor) to obtain a quantity (dose equivalent) which is more truly indicative of the biological effect.

Values currently used for the quality factor (QF) are:

. X-rays	1
. thermal neutrons	3
. naturally occurring alpha particles	10
. fast neutrons and protons up to 10 MeV	10
. heavy recoil nuclei	20

The dose equivalent (the unit of which is the rem) is defined as the product of absorbed dose, quality factor and any other necessary modifying factors (e.g. a distribution factor to take account of non-uniform distribution of internally deposited radionuclides). Thus:

dose equivalent (rems) = absorbed dose (rads) x QF.

6. DOSE LIMITS

The objectives of radiation protection are to prevent acute radiation effects and to limit the risks of late effects to an acceptable level. (Acute effects usually manifest themselves within a few weeks after the exposure whilst late effects may have a latent period of tens of years.)

Maximum permissible levels of exposure to ionising radiations and radioactive materials are stated in the recommendations of the International Commission on Radiological Protection (ICRP 1966). This international body which was established in 1928 has continually revised its recommendations which are published in a series of volumes published by Pergamon Press; they are intended to limit somatic effects in individuals and hereditary effects in the population as a whole. The ICRP thus now considers two categories of individuals (see Table 2):

i) adults exposed in the course of their work;
ii) members of the public.

The ICRP uses the term 'maximum permissible dose' for the exposure of workers under controlled conditions and uses the term 'dose limit' for the corresponding figures for members of the public. The term 'dose limit' is also used in the general sense of recommended limiting figures for either workers or members of the general public.

Since exposure to ionising radiations may involve some degree of risk, the ICRP recommends that any unnecessary exposure be avoided, and that all doses be kept as low as is readily achievable, economic and social conditions being taken into account.

The basic dose limits for individuals are shown in Table 2 (after ICRP 1966) and it will be seen that the annual dose limits for members of the public are one-tenth of the corresponding annual occupational maximum permissible dose.

In any organ or tissue the dose equivalent is the sum of the dose equivalents contributed by both external and internal radiation sources.

In conditions of occupational exposure to radiation, where the maximum permissible dose for whole body irradiation is 5 rem per year, it is often administratively convenient to exercise control of exposure by keeping average dose equivalent rates at levels less than 100 millirem per week or 2.5 millirem per hour.

7. PROTECTIVE MEASURES

Harmful effects arising from exposure to ionising radiations and radioactive materials will be minimised if:

- exposure to external ionising radiation is kept within recommended dose limits;
- intake of radioactive materials into the body is minimised.

Control methods for reducing external radiation exposure are usually quoted as:

- time (i.e. reducing the time of exposure to the minimum possible);
- distance (i.e. invoking inverse square law reduction of radiation);
- shielding (i.e. using appropriate attenuating media).

Uranium miners are exposed to external beta and gamma radiations mainly originating from ore bodies; dose rates in close proximity to high grade pitchblende ores could be expected to range up to about 25 mR/h. Gamma radiation constitutes a source of whole body irradiation and beta radiation constitutes a source of skin irradiation. The only one of the external radiation controls which can be invoked in a mine is time control (e.g. rotation of workers between areas of high and low exposures).

The USA recommended frequency for instrumental gamma radiation surveys in mine working areas, according to the calculated exposure of the workers as a percentage of maximum permissible dose (m.p.d.), is as follows:

Calculated exposure	Survey frequency
< 50% m.p.d.	annually
50-75% m.p.d.	semi-annually
> 75% m.p.d.	quarterly,

or whenever there is a significant increase in the size or quality of the ore body being mined.

External radiation hazards in uranium processing plants may be expected to be generally low so that workers would receive only a fraction of an annual permissible dose of 5 rem. In principle all three methods of control of external radiation could be invoked in such plants should such control be necessary.

An internal radiation hazard exists whenever radioactive materials are taken into the body and this may occur by:

- inhalation (i.e. breathing air contaminated with radioactive materials);
- ingestion (i.e. swallowing radioactive materials);
- entry of contaminated particles or dust into an open cut or abrasion of the skin.

The inhalation route is of most importance in the mining environment since radon (^{222}Rn) the gaseous daughter product of radium (^{226}Ra) in the uranium-238 series will diffuse from ore bodies into the mine atmosphere. When the radium-226 atom disintegrates it yields an alpha particle and a radon atom; the radon atom expends its kinetic energy of recoil ($\simeq 10^5$eV) along a track length of about 3×10^{-6} cm in mineral rock (or 8×10^{-3} cm in air). The atom may then diffuse until it disintegrates or escapes from a mineral grain. The immediate daughters of radon which are particulate, all have short half-lives and will grow rapidly in an atmosphere containing radon. They rapidly attach themselves to dust particles, condensation nuclei or surfaces. A large proportion of the dust particles in mine atmospheres are sub-micron in size and thus most of the radon daughters generated in the atmosphere are respirable. The mass of one curie of radon-222 is extremely small (approx. 6.5 micrograms) and although radon has a low solubility in water, significant radon activities may be carried in mine waters to seep into mine cavities and constitute an additional source of radon.

The main contribution of dose to uranium miners' lungs arises mainly from the alpha particles emitted from RaA and RaC^1 during decay of the radon daughter products, which are filtered out of respired air by the lung; the contribution of alpha particle dose from gaseous radon in the tidal air is small. The beta particles and gamma rays emitted from RaB and RaC give a negligible contribution to the lung dose.

The working level (WL) used in the USA and Canada as a unit of radon decay-product concentration may be defined as any combination of the short-lived decay products of radon (RaA, RaB, RaC and RaC^1) in one litre of air which will result in the ultimate emission by them of 1.3×10^5 MeV of alpha particle energy. This value is derived by summing the alpha particle

energy ultimately delivered by the decay through RaC^1 of the short-lived decay products which are in radioactive equilibrium with 100 pCi of radon (i.e. 100 pCi each of RaA, RaB, RaC and RaC^1). The alpha energy associated with the decay of each atom of RaA is 6.00 MeV from its own disintegration, together with 7.68 MeV as its subsequent daughter RaC^1 disintegrates (i.e. a total of 13.68 MeV). Each atom of RaB and RaC initially present involves an alpha energy contribution of 7.68 MeV as their subsequent daughter RaC^1 disintegrates; each initial atom of RaC^1 also gives an alpha energy of 7.68 MeV.

The relevant data used in deriving the WL are given in Table 3.

The main control measure against the hazard of radon and its daughters is to supply uncontaminated air to mine working areas (i.e. appropriate ventilation). Respirators should be regarded only as an adjunct to sound engineering control measures and should be used only in short term, unusual or emergency conditions. Filter type respirators are ineffective in removing gaseous radon from inspired air; efficient, low impedance filters might be expected to give 5-100 fold reduction in radon daughters.

Contaminated surfaces (e.g. skin, clothing) may constitute a potential source of uranium for ingestion. Figures suggested in Australia for control of surface alpha contamination are:

Type of surface	Maximum permissible level
skin	10^{-5} $\mu Ci/cm^2$
clothing	10^{-4} $\mu Ci/cm^2$

Extensive loose contamination on surfaces may constitute a source of uranic material for redispersion into the atmosphere. The resuspension factor K gives the relationship between airborne concentration and averaged level of ground contamination in the area

$$\text{i.e.} \qquad K = \frac{\text{airborne concentration (units/m}^3\text{)}}{\text{contamination level (units/m}^3\text{)}}$$

For natural uranium (as U_3O_8 from combustion of metal) the above value of K is of the order of 10^{-7} (i.e. a surface contamination level of 1 $\mu Ci/cm^2$, due to dispersion, could give rise to an airborne concentration of 10^{-7} $\mu Ci/cm^3$).

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TABLE 1

URANIUM SERIES (4n + 2)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{238}_{92}U$	Uranium I	4.51×10^{9}y	4.15 (25%) 4.20 (75%)	---	---
$^{234}_{90}Th$	Uranium X_1	24.1d	---	0.103 (21%) 0.193 (79%)	0.063c‡ (3.5%) 0.093c (4%)
$^{234}_{91}Pa^{m}$	Uranium X_2	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
99.87% / 0.13%					
$^{234}_{91}Pa$	Uranium Z	6.75h	---	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (70%)
$^{234}_{92}U$	Uranium II	2.47×10^{5}y	4.72 (28%) 4.77 (72%)	---	0.053 (0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^{4}y	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}Ra$	Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
$^{218}_{84}Po$	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
99.98% / 0.02%					
$^{214}_{82}Pb$	Radium B	26.8m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{218}_{85}At$	Astatine	~2s	6.65 (6%) 6.70 (94%)	? (~0.1%)	---
$^{214}_{83}Bi$	Radium C	19.7m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
99.98% / 0.02%					
$^{214}_{84}Po$	Radium C'	164μs	7.69 (100%)	---	0.799 (0.014%)
$^{210}_{81}Tl$	Radium C''	1.3m	---	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{210}_{82}Pb$	Radium D	21y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{210}_{83}Bi$	Radium E	5.01d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
~100% / .00013%					
$^{210}_{84}Po$	Radium F	138.4d	5.305 (100%)	---	0.803 (0.0011%)
$^{206}_{81}Tl$	Radium E''	4.19m	---	1.571 (100%)	---
$^{206}_{82}Pb$	Radium G	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{206}_{82}Pb$ (4n + 2).....4(51) + 2 = 206

†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.

‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and USNRDL-TR-802.

TABLE 2

BASIC DOSE LIMITS FOR INDIVIDUALS

(From ICRP 1966)

Organ or tissue	Maximum permissible doses for adults exposed in the course of their work	Dose limits for members of the public
Gonads, red bone-marrow (whole body, uniformly irradiated)	3 rems in a quarter 5 rems in a year or if necessary, 5(N-18) rems to date (N is age in years)	0.5 rem in a year
Skin, bone	15 rems in a quarter 30 rems in a year	3 rems in a year
Thyroid	15 rems in a quarter 30 rems in a year	3 rems in a year except for children under 16 years for whom 1.5 rems in a year
Hands and forearms; feet and ankles	40 rems in a quarter (strictly 38 rems) 75 rems in a year	7.5 rems in a year
Other single organs	8 rems in a quarter 15 rems in a year	1.5 rems in a year

Note: These values are modified in a number of cases, e.g. for women, for special or abnormal exposures, for young persons and for persons previously exposed under other dose limits.

TABLE 3

THE RELEVANT DATA USED TO DERIVE THE WL

Nuclide	α Energy (MeV)	Half Life	No. atoms in 100 pCi	Ultimate α energy/atom	Total ultimate α energy (MeV/100 pCi)
RaA	6.00	3.05m	977	6.00 + 7.68	0.134×10^5
RaB	0	26.8 m	8580	7.68	0.659×10^5
RaC	0	19.7 m	6310	7.68	0.485×10^5
RaC[1]	7.68	10^{-6} m	0.0008	7.68	0.000×10^5
				Total	1.278×10^5
				Round up to	1.3×10^5

AAEC SYMPOSIUM

on

ENVIRONMENTAL AND RADIOLOGICAL SAFETY ASPECTS

OF THE MINING AND PROCESSING OF URANIUM

LUCAS HEIGHTS, 9 – 10 DECEMBER 1971

PAPER VII

RADIOLOGICAL HEALTH AND SAFETY ASPECTS OF URANIUM MINING AND ORE TREATMENT A BIBLIOGRAPHY

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1. INTRODUCTION

This short bibliography is compiled under the following fourteen broad headings:

- environmental problems;
- external radiation measurement;
- general radiological health and safety aspects;
- historical aspects;
- internal contamination hazards;
- internal contamination measurement;
- internal contamination protection;
- medical aspects;
- monitoring programmes;
- radioactivity fundamentals;
- radiological exposure limits;
- standards and regulations;
- ventilation;
- waste management.

The items under each heading are arranged in alphabetical author order.

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AAEC SYMPOSIUM

on

ENVIRONMENTAL AND RADIOLOGICAL SAFETY ASPECTS OF THE MINING AND PROCESSING OF URANIUM

LUCAS HEIGHTS, 9 – 10 DECEMBER 1971

PAPER VIII

BIOLOGICAL EFFECTS OF RADIATION

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1. INTRODUCTION

The potential hazards of radiation often have an undue prominence in people's minds. This may arise from the intangible nature of ionising radiation, from fear or guilt over the use of nuclear weapons, the indestructibility of radioisotopes, or because the consequences of exposure may be visited on later generations. Whatever the reason, the fear is irrational; the biological effects of radiation do not differ essentially from those of other agents.

There is a continually expanding list of purely chemical agents which, applied to individuals or loose in the environment, produce the same unpleasant consequences of cancer or genetic damage as does radiation. Other agents are used to kill cells acutely, just as the radiotherapist uses radiation.

What is different about radiation hazards is that they have been studied more exhaustively than any other and we are in a better position to predict possible effects. If we are to go ahead with the introduction of nuclear power, we have to look at these things rationally and assess risks in their proper perspective in relation to benefits.

2. THE NATURE OF RADIATION INJURY

In chemical terms biological material is immensely complex and its make-up is far from understood. Since even the radiolysis of water is thought a difficult subject by radiation chemists, it is obviously hard to identify precisely what ionising radiation does to a biological cell, but there are some things we can say.

Biological radiation injury is essentially cellular; we can disregard effects on extracellular fluids or structures. Since the energy of ionising radiation is deposited randomly in packets averaging much larger than is necessary to break any organic chemical bond, in principle any biological structure or function can be injured. In practice, the amounts of energy needed to inactivate the dividing cells of higher organisms are so small (of the order 10^{-3} cal/g) that we cannot hope to identify primary chemical effects. Because fatal doses to cells are so small, an explanation has to found by implicating some cellular structure which is unique and irreplaceable if damaged, or whose injury leads to an automatically propagated reaction of some kind. Such chain reactions are not seen, and the most plausible site for radiation injury in the cell is the deoxyribonucleic

acid (DNA) in its chromosomes, which carries the genetic code or basic blueprint. Most current thinking on radiation effects is based on injury to DNA; it is fairly plausible for delayed effects, but less so for acute injury.

3. PRINCIPAL BIOLOGICAL EFFECTS OF RADIATION

These are simply categorised as acute or short term effects, delayed somatic effects, and genetic effects.

Short-term effects

By this we mean consequences which appear at intervals after a radiation exposure which vary from minutes to a few weeks depending on dose and dose rate. At the cellular level, they usually mean cell death, the effect which radiotherapists use in treating cancer; at the whole-body level, they vary from trifling illness to death. Accidents producing such effects are so uncommon we need not consider them further here.

Delayed somatic effects

These are effects which appear months or years after exposure and are of several kinds. Two, of relatively minor importance, which may be mentioned are cataract (opacity of the eye lens), which can be a sequel of moderate exposures, and premature aging which can be demonstrated in laboratory animals after whole-body exposure but is of doubtful significance in man exposed at occupational levels.

The most important delayed somatic effect is the induction of malignant disease, that is, cancer, sarcoma or leukaemia. By 'somatic' is meant an effect on cells other than germ cells. Cancers of various kinds are readily produced in experimental animals by single large or repeated small doses of radiation but, since the genetically pure strains of mice generally used in these experiments vary greatly in their responsiveness, it is not possible to extrapolate directly to man from the laboratory experiments. However, there is no reason to doubt that radiation exposure can induce most or all types of human cancer. Different organs appear to vary in susceptibility and there are variations in the latent period required after exposure for disease to develop. What is most in doubt, unfortunately, is the precise form of the dose-response relationship at low doses and low dose rates. We have fairly good evidence on the incidence of leukaemia, the most likely consequence of whole-body over-exposure, at doses of 100 rads and above given quickly, but only meagre evidence for low doses and dose rates. This is of course precisely where we most want information for setting occupational and environmental limits.

Genetic effects

The effects of induced mutations are not seen in the recipient of a radiation exposure but in his offspring or in subsequent generations. There is no means of recognising the primary radiation injury. As with the induction of cancer we have built up a fairly extensive knowledge of the dose-response relationship for laboratory species, but we cannot extrapolate it directly to man. For instance, there undoubtedly are some dose-rate effects in the radiation induction of mutations in mammals, but we cannot apply this knowledge in defining exposure limits. Although genes may vary in radiosensitivity, probably all are subject to radiation-induced mutation. It can be taken as dogma that induced mutation will be harmful rather than beneficial.

4. IMPLICATIONS FOR RADIATION PROTECTION

The appropriate advisory bodies of most countries, including Australia, have suggested that legislators endorse (except in minor detail) the recommendations of the International Commission on Radiological Protection with respect to radiation exposure limits for those occupationally at risk and for members of the public. Environmental limits can be derived from the dose limits for the public.

The ICRP makes the conservative assumption that any exposure to radiation, however small the dose or low the dose-rate, carries some risk for the development of malignant disease or of genetic effects. That is, there is no wholly safe dose of radiation and the policy of assuming some risk at low doses is the most reasonable basis for radiation protection. In the face of the uncertainty of the form of dose-response relationships at low doses, the ICRP assumes that effect is proportional to dose, right down to the lowest levels and irrespective of dose rate. This may of course lead to an overestimate of the incidence of effects from continued low-level exposure, but it is the only approach which can reasonably be adopted in our present state of knowledge. It is implicit in this thinking that some level of risk is an acceptable one in relation to the benefits which derive from the activities producing it.

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Many popular and semi-popular books have covered this field in recent years but there is no comprehensive and acceptable treatise. The book listed below is selected because it is short, cheap, affords an adequate introduction to the subject, and has a substantial bibliography of its own.

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PAPER IX

HISTORY OF RADIATION EFFECTS AND CONTROL IN URANIUM MINING

by

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1. RADIATION-INDUCED LUNG CANCER IN MINERS

The mines in the Schneeberg-Jachymov areas of the Erz mountains, on either side of what is now the border between East Germany and Czechoslovakia, have been mined for many different metals since about 1400 A.D. From the fifteenth century onwards it was known that miners in these areas were prone to suffer and die from mysterious lung disease, known simply as 'mountain sickness'. This disease was not seriously investigated until 1879, when investigators on the German side of the border showed that many of the deaths were due to lung cancer. The proportion attributable to cancer lay between 50 and 75%. At that time the cause of the disease was not known, and it was attributed to various components of the ores, notably arsenic and cobalt. The incidence of lung cancer was about 50 times that found in men of Vienna, a city with good health records.

In the early 1920's it was suggested that the cause of the lung cancer in these miners was the presence of radon in the mine atmospheres, by then known to be present in relatively high concentrations in some of the mines. Observations and experiments over the next 20 years, on both sides of the border, caused this concept to be generally accepted by about 1940. It is now clear that the hazard concerned was lung cancer and its radiogenic origin is clearly established. However, some additional points should be kept in mind:

- Mine atmospheres may contain certain other carcinogens in the form of metallic dusts.
- Radon may present a hazard in mines other than uranium mines, e.g. the Newfoundland fluorspar mines and perhaps some British haematite mines.
- Almost any sort of mine may possess a silica hazard; silica is not (under ordinary circumstances) a carcinogen but is a common cause of morbidity.

2. THE IMPORTANCE OF RADON DAUGHTERS

The principal radiation dose to the lungs of miners is attributable to α-radiation from the short-lived radon daughters to ^{214}Po, whose half-lives are short in relation to any possible mode of elimination from the lung. External β- and γ-irradiation will not often be significant.

3. ALLOWABLE ATMOSPHERIC CONCENTRATIONS OF ALPHA-EMITTERS

The setting of a maximum allowable concentration of radon or radon daughters needs to be based on human experience, since models for dosimetry

The dose limit for occupational whole body irradiation is 5 rem per year, recommended by the International Commission on Radiological Protection (ICRP 1966) and generally accepted by responsible authorities. Canadian experience with ore up to 2 per cent U_3O_8 showed exposure rates up to 10 milliroentgens per hour, at 3 feet from mine surfaces, and, with no particular attention to controlling external radiation exposure, all weekly doses were less than 100 millirem and over half less than 50 millirem, i.e. annual doses probably averaging around 2 rem.

3. EXPOSURE TO URANIUM

Inhaled uranium is partly retained in the lungs, and partly excreted via the gut. From the lungs some may be transferred to the blood and thence partly retained in various body organs, and partly excreted via the kidneys. The uptake of uranium from the gut is small. Consequently, inhalation rather than ingestion is generally the more significant exposure route. The ICRP has derived daily intakes by inhalation and ingestion using available metabolic information, such that resultant annual doses to the critical organs (lungs, kidneys) do not exceed the appropriate dose limits. From the daily intakes and further data on breathing rates, and conservative assumptions on particle sizes for airborne material, and on water intake for ingested material, the ICRP has derived maximum permissible concentrations in air and water.

Uranium is also chemically toxic, affecting kidney function. The maximum permissible daily intake of soluble uranium based on toxicity considerations is the same as that derived on radiological grounds.

Internal uranium burdens can be assessed by measuring urinary excretion. Such measurements show levels for uranium miners significantly below those corresponding to the ICRP maximum permissible intakes and generally so for process operators. No adverse effects on health in miners, or other workers, attributable to uranium dust intake have been reported.

4. EXPOSURE TO RADON WITH ITS DAUGHTER PRODUCTS

Radon, being an inert gas, diffuses out of uranium ore into the surrounding air, giving rise, under conditions of poor ventilation, to air levels greatly exceeding those which would be achieved simply by disturbing the ore. It also goes readily into solution in water and may be transported in such cases considerable distances from its source.

Table 1 lists the decay products of radon.

of Labour in 1967 issued an order limiting exposure of uranium miners to 3.6 'working level months' (WLM) per annum. This figure was amended to 12 WLM's a month later. Definition of the standard in the U.S. is now the responsibility of the Environmental Protection Agency, and it has finally adopted a figure of 4 WLM/year from July 1971. It is unclear how far this has been implemented.

The actual situation in American mines can be summarised as follows. Up to about 1950, mines had only natural draft; median radon levels were about 2500 pCi/ℓ in Colorado and 5000 pCi/ℓ in Utah. From 1951 mining companies were given advice and help on health hazards and the working level concept evolved. In 1952, 44% of mines had radon levels above 10 WL's and 10% above 50. By 1957, the proportion above 10 WL's was down to 23%. The most recent figures (1970) indicate that 60% of mines exceed 0.3 WL's, and 30% exceed 1 WL, the figures corresponding to 4 and 12 WLM respectively.

4. LUNG CANCER IN AMERICAN URANIUM MINERS

There has been a well-documented increase in the incidence of lung cancer among American uranium miners, and this appeared in spite of the fact that the relation between radioactivity and lung cancer in miners was well-known from the European example. In recent years very careful studies have been published on the health of some 3,500 American uranium miners. Lung cancer cases found were 62, as against the 10 expected in a comparable non-mining population. The increase is now significant at all exposure categories including that of 0-120 cumulative WLM. Although the significance of results in the lowest categories has been questioned, and there is a possibility in some cases of some radon exposure in mines other than uranium, it is clear that there is no justification for any standard less rigorous than that recommended by the ICRP and in fact that figure may be too high.

Future practice should be determined by the results of current and future studies of the U.S. uranium mining population, and any other available human material, including non-uranium miners. It may be possible to improve or verify experimentally dosimetry models already proposed for the inhalation of radon daughters, but at present human experience appears to be the best guide.

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PAPER X

URANIUM MINING – THE NATURE OF THE DOSIMETRY PROBLEM

by

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1. INTRODUCTION

The assessment of radiological hazards in a particular operation requires identification of the various ways in which persons may be exposed to radiation, assessment of the magnitude of such exposures, prediction of the resultant doses and comparison of these doses with appropriate recommended dose limits. The magnitudes of the predicted doses relative to the appropriate dose limits give an indication of the magnitude of the radiological hazard. If the predicted doses are greater than the appropriate dose limits, it is necessary to introduce into the operation methods of reducing exposure. It is also necessary, once the operation begins, to check at intervals that actual exposures do not differ significantly from the previously assessed levels and, where they do, to modify control procedures.

In uranium mining and milling a number of exposure routes are present, each of which may require its own particular assessment and control procedure. The major exposure routes are as follows:

- Exposure to external gamma radiation emitted by decay products of natural uranium, chiefly the daughter products of radium.
- Exposure to uranium and decay products in mine dusts and to extracted uranium dusts in processing operations.
- Exposure to radon and its decay products as a result of diffusion of the radon from the ore into the atmosphere.

Of these, exposure to radon has been found to be the major hazard in underground mining. Experience with each of the above exposure routes will be considered briefly and attention given in particular to the problems that have arisen in the dosimetry of radon exposures and the derivation of appropriate dose limits.

2. EXTERNAL GAMMA RADIATION EXPOSURE

Gamma radiation readily penetrates body tissue and thus the gamma radiation fields associated with uranium ores give rise to reasonably uniform irradiation of miners and the resultant whole body doses are taken to be directly proportional to exposure. Exposure to gamma radiation is measured in roentgens (R) and doses expressed in rads (absorbed dose) or rem (dose equivalent). A whole body exposure of 1 roentgen of gamma radiation is assumed to give a whole body dose of 1 rad or dose equivalent of 1 rem.

The dose limit for occupational whole body irradiation is 5 rem per year, recommended by the International Commission on Radiological Protection (ICRP 1966) and generally accepted by responsible authorities. Canadian experience with ore up to 2 per cent U_3O_8 showed exposure rates up to 10 milliroentgens per hour, at 3 feet from mine surfaces, and, with no particular attention to controlling external radiation exposure, all weekly doses were less than 100 millirem and over half less than 50 millirem, i.e. annual doses probably averaging around 2 rem.

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4. EXPOSURE TO RADON WITH ITS DAUGHTER PRODUCTS

Radon, being an inert gas, diffuses out of uranium ore into the surrounding air, giving rise, under conditions of poor ventilation, to air levels greatly exceeding those which would be achieved simply by disturbing the ore. It also goes readily into solution in water and may be transported in such cases considerable distances from its source.

Table 1 lists the decay products of radon.

TABLE 1

RADON AND DECAY PRODUCTS

Name	Isotope	Half-Life	Charged Particles Emitted			
			Alphas		Betas	
			Energy MeV	Range in Tissue	Energy	% per Disintegration
Rn	^{222}Rn	3.8 day	5.5	41	-	-
RaA	^{218}Po	3.05 min	6.0	47	-	-
RaB	^{214}Pb	26.8 min	-	-	0.65 0.71 0.98	50 40 6
RaC	^{214}Bi	19.7 min	-	-	1.00 1.51 3.26	23 40 19
RaC[1]	^{214}Po	164 μsec	7.7	71	-	-
RaD	^{210}Pb	21 year	-	-	0.016 0.061	85 15
RaF	^{210}Pb	138 day Stable	5.3	39	-	-

In a mine atmosphere, the products of interest are RaA, RaB, RaC and RaC^1. Because of the relatively long half-life of RaD (21 years) compared with removal rates by deposition and ventilation, there are normally only very small quantities of RaD and RaF present as a result of radon decay.

The radiological significance of inhaled radioactive material is generally assessed by estimating the subsequent distribution of the material retained in the body, calculating the dose rates in the organs of interest and comparing these with the ICRP annual dose limits. Normally dose rates are calculated by averaging the energy absorbed in the organ of interest over its total mass. In the case of inhalation of radon and its short-lived daughter products, the organ of interest is the lung, but because of the very non-uniform deposition of energy within the lung as a result of the very short range of alpha particles in tissue and the fact that most of the activity is deposited on the walls of the trachea and bronchi, the value of calculating the dose averaged over the whole lung is questionable. As experience has shown that the hazard from overexposure in uranium mines is lung cancer, originating in the bronchi, efforts have been made to estimate the dose to the walls of the bronchi and, using the ICRP's generalised annual dose limits, derive an MPC for radon and daughters. Table 2 shows estimates of the annual dose for occupational exposure at the US working level to those parts of the bronchial epithelium (the outer surface of the walls of the bronchi) most heavily exposed.

TABLE 2

ESTIMATES OF ANNUAL DOSE TO MOST HEAVILY EXPOSED PARTS OF THE BRONCHIAL EPITHELIUM FOR OCCUPATIONAL EXPOSURE AT THE US WORKING LEVEL

Authors	Annual Dose, Rads
Chamberlain and Dyson (1956)	5
Altshuler, Nelson and Kuschner (1964)	18
Haque and Collinson (1967)	100

The differences in these figures are a consequence of the differences in assumptions made by the various authors. Chamberlain and Dyson (1956) derived their figures solely from the deposition of unattached RaA. Altshuler, Nelson

and Kuschner (1964) also included the deposition of RaB and RaC, and of both unattached and particulate activity, as did Haque and Collinson (1967), but the latter authors used a larger fraction of unattached activity and different model for deposition in the lungs. The models used for calculating dose as a function of depth were also improved from one paper to the next.

The ICRP annual dose limit for the lung is 15 rem, and in the absence of specific information the ICRP assumes that 1 rad from alpha radiation (the radiation giving the dose to the bronchi) is equivalent to 10 rem. The ICRP (1959) recommendation of 3×10^{-8} $\mu Ci/cm^3$ for radon is based on the Chamberlain and Dyson figure above, since the annual dose at 30 per cent of the working level is 15 rem. Use of the more recent calculations above and the ICRP reasoning would suggest that the MPC should be reduced below 3×10^{-8} $\mu Ci/cm^3$. It is not at all clear, however, that it is appropriate to use the doses to the most heavily exposed parts of the bronchial epithelium rather than, say, the average dose, which would not be as restrictive.

The US collection of data on the medical histories of uranium miners related to their estimated exposure (Lundin et al. 1969) gives an overall risk of subsequently developing lung cancer of about 5×10^{-4} after a year's exposure at the working level. (This figure assumed a linear relationship between risk and exposure and 20 years as the period at risk.) It is of interest to note that a current estimate of the overall risk of subsequently developing cancer generally following a whole body dose of 5 rem (the ICRP's annual dose limit) is also 5×10^{-4} (Dolphin and Marley 1969). If we equate these two situations it may be argued that the present working level is appropriate if 5 rem per year whole body is appropriate. However, the whole body risk figure is derived from experience of the subsequent development of cancer following doses received over short or very short periods, and may well be an overestimate where doses are received at much lower dose rates as is generally the case for occupational exposure.

One further US observation of some relevance is that smokers are ten times more likely to develop radon-induced lung cancer than non-smokers, i.e. the risk for non-smokers is only about 0.5×10^{-4} for a year's exposure at the working level. It is not known, however, whether this lower risk holds if smokers refrain from smoking while mining or only for those who never smoke.

It is concluded that at present the calculation of lung doses and the application of current ICRP generalised dose limit concepts gives a less reliable guide to the choice of the maximum permissible concentrations of radon and its

short-lived daughter products than does accumulated experience of risks as a function of exposure.

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PAPER XI

PRACTICAL DOSIMETRY IN URANIUM MINING

by

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1. INTRODUCTION

The need for dosimetry measurements in the uranium extractive industry arises in four ways:

1. to meet legislated obligations under the appropriate State or Commonwealth Territory Radioactive Substances Act and allied uranium mining code,
2. to demonstrate the adequacy and reliability of plant equipment designed to reduce any potentially hazardous operations,
3. to demonstrate the adequacy of administrative control over prescribed procedures, and
4. to make administrative decisions on duty roster etc.

In essence, these needs are met by determining:

- External irradiation levels (whole body gamma and surface β/γ dose and dose-rates).
- Exposure due to inhalation (U, Ra particulate activity, levels of Rn and associated daughter products).
- Exposure due to ingestion (U, Ra in drinking water, local food supplies etc.).
- Surface contamination levels for α emitting contaminants.

Naturally the accuracy and thus the practicability of each of these determinations depends on the reason for the measurement.

Each type of measurement is now considered in turn, discussing the range in methods of detection and the associated accuracy.

2. EXTERNAL RADIATION

2.1 Whole Body Gamma Irradiation

2.1.1 Gamma surveys

Ore bodies, primary ore stock piles, stored yellow cake, and tailing dumps are essentially infinite with respect to the mean free path of gamma rays. The gamma spectrum from such systems therefore contains a large percentage of low energy photons and it is essential that the dose meters have a response that is reasonably independent ($\pm$ 20%) of photon energy. In the main, this means that the detector should be an ionisation chamber with an effective cut-off energy of ~ 50 keV. Suitable instruments of the type are readily available.

The frequency with which gamma surveys should be made will probably be covered by the appropriate legislation; it can be expected to range from quarterly (calculated exposure ~ 75% of allowable limit) to yearly (calculated exposure ~ 50% of allowable limit).

A guide to suggested procedures for the measurement of external radiation is given in American National Standards Institute (1960).

2.1.2 Personnel dosimetry

Personnel dosimetry of gamma rays in Australian facilities normally involves the use of film badge packs. However the high humidity and temperatures together with the rough handling to be expected in uranium mining, indicate that a more satisfactory solution might be the use of thermoluminescence dosemeters (the quantity of light given off from a heated quantity of activated lithium fluoride is proportional to the dose).

While it is not clear which authorities would be responsible for the personnel dosimetry service in order to meet legal requirements, most State legislation is sufficiently flexible for a private company to be made 'an approved laboratory' for the purpose.

2.2 Surface β Irradiation

Surface β dose rates from uranium ore and stocked yellow cake are generally not significant and would not be monitored routinely.

The better class of survey instruments used as γ monitors can, by removal of an end cap, provide an estimate of β + γ dose rate.

3. INHALATION

Radon daughters are normally of primary concern in uranium mines although other radioactive dusts are produced by mining operations. Radon emanates continuously from all ore bodies and needs to be routinely monitored.

3.1 Uranium/Radium

The distribution of a given amount of uranium ore in equilibrium with a body of air will involve equal amounts of activity of uranium-238 and its daughters e.g. radium-226. The maximum permissible concentration (mpc) values for both soluble and insoluble forms of uranium and radium vary little, one from the other. Thus air contaminated with uranium ore as a result of mining, grinding or crushing etc., will be equally hazardous with respect to uranium and radium and no attempt need be made to identify these activities separately.

Of course the radon daughter alpha activity must be allowed to decay before the long lived U and Ra activities are estimated from the particulates collected on a filter paper during an air sampling survey. A 24 hour decay period is more than ample for this.

3.2 Radon Daughters

The hazard associated with atmospheric levels of radon gas arises from the presence of the daughter products. This is shown in Table 1 where the daughter ratios shown as (1, ℓ, m, n) refer respectively to radon-222, polonium-218 (RaA), lead-214 (RaB) and polonium-214 (RaC^{-}). As discussed in a subsequent paper, the ratios of the various daughter products depend markedly on the origin of the radon, the age of the air mass (in terms of the half-life of radon-222), ventilation rate etc. Since the half-lives of the various daughter products are different, the α activity on a filter paper, obtained during air sampling, is a complex function of initial disequilibrium ratios, duration of sampling and subsequent decay period. These relationships are discussed in the paper by Evans (1969).

For practical dosimetry, a method must be found for relating the measured α activity on the filter paper back to an atmospheric concentration of radon daughters (i.e. to working levels (WL's)). Many methods have been reported.

3.2.1 The Kusnetz method

This was one of the earliest methods reported (US Public Health Service 1957) for converting gross α activity to WL and remains the most widely used.

A 5-10 minute air dust sample is collected at a constant flow rate on a suitable filter (5μ pore size membrane paper) and allowed to decay for 40 minutes. The α activity remaining on the paper over the next 50 minutes is counted and the average decay rate computed.

This value is converted to WL units by means of standard factors of theoretical origin.

In practice the uncertainties in this method are less than expected on theoretical grounds ($\sim \pm$ 10%) and it is now the most convenient method in use.

In some applications the α activity is simply measured with a countrate meter after 40 - 90 minute decay. This approach is not recommended since much accuracy is lost simply as a result of counting statistics.

With this method, as with all others that demand a knowledge of volume of air sampled, the rotameter or other flow measuring device needs frequent calibration checks.

3.2.2 The Tsivoglou method

In this method (Tsivoglou, Ayer and Holaday 1953) the decay curve is recorded over a 90 minute period from the end of air sampling. Effective half-lives at specified decay times are determined from this curve and a set of simultaneous equations is then solved to give specific concentrations for each of the radon daughters.

Because poor counting statistics normally apply in this method, any particular result is fairly unreliable and it is generally only used in computing average weekly values from 10 or more separate determinations.

3.2.3 The least squares regression analysis method

In this technique (Raabe and Wrenn 1969) full use is made of the counting statistics available from sequential counting. The calculation proceeds in three parts; first, the differential equations which describe the collection and the decay during collection of the daughters are solved; then the differential equations which describe the decay of the daughters on the sample after collection is complete are solved; and lastly, a weighted least-squares regression analysis is performed to fit the observations of counts during various counting periods to the general decay equation for the sample.

Computer facilities are needed for this approach but it is the only suitable method for dealing with an atmosphere containing significant and varying amounts of ^{222}Rn (radon) and ^{220}Rn (thoron).

3.2.4 The two-filter method

Strictly speaking, this is a method for measuring the concentration of radon gas (Thomas and Le Clare 1970). If used for determining WL values, severe over-estimation would result because of the need to assume complete equilibrium between the various daughter products.

However, if run in parallel with one of the above methods it allows an estimate of the degree of disequilibrium (the so-called WL ratio) and thereby provides guidance on how much more control could be effected by increasing ventilation rates.

Briefly, air to be assayed is drawn through two filters in series which are separated by a delay volume to permit radon decay. The first filter removes the radon daughters present in the air, while the radon concentration is calculated from the decay products (formed in the delay volume) caught on the downstream filter.

3.2.5 Personnel radon monitors

The methods described above are most useful for determining the radon hazard at particular locations. If the hazard is not easily controlled then some form of staff roster may be necessary and the use of personnel radon monitors becomes mandatory.

In practice, the change of emphasis for personnel dosimetry relates to the method of detecting the α activity on the filter paper. For station monitors, standard ZnS-photomultiplier scintillation probes are used. For personnel dosimeters, a more convenient method is to use track etch films. In this method suitably prepared 0.0007 cellulose nitrate films are placed close to the filter paper in the air sampling device. Any α particle of energy between limits that are characteristic of the film material, will, on striking the film, produce bulk damage. This 'latent image' can subsequently be 'developed' with caustic soda solution and then counted optically or with a spark counter.

With this method, a personnel dosimeter, battery, air pump, filter detector, can be built into a 4 inch x 1 inch cylinder weighing approximately 2 ounces. We have had little difficulty perfecting methods for manufacture of the film or with the operation of the spark counter. We have not attempted to build up the air sampler believing that commercial units will be available, at least from the USA.

Dosimeters of this class will be suitable for integrating the WL exposure to miners over periods of a week or more (Auxier et al. 1971).

3.3 Unattached RaA

As explained in Mr. Cook's paper, the significance of unattached RaA daughters has been questioned by the ICRP Task Group on Lung Dynamics. Nevertheless, the current ICRP recommendation specifically includes the percentage of unattached RaA in their derivation of mpc levels for radon gas. Unless the Mining Code deliberately supersedes these recommendations, the unattached RaA percentage will need to be measured, because the probably conservative value of 10%, as used by the ICRP, would otherwise have to be assumed.

There are two basic approaches for the measurement of unattached RaA. In the first (Chamberlain and Dyson 1956) the windpipe is simulated by a tube 15 cm long, 5.7 cm circumference, with a smooth paper insert. Air is drawn through the tube at 16 ℓ/min for about 5 minutes; the paper is removed and

the deposited α activity determined. It is assumed that only RaA is unattached and that plate-out effectively removes any unattached RaA that is present.

For the second method, much care is taken to design a diffusion battery for the complete removal of unattached products and the RaA component is determined by spectroscopically comparing two parallel sampling systems, one of which is preceded by the diffusion battery (Duggan and Howell 1969).

The first method will invariably produce the lower result but the question as to which is more correct depends solely on the rationalisation behind the recommendation on the significance of unattached RaA.

4. INGESTION HAZARD

The determination of any ingestion hazard would normally be the responsibility of the appropriate Health Department but the techniques involved would be no different to those that the mining companies would need in order to demonstrate compliance with criteria for effluent release. The determination of U, Cu, Pu, As, etc. involves well developed chemical methods and only the determination of radium-226 will be discussed here.

4.1 Radium-226 Determination

Radium-226 is determined by the emanation method. This procedure is capable of measuring with high accuracy quantities of radium-226 as low as 2.10^{-14}g; it discriminates against other radium isotopes, as well as all other radioactive elements which may be present.

Radium-226 is determined through its daughter, the noble gas radon-222. The daughter is purged from a solution of its parent with an inactive gas and collected on activated charcoal at -80°C. The charcoal is then heated and the radon transferred to a zinc sulphide coated counting vessel where after 3 hours during which radioactive equilibrium between radon and its daughters has been established it is counted by scintillation techniques.

4.1.1 Preparation of samples

All samples are taken into solution by various means or an acid extraction is carried out on them; they are then made up to 200-400 mℓ with distilled water, placed into a special flask, the residual radon is purged out with an inactive gas and the flask sealed for 1-30 days to allow the daughter radon-222 to establish equilibrium with its parent radium-226. The methods used to bring the samples into solution for radium-226 analysis by the emanation technique vary with the nature of the sample.

Water samples: Water samples are collected in polythene bottles and acidified with 4 mℓ concentrated HNO_3/ℓ . The samples are then filtered through a 0.47 μ filter and a separate analysis is carried out on the water and the suspended sediment. The suspended sediment is taken into solution by a nitric acid/perchloric acid digestion.

Organic samples: These samples are first dried, ashed at 450°C, and then the ash is digested with concentrated nitric acid/perchloric acid, evaporated to near dryness and taken up in distilled water.

Soils and sediments: These samples are dried, ashed at 450°C and then digested for one hour in 2M HNO_3 and the resulting solution used for radium-226 analysis.

5. SURFACE CONTAMINATION

The question of surface contamination was fully discussed in an earlier paper. To reiterate, no radiological hazard from surface contamination is expected to exist but there is certainly a nuisance value with respect to counting laboratories etc. In practice, the greatest source of yellow cake contamination will be at the drum packing end. Suffice to say that manual stirring of uncovered drums which was acceptable in the past would no longer be tolerated.

6. SUMMARY

While there are many dosimetry measurements that must be made in the uranium extractive industry, all involve well established techniques and employ commercially available instrumentation.

The instruments themselves, though 'ruggedised', are still essentially laboratory equipment and must be treated accordingly. In planning a mining operation, it is essential to provide adequate laboratory space that is both airconditioned and free of airborne contamination, as well as adequate staff so that all equipment can be calibrated and standardised on a routine basis.

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TABLE 1

INHALATION HAZARD OF NON-EQUILIBRIUM

RADON-DAUGHTER MIXTURES

Equilibrium Ratios	% of Equilibrium Dose
1, 1, 1, 1.	100
1, 1, 0.90, 0.80	87.5
1, 0.90, 0.80, 0.70	77.4
1, 0.85, 0.65, 0.45	59.8
1, 0.75, 0.50, 0.30	45.3
1, 0.75, 0.40, 0.15	34.3
1, 0.50, 0.25, 0.10	21.9
1, 0.35, 0.15, 0.05	13.4
1, 0.25, 0.10, 0.05	9.6
1, 0.15, 0.08, 0.03	6.9

AAEC SYMPOSIUM

on

ENVIRONMENTAL AND RADIOLOGICAL SAFETY ASPECTS

OF THE MINING AND PROCESSING OF URANIUM

LUCAS HEIGHTS, 9 – 10 DECEMBER 1971

PAPER XII

PROSPECTS FOR CONTROL OF RADIOLOGICAL HAZARDS IN URANIUM MINING

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1. INTRODUCTION

This discussion period is to be on methods for control of the radiological hazards associated with uranium mining. It is a field in which we find it easy to pose questions but difficult to supply answers. Nor are we alone in this; for example, the US mining code (American National Standards Institute 1960) in discussing ventilation requirements for underground workings, states both that 'the best way is to develop the ventilation programme as part of the mining plan' and that it is 'difficult to estimate what the situation will be in any mine before operations are started'. The reason for this is easy to find; there are very few generalisations that can be made. It is a field where engineering judgement based on experience is of prime importance and we have had extremely limited experience.

The approach adopted is to summarise the few generalisations that can be made, to refer to the appropriate appendix of the US code (American National Standards Institute 1960), to reference the only report that summarises mining experience (Breslin, George and Weinstein 1969) and to discuss what I think may be one or two misconceptions.

2. EMANATION OF RADON

Radon is a gas which may be inhaled. The US code quotes a range of 0.5 - 35.0 μCi per min/1000 ft^3 of stope volume for radon emanation but these figures are of little use without knowing the contribution of radon from the host rock, the grade of the ore and the radon contribution from water seepage.

For ore grades of 8 lb/ton to 20 lb/ton under dry conditions and little or no radon contribution from the host rock, our measured values range from 0.5 - 3.0 μCi per min/1000 ft^3 of stope volume (See Section 7 Turner and Davy, unpublished). In more useful units, and bear in mind our limited experience, a sufficiently conservative design figure would be 1 μCi per min/1000 ft^2 of exposed ore vein/1 lb/ton ore grade. Thus, very high grade ore occurring in thin veins need represent no greater potential radon hazard than does a low grade bulk deposit.

3. THE EFFECT OF VENTILATION

While ventilation does prevent the growth to equilibrium of radon gas levels, its more important role as a safety measure is to reduce the non-equilibrium ratios for the radon daughters. This is shown in Figure 1 (from Breslin, George and Weinstein 1969) (I believe that each of the ventilation rates should read a factor of 10 higher in this curve).

Since increasing ventilation reduces both the amount of radon present and each subsequent daughter ratio, the radon hazard is reduced by a greater proportion than the percentage increase in ventilation rate. For example, all else being equal, an increase in ore grade by a factor of 10 requires only a factor of 3 increase in ventilation rate for the same degree of hazard. Note however that this is true only if the legislation is in terms of working levels (WL); it is not true for current ICRP recommendations.

A very important component of the ventilation for an underground miner is the air supplied to his drill. This should be from an uncontaminated supply.

4. MINE SEEPAGE WATER

In underground workings, the seepage of water into the mine can be a serious source of radon. If seepage occurs, it is best to collect it in such a way that it has a minimum surface area and to remove it on a continuous basis.

For open-cut operations, seepage is of less importance radiologically but the consequences of discharging it to the environment have to be carefully considered.

5. OPEN-CUT CHARACTERISTICS

Intuitively one would expect two components of natural ventilation to be involved in open-cut operations. Firstly, strong solar radiation heating of the floor of the open-cut will lead to buoyant transfer of heat, mass and momentum. Secondly, the degradation of smooth air flow into turbulent eddies when passing over surface irregularities (e.g. over-burden dumps) will lead to mechanical mixing.

An indication of the relative importance of these two components can be obtained from the situation at Rum Jungle Creek South in June 1962. Approximately 10^5 ft^2 of ore was exposed at, say, an average grade of 10 lb/ton. Thus, from the above figures, about 1 mCi of radon was being liberated per minute. Maximum solar radiation heating will lead to a vertical wind speed of 35 ft/min, i.e. to a radon level of 10 pCi/ℓ. The measured radon concentration in the general air of the open-cut was 0.6 pCi/ℓ.

While there must be considerable uncertainties in this calculation, it does indicate the need to optimise the open-cut geometry for solar heating in order to minimise the radon hazard and that even for very rich ore bodies, there should be no significant radon levels.

6. EXTERNAL RADIATION

For a given ore body and grade, the only factor related to the external radiation hazard that can be controlled by the operators is the geometry of the mine development.

Accurate dose rate calculations should therefore be made for each mine development proposal and the radiation hazard assessed. The calculations need to have a sound mathematical basis but an adequate selection of solutions, with graphical evaluations of the numerical integrations involved, is available (Fitzgerald, Brownell and Mahony 1967). For example, the solution for the truncated right-circular cone with uniform activity distribution is, for a field position at the cone apex,

$$\text{rad/hr} = 1.07\text{x}10^{6} \frac{\mu_{en}}{\mu_s} C_v E \left[\frac{E_2(b \sec \theta)}{\sec \theta} - E_2(b) + 1 - \cos \theta \right]$$

where μ_{en} = mass energy absorption coefficient of tissue for photons of energy E (MeV).

μ_s = linear energy absorption coefficient of the ore material for photons of Energy E.

C_v = volume activity of the ore (Ci cm^{-3})

$$E_2(b) = b \int_b^{\infty} \frac{e^{-t}}{t^2} \, dt$$

and $b = \mu_s h$ where h is the length of the truncated cone, and θ its defining angle at the apex.

Calculations of this type will reveal that for high grade ores it is the external gamma irradiation that is most limiting. In this respect it is likely that open-cut workings will offer few advantages over a well planned underground mine.

7. EXTRACTS FROM UNPUBLISHED DATA OF H. TURNER AND D. DAVY

7.1 Site B. 65 North Winze and Stope

All sampling at site B was made in a relatively dust-free atmosphere as mining was stopped during the survey. The ore being mined averages about 7 lb oxide per ton of ore.

Monitoring

Sketch of site area.

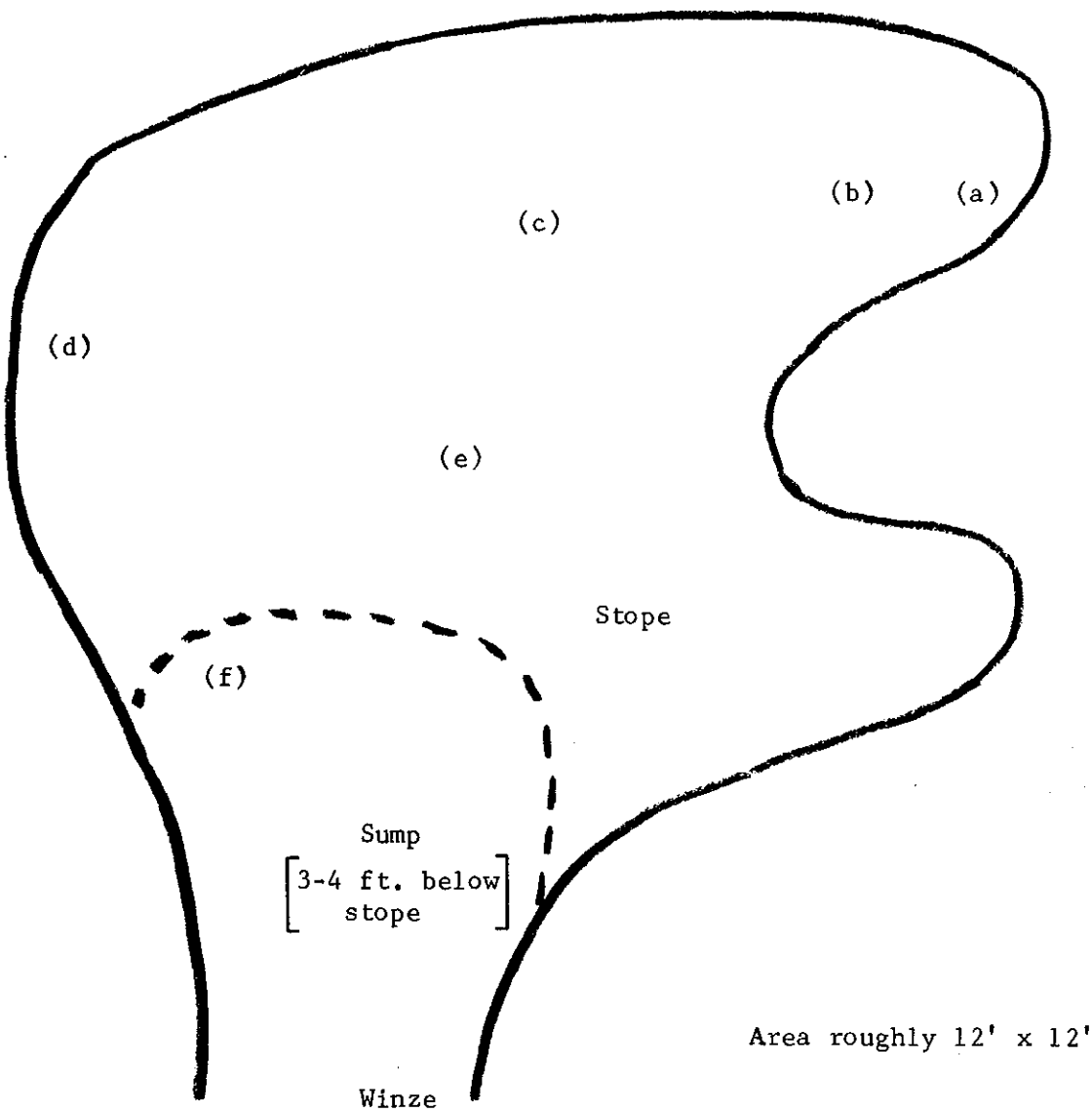

TABLE 1

DOSE-RATE LEVELS IN STOPE FOR 65 N WINZE

Monitoring points	1368 (mR/hr)	1320 c.p.s.	
		γ	"β+γ"
(a) wall surface	0.25	20	20
(b) 2'6" above floor	0.3	25	25
(c) 1' above floor (air sampling point)	1.4	70	220
(d) sludge from drill hole	3.5	300	600
2' above sludge	2.5	170	300
(e) ore body 2' diam.	5.5	480	600
1' above ore body	3.0	250	300
(f) hole in sump	2.8	180	220

Radon sampling

TABLE 2

RADON SAMPLING IN 65 N WINZE AND STOPE

Position	Radon level	
	mV	μμCi/ℓ (approx)
Top of winze	4	120
8 steps down	4	120
13 steps down	5.5	170
Hole in sump of winze	18	600
Two feet above sump	5.5	170
Drill hole	15	500
Air sampling position	3	90
Average for stope	5	150

Air sampling

TABLE 3

1195 SAMPLING DATA FOR 65 N WINZE

Sample No.	Date	Time (hrs)	Ventilation	Sample air flow		
				min	feet	litres
1	5 Aug. 61	2055	On all day	5	532	325
2	6 Aug. 61	0917	Off 2230 - 0954	5	645	393
3	"	0954	On 0954	5	600	366
4	"	1004	" "	5	599	365
5	"	1014	" "	5	595	360
6	"	1024	" "	5	614	379

Ventilation air flow, 30 linear feet/minute through approximately 6' x 6' i.e. about 1000 c.f.m.

The filter paper for these air sampling measurements were measured for alpha activity with a 1320 alpha probe standing on a 1/8" perspex spacer and operating a N 522 ratemeter on a time constant of 80 seconds. Each filter paper was set on clean polythene in the centre of the perspex spacer and once counting commenced no further adjustments were made to the probe-filter paper positions until the counting was concluded. With this method the counting ratemeter needle steadily fell, with only a slight statistical fluctuation, and could readily be noted at any time on the stop-watch.

TABLE 4

CONCENTRATION OF RADON DAUGHTER PRODUCTS AT SITE B

Sample No.	Ventilation c.f.m.	α c.p.s. at			μμCi/ℓ		Equilib.ratios relative to RaA		Total MeV/ℓ x 10^5
		5 min	10 min	30 min	Rn	RaA	RaB	RaC	
1	1000	20.5	10.9	9.4	90	42	0.152	0.127	0.125
2	Natural	76	51.5	43.3	100	81	0.357	0.336	0.43

Taking 20 minutes after the end of sampling as being representative of the total level of activity, it may be seen from Table 5 that within 10 minutes, the ventilation has considerably reduced the overnight build-up, but that after the initial main reduction, further changes are slow, taking probably some hours before a final steady state is reached.

TABLE 5

EFFECT OF VENTILATION AT SITE B

Sample No.	2	3	4	5	6	1
Ventilation time (min) at start of 5 minutes sample	- 37	0	10	20	30	775
α c.p.s. at 20 minutes after end of sampling	48	47	17.3	17.5	17.0	10.3

8. REFERENCES

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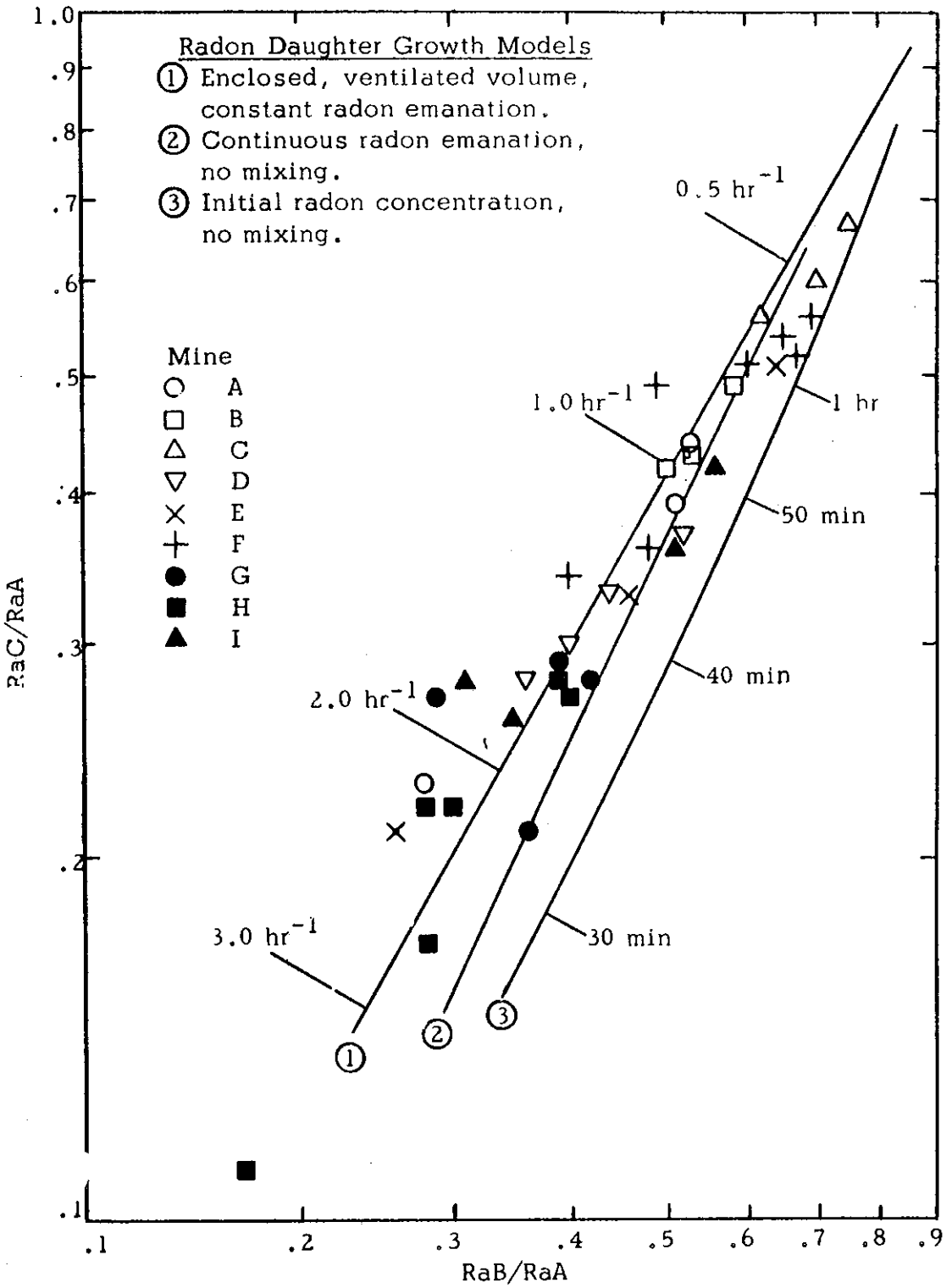

FIGURE 1 LOCATION – AVERAGE RADON DAUGHTER RATIOS, NORMALIZED TO RADIUM–A, COMPARED WITH RADON DAUGHTER GROWTH MODELS
(After Figure 11 in HASL–220)