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Review of risk assessments associated with the proposal to establish a national radioactive waste repository

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This report should be cited as follows:

Johnston A & Zapantis A 2003. *Review of risk assessments associated with the proposal to establish a national radioactive waste repository*. Supervising Scientist Report 174, Supervising Scientist, Darwin NT.

The Supervising Scientist is part of the Australian Government Department of the Environment and Heritage.

Supervising Scientist
Department of the Environment and Heritage
GPO Box 461, Darwin NT 0801 Australia

ISSN 1325-1554

ISBN 0 642 24381 6

Printed and bound in Darwin by NTUniprint, Darwin

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Executive summary

On 12 February 2003, the Minister for the Environment and Heritage, Dr David Kemp, requested that the Supervising Scientist provide scientific and technical advice on certain aspects of a proposal to construct a National Radioactive Waste Repository (NRWR). The specific issue on which advice has been sought is the risk to the proposed repository associated with activities of the Department of Defence in the Woomera Instrumented Range. This report has been prepared in response to the Minister's request.

A complete review of all aspects of the risks assessed in the Environmental Impact Statement has not been attempted. Rather, consistent with the Minister's request, we have focused on the primary area where significant disagreement remains between the assessments by the proponent, the Department of Education, Science and Training (DEST), and by the Department of Defence, namely the risk assessment associated with Defence operations in the Woomera Instrumented Range. Our report includes the derivation of estimates of the probability that Defence operations could lead to a breach of the NRWR and a review of the radiological dose calculations relevant to such a breach. Our review of these issues identified a need for a full review of all radiological dose calculations in the EIS (Environmental Impact Statement). This review has been conducted and the results are included in this report.

We have concluded that, in the absence of any more detailed information from Defence, the probability of breaching the NRWR as a result of Defence activities is likely to be in the range 0.1% to 2% per annum. These values are higher than the probability values adopted by DEST in the EIS by factors of 25 and 500 respectively.

Our estimate of the radiation dose to members of any recovery crew following a missile strike or aircraft strike on the repository is lower than that provided in the EIS by a factor of almost ten. The consultants who derived the estimates contained in the EIS have now acknowledged this error. Our radiological risk assessment has concluded that the risk of a fatal cancer subsequently arising from recovery operations following a missile impact on the repository is probably less than $1x10^{-6}$ per annum (one chance in a million). Hence, location of the repository at Site 52a would probably satisfy requirements of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

However, our assessment of non-radiological risks reaches a different conclusion. We found that the general risk assessment in the EIS was in error because it used the annual probability of breaching the repository rather than the probability of breaching the NRWR over its lifetime. If the probability estimates contained in the EIS had been used correctly, the conclusion should have been that the suitability of Site 52a is questionable.

Further, using the probability estimates derived in this review, the probability of a breach of the NRWR occurring as a result of a missile strike during the operational stage of the repository lies between 5% and 100%. We conclude that Site 52a is an unsuitable location for the NRWR. This conclusion becomes even more firm if the life of the repository is considered to include the Institutional as well as the Operational period.

The scenarios considered in the EIS for accidental human intrusion of the repository after the institutional control period have been assessed as constituting a very comprehensive range of possible or plausible scenarios. Our review has found that the radiation dose values listed in the various appendices of the EIS could not be reproduced precisely. With the exception of the dose associated with a missile strike or aircraft crash, which has already been considered above, all discrepancies are relatively small and have probably arisen from unspecified assumptions made in the EIS. The residual differences in dose estimates do not affect any conclusions on the acceptability of the repository. We have concluded that the establishment of the repository at a site other than Site 52a should not be precluded on radiological safety grounds.

However, we make the following two recommendations on radiation safety issues that should be addressed when a licence is being considered:

- If the establishment of the NRWR is approved, ARPANSA should determine appropriate waste acceptance criteria and waste conditioning requirements for high intensity gamma sources.
- If the establishment of the NRWR is approved, ARPANSA should consider requiring the integration of barriers within the waste to impede radon emanation.

The overall conclusions of this review are:

- Site 52a in the Woomera Intrumented Range is not a suitable location for establishment of the National Radioactive Waste Repository because the probability of breaching the repository by Defence Force activities is considered to be unacceptably high.
- Estimates of both short-term and very long-term radiation exposure to members of the public arising from accidental intrusion into the National Radioactive Waste Repository have demonstrated that establishment of the repository at another site would be acceptable on radiological safety grounds.

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Review of risk assessments associated with the proposal to establish a national radioactive waste repository

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1 Introduction

On 12 February 2003, the Minister for the Environment and Heritage, Dr David Kemp, requested that the Supervising Scientist provide scientific and technical advice on certain aspects of a proposal to construct a National Radioactive Waste Repository (NRWR). The specific issue on which Environment Australia has sought advice is the risk to the proposed repository associated with activities of the Department of Defence in the Woomera Instrumented Range. This report has been prepared in response to the Minister's request.

The Commonwealth Department of Education, Science and Training (DEST) submitted a Draft Environmental Impact Statement (DEST 2002a) to Environment Australia (EA) for the establishment of a National Radioactive Waste Repository on 31 May 2002. The EIS proposed three possible locations for the repository:

- Site 52a near Koolmilka, Woomera Prohibited Area (WPA), South Australia
- Site 40a about 20 km east of Woomera
- Site 45a about 50 km northeast of Woomera.

Following a public comment process, DEST submitted a Supplement (DEST 2002b) to the Draft EIS in December 2002. Together these documents (the Draft EIS Main Report, the Appendices to the Main Report and the Supplement) comprise the final EIS.

Prior to submission of the Draft EIS, the Department of Defence had provided to DEST a report by HLA – Envirosciences entitled 'Impact on Australian Defence Force Operations of locating the National Waste Repository at Site 52a within the Woomera Prohibited Area' (HLA 2001). This report contained an assessment of some of the perceived risks associated with the proposed project. DEST took this assessment into account when it prepared the Draft EIS following receipt of a report to DEST by Halliburton KBR Pty Ltd dated February 2002 (Halliburton 2002).

The Department of Defence did not make a submission on the Draft EIS but it did provide interdepartmental advice to DEST on 18 October 2002. That advice, contained in a report entitled 'Consolidated EIS Response for the NRWR' (Defence 2002), was critical of the risk assessment contained in the Draft EIS and concluded that risks were much higher than the numerical values provided in the Draft EIS.

A number of the submissions received during the public comment phase also criticised the risk assessments contained in the EIS and DEST provided responses to these criticisms in the Supplement. Since Defence (2002) was not a submission on the Draft EIS, specific reference was not made to it in the Supplement but the issues raised by Defence in the report were addressed through the responses to public comments in the Supplement. In addition, on

5 December 2002 DEST provided to Environment Australia its response (DEST 2002c) to the issues raised in Defence (2002).

Our report provides a review of the risk assessments contained in all of these documents. However, a complete review of all aspects of these risk assessments has not been attempted. Rather, consistent with the Minister's request, we have focused on the primary area where significant disagreement remains between the assessments by DEST and by Defence, namely the risk assessment associated with Defence operations in the Woomera Instrumented Range. This review includes an estimate of the probability that Defence operations could lead to a breach of the NRWR and a review of the radiological dose calculations relevant to such a breach. Our review of these issues led to a full review of all radiological dose calculations in the Environmental Impact Statement.

2 DEST risk assessment methods

The EIS contains two risk assessments relevant to the location of the repository within the Woomera Instrumented Range. The first, presented in section 10.7 of the Main Report, adopts the methodology used by the US Department of Defense. This is a semi-quantitative risk assessment method. An estimate is made of the probability of a mishap occurring and this estimate is used to describe the probability as being in one of five categories ranging from Improbable to Frequent. An assessment is then made of the consequences arising if the mishap were to occur. Hence, the severity of the mishap is classified into one of four categories ranging from Negligible to Catastrophic. The overall risk is then determined to be High, Serious, Medium or Low according to where the mishap fits in a Risk Assessment Matrix according to the assessed probability and severity of the mishap.

The second risk assessment is described in chapter 12 of the EIS Main Report. A number of risks are identified and assessed both for the Operational phase and the Institutional Control phase of the repository. In particular, section 12.7 addresses risks of radiation exposure arising from activities of the Department of Defence in the Woomera Prohibited Area. This second risk assessment is quantitative. As in the semi-quantitative assessment described above, an estimate is made of the probability of a missile or aircraft accidentally striking and breaching the repository. In addition, estimates are made of the probable radiation exposure resulting from such an event and the resulting probable fatality rate (from subsequently developed cancer) arising from the exposure. The product of the probability of a missile or aircraft strike on the repository and the estimated fatality rate provides an estimate of annual risk of fatality and this is compared with the requirements of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) which would be the regulator of the repository.

3 Probability of missile breach of the NRWR

3.1 Review of probability estimates

The site for the repository preferred by DEST, site 52a, lies within the Woomera Instrumented Range (WIR) which is used by Defence as a weapons practice area. Within the WIR is the Range E target area and the distance between site 52a and Range E is about 3 km. Defence has provided information on the number of weapons used on the WIR each year that are capable of penetrating and breaching the NRWR. It has also differentiated these weapons according to weapon type and safety template area. The details provided by Defence (Defence 2002) are summarised in table 1.

Table 1 Weapons capable of breaching the NRWR if they land on it or very close to it

Weapon type	No of weapons per annum	Safety template area (km^2)
Ballistic weapons	18	25
Laser guided weapons	17	70
Standoff weapons	7	2500

The safety template area is determined by Defence to ensure the safety of Defence personnel working on the WIR. Outside the safety template the probability of a fatality is estimated to be less than $1x10^{-6}$ (one chance in a million). The actual distribution of the probability of impact within the safety template (ie the likelihood of a mishap at any point within the safety template) is not known, although Defence may have more detailed information. In the absence of knowledge of the actual distribution, estimates of likely probability ranges can be made from general considerations. Because the objective is to make a risk assessment, it is essential that any general approach errs on the safe side and uses assumptions for probability distributions that are conservative but not unreasonable. It would clearly be better to use real data on probability contours if available.

Full details are given in Appendix 1 of the assumptions adopted and the methods used in this review to estimate the annual probability that a weapon will breach the NRWR if it is located at site 52a within the Woomera Instrumented Range.

Two estimates of probability were obtained for each of the weapon types listed in table 1 based upon two different assumptions for the shape of the probability distribution. The two distributions considered were the 'normal'[1] distribution and the 'uniform' distribution. The 'normal' distribution is considered to be, in the absence of reliable data, a reasonable representation of the way in which weapons would fall around a target while the 'uniform distribution' is considered to be at the edge of what might be considered reasonable but which can assist in setting limits for the expected probabilities. Use of these distributions allowed a maximum and minimum value to be estimated for the probability with which each weapon would breach the repository. Hence estimates could be made of the maximum and minimum values of the overall probability of breaching the repository. The results of these calculations are provided in table 2.

Table 2 For each weapon type, the maximum and minimum estimates for the probability per annum that the NRWR will be breached

Weapon type	Maximum probability of breaching NRWR (y^{-1})	Minimum probability of breaching NRWR (y^{-1})
Ballistic weapon	3.6×10^{-3}	0
Laser guided weapon	2.2×10^{-2}	1.1×10^{-3}
Standoff weapon	3.0×10^{-3}	2.6×10^{-4}
Total	2.9×10^{-2}	1.4×10^{-3}

The reliability of these estimates is considered in Appendix 1 and the overall conclusion is that a reasonable range to consider for the annual probability of breaching the NRWR would be $0.1x10^{-2}$ to $2.0x10^{-2}$ (0.1 % to 2%).

[1] The normal and uniform distributions are described in Appendix 1 and their shapes are illustrated in figure A1.3 of Appendix 1

These probability estimates could still be in error. For example, the true situation may be that most of the time the weapons used are highly accurate but when a mishap occurs the weapon can land anywhere within quite a large radius of the target. The probability distribution could then, for example, be the sum of two normal distributions: a dominant component (representing the normal highly accurate weapons) with a very small standard deviation (eg tens or hundreds of metres) and a second smaller component (representing the mishaps) with a standard deviation in the kilometre range.

We have checked this scenario by assuming, arbitrarily, that 90% of weapons are highly accurate and would have a negligibly low probability of striking the repository. The standard deviation for the second component was then calculated using the requirement that the safety template remains at the value specified by Defence for each weapon. Under this scenario we estimated an annual probability of breaching the NRWR of 0.5×10^{-3} (0.05%). This value is slightly lower than, but close to, the minimum estimated probability using the previous analysis. This analysis simply confirms that the current probability estimates could still be in error but, in the absence of any detailed information from Defence, we believe that the type of approach adopted here is appropriate in undertaking a risk assessment.

Overall, therefore, it would be reasonable to proceed with risk assessments based upon the use of probabilities of breaching the NRWR from a missile strike in the range 0.1×10^{-2} to 2×10^{-2} (0.1% to 2%) per annum. The estimates obtained using two normal distributions tend to indicate that the real situation may be towards the lower end of this range.

3.2 Comparison with DEST estimates of probability

As described in section 2 of this review, DEST carried out two risk assessments in the EIS. For the semi-quantitative assessment using the methodology of the US Department of Defense (described in section 10.7.5 of the EIS) DEST states that the information provided by Defence led to the conclusion that, for all weapons used on the WIR, the repository would be 'in an area where the risk is 1×10^{-6}'. This implies that for all weapons the repository is outside the safety template. On this basis DEST estimated the probability of breaching the NRWR to be 4.2×10^{-5} per annum, a value that is lower than our minimum estimate by a factor of about 25 and lower than our maximum estimate by a factor of almost 500.

In the report HLA (2001) provided to DEST prior to submission of the Draft EIS, Defence noted that the safety template of some of the weapons used in the WIR included site 52a. It provided little additional or supporting information.

The review of HLA (2001) by Halliburton (2002) noted that the template information provided in HLA (2001) could give rise to an increased probability of breaching the NRWR but states that it is probably an overestimate and proposes that Defence should provide more detailed information on probability contours, numbers of weapons capable of penetrating the NRWR etc. Some of this information was subsequently provided by Defence (eg number of weapons tested per annum capable of penetrating the NRWR) but the information sought on probability contours was not provided.

It is our view, however, that a more comprehensive approach should have been adopted in estimating the probability of breaching the NRWR.

For the radiological risk assessment carried out by DEST, the probability of a missile striking the NRWR was deduced using the uniform distribution assumption (described in section 12.5.3 of the EIS). As discussed in Appendix 1, if the probability of a missile strike is constant over an area A, then the probability of striking the repository with an area A_R is simply the ratio of the two areas provided that the repository is within the area A. Otherwise the probability is zero. Hence the annual probability of breaching the NRWR becomes:

$$P = nA_R / A$$

where n is the number of weapons tested each year with the capability of breaching the NRWR.

In the EIS, DEST assumed that the area over which the probability is constant would be the whole of the Woomera Prohibited Area, ie about 130 000 km^2, and on this basis deduced that the annual probability of breaching the NRWR is about $3x10^{-5}$, a value similar in magnitude to that used in the DEST semi-quantitative risk assessment. No rationale was presented for the choice of this area. In our opinion, the choice of the area over which constant probability could be assumed was unrealistically large and resulted in a very low value for the probability of breaching the NRWR. One could have chosen the whole area of South Australia with equal justification.

We note that, in its response (DEST 2002c) to the issues raised in Defence (2002), DEST states that it did 'not base its estimate of probability on the relative areas of the national repository and the WPA'. This statement by DEST is, however, in direct contrast to the information provided in section 12.5.3 of the EIS in which the individual risk estimate of $6.9x10^{-9}$ per year is based directly on the probability of breaching the NRWR, $3.0x10^{-5}$ per year, that was calculated using the ratio of area method described above. We also note that similar criticisms of DEST's probability estimates were contained in public submissions on the Draft EIS. It is our view that DEST's rejection of the criticisms of its probability estimates in the Supplement was dismissive and unjustified.

Our conclusions on the annual probability of breaching the NRWR are as follows:

- The two probability values adopted by DEST in the Draft EIS are probably underestimates of the true probability of breaching the NRWR following a missile strike. DEST's rejection of criticism of its probability estimates in the Supplement was dismissive and unjustified.
- In the absence of any more detailed information from Defence on the actual probability distributions, the risk assessments should be repeated using probabilities for breaching the NRWR in the range $0.1x10^{-2}$ to $2x10^{-2}$ per annum.
- A brief analysis based on the assumption that there may be two components in the probability distribution, a highly accurate component and a smaller contribution attributable to mishaps, indicates that the true probability may be at the lower end of the above range.

4 Risk assessments for breach of the NRWR following a missile strike

The two risk assessments in the EIS are briefly reviewed below taking into account the revised estimates of probability of breaching the NRWR and, in the case of the radiological risk assessment, the results obtained in Appendix 2.

4.1 Semi-quantitative risk assessment

The DEST semi-quantitative risk assessment, presented in section 10.7 of the EIS, adopted the methodology used by the US Department of Defense. In this method, the overall risk is determined to be High, Serious, Medium or Low according to where the mishap fits in a risk assessment matrix according to the assessed probability and severity of the mishap.

In the EIS, DEST used the estimate of annual probability of breaching the NRWR, 4.2×10^{-5}, to classify the event as Remote (Level D). This classification corresponds to a probability of the mishap occurring over the life of the repository of between 10^{-6} and 10^{-3}. This appears to have been an error by DEST since, using its own annual probability value, the probability of a breach over the life of the repository, considering only the operational life of 50 years, would be 2×10^{-3} and the probability should have been classified as Occasional (C). This would still have resulted in an overall assessment of the risk as Medium. The error seems to have arisen from the use of the annual probability of breaching the repository in the risk assessment rather than the probability over the life of the repository. It is the latter that is required by the risk assessment method adopted (see table 10.1 of the Main Report).

If one considers the life of the repository to be the total operational and institutional life, the overall probability to be assessed in the risk assessment becomes 1×10^{-2} and the classification would be at the lower end of Probable (B). This would have led to an overall risk classification of Serious.

Thus, even if one uses the annual probability of breaching the NRWR adopted in the EIS, a correct use of the probability over the life of the repository should have resulted in a questionable conclusion on the suitability of Site 52a. We note that the error in DEST's risk assessment was identified in public submissions on the Draft EIS but was dismissed by DEST in the Supplement.

If we now use the range of annual probabilities for breach of the NRWR deduced on the basis of the analysis in Appendix 1, 0.1×10^{-2} to 2×10^{-2}, the maximum and minimum probabilities of breaching the NRWR over the operational life of the repository become 100% and 5% respectively. In the terminology of the Mishap Probability Levels described in table 10.1 of the Main Report, these probabilities would be described as Frequent (Level A) and Probable (Level B) respectively. Without questioning the assessment that the severity of the mishap should be classified as Marginal, both of these assessments of probability, when combined with the Marginal assessment of Impact, give rise to an overall assessment of risk in the 'Serious' category. As such, it should be concluded that Site 52a is an unsuitable location for the repository.

If one then assesses the probability that the repository would be breached during either the operational period or the institutional control period, the assessment of probability is 'Frequent' even if one assumes that the annual probability is the minimum derived in Appendix 1. This strengthens the conclusion that Site 52a is an unsuitable location for the repository.

4.2 Radiological risk assessment

The radiological risk per annum associated with any potential breach of the NRWR is given by:

$$R = rPH$$

where r is the dose-to-risk conversion factor (per Sievert), H is the effective dose (Sv) assuming the event takes place, and P is the probability of exposure in any one year.

A review of the radiological dose estimates relevant to missile or aircraft striking the NRWR is presented in Appendix 2. The principal conclusions of this review are:

- Most aspects of the scenarios envisaged and described for breaching of the NRWR by a missile or aircraft and the methods used in dose calculations appear to be reasonable and conservative.
- However, the EIS did not consider the scenario where a high activity gamma source is released from its packaging and shielding by the intrusion and is subsequently collected with the remains of the aircraft/missile by the recovery personnel. In this scenario, it is possible for recovery personnel to receive a radiation dose significantly larger than in the scenarios considered in the EIS. Assessment of the significance of this scenario is required.
- Errors and inconsistencies are present in the dose calculations reported in the EIS. The systematic nature of these errors and inconsistencies indicates that all the dose calculations related to aircraft/missile intrusion are similarly affected and result in an overestimate of the radiation dose by a factor of about eight (8).
- In view of these errors and inconsistencies, it would be prudent to undertake a thorough check of all radiological calculations in Appendix E of the EIS. This should be done even if site 52a is not preferred because the calculations in Appendix E not only refer to the intrusion scenarios considered here but also to normal operations of the NRWR and intrusion in the post-institutional control period wherever the NRWR is located.
- The dose-to-risk conversion factor used in Appendix E7 (0.06 per Sievert) is conservative because the value used refers to the whole population rather than working adults. It would have been more appropriate to use the risk coefficient for the development of fatal cancer for an adult, that is 0.04 per Sievert.

Full details of the errors and inconsistencies in the dose calculations are provided in Appendix 2. The overall effect, however, is that the dose estimate for the missile and aircraft scenarios assessed in the EIS should be reduced by a factor of about eight (8).

Using the revised results obtained in both Appendix 1 and Appendix 2, the estimates for the radiological risk, R, range between:

$$R_{\max} = 0.04(Sv^{-1})x2x10^{-2}(y^{-1})x3.7x10^{-3}(Sv)/8 = 3.7x10^{-7}(y^{-1}) \text{ and}$$

$$R_{\min} = 0.04(Sv^{-1})x0.1x10^{-2}(y^{-1})x3.7x10^{-3}(Sv)/8 = 1.9.10^{-8}(y^{-1})$$

These estimates are below the risk assessment level established by ARPANSA for approval of a National Radioactive Waste Repository. In addition, the discussion in Appendices 3 and 4 on the specific activity of the repository indicate that these risks may be further reduced by up to a factor of ten at the extreme.

5 Assessment of general radiological exposure associated with the NRWR

In the previous section, it was concluded that, because errors and inconsistencies had been found in the radiological dose estimates for the missile strike or aircraft crash scenario, a comprehensive check should be carried out on the radiological dose calculations for the NRWR wherever it might be located. In addition, it was concluded that further assessment was required for the scenario where a high activity gamma source is released from its packaging and shielding by the intrusion and is subsequently collected with the remains of the aircraft/missile by the recovery personnel.

The Supervising Scientist requested that the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) conduct a review of these dose estimates.

Specifically, a review has been carried out by ARPANSA of the assessments contained in Appendices E6, E7 and E8 of the EIS. An assessment has been made of the rationale adopted, the methodology used and the appropriateness of the assumptions made in the analysis. In addition, checks have been made on a selection of the calculations presented. The choice of calculations to be checked was made on the basis of the relative significance of the calculated doses for the pathway being assessed. In addition, the significance of possible gamma-ray exposure from small high intensity sources has been assessed for the scenario of intrusion of the NRWR following an aircraft crash. The detailed ARPANSA report is included at Appendix 3.

Following receipt of ARPANSA's review of dose estimates, we have assessed the significance of the various exposure pathways considered in the EIS. In particular, we have assessed the repository against the criteria recommended by the International Commission on Radiological Protection for assessing accidental human intrusion after the institutional control period. This assessment is in Appendix 4.

The ARPANSA report draws attention to an apparent discrepancy in the area and volume of the repository assumed in the EIS. In summary, ARPANSA notes that the surface area of the repository is assumed to be 10 000 m^2 (or 100 m by 100 m) in calculating the probability of intrusion, whilst the dimensions for the purpose of radiation dose calculations are assumed to be 100 m long by 10 m wide by 10 m deep, corresponding to a surface area of only 1000 m^2. The use of a single trench in the dose calculations is, we conclude, a reasonable and conservative response to an absence of knowledge on the number and layout of the trenches and boreholes in the repository. The principal result of its use, however, is that the dose calculations in Appendix E7 and almost all in Appendix E8 are overestimated by a factor that could be as high as ten.

ARPANSA checked the dose calculations in Appendix E6 which considers the radiation dose to construction workers of the repository and found errors that result in slightly different dose estimates being obtained. However, all dose estimates are very low and Appendix E6 is not really required since it contains calculations of dose to construction workers due to natural background radiation. It is inappropriate to compare these very small natural doses with dose or risk constraints.

Appendix E7 considers the radiation dose to personnel recovering a missile or aircraft that has crashed onto the repository exposing radioactive material. ARPANSA confirms the significant error in the gamma dose calculations discussed in Appendix 2 of our review. The result of that error is that all calculations of dose to recovery personnel due to external gamma irradiation in Appendix E7 are high by a factor of almost ten. In addition, ARPANSA identifies parameters that have been selected such that the radiation doses calculated are maximised. The overall effect of the conservatism adopted in the analyses in the EIS is that the actual dose received by aircraft or missile recovery personnel would probably be lower than those reported in the EIS by between one and two orders of magnitude.

Following our recommendation that the scenario involving the release of a high activity gamma source from its shielding and packaging by the impact of a missile or aircraft on the repository be further assessed, ARPANSA undertook calculations of dose to the recovery personnel. In summary, estimates of doses to recovery personnel in the range of 10 mSv to 100 mSv were obtained. The variability arises from the many uncertainties associated with the work practices of the recovery personnel and the activity of the source itself. Simple parameters such as the period of the exposure and the distance of the personnel from the source can alter the dose by an order of magnitude or more.

What is much better known, however, is the physical security of these sources within the repository. It should be noted that sources of this type would be required to be contained within very robust packaging incorporating radiation shielding to enable safe handling and transport. High activity gamma sources are required to be transported in containers that can withstand severe transport accidents without loss of containment. Waste conditioning practices, such as encapsulation in solid concrete within steel drums further increases the physical security of the source. It has been concluded that the fatality probability would be very small because the likelihood of release from transport containers encapsulated in concrete within steel drums under a cover of five metres of soil is considered to be implausible.

Appendix E8 considers accidental human intrusion after the institutional control period. The scenarios presented in the EIS are considered to adequately represent the range of possible human intrusion scenarios. ARPANSA's calculations of dose for each of the scenarios at the time of closure of the repository produce similar but not identical results to those in the EIS. ARPANSA was unable to determine the reason for the difference because insufficient information on the dose calculations was provided in the EIS.

The rationale that should be used for assessing accidental human intrusion after the institutional control period is that recommended by the International Commission on Radiological Protection (ICRP Publication 81), namely:

> The Commission considers that in circumstances where human intrusion could lead to doses to those living around the site sufficiently high that intervention on current criteria would almost always be justified, reasonable efforts should be made to reduce the probability of human intrusion or to limit its consequences. In this respect, the Commission has previously advised that an existing annual dose[2] of around 10 mSv may be used as a generic reference level below which intervention is not likely to be justifiable. Conversely, an existing annual dose of around 100 mSv per year may be used as a generic reference level above which intervention should be considered almost always justifiable. Similar considerations apply in situations where the thresholds for deterministic effects in relevant organs are exceeded.

Applying this philosophy, realistic dose estimates for plausible scenarios involving human intrusion into the repository should be made and the doses calculated should be considered in the context of current ICRP recommendations on intervention. If the best estimate of the annual radiation dose for a scenario is below 10 mSv, the conclusion from the consideration of that scenario is that the repository is acceptable from the perspective of human intrusion after the institutional control period. If the annual dose lies between 10 mSv and 100 mSv, then reasonable efforts to reduce the likelihood or consequences of the intrusion scenario should be considered. If the annual dose is above 100 mSv, then reasonable efforts to reduce the likelihood or consequences of the intrusion scenario should be required. This process should be repeated for each plausible scenario.

The doses reported in the EIS for all scenarios except those relating to a high activity gamma source and radon, are below the level (10 mSv) at which the ICRP recommends that modification to the repository could be considered to reduce the likelihood or consequences

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[2] The term 'existing annual dose' is used by the Commission to mean the existing and persisting annual dose incurred by individuals in a given location. The exposure that may occur from a repository is a component of the existing annual dose.

of human intrusion. Further, in reviewing these calculations, ARPANSA notes that conservative assumptions have been made for every parameter. When these conservative assumptions are coupled with the additional factor of conservatism arising from the assumption of a repository volume of 10 000 m^3 (see discussion above), it has been concluded that the actual doses that would be received under all of the scenarios (except one for which the dose is already small) could be lower than those reported in the EIS by more than a factor of ten.

Radon is a radioactive gas that occurs wherever uranium is found. Because it is a gas, radon can leave the soil in which uranium occurs (radon emanation) and disperse in the atmosphere. We have concluded that the scenario considered for radon emanation in the EIS is a worst case scenario that could, at the extreme, overestimate dose by up to a factor of 1000. Using more realistic parameters, the dose from radon progeny to people who reside in a dwelling built directly upon the repository contents is estimated to be between one and two orders of magnitude lower than that reported in the EIS, ie between 1 mSv and 10 mSv per year, which is acceptable according to ICRP recommendations.

The key conclusions relating to the review of Appendices E6, E7 and E8 are presented below, together with recommendations.

- The scenario where, during the operational period, a high activity gamma source is released from its packaging and shielding by the impact of a missile or aircraft on the repository and subsequently recovered by the recovery personnel was not assessed in Appendix E7. Following an assessment of this scenario, we have concluded that the fatality probability would be very small because the likelihood of release from transport containers encapsulated in concrete within steel drums is considered to be implausible.
- The scenarios for accidental human intrusion into the repository after the institutional control period considered in Appendix E8 adequately cover the range of possible intrusion scenarios. With the exception of the scenario involving high activity gamma sources, the dose estimates for all post institutional control period scenarios are very low and require no further assessment.
- Because of certain plausible post institutional control period scenarios, disposal of high intensity gamma sources at the repository should be subject to waste conditioning requirements. Although appropriate waste conditioning techniques exist for most such sources, it is possible that the highest activity gamma sources are unsuitable for disposal in the repository. These are matters that should be subject to detailed assessment by ARPANSA as part of the licensing process. Thus it is recommended that:
  – If the NRWR is approved, ARPANSA should consider high activity gamma sources in the context of accidental human intrusion after the institutional control period and determine appropriate waste acceptance criteria and waste conditioning requirements for such sources.
- Radiation exposure due to radon emanation from the repository in the long term is not an impediment to construction of the repository because such exposure can be significantly reduced by the incorporation of barriers within the waste to impede radon emanation. It is, therefore, recommended that:
  – If the NRWR is approved, ARPANSA should consider requiring the integration of barriers with the waste to impede radon emanation.

6 Conclusions and Recommendations

In this report, we have reviewed some aspects of the risk assessments carried out by DEST in the Environmental Impact Statement for the National Radioactive Waste Repository. The review has been limited in scope in that the primary objective was to review the risks associated with the possible impact of a missile on the repository at DEST's preferred site 52a within the Woomera Instrumented Range.

Specifically, we have reviewed the estimates of the probability that Defence operations could lead to a breach of the NRWR and the radiological dose calculations relevant to such a breach. Our review of these issues led to a full review of all radiological dose calculations in the Environmental Impact Statement.

The principal conclusions and recommendations arising from this review are given below.

Estimates of probability of breaching the NRWR

In conducting this review, we have estimated the maximum and minimum probabilities attributable to an event where a missile breaches the NRWR. These estimates have been deduced using two different assumptions for the probability distribution for weapon strikes as a function of distance from the target – a normal distribution and a uniform distribution. It has been necessary to make these assumptions because probability contour information has not been provided by the Department of Defence. In the absence of such information, we considered that, in a risk assessment process, assumptions need to be conservative but not unreasonable.

We have also checked our analysis by examining a model based on the assumption that there may be two components in the probability distribution, a highly accurate component and a smaller contribution attributable to mishaps. The latter analysis indicates that the true probability may be at the lower end of our estimates based upon the use of the normal and uniform distributions.

Our conclusions on the annual probability of breaching the NRWR are as follows:

- The probability values adopted by DEST in the EIS are probably underestimates of the true probability of breaching the NRWR following a missile strike. DEST's rejection of criticism of its probability estimates in the final EIS was dismissive and unjustified.
- In the absence of any more detailed information from Defence on the actual probability distributions, an appropriate range for the probability of breaching the NRWR by a defence weapon is $0.1\text{x}10^{-2}$ to $2\text{x}10^{-2}$ (0.1% to 2%) per annum.

Radiological dose estimates for potential breach of the NRWR

The review of radiological dose estimates associated with a possible breach of the NRWR by a missile or aircraft found the scenarios considered and the methods used in dose calculations were reasonable and conservative. One scenario that had not been adequately assessed, the release of a high activity gamma source by the intrusion, has been assessed in this review and it has been concluded that the associated risks are not significant.

The principal conclusions arising from the review of the dose estimates are:

- Errors and inconsistencies are present in the dose calculations reported in the EIS for the missile strike and aircraft crash scenarios. Principal among these is the use of an incorrect value of the density of repository materials leading to an overestimate of the external gamma radiation doses by almost a factor of ten.

- The overall result of these errors is that the estimates of dose for these scenarios in the EIS have been overestimated by a factor of about eight (8).

In view of these errors and inconsistencies, it has been necessary to undertake a thorough check of all radiological calculations in Appendix E of the EIS that are relevant to the repository wherever it is located.

Risk assessments associated with Defence Force activities

Following the above reassessments of the probability of a missile breach of the repository and the associated radiological doses, we have reviewed both risk assessments carried out in the EIS, the general semi-quantitative risk assessment and the radiological risk assessment.

The revised radiological risk assessment carried out in this review has concluded that the risk of a fatal cancer subsequently arising from recovery operations following a missile impact on the NRWR is probably less than $1x10^{-6}$ per annum (one chance in a million). Hence, location of the repository at Site 52a would probably satisfy requirements of the Australian Radiation Protection and Nuclear Safety Agency.

However, our conclusions on the more general risk assessment are as follows:

- The risk assessment in the EIS was in error because it used the annual probability of breaching the repository rather than the probability of breaching the NRWR over its lifetime. If the probability estimates contained in the EIS had been used in the EIS risk assessment, the conclusion should have been that the suitability of Site 52a is questionable.
- Using the probability estimates derived in this review, however, the probability of a breach of the NRWR by a missile during the operational stage lies between 5% and 100%. Consideration of other possible distributions indicates that the lower end of this range is likely. Use of these probabilities in the general risk assessment leads to a conclusion that the risk is Serious.
- In these circumstances we conclude that Site 52a is an unsuitable location for the NRWR. This conclusion becomes even more firm if the life of the repository is considered to include the Institutional period as well as the Operational period of the repository.

Radiological dose estimates relevant to the NRWR wherever it is located

In view of the errors and inconsistencies found in the radiological dose estimates associated with a potential breach of the NRWR by a missile strike or aircraft crash, we have carried out a thorough check of the radiological dose calculations for the NRWR wherever it is located.

This review found that the radiation dose values listed in the various appendices of the EIS could not be reproduced precisely. With the exception of the gamma dose associated with a missile strike or aircraft crash, which has already been considered above, all discrepancies are relatively small and have probably arisen from unspecified assumptions made in the EIS. The residual differences in dose estimates do not affect any conclusions on the acceptability of the repository.

All dose estimates associated with construction of the repository are very small. Such doses arise from naturally occurring radiation and it is not, in any case, appropriate to compare them to dose limits or dose constraints.

The scenarios considered in the EIS for accidental human intrusion of the repository after the institutional control period have been assessed as constituting a very comprehensive range of possible or plausible scenarios.With the exception of the scenario involving high activity gamma sources (considered separately below), the dose estimates for all post-institutional control period scenarios are very low and require no further assessment.

Because of certain plausible post institutional control period scenarios, disposal of high intensity gamma sources at the repository should be subject to waste conditioning requirements. Although appropriate waste conditioning techniques exist for most such sources, it is possible that the highest activity gamma sources are unsuitable for disposal in the repository. These are matters that should be subject to detailed assessment by ARPANSA as part of the licensing process. Thus it is recommended that:

- If the establishment of the NRWR is approved, ARPANSA should determine appropriate waste acceptance criteria and waste conditioning requirements for high intensity gamma sources.

Radiation exposure due to radon emanation from the repository in the long term is not an impediment to construction of the repository because such exposure can be significantly reduced by the incorporation of barriers within the waste to impede radon emanation. It is, therefore, recommended that:

- If the NRWR is approved, ARPANSA should consider requiring the integration of barriers within the waste to impede radon emanation.

Overall conclusions

The overall conclusions of this review are:

- Site 52a in the Woomera Intrumented Range is not a suitable location for establishment of the National Radioactive Waste Repository because the probability of breaching the repository by Defence Force activities is considered to be unacceptably high.
- Estimates of both short-term and very long-term radiation exposure to members of the public arising from accidental intrusion into the National Radioactive Waste Repository have demonstrated that establishment of the repository at another site would be acceptable on radiological safety grounds.

A Johnston
Supervising Scientist
21 March 2003

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Appendices

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Appendix 1 Estimates of the probability of breaching the National Radioactive Waste Repository by a missile within the Woomera Instrumented Range

1 Introduction

The risk associated with a potential breach of the National Radioactive Waste Repository (NRWR) by weapons being used by the Department of Defence in the Woomera Instrumented Range (WIR) requires the assessment of both the probability of an event occurring and the effect of the event should it occur. Appendix 2 of this report addresses the radiological consequences of such a breach. The probability of breaching the NRWR from Defence activities is reviewed in this Appendix.

2 Basic data and assumptions

Defence has provided information on the number of weapons that are used on the Woomera Instrumented Range each year that are capable of penetrating and breaching the NRWR. It has also differentiated these weapons according to weapon type and safety template area. The details provided by Defence (Defence 2002) are summarised in table A1.1.

Table A1.1 Weapons capable of breaching the NRWR if they land on it or very close to it

Weapon type	No of weapons per annum	Safety template area (km^2)
Ballistic weapons	18	25
Laser guided weapons	17	70
Standoff weapons	7	2500

The analysis presented in this review only addresses the risks associated with the use of the weapons characterised in table A1.1. A risk assessment, however, ought to include an assessment of possible or likely developments over the life of the proposed development. Thus, some attempt should have been made in the EIS to assess possible developments in the use of the Woomera Instrumented Range over the next 50 years (Operational Life) or 250 years (Operational plus Institutional Control Period). The absence of such an assessment could give rise to future limitations on the use of weapons on the range and other uses of the range.

The safety template area is determined by Defence to ensure the safety of Defence personnel working on the WIR; outside the safety template the probability of a fatality is estimated to be $<1x10^{-6}$. The precise definition of what is meant by the safety template is unclear in the documentation that we have sighted. In the analyses presented in this paper, we assume that it means that the total probability of a missile strike occurring at any location outside the safety template is less than $1x10^{-6}$. There are some indications in some of the Defence papers (eg in section 4.3 of Appendix A in HLA 2001) that the quoted probability refers to a restricted area (eg 400 m^2) where personnel may be located. If the latter interpretation is correct, actual probabilities of breaching the repository will be *higher* than those deduced in this review.

The safety templates deduced by Defence are not in general circular because they are likely to be elongated along the flight path of the weapon or the delivery aircraft. However, for simplicity we will initially assume a circular template and later consider the significance of non-circular templates.

The actual distribution of the probability of impact within the safety template is not known although Defence may have more detailed information. In the absence of knowledge of the actual distribution, estimates of likely probability ranges can be made from general considerations. Two estimates of probability will be considered for each weapon type based upon two different assumptions for the shape of the probability distribution. In the first case, we consider a normal distribution and in the second case the distribution is assumed to be uniform within the safety template. Use of the normal distribution is considered to be a reasonable approach to estimating the probability while the uniform distribution should assist in estimating limits.

3 Probabilities calculated using a normal distribution

For a missile aimed at a target, the probability of landing at a distance ***r*** from the target will, in general, be similar to the curve in figure A1.1. That is, the probability of landing close to the target is high and the probability falls away rapidly as the distance from the target increases. For this curve, the approximate position of the radius of the safety template is indicated on the diagram. A commonly used distribution that has these characteristics is the normal distribution.

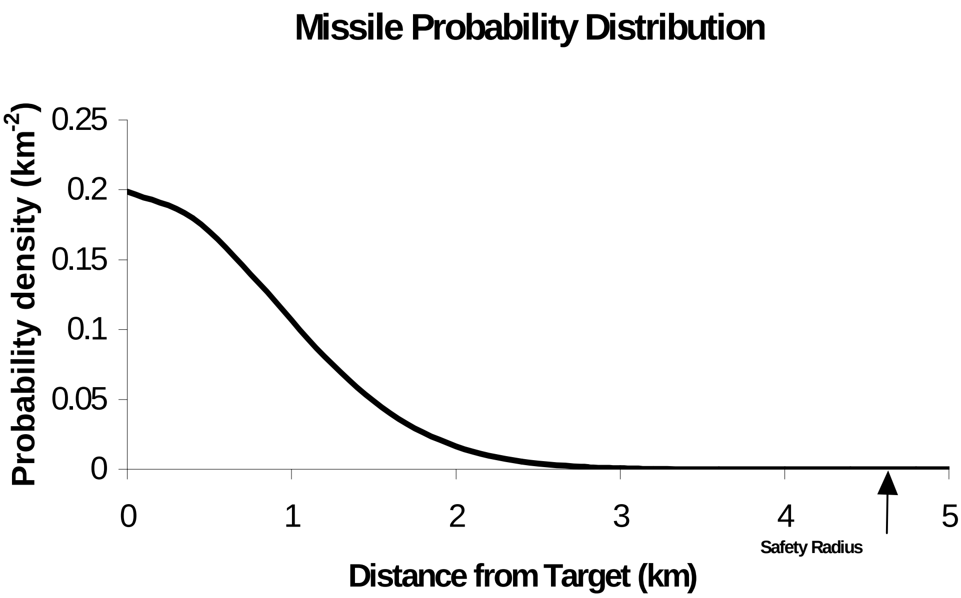


Figure A1.1 The distribution of missile strikes as a function of distance from the target assuming a normal distribution

For a normal distribution, the probability density of a weapon landing at a distance *r* from the target is given by

$$f(r) = (1/2\pi\sigma^2)\exp[-r^2/2\sigma^2]$$

and the probability that the weapon will land inside radius R is given by

$$P(r < R) = (1/2\pi\sigma^2)\int_0^R \exp[-r^2/2\sigma^2].2\pi r dr$$

Hence,

$$P(r < R) = 1 - \exp[-R^2 / 2\sigma^2]$$

The safety template for a weapon has a safety radius R_S at which the probability of landing outside R_S is 1×10^{-6}. Using this definition,

$$\exp[-R_S^2 / 2\sigma^2] = 10^{-6} \text{ and therefore } \sigma = R_S / 5.26 .$$

Using the data in table A1.1 for the template area for each weapon, the corresponding values of the template safety radius (R_S) and the standard deviation (σ) derived using the above equation for the three weapon types are given in table A1.2.

For these values of the standard deviation, the probability of landing in the repository is given by

$$P_R = (A_R / 2\pi\sigma^2)\exp[-R_R^2 / 2\sigma^2]$$

$$= (27.7 A_R / 2\pi R_S^2)\exp[-27.7 R_R^2 / 2 R_S^2]$$

where R_R is the distance from the target to the repository, A_R is the area of the repository and R_S is the safety template radius. If the number of weapons of a given type used each year in the WIR is *n*, then the annual probability of breaching the NRWR, P_B, is given by

$$P_B = nP_R$$

Table A1.2 The safety radius, standard deviation and annual probability for a breach of the NRWR for each weapon type using the assumption that weapon strikes are normally distributed within the safety tTemplate

Weapon type	Safety radius (km)	Standard deviation (km)	Annual probability of breaching the NRWR (y^{-1})
Ballistic weapon	2.8	0.53	1.2 x 10-7
Laser guided weapon	4.7	0.90	1.1 x 10-3
Standoff weapon	28	5.33	3.0 x 10-3

As stated above, Defence has provided data on the type and number of weapons used in the WIR. There are three targets identified in this area and DEST has noted (section 10.7.5 of the EIS) that weapons are predominantly fired at Range E. We have therefore adopted the conservative approach of assuming that Range E, nearest to the proposed repository site at 52a, is the sole target. Hence the distance to the repository, R_R, is assumed to be about 3 km for all weapons used each year. The effective area of the repository, A_R, is taken to be 0.09 km^2 as used by DEST and Defence. This takes into account possible travel by a missile underground after striking the ground surface and then breaching the repository.

The results obtained for the annual probability for a breach of the NRWR for the three types of weapon identified in table A1.1 are given in table A1.2. The probability distributions for each weapon type are shown in figure A1.2 and the position of the repository is indicated for comparison.

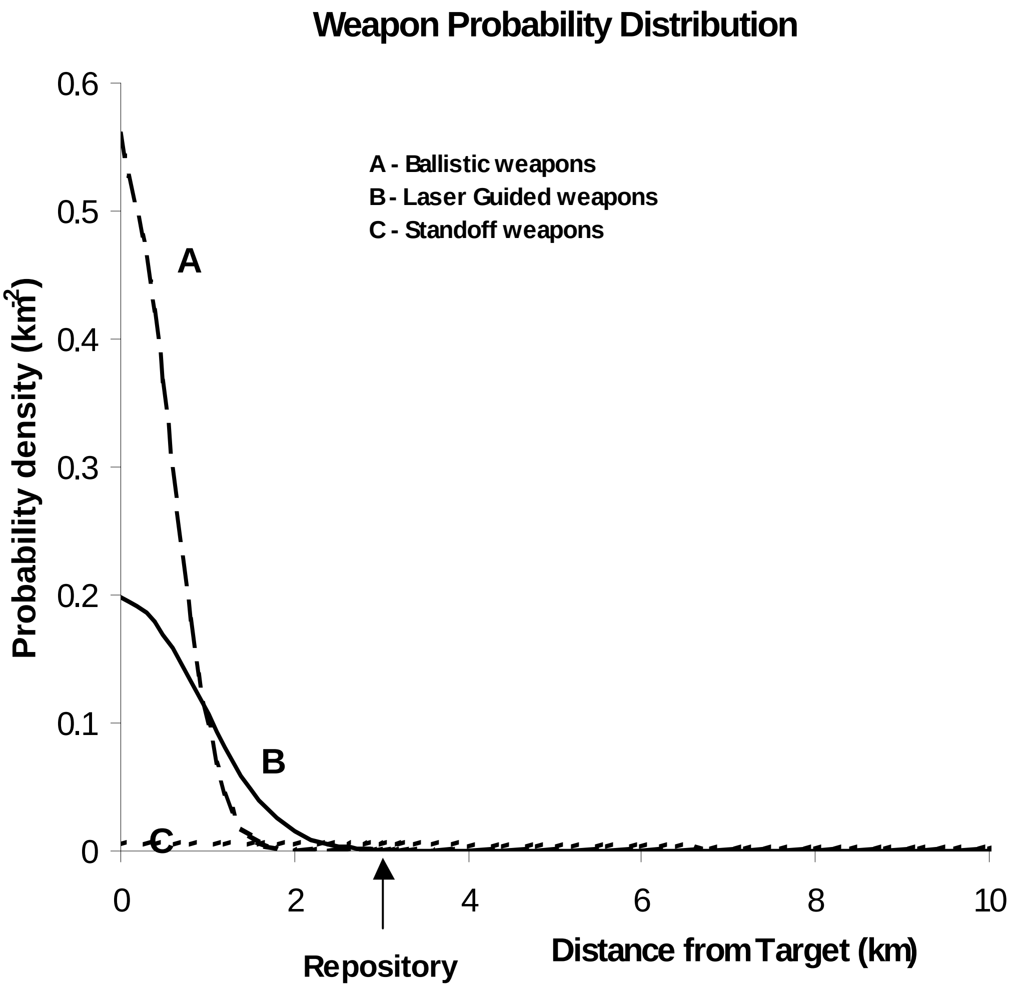


Figure A1.2 Normal probability distributions for each weapon type derived from the safety template areas provided by Defence. The position of the NRWR is indicated.

The results given in table A1.2 indicate that, for a normal distribution, the probability of a Ballistic Weapon striking the repository is extremely low. This is primarily because, for this weapon, the repository is outside the safety radius. It is also, however, attributable to the assumption that the safety template is circular. This latter effect needs to be investigated.

The Defence report (HLA 2001) provides some information on safety templates. Figure 3 of that report provides an illustration of an approximately rectangular template which, if applied to the template for Ballistic Weapons, would bring the repository well within the safety radius when the delivery trajectory is approximately along a line linking the target with the repository. Thus the probability of breaching the repository would be much greater than indicated in table A1.2.

While non-circular templates would also affect the results for laser guided weapons and standoff weapons, the effect would be much less than for ballistic weapons because, for these weapons, the values of the safety radius given in table A1.2 are greater than the distance from the target to the repository. We will, therefore, only estimate the effect of non-circular templates for ballistic weapons.

The ratio of the length of the rectangular template to its width is approximately 2.3:1 for the template given in figure 3 of HLA (2001). For a ballistic weapon safety template area of

25 km^2 (table A1.1) this ratio corresponds to a template length along the flight path of about 7.6 km. Using a safety radius of 7.6 km the probability that a ballistic weapon would land in the repository becomes 8×10^{-4}. However, using the above ratio of length to width of the template, one can estimate that the template length would encompass the repository for only 25% of possible flight paths. Hence our best estimate of the probability that a ballistic weapon would land in the repository reduces to 2×10^{-4}. Thus, for the number of ballistic weapons used in the WIR by Defence each year, 18, the corresponding annual probability of breaching the NRWR becomes 3.6×10^{-3}. This result is taken into account in the revised estimates of probability in table A1.3.

Table A1.3 Revised estimates of the annual probability of breaching the NRWR taking into account non-circular safety templates for ballistic weapons

Weapon type	Safety radius (km)	Standard deviation (km)	Annual probability of breaching the NRWR (y^{-1})
Ballistic weapon	2.8	0.53	3.6×10^{-3}
Laser guided weapon	4.7	0.90	1.1×10^{-3}
Standoff weapon	28	5.33	3.0×10^{-3}

4 Probabilities calculated using a uniform distribution

A simplified approach is often taken in risk assessment and is based upon the assumption of a constant (or uniform) probability out to a certain distance and then zero probability beyond that distance. In the current case, this approach would lead to the assumption that the probability is constant out to the radius R_s, which is the radius of the safety template, and is zero beyond R_s. Under this assumption, the probability function is given by

$$f(r) = (1/\pi R_s^2) \text{ for } r<R_S \text{ and}$$

$$f(r) = 0 \text{ for } r>R_S$$

Using this approach, the probability, P_B, of breaching the repository will be given by:

$$P_B = n.[A_R / \pi R_S^2] \text{ when } R_R < R_S \text{ and}$$

$$P_B = 0 \text{ when } R_R > R_S$$

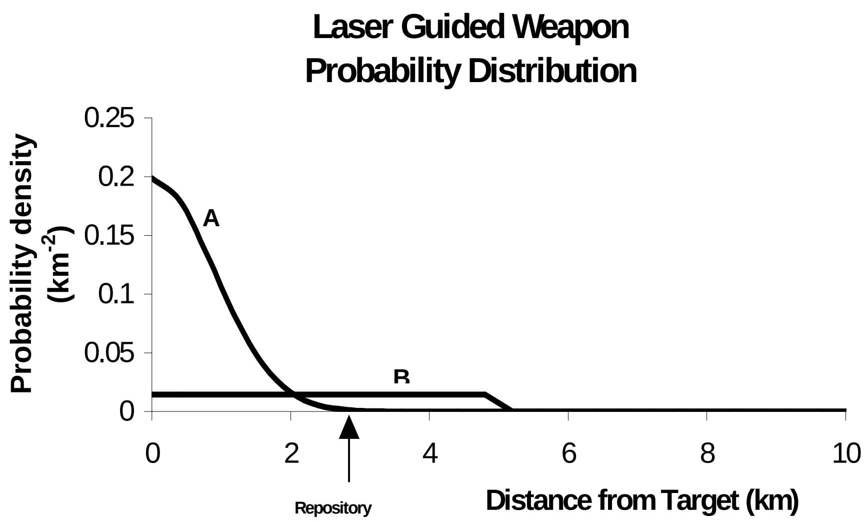
where n is the number of weapons used per annum that are capable of breaching the NRWR. The results obtained for the annual probability of breaching the NRWR are given in table A1.4 for the uniform distribution.

Table A1.4 The safety radius and the annual probability of breaching the NRWR for each weapon type using the assumption that weapon strikes are uniformly distributed within the safety template

Weapon type	Safety radius (km)	Annual probability of breaching NRWR (y^{-1})
Ballistic weapon	2.8	0
Laser guided weapon	4.7	2.2×10^{-2}
Standoff weapon	28	2.6×10^{-4}

5 Range of probabilities

The results obtained above for the two different assumed distributions can be used to provide estimates of the maximum and minimum annual probabilities of breaching the NRWR. This is illustrated in figure A1.3. The upper graph shows the normal and uniform distributions for the laser guided weapons and the position of the repository is indicated. It is clear that an estimate of the maximum likely probability will be obtained using the uniform distribution and an estimate of the minimum likely probability will be obtained using the normal distribution. The position is reversed for the standoff weapons (lower graph) where the normal distribution gives the best estimate of the maximum likely probability.



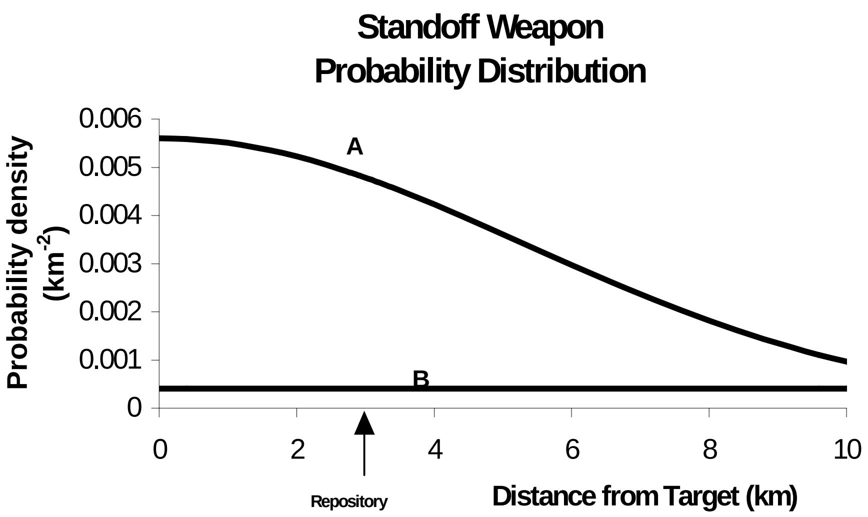


Figure A1.3 Probability distributions for laser guided weapons (upper graph) and standoff weapons (lower graph) assuming a normal distribution (curve A) and a uniform distribution (curve B). The probability of landing in the repository is the probability density at the location of the repository multiplied by the repository area.

Since the position of the repository is outside the safety template for ballistic weapons, we assume that the maximum likely probability is given by the normal distribution corrected for non-circular templates and the minimum likely probability is zero.

The maximum and minimum estimates of the annual probability of breaching the NRWR using this approach are shown in table A1.5 for each weapon type and the overall maximum and minimum values are obtained by summing the results for the individual weapons.

Table A1.5 Maximum and minimum estimates for the annual probability that each weapon type will breach the NRWR

Weapon type	Maximum probability of breaching NRWR (y^{-1})	Minimum probability of breaching NRWR (y^{-1})
Ballistic weapon	3.6×10^{-3}	0
Laser guided weapon	2.2×10^{-2}	1.1×10^{-3}
Standoff weapon	3.0×10^{-3}	2.6×10^{-4}
Total	2.9×10^{-2}	1.4×10^{-3}

6 Discussion and conclusions

In this review we have derived estimates of the probability that a weapon will breach the NRWR if it is located at site 52a within the Woomera Instrumented Range. These estimates have been based upon the use of two different probability distributions, the normal distribution and the uniform distribution. Use of the normal distribution is considered to be a reasonable approach to estimating the probability while the uniform distribution should assist in estimating limits.

The use of these distributions has enabled derivation of estimates for the maximum and minimum values of the probability per annum that the NRWR will be breached. It needs to be stressed that these values are only *estimates* and it would have been more satisfactory if information had been available on the actual distributions observed by Defence. It is, nevertheless, worthwhile examining the results to assess how reliable they might be.

The minimum probability estimate (table A1.5) is dominated by the normal probability result for laser-guided weapons with a smaller contribution from the uniform distribution for standoff weapons. It is clear from figure A1.3 (lower graph) that the uniform model gives a very low estimate of the probability for standoff weapons and, if these probability densities represent reasonable limits, it could almost be described as unrealistically low. From this consideration alone, it would appear that the annual probability of breaching the NRWR would be larger than about 5×10^{-4}. The normal probability result for laser-guided weapons is very sensitive to the actual value of the repository distance used. Thus, a 10% change in the value of R_R would change the probability by more than a factor of 2. Of greater significance, however, is the assumption of a circular template for the laser-guided weapon. As was seen for ballistic weapons, adopting a rectangular template gives rise to a significant increase in the calculated probability for a normal distribution. On balance, therefore, we believe that the value adopted for the minimum probability is not significantly overestimated.

The largest contribution to the maximum probability estimate is the uniform model estimate for laser-guided weapons. Examination of the graphs in figure A1.3 indicates that this estimate could be considered unrealistically large. However, even if this value were reduced to zero the estimate of the maximum probability would still be about 1×10^{-2} because of the contributions (see values in table A1.5) from the other weapon types. As discussed above, the normal distribution result for standoff weapons would appear to be a much more reasonable estimate than the result obtained from the uniform distribution so we would not expect the maximum probability to be much less than $3x10^{-3}$. On balance, therefore, we believe that the value given in table A1.5 for the maximum probability is not overestimated by a highly significant factor although it could be high by a factor of two or three.

Based on these considerations, it would appear that a reasonable range to consider for the annual probability of breaching the NRWR would be $0.1x10^{-2}$ to $2.0x10^{-2}$.

It needs to be stressed that these probability estimates could still be in error. For example, the true situation may be that most of the time the weapons used are highly accurate but when a mishap occurs the weapon can land anywhere within quite a large radius of the target. The probability distribution could then, for example, be the sum of two normal distributions: a dominant component (representing the normal highly accurate weapons) with a very small standard deviation (eg tens or hundreds of metres) and a second smaller component (representing the mishaps) with a standard deviation in the kilometre range.

We have checked this scenario by assuming, arbitrarily, that 90% of weapons are highly accurate and would have a negligibly low probability of striking the repository. The standard deviation for the second component was then calculated using the requirement that the safety template remains at the value specified by Defence for each weapon. Under this scenario we estimated that the annual probability of breaching the NRWR would be about $0.5x10^{-3}$. This value is slightly lower than, but close to, the minimum estimated probability using the previous analysis.

This analysis simply confirms that the current probability estimates could still be in error but, in the absence of any detailed information from Defence, we believe that the approach adopted here is appropriate in undertaking a risk assessment.

Overall, therefore, we conclude that it would be reasonable to proceed with risk assessments based upon the use of probabilities of breaching the NRWR from a missile strike in the range $0.1x10^{-2}$ to $2x10^{-2}$ (0.1% to 2%) per annum. The estimates obtained using two normal distributions tend to indicate that the real situation may be towards the lower end of this range.

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Appendix 2 Radiological dose estimates relevant to breach of the National Radioactive Waste Repository

1 Introduction

The risk associated with a potential breach of the National Radioactive Waste Repository (NRWR) by weapons being used by the Department of Defence in the Woomera Instrumented Range (WIR) requires the assessment of both the probability of an event occurring and the effect of the event should it occur. Appendix 1 of this report addresses the probability of breaching the NRWR from Defence activities. The radiological consequences of such a breach are reviewed in this Appendix.

Specifically, this Appendix reviews the assessments contained within Section 12.5 and Appendix E7 of the EIS for the National Radioactive Waste Repository with respect to radiological aspects of accidental intrusion caused by Defence activities. This review is by no means comprehensive. That is, the rationale and assumptions used to calculate the doses have been reviewed and the general parameters used in those calculations have been checked. In addition, the specific parameters for the three dominant radionuclides (in terms of potential contribution to dose) have been checked. These radionuclides are Co-60, Cs-137, and Am-241. The dose calculations for one of the scenarios involving breach of the NRWR (aircraft crash) have been reviewed. Conclusions have been drawn for other scenarios.

2 Scenarios considered in the EIS

The EIS considers two broad scenarios for accidental intrusion of the NRWR resulting from Defence activities: impact upon the repository by a missile and impact upon the repository by an aircraft. The common elements of these scenarios are summarised below:

- The repository contains the entire waste inventory (ie current plus future arisings over the next 50 years) at the time of the intrusion.
- The repository is not manned at the time of the intrusion; the NRWR management regime proposed in the EIS specifically excludes operational activities at the NRWR when Defence activities are underway on the WIR.
- The inventory of the repository is distributed homogeneously throughout the repository.
- The impact of a missile or aircraft penetrates the 5 m thick cover over the material stored in the repository and radioactive materials are homogeneously dispersed over the immediate impact area.
- Personnel who respond to the incident to retrieve the missile/aircraft are unaware of the radiological risk and take no radiological precautions.
- These personnel receive a radiation dose due to the inhalation and ingestion of radioactive materials and external gamma irradiation.

The only difference between the missile scenario and aircraft scenario is the time taken to retrieve the remains of the missile or aircraft. The EIS assumes an exposure time of 10 hours for the missile crash scenario and 25 hours for the aircraft crash scenario. The dose to the recovery personnel is calculated assuming no mixing of repository materials with inert soils. The calculation is then repeated assuming dilution of repository materials by a factor of 0.66 with inert soils.

Comment on the assumed scenarios

Personnel involved in the current review have no knowledge of the time typically taken to clear a crash site and complete on-site investigations. Hence, an assessment cannot be made on how reasonable are the assumed time periods of 10 hours and 25 hours periods for missiles and aircraft crashes respectively. However, it does seem reasonable that these times represent the maximum periods (ie one or two days) during which site activities by the recovery personnel could continue before it was noted that the crash site was on the repository and appropriate and effective radiation protection procedures were implemented. It has been assumed that the repository would be prominently and appropriately marked on the ground and that Defence would include the location of the NRWR in its internal procedures relating to the WIR.

The assumption that the NRWR contains the current inventory of radioactive materials plus the arisings from the next 50 years is clearly a worst-case assumption. Short-lived radionuclides will decay significantly over that period. Notably, Co-60 and Cs-137 ranked second and third in the repository inventory in terms of total activity have half lives of only 5 and 30 years respectively and hence will undergo significant decay in a 50 year period.

It is reasonable to consider a scenario where the radioactive material liberated from the repository as a consequence of the intrusion is homogeneously spread over the effected area. This was the approach adopted in the EIS. In reality, however, the radioactive material will not be homogeneously distributed throughout the volume of the repository. Consequently, liberated radioactive material will almost certainly not be homogeneously spread over the affected area.

Discrete radioactive sources with small physical dimensions (eg the size of a marble) will be stored in the repository. Some of these sources, such as those that were used for radiation therapy, industrial gauging or borehole logging may have quite high activities. These sources will be stored in the repository within shielded containers which will then probably be encased in concrete filled drums.

The EIS does not consider the scenario where a high activity gamma source is released from its packaging and shielding by the intrusion and is subsequently collected with the remains of the aircraft/missile by the recovery personnel. In this scenario, it is possible for recovery personnel to receive a radiation dose significantly larger than in the scenarios considered in the EIS.

For example, consider a hypothetical 37 GBq Co-60 source. The dose rate at 1 m from this source would be approximately 9 mSv/h. This is a large activity source compared to sources used in most industrial applications. However, very much higher activity sources previously used for irradiation or radiation therapy could be stored in the repository. Without a detailed knowledge of the process or work practices of the Defence recovery personnel, it is not possible to reliably estimate the radiation dose that would be received by personnel during the recovery of this hypothetical source with the remains of the missile/aircraft. However, if a person remained at a distance of approximately 1 m or less from this source in the absence of any radiation shielding for 1 hour or more, the radiation effective dose received could exceed 9 mSv due to external gamma irradiation from this source alone. It is recommended that the scenario involving the release of a high activity gamma source from its shielding and packaging by the impact of a missile or aircraft on the repository be further assessed.

3 Dose calculations

The EIS assumes that the radioactive material in the repository is homogeneously distributed throughout its entire volume. The specific activity of each radionuclide in this homogeneous mass is simply the total inventory of that radionuclide divided by the total mass of all materials within the inventory assuming a density of 1500 kg/m^3. For the purposes of this discussion, this homogeneous mass will be referred to as the repository contents.

The EIS calculates the radiation dose received by recovery personnel due to external gamma ray irradiation, ingestion and inhalation of radionuclides. External gamma irradiation dose is calculated assuming the individual is standing on an infinite slab of repository contents. The ingestion radiation dose is calculated on the basis that the recovery personnel ingests 12.5 mg of the repository contents per hour in the form of dust. The inhalation radiation dose is calculated assuming that the recovery personnel is continuously exposed to repository contents dust at a concentration in air of 1 mg/m^3.

Comments on methodology

The duration of exposure assumed in the calculations is considered appropriate. Similarly, the dust load of 1 mg/m^3 used in the calculations is also considered appropriate. As stated in the EIS, this dust load reflects a moderately dusty environment. The rate of dust ingestion used in the calculations appears reasonable although some justification for this figure would be desirable. However ingestion is a relatively insignificant exposure pathway in these scenarios so the magnitude of the rate of ingestion is not critical to the overall estimated dose.

A breathing rate of 1.2 m^3/hour is used in the calculations. This is the ‘standard’ breathing rate used in occupational scenarios assuming an 8 hour day comprised of 2.5 hours of ‘sitting’ at a breathing rate of 0.54 m^3/hour and 5.5 hours of ‘light exercise’ at 1.5 m^3 per hour. It could be argued that the ‘light exercise’ breathing rate would be more appropriate to the most exposed members of the recovery personnel. That being the case, the calculated radiation dose due to inhalation would increase by 25%, which, considering the considerable uncertainties inherent in the scenario and the dose calculations, is not considered significant.

The EIS uses the most conservative dose inhalation coefficients for Am-241, Cs-137 and Co-60, which would tend to overestimate rather than underestimate the actual dose that would be received under the exposure scenarios.

Overall, therefore, this review has concluded that the methods adopted in the EIS in estimating radiation doses that could arise following breach of the NRWR by a missile or aircraft were appropriate and conservative, noting that the scenario involving a high intensity gamma source should be considered.

Comments on dose calculations

Of the two scenarios considered in the EIS, the larger dose estimate occurs for the aircraft crash scenario. For this reason, a check was carried out on the dose calculation for this scenario.

Only a limited check was carried out using the aircraft impact scenario (ie exposure time = 25 hours) with no dilution of repository contents at time =0 (ie no decay of inventory) using the parameters and the equations quoted in the EIS for the most significant isotope in each exposure pathway. These are Co-60 for external irradiation and Am-241 for ingestion and inhalation.

The results of our calculations and the corresponding results reported in the EIS are summarised table A2.1.

Table A2.1 Comparison of current dose estimates with those given in the EIS for the principal isotopes contributing to each exposure pathway following an aircraft crash

Exposure Pathway	Isotope	Dose reported in EIS (Sv)	Current dose estimate using EIS parameters (Sv)	Ratio of dose reported in EIS to current dose estimate
External irradiation	Co-60	6.93×10^{-3}	1.58×10^{-10}	44×10^{6}
Inhalation	Am-241	3.91×10^{-5}	4.49×10^{-5}	0.87
Ingestion	Am-241	8.48×10^{-7}	9.75×10^{-7}	0.87

Because of the discrepancies between the dose estimates in table A2.1 and because the gamma ray dose rate factors (H_4 using the EIS nomenclature) needed to be checked against original references, an arrangement was made through EA and DEST for direct contact between staff of the Supervising Scientist and the consultant who carried out the calculations reported in the EIS. These discussions revealed that a number of errors occurred in the preparation of the dose estimates reported in the EIS. These included the following.

a) The dose calculations reported in the EIS were carried out under the assumption that the repository volume would be 11 500 m^3. In the EIS, however, the volume was 'rounded' down to 10 000 m^3 without any change to the total inventory of radionuclides. The decrease in the assumed volume causes an increase in the specific activity of the repository contents and a proportional increase in the dose estimate. The change in volume explains why the doses reported in the EIS for inhalation and ingestion are only 87% of the doses calculated in the current review.

b) The infinite slab gamma dose rate factors (H4 in EIS Appendices) listed in table E7.2 are all incorrect. Information provided in a footnote to the table states that the units of H4 are $Sv.h\text{-}1/Bq.kg^{-1}$ but the values listed for H4 are actually in units of $Sv.s\text{-}1/Bq.m^{-3}$. This correction accounts for a substantial part of the discrepancy for the Co-60 external radiation dose in table 1. However, after converting the H4 value to the correct units, and taking account of the lower specific activity (larger repository volume) assumed by the consultant, the dose calculated is still only approximately 11% of that reported in the EIS.

c) The spreadsheet used by the consultant to convert the infinite slab gamma dose rate factors from units of $Sv.s\text{-}1/Bq.m^{-3}$ to units of $Sv.h^{-1}/Bq.kg^{-1}$ mistakenly used a repository contents density of 14 000 $kg.m^{-3}$ instead of 1500 $kg.m^{-3}$. This accounts for the remaining discrepancy.

Table A2.2 provides a comparison between the dose reported in the EIS from the most significant isotope for each of the three exposure pathways for the aircraft impact scenario with the final dose that is calculated using the assumptions outlined in the EIS but after eliminating the three sources of error outlined above.

Table A2.2 Comparison of current dose estimates with those given in the EIS for the principal isotopes contributing to each exposure pathway following an aircraft crash but revised after eliminating the three sources of error identified

Exposure pathway	Isotope	Dose reported in EIS (Sv)	Current revised dose using EIS assumptions (Sv)
External Radiation	Co-60	6.93×10^{-3}	8.54×10^{-4}
Inhalation	Am-241	3.91×10^{-5}	4.49×10^{-5}
Ingestion	Am-241	8.48×10^{-7}	9.75×10^{-7}

The differences in table A2.2 for the inhalation and ingestion doses are small and do not affect overall conclusions on dose estimates in any significant way. As stated above, the difference has arisen because the repository volume assumed by the consultant does not match the volume printed in the EIS.

The difference between the EIS and the current review for the external radiation pathway is, however, significant. Our estimate of dose for this pathway is a factor of eight (8) lower than the doses calculated in the EIS. This is the combined effect of the small difference in the assumed repository volume and, more significantly, the use of the wrong density for repository material by the consultant. Since both the repository volume and the density would have been single entries in the consultant's spreadsheet, it is reasonable to assume that, for the aircraft/missile intrusion scenario, all external radiation doses need to be decreased by a factor of eight (8) and all inhalation and ingestion doses should be increased by 15%.

4 Risk coefficient

Appendix E7 of the EIS uses a risk coefficient of 0.06 per Sievert to convert effective dose to risk. This is the sum of the risk coefficient for the development of fatal cancer (0.05 per Sievert) and the risk coefficient for severe hereditary effects in the progeny of the exposed individual (0.01 per Sievert) for the whole population.

Comment on the risk coefficient

Strictly speaking, the risk coefficient for the whole population should not be applied. These risk coefficients were developed considering people of all ages including children. The recovery personnel will all be working adults, so the risk coefficients for adult workers should be applied. These are 0.04 per Sievert for the development of fatal cancer and 0.008 per Sievert for severe hereditary effects in progeny. If the doses calculated in the EIS were correct, the 'Conditional Risks' quoted in the EIS (ie risk due to the calculated radiation doses) would be high by approximately 25%. Of course this is somewhat academic considering the much more significant errors in the dose calculations previously discussed.

5 Conclusions

This Appendix contains a review of the assessments contained within Section 12.5 of the Main Report and Appendix E7 of the EIS for the National Radioactive Waste Repository with respect to radiological aspects of accidental intrusion caused by Defence activities. The review has not been comprehensive. Rather, the rationale and assumptions used to calculate the doses have been reviewed and the general parameters used in those calculations have been checked. In addition, the specific parameters for the three dominant radionuclides (in terms of potential contribution to dose) have been checked. The dose calculations for one of the scenarios involving breach of the NRWR (aircraft crash) have been reviewed.

The principal conclusions reached are:

a) Most aspects of the scenarios envisaged and described for breaching of the NRWR by a missile or aircraft and the methods used in dose calculations appear to be reasonable and, where appropriate, conservative.

b) However, the EIS did not consider the scenario where a high activity gamma source is released from its packaging and shielding by the intrusion and is subsequently collected with the remains of the aircraft/missile by the recovery personnel. In this scenario, it is possible for recovery personnel to receive a radiation dose significantly larger than in the scenarios considered in the EIS. This scenario should be considered further.

c) Errors and inconsistencies are present in the dose calculations reported in the EIS. The systematic nature of these errors and inconsistencies indicates that all the dose calculations related to aircraft/missile intrusion are similarly affected and result in an overestimate of the radiation dose by a factor of about eight (8).

d) In view of these errors and inconsistencies, it would be prudent to undertake a thorough check of all radiological calculations in Appendix E. This should be done even if site 52a is not preferred because the calculations in Appendix E not only refer to the intrusion scenarios considered here but also to normal operations of the NRWR and intrusion in the post-institutional control period wherever the NRWR is located.

e) The dose-to-risk conversion factor used in Appendix E7 of the EIS (0.06 per Sievert) is conservative because the value used refers to the whole population rather than working adults. It would have been more appropriate to use the risk coefficient for the development of fatal cancer for an adult, that is 0.04 per Sievert.

The additional assessments recommended in paragraphs (b) and (d) are presented in Appendix 3 and Appendix 4 of this report.

Appendix 3

National Radioactive Waste Repository

A Critique of Appendices E6, E7 and E8 of the EIS by the Environmental and Radiation Health Branch, ARPANSA

Report for the Office of the Supervising Scientist

1 Introduction

The Office of the Supervising Scientist has asked the Environmental and Radiation Health Branch of the Australian Radiation Protection and Nuclear Safety Agency to verify the calculations in Appendices E6, E7 and E8 in the Draft Environmental Impact Statement for the National Radioactive Waste Repository. The Appendices cover the following topics.

- Appendix E6 presents Calculation of Radiological Risks to Construction Workers
- Appendix E7 presents Radiological Risks from Missile or Aircraft Impact (in the operational phase)
- Appendix E8 presents the Post Institutional Control Risk Assessment.

This review includes:

- Checks of the radiation dose calculations to determine if they are numerically correct and provision of corrections where necessary.
- Comments on the appropriateness of the rationale, parameters and assumptions used in the scenarios for radiation dose calculations, and provision of corrected radiation dose estimates if any rationale, parameter or assumption is considered to be inappropriate.
- Estimates where possible of the radiation dose to personnel who unknowingly recover an unshielded high-activity gamma source with the remains of an aircraft/missile that has crashed onto the NRWR breaching its cover. Reference has been made to the intrusion scenarios described in Appendix E7 of the Draft EIS.

2 General comments

1. Source references for the input data including dose coefficients, dose rates, and environmental transfer parameters need to be clearly stated. In the absence of this information, we have found it impossible to directly check and verify the calculations underlying the results presented in these appendices.
2. There is a difficulty in understanding which inventory has been used in the calculations, and more importantly which inventory should be used. Some of the scenarios are stated to only produce significant doses well after closure of the repository. Was the appropriate inventory used (ie. were short-lived radionuclides neglected?). We cannot determine this, as our calculations do not exactly reproduce the results presented in the report, and the reasons for such discrepancies could not be clearly established.
3. In all cases, we have used the inventory given in the Draft EIS at time of closure (table E8.1) for purposes of checking the calculations given. We have also assumed that the

event took place the day after closure, which we assume corresponds to year 0 in the EIS. We note that a corrected inventory is given in the recently released Supplement to the Draft EIS (Appendix C, page 5, table C.1). Calculations should presumably be repeated using these revised data.

4. Have appropriate solubility classes been assumed for radionuclides used in the ingestion and inhalation dose calculations? For example, we query the use of the solubility class F for what should effectively be environmental ^{232}Th and ^{230}Th in the Appendix 6 calculations. Class S would seem more appropriate. It is unclear (without going to ICRP) which solubility classes have been assumed for the nuclides in table E8.6. This information should be clearly stated, and reasons given.

5. In the main report (Page 11, Figures 6 and 7) the area of the repository is given as 10,000 m^2 (100 m by 100 m) and the waste is assumed to be contained in several trenches 10 m deep, whereas in Figure E8.2 all the waste is shown to be in one trench described as 100 m x 10 m by 10 m deep (area 1,000 m^2 and volume 10,000 m^3). In most of the calculations of probability of occurrence, an area of 10,000 m^2 is used to calculate risks. The Draft EIS should clearly state the assumptions on which the calculations are based, together with the consequences of varying those assumptions.

6. There is a problem with the dose rate coefficient H_4 in E7.2 and E8.6. The units for H_4 are quoted as Sv h^{-1} (Bq kg^{-1})$^{-1}$. Although no reference is given for the external dose rate coefficient for ^{60}Co, the value taken from Eckerman and Ryman (1993) for an infinite slab is 8.68×10^{-17} Sv s^{-1} (Bq m^{-3})$^{-1}$ for material of density 1600 kg m^{-3}. The Draft gives it as 8.25×10^{-17} Sv h^{-1} (Bq kg^{-1})$^{-1}$.

7. In the tables the dose coefficients are listed as H_2 for inhalation and H_3 for ingestion. In the equations they are defined as the other way around. This error does not seem to have been propagated through the dose calculations.

3 Calculation of the Radiological Risk to Construction Workers

Section E6.1 Exposure Scenario calculates the radiation exposure to the trench construction workers arising from the presence of naturally occurring radionuclides in the local soils and rocks.

It is not appropriate to calculate the dose to workers from natural sources of radiation and assign this as occupational exposure or environmental impact. If terrestrial sources are to be assessed then all sources of exposure to natural sources should be included such as cosmic radiation. In any event the attempt to estimate terrestrial exposure underestimates it by about 70%.

In doing the calculations there is no indication which decay products are assumed to be in equilibrium with the nuclides listed. In that this is a stable undisturbed environment it would be reasonable to assume that ^{232}Th and ^{238}U are in equilibrium with their decay products. The calculation for external dose rate yields a dose rate of approximately 30% of terrestrial levels and this is predominantly from ^{226}Ra. The contribution from the ^{40}K and the decay products of ^{232}Th (particularly ^{228}Ac, ^{212}Pb and ^{208}Tl) have been ignored. The dose from this pathway should be approximately 8 μSv instead of 2 μSv.

For the inhalation and ingestion calculations it has also been assumed, without explanation, that the solubility of ^{232}Th and ^{230}Th are Class F and that everything else including ^{228}Th is Class S. This does not seem reasonable for environmental material. In BSS 115 thorium oxides and hydroxides are listed as Class S with an ‘f’ of 5 × 10^{-4} and all other compounds are Class M with an ‘f’ of 2 × 10^{-4}.

The calculation of the inhalation dose is dominated by the assumption of Class F solubility for ^{232}Th and ^{230}Th, giving doses 10 times higher for these nuclides. If they were assumed to be Class S the total dose from inhalation would be approximately 5 μSv instead of 15 μSv.

Again for ingestion high solubility has been assumed for ^{232}Th and ^{230}Th giving a dose conversion factor for these nuclides 2.5 times higher than would have applied for insoluble material. The doses for ingestion are less than 0.1 μSv and therefore do not contribute very much to the overall dose.

The estimate of dose is approximately right but should comprise a higher external dose component and a lower inhalation dose component.

4 Radiological Risks from Missile or Aircraft Impact in the Operational Phase

Missile Strike Scenario

This scenario calculates the dose to a recovery team that investigates the crash of a missile that strikes the Repository. It is assumed that the crash exposes radioactive waste and that no health physics precautions are taken. Table E7.2 gives the dose coefficients used, table E7.3 gives the repository parameters and table E7.4 gives the scenario parameters. The dust load parameters are conservatively high.

Unless the contaminated material is exposed by a missile or aircraft impact the only exposure pathway that will be relevant to these scenarios will be the external exposure pathway. Even that exposure pathway is not likely to be significant if the missile or aircraft penetrates less than 4 metres into the ground, as very little of the gamma radiation from the waste material will penetrate through more than 1 metre of soil.

The exposure pathways considered are external irradiation, inhalation and ingestion. The maximum doses calculated in the EIS for the 1st year were:

1. External irradiation – 3690 μSv
2. Inhalation – 17.5 μSv
3. Ingestion – 0.6 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 223 in one million
2. Annual risk (including probability of occurrence) – 0.005 in one million

External Dose

In the calculations of the dose to an individual, the inventory in table E7.1 was used and the γ-ray dose coefficients are as given in table 7.2 column H_4. For uranium the γ-rays for the decay products seem to have been included in the ^{226}Ra contribution but for ^{232}Th the ^{228}Ac does not seem to have been included and for ^{228}Th the ^{212}Pb and the ^{208}Tl do not seem to have been included.

The dose rate coefficients used in the ARPANSA calculations were taken from *External Exposure to Radionuclides in Air, Water, and Soil* (Eckerman and Ryman, 1993), table III.7. These coefficients give the effective dose rate for an adult standing on the ground and exposed to external radiation from soil of infinite lateral extent and contaminated uniformly to infinite depth. The coefficients quoted in the Draft EIS seem to be slightly lower. In Eckerman & Ryman the coefficients are in units of Sv s^{-1} (Bq m^{-3})$^{-1}$ whereas in the Draft EIS they are given as Sv h^{-1} (Bq kg^{-1})$^{-1}$, a factor of 5.4×10^6 times lower. It is apparent that this coefficient was modified before it was used in Equation 2 in E7.7 as the results are not in error by this amount.

If the calculations are done in accordance with Equation 2, assuming that the total volume of the waste is 10000 m^3, and that the inventory given in table E8.1 of the Draft EIS is uniformly distributed throughout this volume, the estimated external dose is 400 μSv for the case where no dilution is considered; this is approximately nine times lower than the value quoted in the Draft EIS. Increasing the volume by a factor of 10 (10 trenches) *without changing the inventory* would dilute the radionuclide concentrations in the waste and therefore reduce the doses by the same factor. However, for most scenarios, this will increase the probability of impact or intrusion into the active waste.

Inhalation

For the inhalation and ingestion calculations it has again been assumed that the solubility of ^{232}Th and ^{230}Th are Class F and that everything else including ^{228}Th is Class S. No reason has been advanced to support this. In BSS 115 thorium oxides and hydroxides are given as Class S with an 'f' of 5×10^{-4} and all other compounds are Class M with an 'f' of 2×10^{-4}. In any event (using class S for ^{232}Th and ^{230}Th) the calculation is dominated by ^{241}Am. Our estimate of the inhalation dose is 17 μSv (using the same assumptions as above for the inventory and total volume).

Ingestion

Class F coefficients are used for ^{90}Sr, ^{137}Cs, and ^{232} Th. The result is dominated by ^{241}Am, ^{226}Ra and ^{137}Cs. Our estimate of the ingestion dose is 1 μSv (using the same assumptions as above for the inventory and total volume).

Summary

- The equations in E7.7 of the Draft EIS are valid for concentration as well as for total activity.
- The Draft EIS does not state the source of the dose (rate) coefficients used for the external exposure calculations, nor the inhalation dose coefficients used for the dust inhalation calculations. This makes it impossible to fully compare the methodologies used here with those used in the Draft EIS.
- In Appendix E7, page 10, equations (2), (3) and (4), the time T_{excav} (the time over which contaminated material is exposed) is not the appropriate parameter. It should be replaced by T_{exp}, the time for which an individual is exposed to the contaminated material. The same comment applies to equations (5.5), (5.6) and (5.7) in Appendix E8.5.2.
- The most significant pathway is external dose and the estimate presented in the Draft EIS appears to be approximately 9 times too high. Thus the overall dose is about an order of magnitude too high, which follows through to the risk estimates.

Aircraft Crash

This scenario calculates the dose to a recovery team that investigates the crash of an aircraft that strikes the repository. The exposure time is taken as 25 hours. It is assumed that the crash exposes radioactive waste and that no health physics precautions are taken. Scenario parameters are given in table E7.5 and the exposure pathways considered are external irradiation, inhalation and ingestion.

The justification for choosing substantially different exposure times for the aircraft crash scenario over the 'errant missile' case should be stated.

Dose and Risk Calculations

1. External irradiation – 9220 μSv
2. Inhalation – 44 μSv
3. Ingestion – 1.6 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 560 in one million
2. Annual risk (including probability of occurrence) – 0.00005 in one million

The calculation is essentially the same as for the missile crash with the exception that the exposure period is 25 hours. The same comments re the dose conversion coefficients in the 'errant missile' scenario apply equally to this scenario. External dose is again the biggest contributor to overall dose and the value given in the Draft EIS is again higher than our estimate by about an order of magnitude. The results for inhalation and ingestion appear consistent with our estimates.

The dose rates calculated for the missile and aircraft crash scenarios should be the same for the case where the waste is penetrated. This is not noted in the Draft EIS, but the doses in tables E7.7 and E7.8 appear to satisfy this criterion.

5 Post Institutional Control Risk Assessment

Preamble

Appendix E8 of the Draft EIS considered the risks after institutional control has ended. A number of scenarios were considered that considered pathways associated with ground water, gas emissions, human intrusion and natural disturbances. Section E8.3 sets out the approach to assessment, and Section E8.4 the scenarios and critical groups. These are:

- E8.4.1 Borehole Drilling
- E8.4.2 Bulk Excavation
- E8.4.3 Road Building
- E8.4.4 Archaeological Dig
- E8.4.5 Long-term Exposure Following Excavation – Settlers and Nomads
- E8.4.6 Rocket or Weapon Crash – Settlers and Nomads
- E8.4.7 Aircraft Crash
- E8.4.8 Agricultural Land Usage Following Climate Change – Settlers and Nomads
- E8.4.9 Gross Erosion – Settlers and Nomads
- E8.4.10 Site Flooding – Settlers and Nomads
- E8.4.11 Consumption of Contaminated Waters
- E8.4.12 Effects of Gas

In making these assessments conservative assumptions have been made for every parameter. These include the probability of events occurring, the level of disruption should an event occur, the duration of occupancy for exposed individuals and the dose conversion factors used in dose assessments.

Equations for the calculation of doses are given in E8.5 together with parameter that quantify the scenarios in E8.4. In E8.6 results are given for each scenario for the time interval starting at closure of the repository and extending for 100 million years. In the assessment the dose at the critical time for each scenario is given, usually at the finish of institutional control at 200 years. An assessment of the associated risk is also given for both the conditional risk assuming that the event occurs and for the annual risk, which includes the probability per year of the event occurring.

The Borehole scenario assumes exposure to an isolated source, whereas the assessment for the next six scenarios is essentially the same considering exposure to broad scale contamination, with different exposure parameters and occupancy factors. These are Bulk Excavation, Road Building, Archaeological Dig, Long-term Exposure Following Excavation (settlers and nomads), Rocket or Weapon Crash (settlers and nomads) and Aircraft Crash. Agricultural Land Usage Following Climate Change, Gross Erosion and Site Flooding for settlers and nomads are also variants on the same scenario, which consider consumption of animal and plant foodstuffs. The last two scenarios are the Contaminated Ground Water and Gas Emission scenarios.

ARPANSA's assumptions

For the six broad scale scenarios, external, inhalation and ingestion doses are calculated. The calculation is similar to that for the missile and aircraft crash and the same comments that apply to the dose conversion coefficients for external dose, inhalation and ingestion apply equally to these scenarios. The problems with the dose coefficient for external dose calculations in E7 do not seem to have been repeated here as the doses reported are not ten times higher that expected.

To verify the validity of the calculations the doses were calculated for the first year after closure. It was assumed that the inventory in table E8.1 applied at closure and that the event occurred immediately afterwards and no radioactive decay has been allowed for. In doing this the result is never the same as in the Draft but are usually within 10 to 20% and in some cases the difference is 50%. Given the orders of magnitude conservatism in the assumptions, this is not significant but it is interesting that application of the equations to the parameters provided does not yield the same result. In some cases the equations are not complete in that an assumption, such as the nomadic peoples being present for 6 weeks per year, is not reflected in the equation but has been used in the calculation. The calculation for nomads has an occupancy factor of 0.66 but there is no parameter in table 8.11 or equations 5.8 and 5.9 to allow for the fact that nomads spend only 6 weeks a year at the site.

EIS Scenarios and Assumptions

E8.4.1 Borehole Drilling

The suggested exposure pathways (inhalation, ingestion and external irradiation) are agreed. The assumed 'frequency of occurrence' for borehole drilling of 10^{-4} boreholes a^{-1} in the remote and restricted Woomera Prohibited Area is considered a cautious estimate, although not unreasonable, based as it is on drilling of 1 borehole per square km per hundred years, and a repository surface area of 10,000 m^2.

E8.4.2 Bulk Excavation

The suggested exposure pathways (inhalation, ingestion and external irradiation) are agreed. The assumed 'frequency of occurrence' for bulk excavation (prior to a building development, for instance) of 10^{-4} excavations a^{-1} in a remote and restricted area such as the Woomera Prohibited Area is used for consistency, with a repository surface area of 10,000m^2.

E8.4.3 Road Building

The assumptions here are considered unrealistically conservative. It is unlikely that a team of road workers would spend 6 working days (50 hours) working on top of the completed repository trench. Equally, as the authors concede, within the institutional control period of the repository and for a considerable period thereafter, there is an essentially zero risk of road-building operations penetrating the 5 m cap that overlays the repository.

Nevertheless, in order to verify the calculations in the Draft EIS, the assumed parameters given in the Draft EIS are used.

E8.4.4 Archaeological Activity

If archaeologists of the future discovered the long-abandoned repository site, and considered the repository contents themselves of archaeological interest (as suggested), it is reasonable to assume that such learned archaeologists would possess the knowledge to protect themselves from exposure to radiation in their endeavours.

However, for purposes of verifying the EIS calculations, the assumptions of 200 hours exposure, pathways of inhalation, ingestion and external irradiation, and a probability of such an archaeological dig of 10^{-4} digs a^{-1} are used.

E8.4.5 Long-term Exposure Following Excavation

Acknowledging that two events are required to occur for this exposure scenario (*viz*. firstly an intrusion that exposes contaminated material on the surface, then a subsequent usage of that contaminated material by a resident population), the assumed probability of such exposure of 10^{-3} is used in the absence of any better guess.

It is agreed that risks associated with this scenario are long-term (for the duration of residence in the location of the exposed contaminated material) and hence estimation of annual risk is appropriate.

The suggested exposure pathways (inhalation, ingestion and external irradiation) are agreed.

E8.4.6 Rocket or Weapon Crash

For purposes of verifying the EIS calculations, the given probability of 3.0×10^{-5} 'disruptions' per year is used.

The time that an individual is exposed to the contaminated material (T_{exp}) should be considerably less than the time over which contaminated material is exposed (T_{excav}).

Unless the contaminated material (buried below 5 m of clean fill) is actually exposed, the only relevant exposure pathway is external irradiation. It seems unlikely in the 'errant missile' scenario that contaminated material would be exposed in any significant quantity.

The suggested exposure pathways (inhalation, ingestion and external irradiation) are otherwise agreed (assuming exposure of significant contaminated material).

E8.4.7 Aircraft Crash

The probability of an aircraft crash is estimated as 7.0×10^{-8} crashes a^{-1}.

The exposure time is taken as 25 hours, against 10 for the 'errant missile' scenario..

Again, unless the contaminated material (buried below 5 m of clean fill) is actually exposed, the only relevant exposure pathway is external irradiation. It seems unlikely in the 'aircraft crash' scenario that contaminated material would be exposed in any significant quantity.

The suggested exposure pathways (inhalation, ingestion and external irradiation) are agreed (assuming exposure of significant contaminated material).

E8.4.8 Agricultural Land Usage Following Climate Change (Settlers)

We have no better guesses and accept (for purposes of verifying the EIS calculations) the scenario and parameters given.

If the current dry and arid climate were replaced by a much wetter climate that would support agriculture, then leaching of radionuclides from the waste would increase. In addition, the only waste that would be accessible to plants or animals would be the material within the root zone. These points do not seem to have been mentioned.

E8.4.9 Gross Erosion

We have no better guesses and accept (for purposes of verifying the EIS calculations) the scenario and parameters given.

E8.4.10 Site Flooding

It is assumed in the EIS that:

1. the waste inventory is uniformly distributed throughout the repository;
2. the projected final trench volume is 10,000 m^3;
3. 'nomads' inhabit the area for a period of 6 weeks per year;
4. the probability of occurrence of 'bath-tubbing' is unity; and
5. for the 'Inhalation of resuspended material', 'radionuclides of interest partition strongly on to the solid'.

These assumptions seem reasonable, noting that point 4 appears to be a very conservative assumption.

It is suggested that the climatic conditions in the area are not expected to change in the next 10,000 years. However, for the estimation of radiological doses, site flooding is manifested 5000 years post-closure. Based on the climatic assumptions elsewhere in the EIS this assumption is conservative.

It is commented that contaminated water discharged to the ground surface will have a lower radionuclide concentration than in the waste, owing to dilution and dispersion in uncontaminated waters. And that surface soils and sediments become contaminated to a level equal to that in repository pore-water. These assumptions seem reasonable.

The exposure pathways considered were external, ingestion of dust/plants/animals and inhalation of dust. These exposure pathways seem reasonable. table E8.5 also indicates consideration of ingestion of water; however this pathway was not considered in the relevant sections E8.4.10, E8.5.9 and E8.6. Why is it that this exposure pathway was indicated in table E8.5 as being of relevance and was then not considered in the assessment?

E8.4.11 Consumption of Contaminated Waters

It has been assumed in the EIS that:

1. the waste inventory is uniformly distributed throughout the repository;

2. the projected final trench volume is 10,000 m^3;
3. a well would be drilled at the repository site during wetter climate conditions, during which the watertable may be sufficiently close to the ground surface to warrant the well; and
4. the frequency of well drilling will be 10^{-4} wells a^{-1}.

These assumptions seem reasonable. We note that cross-sectional area of the repository trench has been assumed (in the Draft EIS) to be 1,000 m^2 in this case.

It is suggested that the climatic conditions in the area are not expected to change in the next 10,000 years. However, for the estimation of radiological doses site flooding is manifested 5000 years post-closure. Based on the climatic assumptions elsewhere in the EIS this assumption is conservative.

It is stated that water extracted from a well drilled through the repository footprint will be used for drinking purposes only. However, these extracted waters could also be used for irrigation, domestic use and drinking water for animals. Each of these pathways could result in an increased dose.

E8.4.12 Effects of Gas

The assumptions used in this scenario are accepted as appropriately conservative.

E8.5 Radiological Dose Equations

The sources of the transfer and consumption parameters in tables E8.6 and E8.7 are not given. References should be provided.

Table E8.6 labels H_2 as inhalation and H_3 as ingestion. In other sections (for instance, E8.5.4, E8.5.7 and E8.5.10) these labels are reversed whereas they should be used consistently throughout.

The units for H_4 in table E8.6 are quoted as Sv h^{-1} (Bq $kg^{-1})^{-1}$. The external dose rate for ^{60}Co from Eckerman and Ryman for an infinite slab is 8.68×10^{-17} Sv s^{-1} (Bq $m^{-3})^{-1}$ for material of density 1600 kg m^{-3}. Multiplying by this density gives a dose rate coefficient of 5.0×10^{-10} Sv h^{-1} (Bq $kg^{-1})^{-1}$. From table E8.1, the inventory of ^{60}Co in the waste is estimated to be 1.15×10^{12} Bq. If the volume of the waste is 10000 m^3, then the volume concentration of ^{60}Co in the waste will be 1.15×10^8 Bq m^{-3}. If the density of the waste is assumed to be 1500 kg m^{-3}, the mass concentration of the ^{60}Co in the waste will be 7.67×10^4 Bq kg^{-1}. Multiplying by the appropriate dose rate coefficient gives a dose rate of approximately 38 μSv h^{-1}, which is consistent with the value derived earlier.

Therefore the values and units in this table are not consistent.

Also in table E8.6, does K_D equal the K_d referred to in section E8.5.4?

Table E8.7 does not indicate any consumption of root vegetables by nomads. This may not be appropriate for all population groups.

The forage intake rates quoted in table E8.7 appear to have been corrected for the fraction of intake that is likely to be contaminated, but this does not seem to be mentioned in the text. The fraction of contaminated food assumed in the calculations needs to be clearly stated and justified.

The source of consumption rates in this table is cited as ICRP 1975. However, in the references at the end of Appendix E.8, this reference appears to be to Reference Man (ICRP Publication 23), which would not be the correct source.

In Section E8.5.2 (Bulk Excavation), the time T_{excav} (the time over which contaminated material is exposed) in equations (5.5), (5.6) and (5.7) is not the appropriate parameter. It should be replaced by T_{exp}, the time for which an individual is exposed to the contaminated material.

Section E8.5.7 gives η_{plant} as 'kg dry weight soil per kg fresh weight plant'. This should be reversed.

Equation 5.19 should be referenced or the information enabling its derivation supplied.

Calculations and Doses

As a point of comparison, the doses and risks calculated by RWE Nukem for the year after closure are reproduced below, as are the estimated risks. The doses calculated by ARPANSA for comparison are all based on the inventory at time of closure of the repository (ie. at time zero, hence no decay factors required), and use the dose coefficients given in the EIS (even when these are not believed to be correct).

The ARPANSA calculations are compared with the results in the EIS for t = 0.

We note that the dose rates for all scenarios in which the waste is exposed should be the same, in the worst case.

E8.6.1 Borehole Drilling

Draft EIS calculations:

1. External irradiation – 1.3 μSv
2. Inhalation – 1.98 μSv
3. Ingestion – 0.09 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 0.2 in one million
2. Annual risk (including probability of occurrence) – 0.00002 in one million

Recalculation of doses by ARPANSA of the dominant nuclide for each exposure pathway (Co-60, Am-241, Am-241 for external, inhalation, and ingestion pathways respectively) provides results within 10% of the values given in the EIS.

E8.6.2 Bulk Excavation

Draft EIS calculations:

1. External irradiation – 118 μSv
2. Inhalation – 39.5 μSv
3. Ingestion – 0.34 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 9.4 in one million
2. Annual risk (including probability of occurrence) – 0.0009 in one million

Recalculation of doses by ARPANSA gives total (all nuclides included) doses of 188, 42 and 0.36 μSv for the external, inhalation and ingestion pathways respectively.

E8.6.3 Road Building

Draft EIS calculations:

1. External irradiation – 1030 μSv
2. Inhalation – 69 μSv
3. Ingestion – 3.0 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 66 in one million
2. Annual risk (including probability of occurrence) – 0.001 in one million

Recalculation of doses by ARPANSA gives total (all nuclides included) doses of 1647, 73 and 3 μSv for the external, inhalation and ingestion pathways respectively.

E8.6.4 Archaeological Dig

Draft EIS calculations:

1. External irradiation – 5880 μSv
2. Inhalation – 1980 μSv
3. Ingestion – 17 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 472 in one million
2. Annual risk (including probability of occurrence) – 0.047 in one million

Recalculation of doses by ARPANSA gives total (all nuclides included) doses of 9409, 2081 and 18 μSv for the external, inhalation and ingestion pathways respectively.

E8.6.5 Long-term Exposure to Future Settlers Following Excavation

Draft EIS calculations:	Settlers	Nomads
1. External irradiation	34,100 μSv	7,900 μSv
2. Inhalation	229 μSv	53 μSv
3. Ingestion	32 μSv	184 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 2060 in one million (settlers)
2. Annual risk (including probability of occurrence) – 2 in one million (settlers)
3. Conditional risk (if the event occurs) – 448 in one million (nomads)
4. Annual risk (including probability of occurrence) – 0.5 in one million (nomads)

Recalculation of doses by ARPANSA gives total (all nuclides included) doses of 54400, 241 and 33.6 μSv for the external, inhalation and ingestion pathways respectively for settlers. For nomads, the respective doses are 12519, 55 and 199 μSv.

E8.6.6 Rocket or Weapon Crash

Draft EIS calculations:	Settlers	Nomads
1. External irradiation	10,700 μSv	1,230 μSv
2. Inhalation	721 μSv	83 μSv

3. Ingestion 10 μSv 29 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 690 in one million (settlers)
2. Annual risk (including probability of occurrence) – 0.02 in one million (settlers)
3. Conditional risk (if the event occurs) – 81 in one million (nomads)
4. Annual risk (including probability of occurrence) – 0.002 in one million (nomads)

Recalculation of doses by ARPANSA gives total (all nuclides included) doses of 17172, 760 and 33.2 μSv for the external, inhalation and ingestion pathways respectively for settlers. For nomads, the respective doses are 1976, 87 and 3.8 μSv.

Detailed calculations are presented in Annex 1 below.

E8.6.7 Aircraft Crash

Draft EIS calculations:

1. External irradiation – 740 μSv
2. Inhalation – 49 μSv
3. Ingestion – 2.1 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 47 in one million
2. Annual risk (including probability of occurrence) – 0.000003 in one million

Recalculation of doses by ARPANSA gives total (all nuclides included) doses of 1176, 52 and 2.3 μSv for the external, inhalation and ingestion pathways respectively for recovery workers.

E8.6.8 Agricultural Land Usage Following Climate Change (Settlers)

Draft EIS calculations:

1. External irradiation – ≤850 μSv
2. Inhalation – 57 μSv
3. Ingestion – 860 μSv (not including ingestion of water or dust)

The figure for external irradiation can only be calculated as a range as the dose due to this particular pathway is not provided in the EIS.

The calculated risks were:

1. Conditional risk (if the event occurs) – 106 in one million
2. Annual risk (including probability of occurrence) – 106 in one million

NB. In the EIS (tables E.26 and E8.27), the total dose is greater than (ie. not equal to) dose(inhalation) + dose(ingestion of plants) + dose(ingestion of meat).

In table E8.26 (t = 0) the difference between the total dose and the sum of the doses from inhalation, ingestion of plants and ingestion of meat is almost a factor of two higher than the largest of these three doses. This suggests that the most important exposure pathway may be a pathway that is not included in the table, but there is no discussion of this in the EIS.

The same comment applies to table E8.27 (t=0).

E8.6.9 Gross Erosion

Draft EIS calculations for settlers:

1. Inhalation – 5.7 μSv
2. Ingestion – 86 μSv (not including ingestion of water or dust)

The calculated risks were:

1. Conditional risk (if the event occurs) – 14 in one million
2. Annual risk (including probability of occurrence) – 14 in one million

The same comment applies to tables E8.28 (t=0) and E8.29 (t=0) in the EIS as for the agricultural land usage scenario. The total dose is considerably larger than the sum of the doses from the three pathways included in these tables, and there is no discussion of the discrepancy.

E8.6.10 Site Flooding

Draft EIS calculations for settlers:

1. Inhalation – 40 μSv
2. Ingestion – 602 μSv (not including ingestion of dust)

The calculated risks were:

1. Conditional risk (if the event occurs) – 74 in one million
2. Annual risk (including probability of occurrence) – 74 in one million

The same comment applies to tables E8.29 (t=0) and E8.30 (t=0) as for the agricultural land usage scenario. The total dose is considerably larger than the sum of the doses from the three pathways included in these tables, and there is no discussion of the discrepancy.

The inhalation dose to nomads in table E8.31 is consistent with that calculated for a different time span for settlers in table E8.30.

Section E8.6.10 says, 'the most important exposure pathway is ingestion of meat'. table E8.30 for settlers shows this to be incorrect. At 5000 years, the dose is larger for ingestion of plant materials.

In section E8.6.10, after assuming that site flooding *will* occur, and then deriving a risk larger than the level of 1×10^{-6} a^{-1}, the EIS states that 'the degree of belief associated with the occurrence of this scenario will be somewhat less than unity, and as such the individual risk is likely to be below the risk target'. The words 'the occurrence of this scenario will be somewhat less than unity' are equivalent to 'site flooding *may* occur', which contradicts the original assumption. The probability of site flooding under current climatic conditions could be used as a basis for this scenario.

For inhalation, where ^{241}Am is dominant, we calculate 1.56×10^{-4} Sv a^{-1} compared with 3.54 $\times 10^{-5}$ Sv a^{-1} (but with difficulties in knowing what values were used in the Draft EIS for several of the input parameters). Making reasonable assumptions all through the calculation, we obtain quite different values from those in the Draft EIS for consumption of food.

E8.6.11 Consumption of Contaminated Waters

Draft EIS calculations:

1. Ingestion – 4,900 μSv

The calculated risks were:

1. Conditional risk (if the event occurs) – 294 in one million
2. Annual risk (including probability of occurrence) – 0.3 in one million

In section E8.6.11, at 5000 years, the dose from ingesting (drinking) water should be 3.11×10^{-3} Sv a^{-1}, with ^{238}U contributing approximately 89% of the total. This gives Risk(drinking water) = 1.9×10^{-8} a^{-1}. The Dose(drinking water) value used in the Draft EIS calculation was incorrectly derived from the dose due to the dominant nuclide (^{238}U) at repository closure.

Without knowing the values used in the Draft EIS for rate of water consumption and the average concentrations of radionuclides in ingested waters (or the assumptions made to estimate these), it is not possible to verify the EIS calculations.

E8.6.12 Effects of Gas

Radon

Appendix E8.8.5

The derivation of the expression for the radon flux is not self-consistent. It is assumed that the source is of finite horizontal extent and that there is no horizontal component to the radon flux. These two assumptions are mutually incompatible.

The only way that the radon flux will have no horizontal component is if the ^{226}Ra concentration is horizontally homogeneous, and this will not be the case if the source (ie. the buried waste) is assumed to be of finite horizontal extent.

If it is desired to estimate an upper limit to the effect of radon exhalation above the waste, it can be assumed that the waste is horizontally infinite in extent. The approach used by Hart et al. (1986) and O'Brien et al. (1995) can then be adopted. Since a house built on top of the waste will then have a floor area much smaller that the horizontal area of the buried waste, no significant error will be introduced into the estimate of the indoor radon concentration, and the estimated radon concentration will be a true upper limit.

The value for the radon diffusion coefficient given in the Appendix (page 70) should be referenced.

Some further detailed comments are presented below in Annex 2.

E8.9.1 Groundwater Pathway

It is assumed that the water in the aquifer below the proposed waste site is potable, for purposes of analysis. The preliminary studies on the site should have clearly shown whether the water is or is not potable. If the water is not potable then the EIS should clearly state this and point out that the aquifer beneath the proposed site cannot be connected to any other aquifers in the area that bear potable water. Over geological time-scales the water in all connected aquifers in the area of the proposed site would have the same characteristics. If there is no aquifer below the proposed site, then the EIS should clearly point this out, and no further discussion is necessary.

E8.9.2 Analysis of Groundwater Pathway

The equations used here are agreed.

6 Conclusions

The presentation of the assessment makes it very difficult to follow the argument for each scenario. The tables of parameters are separated from the equations, no justification is presented in many cases for the equations that have been used, and assumptions are not stated clearly.

We have consistently been unable to reproduce the results presented in the EIS exactly, and we presume that this is because of our uncertainty as to how the EIS treated the inventory decay during operation of the site. Other parameters such as external dose coefficients, rate of water consumption, radionuclide concentrations in soil, water-filled porosity of spoil etc. are not specified and make specific calculations difficult to verify.

The source of the data used in the Draft EIS for the external dose conversion factors should be clearly stated.

The largest discrepancies in dose calculations between our estimates and those in the Draft EIS appear to be in the missile and aircraft crash scenarios, where calculated doses in the Draft EIS were higher by factors of about 10. The exact source of these discrepancies is unclear because of our uncertainty about several of the input parameters. However, RWE Nukem had advised of a mistake of a factor of 10 in the soil density parameter in some of these calculations. Exactly how this error was propagated, and how it affected the estimated doses, is not clear without access to the details of the calculations.

Forage intake rates for cattle and sheep should be justified.

A dose estimate for a further scenario (contact with an intact gamma-emitting source) is presented below in Annex 3.

References

Eckerman, K.F., Ryman, J.C. Federal Guidance Report No. 12: External Exposure to Radionuclides in Air, Water, and Soil. USEPA, Washington D.C.; 1993.

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International Atomic Energy Agency. Safety Series No. 115: International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources. IAEA, Vienna, 1996.

Langroo, M.K., Wise, K.N., Duggleby, J.C., Kotler, L.H. A nation-wide survey of ^{222}Rn and gamma radiation levels in Australian homes. Health Physics; 61(6):753-761; 1991.

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United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, effects and risks of ionizing radiation. New York: United Nations; 1988.

Webb, D.V., Solomon, S.B., Thomson, J.E.M. Background Radiation Levels and Medical Exposure Levels in Australia. Radiation Protection in Australia; 16:25-33, 1999.

Annex 1: ARPANSA Dose Estimates for Missile Strike Scenario and Aircraft Crash

E8.6.6 Missile Strike

Estimation of external dose (ARPANSA)

The inventory in table E8.1 was used – decay products were added to the inventory where considered appropriate

The dose rate coefficients, in units of Sv s^{-1} (Bq $m^{-3})^{-1}$, were taken from table III.7 in Eckerman and Ryman (1993). These coefficients give the effective dose rate for an adult standing on the ground and exposed to external radiation from soil of infinite lateral extent and contaminated uniformly to infinite depth. To change to units of Sv s^{-1} (Bq $g^{-1})^{-1}$, the dose rate coefficients quoted in Eckerman and Ryman should be multiplied by the assumed density to give dose rate coefficients in units of Sv s^{-1} (Bq $g^{-1})^{-1}$.

The total volume of waste was assumed to be 10000 m^3. Including appropriate radioactive decay products, estimated external dose for an adult exposed for 10 hours will be approximately 400 µSv, or a dose rate of approximately 40 µSv h^{-1}.

The results showed that ^{60}Co accounts for approximately 90% of the dose, for the given inventory. The external dose is approximately a factor of 10 lower than that given in the Draft EIS. As the Draft EIS does not clearly explain how the results were calculated in the Draft EIS, it is extremely difficult to establish the reason for this large discrepancy.

Inhalation Dose (Dust)

The same inventory and waste volume were used. The dose coefficients (Sv Bq^{-1}) were taken from BSS-115 (IAEA, 1996), table II-III. Doses were calculated for particle diameters of 1 µm and 5 µm. Where more than one coefficient was given for the same nuclide, the higher value was chosen was generally chosen, but the value for the slowest dissolving case was always chosen. The results indicate that for an assumed breathing rate of 1.5 m^3 h^{-1}, an exposure time of 10 hours, a waste (mass) density of 1500 kg m^{-3} and an atmospheric dust loading of 1 mg m^{-3} (the nuisance dust limit) the doses would be approximately 30-40 :Sv, comparable with the external doses. The breathing rate used here is higher than in the EIS because it is assumed that the exposed individuals would be workers.

It is not always clear in BSS-115 whether the quoted dose coefficients include the contribution from radioactive progeny. However, in many cases the dose coefficients for the progeny are not given in table II-III, so it is assumed that they have been included in the dose coefficient for the parent.

E8.6.7 Aircraft Crash

The dose rates for this scenario should (in the worst case) be the same as for the missile impact scenario. Therefore any differences in the estimated risk factors should be due to differences in exposure time and in the probability of the event occurring.

Parameter	RWENukem	This report	Check
inventory	table E8.1	table E8.1	yes
cover	nil	nil	yes
soil density	1500 kg m^{-3}	1500 kg m^{-3}	yes
exposure time	10 h	10 h	yes
dose rate coefficients	?	Eckerman and Ryman, 1993	uncertain(1)
external dose	3.69 mSv	0.42 mSv	no(2)
dust loading	1 mg m^{-3}	1 mg m^{-3}	yes
breathing rate	1.2 m^3 h-1	1.5 m^3 h^{-1}	no(3)
inhalation dose	0.044 mSv(4)	0.03 mSv (5 micron)	yes
		0.04 mSv (1 micron)	yes

(1) As the source of the dose rate coefficients used in the Draft EIS is not cited it is not possible to directly check the estimates of external dose. The doses estimated in this work were calculated from first principles.

(2) This discrepancy is significant. However, because the details of the calculations are not presented in the Draft EIS, it is impossible to determine the reasons for the discrepancy without more information.

(3) In this work the higher breathing rate has been assumed, because the value of 1.2 m^3 h^{-1} is usually assumed for a light exercise regime, and this is unlikely to be the case for this scenario.

(4) The Draft EIS makes no mention of the effects of particle size on the dust inhalation calculations.

Annex 2: ARPANSA Comments on Radon

Average atmospheric radon concentrations are of the order of 10 Bq m^{-3} in Australia and average indoor radon concentrations are of the same order (Langroo et al., 1991). This leads to doses from inhalation of radon progeny of the order of 0.5 mSv per year (Webb, Solomon and Thomson, 1999). The world wide average radon exhalation rate is approximately 0.02 Bq m^{-2} s^{-1}, UNSCEAR, 1988) and the corresponding concentration of ^{238}U is approximately 40 Bq kg^{-1}. Using the equation $C = \frac{E}{(\lambda_V + \lambda)h}$ (where E is the exhalation rate and h is the height of the building) suggests that this would produce a concentration (for a house with a ceiling height of 3 m and a ventilation rate of 2 h^{-1}) of 12 Bq m^{-3}, which is certainly consistent with measurements in Australian homes.

The inventory in table E8.1 suggests that the concentration of ^{238}U in the waste will be approximately 1.2×10^{11}Bq ÷ 10000 m^3 ÷ 1500 kg m^{-3}, or 8000 Bq kg^{-1}. This is 200 times the present average concentration of ^{238}U in soil. Using this value as the worst case for the concentration of ^{226}Ra in the waste gives a maximum enhancement factor of approximately 200 for the effect of the waste (assuming that no other parameters are changed), which in turn gives worst case doses from inhalation of radon progeny of the order of 100 mSv a^{-1}. This is consistent with the dose(s) given in the EIS, but the argument presented in the EIS is not convincing. More detail is required.

Assuming that the choice of site for the construction of a house in the vicinity of the proposed repository is truly random (ie. all possible locations for the house are equally likely), then the estimated risk factor is likely to be low, but will be difficult to quantify.

Annex 3: Intact Gamma Sources

During scenarios such bore hole drilling, archeological dig or missile impact there is a small possibility that an intact source or a mostly intact source could be exposed. Prime candidates for this would be industrial gauges containing sources such as ^{60}Co and ^{137}Cs. Such sources are commonly 10GBq in activity and as the inventory for the repository is given as just over 1000 GBq for each of these nuclides these could be hundreds of such sources in the repository. The probability of exposure is very dependent on the conditioning of the waste before placement in the repository. If such gauges are concreted into steel drums then the source is protected by those barriers and by the gauge itself. The sources are usually encapsulated in stainless steel capsules that have been certified as sealed sources when manufactured. Road builders or others digging on the site are more likely to uncover intact drums and not come into contact with exposed sources. Borehole drillers may penetrate a drum and missile impact may expose one. Both events are very unlikely.

The dose rate from such sources could range from 1 to 10 mSv h^{-1} at 1 metre. Allowing 1 hours exposure for borehole drillers and 10 hours of exposure for missile recovery workers yields doses of 1 to 10 mSv for borehole drillers and 10 to 100 mSv for recovery workers. When the probability of occurrence is factored in (10^{-5} for borehole drillers and $3x10^{-5}$ for a missile crash) the risks are below one in a million. Those risks are for the occurrence of the event and do not take into account the risk of exposing a source should such an event occur. After those risks are factored in the annual risk would be even lower. Given the half-lives of ^{137}Cs and ^{60}Co these risks would drop significantly between closure and removal of institutional control.

Appendix 4 Assessment of general radiological exposure associated with the National Radioactive Waste Repository

1 Introduction

At the request of the Supervising Scientist, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) has conducted a thorough review of the radiological dose estimates reported in the EIS for the National Radioactive Waste Repository (NRWR). The results of this review are presented in Appendix 3 of this report. The radiological dose estimates were used in the EIS to assess the significance of a number of potential radiological exposure pathways that could arise during construction and operation of the NRWR, during the Institutional Control period and in the long term. In this Appendix, we review the assessment of these potential exposure pathways.

2 Specific activity of the repository contents

The ARPANSA report (Appendix 3) identifies an apparent inconsistency in the EIS in relation to the area and volume of the repository that should be considered. It notes that the surface area of the repository is assumed to be 10 000m^2 or 100 m by 100 m in calculating the probability of intrusion, whilst the dimensions for the purpose of radiation dose calculations are assumed to be 100 m long by 10 m wide by 10 m deep, corresponding to a surface area of only 1000 m^2. Our assessment of this apparent discrepancy follows.

It is known that the entire radioactive inventory of the repository will be in trenches or boreholes within a 100 m by 100 m area under at least 5 m of cover. However, the actual dimensions of those trenches, their layout and number are not known at this stage. Consequently, for all human intrusion scenarios considered except one, the EIS assumes that the area of the repository is the entire 100 m by 100 m area, ie 10 000 m^2. We consider this to be a reasonable and conservative approach in the absence of detailed information on the dimensions, layout and number of trenches or boreholes.

The general approach used in the EIS for radiation dose calculations is to assume that the radioactive inventory of the repository is distributed homogeneously throughout the entire volume of the repository. The concentration of radioactive isotopes (the specific activity) within that volume is then simply calculated by dividing the total radioactive inventory by the volume of materials in the repository, assuming a certain density. However, in calculating the specific activity of radioisotopes in the repository, the EIS assumes that the entire inventory is in a *single* trench 100 m long, 10 m wide and 10 m deep (covered by 5 m of soil) with a surface area of 1000 m^2 and total volume of 10 000 m^3.

The Main Report of the EIS states that the repository would contain a number of disposal trenches and boreholes indicating that the total active volume of the repository will be greater than 10 000 m^3, with a maximum value of 100 000 m^3. Consequently, the specific activity of the repository contents will actually be less, by up to a factor of ten at the extreme, than that used in the radiation dose calculations. As the radiation doses calculated are in almost all cases directly proportional to the specific activity assumed for the repository contents, they could also be high by up to a factor of ten.

The ARPANSA report also notes that an updated inventory appears in the Supplement. We have compared the updated inventory with the inventory used for radiation dose calculations that appears in the Appendix E7. There are differences, but those differences do not translate to changes in radiation dose estimates significant enough to alter our conclusions.

Consequently, we have used the dose calculations presented in the Appendices and in the ARPANSA report in our assessment.

3 Assessment of radiological risks to construction workers

Appendix E6 calculates the radiation dose received by workers during the construction of the trenches at the NRWR. These radiation doses are natural background radiation doses. Consequently, it is not appropriate to compare the dose and risk estimates calculated in Appendix E6 with dose or risk constraints or targets. Infact, the calculations in Appendix E6 need not have been done at all.

Nonetheless, the radiation dose calculations in Appendix E6 have been checked by ARPANSA. The overall conclusion is that the radiation doses are extremely low, as would be expected considering that they are natural background doses. However, ARPANSA has identified errors in Appendix E6. For example, the contribution to the dose due to external irradiation from potassium-40 and the decay products of thorium-232 have not been included. Hence, the estimate of radiation dose from this pathway is low by a factor of about four (4). However, Appendix E6 assumes, without any justification, that certain radionuclides present naturally in the soils are in a soluble form, which does not appear reasonable for environmental materials which are normally considered insoluble. This results in an overestimate of dose due to inhalation of dust by a factor of three (3). Overall, ARPANSA estimates a dose of approximately 13 μSv to construction workers compared with 15 μSv calculated in Apendix E6 of the EIS. These estimates are extremely low.

As indicated previously, Appendix E6 should be considered an academic exercise only. It is no more required than radiation dose assessments for construction workers employed on building sites in central Sydney.

4 Assessment of radiological risks from missile or aircraft impact

The ARPANSA assessment of Appendix E7 confirms the errors identified in Appendix 2 of this report. The net effect of these errors is that the radiation doses reported in Appendix E7 are high by a factor of about eight (8) if the assumptions used in the EIS (including a repository volume of 10 000 m^3) are correct.

Appendix 2 of this report notes that the most conservative inhalation dose coefficients are used for Am-241, Co-60 and Cs-137. ARPANSA notes that this conclusion also applies to other radioisotopes. In particular, different isotopes of thorium are assigned different solubility classes such that the largest dose inhalation coefficient for each isotope is always applied. Yet, the chemical behaviour including the solubility of different isotopes of the same element is effectively identical. Thus the EIS takes a very conservative approach, using parameters that consistently maximise the radiation doses calculated.

As discussed in section 4.1 above, the actual volume of the repository will probably be larger than that used in radiation dose calculations in Appendix E7. Thus, the specific activity of radioisotopes in the repository and the doses arising from an aircraft or missile crash would be smaller by up to a factor of ten. This is an additional factor of conservatism to that discussed in the previous paragraph.

In summary, the rationale employed in the EIS to calculate radiation doses to missile or aircraft recover personnel during the institutional control period of the repository is appropriate. However, a significant error exists in the radiation dose calculations resulting in calculated doses which are high by about a factor of eight (8). Further, the assumptions and parameters used in these calculations are chosen such that radiation doses are maximised. These introduce additional factors of conservatism. Consequently, the actual dose received by aircraft or missile recovery personnel if the scenarios assessed in the EIS occurred, would likely be between one and two orders of magnitude lower than those reported in the EIS.

4.1 Assessment of a high activity gamma source

Following our recommendation that the scenario involving the release of a high activity gamma source from its shielding and packaging by the impact of a missile or aircraft on the repository be further assessed, ARPANSA undertook calculations of dose to the recovery personnel. In summary, doses to recovery personnel in the range of 10 mSv to 100 mSv were calculated. The variability arises from the many uncertainties associated with the work practices of the recovery personnel and the activity of the source itself. Simple parameters such as the period of the exposure and the distance of the personnel from the source can alter the dose by an order of magnitude or more.

What is much better known is the physical security of these sources within the repository. It should be noted that sources of this type would be required to be contained within very robust packaging incorporating radiation shielding to enable safe handling and transport. High activity gamma sources are required to be transported in containers that can withstand severe transport accidents without loss of containment. Waste conditioning practices, such as encapsulation in solid concrete within steel drums further increases the physical security of the source. If one assumes that high activity gamma sources are stored within their transport containers and then subsequently encapsulated in concrete within steel drums, and buried under at least 5 m of material, the release of one of these sources from its shielding by an aircraft or missile crashing onto the surface of the repository is considered implausible. Thus, it need not be considered further.

5 Assessment of risks following the institutional control period

5.1 Assessment rationale

Before commenting specifically on Appendix E8, it is necessary to discuss the philosophy recommended by the International Commission on Radiological Protection for the assessment of accidental human intrusion in the future after the period of institutional control has ended. ICRP publication 81 states the following:

> (62) Because the occurrence of human intrusion cannot be totally ruled out, the consequences of one or more typical stylised intrusion scenarios should be considered by the decision-maker to evaluate the resilience of the repository to potential intrusion. In principle, the significance of human intrusion ideally might be assessed using a risk-based approach considering both the probability of intrusion and the associated consequences. However, any projections of the magnitude of intrusion risks are by necessity dependent on assumptions that are made about future human behaviour. Since no scientific basis exists for predicting the nature or probability of future human actions, it is not appropriate to include the probabilities of such events in a quantitative performance assessment that is to be compared with dose or risk constraints.
>
> (63) The Commission has previously recommended a dose constraint of 0.3 mSv per year for members of the public for the optimisation of protection in radioactive waste management. This constraint is not applicable in evaluating the significance of human intrusion because, by definition, intrusion will have by-passed the barriers which were considered in the optimisation of protection for the disposal facility.
>
> (64) Nevertheless, a measure of the significance of human intrusion for protection is necessary. Furthermore, since a future society may be unaware of exposures resulting from the intrusion, any

> protective actions required should be considered during the development of the disposal system. Intrusion may lead to acute or prolonged doses to future individuals. The Commission considers that in circumstances where human intrusion could lead to doses to those living around the site sufficiently high that intervention on current criteria would almost always be justified, reasonable efforts should be made to reduce the probability of human intrusion or to limit its consequences. In this respect, the Commission has previously advised that an existing annual dose[3] of around 10mSv may be used as a generic reference level below which intervention is not likely to be justifiable. Conversely, an existing annual dose of around 100mSv per year may be used as a generic reference level above which intervention should be considered almost always justifiable. Similar considerations apply in situations where the thresholds for deterministic effects in relevant organs are exceeded.

Applying this philosophy, realistic dose estimates for plausible scenarios involving human intrusion into the repository should be made and the doses calculated should be considered in the context of current ICRP recommendations on intervention. Intervention is a term that is used in the System of Radiation Protection recommended by the ICRP to mean actions that are taken when the source of the radiation exposure and the radiation doses arising from that source are already occurring prior to the exposure being recognised.

For example, any actions taken to clean up radioactive contamination in an area where residential development has subsequently occurred in the absence of knowledge of that radioactive contamination, is called intervention. Dose limits do not apply in the context of intervention. Rather, the approach adopted is that the reduction in health detriment achieved by the intervention (due to the reduction in radiation dose) should exceed the detriment caused by the intervention (eg the cost, social and environmental impacts of the intervention). ICRP has offered guidance on when intervention will be justified – see the extract from ICRP Publication 81 reproduced above.

Applying ICRP recommendations to the National Radioactive Waste Repository, if the best estimate of the annual radiation dose for a scenario is below 10 mSv, the conclusion from the consideration of that scenario is that the repository is acceptable from the perspective of post institutional control human intrusion. If the annual dose lies between 10 mSv and 100 mSv, then reasonable efforts to reduce the likelihood or consequences of the intrusion scenario should be considered. If the annual dose is above 100 mSv, then reasonable efforts to reduce the likelihood or consequences of the intrusion scenario should be required. This process should be repeated for each plausible scenario.

The EIS describes the ICRP advice on the assessment of accidental human intrusion and summarises the recommendations of a 1995 Nuclear Energy Agency (NEA of the OECD) Working Group Report on the same topic. The EIS presents these two sets of advice in a manner that implies that they are inconsistent. Specifically, the impression is given that the NEA approach requires the use of probabilities together with dose estimates to obtain estimates for the risk of a fatality occurring. This is not the case.

In any case, regardless of the applicability or otherwise of the NEA Working Group document, and the interpretation of that document, ICRP is the peak international body in respect of radiological protection policy, and the recommendations of ICRP on this particular issue post-date those of the NEA Working group.

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[3] The term existing annual dose is used by the Commission to mean the existing and persisting annual dose incurred by individuals in a given location. The exposure that may occur from a repository is a component of the existing annual dose.

Consequently, the approach recommended in ICRP publication 81 is adopted in this report to assess the acceptability of the NRWR with respect to accidental human intrusion after the period of institutional control has ended.

5.2 General intrusion scenarios

Applying the ICRP rationale, the first step is to identify plausible scenarios for accidental human intrusion. Our assessment of the scenarios considered in Appendix E8 is that those considered are appropriate and we could not identify any other scenarios that should be considered.

After identifying plausible scenarios, the next step is to assume that each scenario actually occurs and to estimate in each case the associated dose. ARPANSA has checked the dose calculations for the scenarios considered in the EIS (see Appendix 3 of this report) at a time corresponding to the start of the Institutional Control period. These calculations may be compared with the doses reported in tables E8.17 to E8.31 of the EIS at zero time (ie, no radioactive decay). ARPANSA's dose calculations yield similar although not identical results to those reported in the EIS. The reason for the difference in results is unclear because insufficient information has been presented in the EIS on the details of dose calculations.

Radioactive decay is, however, a highly relevant factor in these calculations since the scenarios do not apply until the institutional control period is over. That period is defined as 200 years after the completion of the operational period and, during this time, the activity of shorter lived radioisotopes will have decayed appreciably. A spot check of one of the dose calculations indicates that it is correctly accounted for in the EIS. That being the case, the doses quoted in the EIS for times after the end of the institutional control period are considered to be adequate for comparison with annual doses of 10 mSv and 100 mSv, and thus for assessing whether the doses arising from the intrusion scenarios are acceptable.

Table E8.35 of the EIS summarises the radiation doses calculated for each of the accidental human intrusion scenarios except those related to radioactive gas and discreet high activity gamma sources (considered later). The annual doses reported in table E8.35, which refer to appropriate periods after the Institutional Control period, range between 0.0017 mSv and 3.1 mSv. These are all below the annual dose of 10mSv above which intervention might be considered justifiable according to the current recommendations of the ICRP.

Thus, in relation to these scenarios and post institutional control accidental human intrusion, the repository is satisfactory. Further, in reviewing these calculations, ARPANSA notes that conservative assumptions have been made for every parameter. When the additional factor of conservatism, of up to a factor of 10, arising from the assumption of a repository volume of 10 000m^3 (see discussion in 4.1 of this Appendix) is considered, the actual doses that would be received if any of these scenarios (except one) occurred could be an order of magnitude lower than those reported in the EIS.

5.3 High Activity Gamma Source Scenario

The EIS considers three sources identified in the inventory of the repository, a 0.185GBq Co-60 source, a 480GBq Cs-137 source and a 0.37GBq Ra-226 source. The dose rate to the hand of someone holding each of these sources, and to the whole body of someone at 1 metre from these sources is then calculated.

The activity of the cobolt and radium sources considered is consistent with many common industrial applications for these isotopes such as gauges. The caesium source considered is a very high activity source, although comparable and higher activity sources are used for irradiation applications.

The dose calculations in Appendix E8 do not take account of the radioactive decay of these sources. If it is assumed that the intrusion occurs immediately after the 200 year institutional control period has ended, the activities of the Co-60, Cs-137 and Ra-226 sources will have reduced by factors of 266 billion, 102, and 1.1 respectively. Thus, the Co-60 source will have completely decayed and may be ignored, the dose rate from the Cs-137 source will have dropped to 1% of that calculated in the EIS and the dose rate from the Ra-226 source will be similar to that calculated in the EIS.

Even considering decay, the Cs-137 and Ra-226 sources could still deliver radiation doses due to external irradiation exceeding 100 mSv if a person remained at a distance of 1m away from them for periods of 200 hours and 1800 hours respectively. Both sources could still cause radiation burns if kept in close proximity to skin for periods of the order of an hour or less. Doses from the inhalation or ingestion of part of these sources would be additional to those discussed immediately above.

Considering that the magnitude of these doses are well above 10 mSv per annum and potentially above 100 mSv per annum, and that deterministic effects (eg radiation burns) are possible, the question that needs to be addressed is whether or not the scenario is plausible.

In section 3.1 of this Appendix, we concluded that the liberation of a high activity gamma source by a missile strike or aircraft crash on the repository during the operational period of the repository was not plausible due to the physical security of these sources. However, it is not possible, without considerable analysis, to draw a similar conclusion regarding post institutional control intrusion scenarios because they include activities such as drilling. Such an analysis may conclude that high activity gamma sources should not be disposed of in the repository, or may identify particular conditioning strategies which must be employed for high activity gamma sources that are stored in the repository. These analyses would form part of the more detailed assessments that are undertaken by ARPANSA, the regulator, during the licensing process for the repository. It is our view that such analyses would be successful in identifying suitable and practical conditioning strategies for the vast majority of high activity gamma sources, although it is possible that the highest activity gamma sources, such as the caesium source considered in the EIS, are not suitable for disposal in the repository.

Thus if the NRWR is approved, it is recommended that ARPANSA consider high activity sources in the context of accidental human intrusion after the institutional control period, and determine waste acceptance criteria and waste conditioning requirements consistent with ICRP recommendations.

5.4 Consideration of Radioactive Gases

The EIS considers the potential of H-3, C-14, Kr-85, Rn-220, and Rn-222 to deliver radiation doses to people who occupy the site of the repository after the institutional control period. Of these radioactive gases, only Rn-222 presents a credible radiation hazard, the doses arising from the other gases combined, even making conservative assumptions, being less than 0.3 mSv per year.

The scenario applied in regard to Rn-222 is that the 5 m cover of material has eroded away and an enclosed dwelling is built directly on the repository contents. The dose reported in the EIS for occupants of the dwelling is 130 mSv per year. ARPANSA reviewed this scenario and, using a different methodology for estimating the concentration of Rn-222 in the dwelling, calculated annual doses to occupiers of the dwelling of the order of 100 mSv per year, assuming full occupancy. This confirms the calculations recorded in the EIS. Given the magnitude of this dose estimate, adoption of the ICRP approach to assessment of the repository requires further assessment of this scenario.

We have identified a number of conservative factors in this dose estimate. The first assumption which introduces a significant factor of conservatism is the assumed volume of the repository, 10 000 m^3. In simple terms, the rate at which radon emanates from the ground into the dwelling is proportional to the concentration of its parent, radium-226 in the ground. That concentration has been calculated by dividing the total activity of Ra-226 in the repository at the time the 5 m cap has eroded away by the volume of the repository assuming a certain density. As noted in section 4.1 of this Appendix, the volume of the repository will actually be greater than 10 $000m^3$, and thus the concentration of Ra-226 in the soil will be less than that used in the dose calculation by up to, at the extreme, a factor of 10. Consequently, the dose could be lower by up to a factor of ten.

Second, the actual occupancy of any dwelling is likely to be less than 100%. It is common practice, in undertaking dose calculations for radon progeny inhalation, to assume 7000 hours per year (or 80% of the year) are spent in the dwelling. The calculations described above assume full occupancy – that is, that the individual spends 24 hours per day, 365 days per year in the dwelling.

Third, and more significantly, the EIS and ARPANSA calculations assume that the material upon which the dwelling is built, has the gas diffusion properties of soil and that the floor of the dwelling does not attenuate the ingress of radon into the dwelling. For comparison, concrete, which will be used in the repository, has a diffusion coefficient two orders of magnitude lower than soil. Thus, at one extreme, if the dwelling was constructed on a concrete pad, the rate at which radon emanates into the dwelling would be up to a factor of one hundred lower, resulting in a similar reduction in dose. Similarly, the calculation assumes that conditioning of the waste (for example, being cemented within steel drums) has completely failed and does not impede the diffusion of radon any more than soil does. This is clearly a worst case scenario.

In summary, the scenario considered in the EIS for radon exposure in the period following institutional control is an extreme, worst case scenario. It is our view that the dose to people occupying a dwelling constructed directly on top of the repository contents following erosion of the 5m cap will conservatively be between one and two orders of magnitude below that estimated by the EIS and by ARPANSA. Our more realistic estimate of the dose is between 1m Sv and 10 mSv per year. We have concluded therefore that the repository is satisfactory with respect to long-term radiation exposure due to radon emanation.

Nevertheless, recognising the very significant reduction in dose from the inhalation of radon that can be achieved by the integration of barriers with the waste, it is recommended that, if the NRWR is approved, ARPANSA consider requiring the integration of barriers with the waste to impede radon emanation.

6 Conclusions

In this Appendix we have interpreted and discussed the radiation dose calculations undertaken by ARPANSA in its review of Appendices E6, E7 and E8 of the EIS for the National Radioactive Waste Repository.

The ARPANSA review identified errors and inconsistencies throughout the radiological dose calculations contained in the EIS. In many cases, ARPANSA reports that insufficient information was presented in the EIS to enable an exact reproduction of the dose calculations.

However ARPANSA was generally able to produce similar results to those presented in the EIS using its own assumptions.

The single exception to this conclusion was the estimated gamma dose to recovery personnel following a missile strike or aircraft crash during the operational period. In this case, a gross error in the calculations presented in the EIS had been identified in Appendix 2 of this report. This error, in which gamma dose rates are overestimated by almost a factor of ten, was confirmed by ARPANSA.

ARPANSA checked the dose calculations in Appendix E6 and found errors which result in a slightly different dose being calculated. However, Appendix E6 is not really required since it contains calculations of dose to construction workers due to natural background radiation. It is inappropriate to compare these very small natural doses to dose or risk constraints.

Of general significance is ARPANSA's conclusion that extreme conservatism has been built into the dose calculations in the EIS. Factors of conservatism are applied on top of factors of conservatism so that, in most cases, the actual dose would probably be between one and two orders of magnitude lower than that reported in the EIS.

The key conclusions relating to the review of Appendices E6, E7 and E8 of the EIS are presented below, together with recommendations.

- The scenario where, during the operational period, a high activity gamma source is released from its packaging and shielding by the impact of a missile or aircraft on the repository and subsequently recovered by the recovery personnel was not assessed in Appendix E7 of the EIS. Following an assessment of this scenario, it has been concluded that the fatality probability would be very small because the likelihood of release from transport containers encapsulated in concrete within steel drums is considered to be implausible.
- The scenarios for accidental human intrusion into the repository after the institutional control period considered in Appendix E8 of the EIS adequately cover the range of possible intrusion scenarios. With the exception of the scenario involving high activity gamma sources, the dose estimates for all post institutional control period scenarios are very low and require no further assessment.
- Because of certain plausible post institutional control period scenarios, disposal of high intensity gamma sources at the repository should be subject to waste conditioning requirements. Although appropriate waste conditioning techniques exist for most such sources, it is possible that the highest activity gamma sources are unsuitable for disposal in the repository. These are matters that should be subject to detailed assessment by ARPANSA as part of the licensing process. Thus it is recommended that:
  - If the establishment of the NRWR is approved, ARPANSA should determine appropriate waste acceptance criteria and waste conditioning requirements for high intensity gamma sources.
- Radiation exposure due to radon emanation from the repository in the long term is not an impediment to construction of the repository because such exposure can be significantly reduced by the incorporation of barriers within the waste to impede radon emanation. It is, therefore, recommended that:
  - If the NRWR is approved, ARPANSA should consider requiring the integration of barriers within the waste to impede radon emanation.