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Human Intruder Dose Assessment for Deep Geological Disposal

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ABSTRACT

For near-surface disposal, approaches to assessment of inadvertent human intrusion have been developed through international cooperation within the IAEA's ISAM programme. Other assessments have considered intrusion into deep geological disposal facilities, but comparable international cooperation to develop an approach for deep disposal has not taken place.

Accordingly, the BIOPROTA collaboration project presented here 1) examined the technical aspects of why and how deep geological intrusion might occur; 2) considered how and to what degree radiation exposure would arise to the people involved in such intrusion; 3) identified the processes which constrain the uncertainties; and hence 4) developed and documented an approach for evaluation of human intruder doses which addresses the criteria adopted by the IAEA and takes account of other international guidance and human intrusion assessment experience.

Models for radiation exposure of the drilling workers and geologists were developed and described together with compilation of relevant input data, taking into account relevant combinations of drilling technique, geological formation and repository material. Consideration has been given also to others who might be exposed to contaminated material left at the site after drilling work has ceased. The models have been designed to be simple and stylised, in accordance with international recommendations. The set of combinations comprises 58 different scenarios which cover a very wide range of human intrusion possibilities via deep drilling.

Keywords: Dose assessment, inadvertent human intrusion, deep geological repository.

SYVÄÄN GEOLOGISEEN LOPPUSIJOITUSTILAAN TAHATTOMASTI TUNKEUTUVIEN IHMISTEN ANNOSARVIOINTI

TIIVISTELMÄ

IAEA:n ISAM-ohjelmassa on kehitetty arviointimenettelyjä tahattoman ihmisen tunkeutumisen käsittelyyn maanpinnan läheisten ydinjätteen loppusijoitusratkaisujen osalta. Muissa turvallisuusarvioissa on tarkasteltu vastaavaa tunkeutumista syviin geologisiin loppusijoitustiloihin, mutta kansainvälistä yhteistyötä yhteisten arviointimenettelyjen kehittämiseksi ei ole ollut.

Näinpä tässä raportissa esitetyssä BIOPROTA-yhteistyöhankkeessa 1) tarkasteltiin miksi ja miten syviin geologisiin loppusijoitustiloihin voitaisiin tahattomasti tunkeutua, 2) arvioitiin miten ja missä määrin tunkeutujat voisivat altistua radioaktiivisille aineille, 3) tunnistettiin tarkastelun epävarmuuksia rajaavat prosessit, ja täten 4) kehitettiin ja dokumentoitiin kansainväliset suositukset ja kokemukset huomioon ottava lähestymistapa tahattoman tunkeutujan säteilyannosten arvioimiseksi.

Työssä kehitettiin ja kuvattiin mallit ja niiden lähtötiedot kairausmiehistön ja tutkimuskairaukseen osallistuvien geologien saaman säteilyaltistuksen arvioimiseksi siten, että kairausmenetelmien, alueen geologian ja loppusijoitustilan materiaalien eri yhdistelmät tulevat katetuiksi. Myös muiden henkilöiden altistuminen kairauksen jälkeen alueelle jätetyille radioaktiivisille aineille käsiteltiin näissä malleissa, joista tehtiin kansainvälisten suositusten mukaisesti yksinkertaisia ja tyyliteltyjä. Eri laskentatapauksia määriteltiin kaikkiaan 58.

Avainsanat: Säteilyaltistuksen arviointi, tahaton tunkeutuminen loppusijoitustilaan, syvä geologinen loppusijoitus.

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PREFACE

BIOPROTA is an international collaboration forum which seeks to address key uncertainties in the assessment of radiation doses in the long term arising from release of radionuclides as a result of radioactive waste management practices. It is understood that there are radio-ecological and other data and information issues that are common to specific assessments required in many countries. The mutual support within a commonly focused project is intended to make more efficient use of skills and resources, and to provide a transparent and traceable basis for the choices of parameter values, as well as for the wider interpretation of information used in assessments. A list of sponsors of BIOPROTA and other information is available at www.bioprota.org.

The general objectives of BIOPROTA are to make available the best sources of information to justify modelling assumptions made within radiological assessments of radioactive waste management. Particular emphasis is to be placed on key data required for the assessment of long-lived radionuclide migration and accumulation in the biosphere, and the associated radiological impact, following discharge to the environment or release from solid waste disposal facilities. The programme of activities is driven by assessment needs identified from previous and on-going assessment projects. Where common needs are identified within different assessment projects in different countries, a common effort can be applied to finding solutions.

This report describes a project to review methods and develop an approach to human intruder dose assessment for deep geological disposal facilities for radioactive waste. The project was financially supported by Posiva (Finland), the SSM (Sweden), NWMO (Canada) and NUMO (Japan). The report was prepared by GMS Abingdon Ltd., Amphos 21 and Eden Nuclear and Environment Ltd. Technical contributions were provided from a range of experts who participated in a project workshop hosted by the SSM.

The report is presented as working material for information. The content may not be taken to represent the official position of the organisations involved. All material is made available entirely at the user's risk.

Version history:

- Version 1.0 DRAFT report prepared by GMS Abingdon, Amphos 21 and Eden Nuclear and Environment Ltd., distributed 8 April 2011 to project participants and sponsors for comment and preparation prior to a project workshop on 27 April 2011, held at SSM, Stockholm.
- Version 2.0 DRAFT final report prepared in light of the workshop held at SSM and further feedback on the workshop report, by GMS Abingdon Ltd., Amphos 21 and Eden Nuclear and Environment Ltd., and distributed 26 June 2012 to project participants and sponsors for comment and approval.
- Version 3.0 final report prepared in light of feedback on Version 2.0 by GMS Abingdon Ltd. and Eden Nuclear and Environment Ltd., and distributed September 2012.
- Version 4.0 for publication by Posiva, prepared by GMS Abingdon Ltd.

EXECUTIVE SUMMARY

For near-surface disposal, approaches to assessment of inadvertent human intrusion have been developed through international cooperation within the IAEA's ISAM programme. Other assessments have considered intrusion into deep geological disposal facilities, but comparable international cooperation to develop an approach for deep disposal has not taken place. In 2011, the International Atomic Energy Agency promulgated updated requirements on solid radioactive waste disposal, which include dose based criteria for inadvertent human intrusion exposure situations.

Accordingly, the objectives of the project presented here were to:

- examine the technical aspects of why and how deep geological intrusion might occur;
- consider how and to what degree radiation exposure would arise to the people involved in such intrusion;
- identify the processes which constrain the uncertainties; and hence
- develop and document an approach for evaluation of human intruder doses which addresses the criteria adopted by the IAEA and takes account of other international guidance and human intrusion assessment experience.

Based on consideration of international recommendations and examples of national application, an approach has been developed for assessing doses arising directly from inadvertent human intrusion.

The most likely mechanisms for human intrusion into deep geological disposal facilities have been reviewed based on previous assessment experience and from further consideration of possible interest in deep geological investigation. It is concluded that deep borehole drilling is the most likely mechanism.

The range of available technologies for deep drilling has been reviewed and described in terms relevant to their application in different geologies and to their potential for bringing contaminated material to the surface where it may give rise to radiation exposure. Such contaminated material could include waste itself, or contaminated near field material, or contaminated wider geosphere material, the latter two situations being relevant only after some release from the waste form.

Consideration has been given to exposure of drilling workers and geologists involved in the drilling activity, and also to others who might be exposed to contaminated material left at the site after drilling work has ceased.

Models for radiation exposure of the drilling workers and geologists have been developed and described, taking into account relevant combinations of drilling technique, geological formation and repository material. The models have been designed to be simple and stylised, in accordance with international recommendations. The set of combinations comprises 58 different scenarios which cover a very wide range of human intrusion possibilities via deep drilling.

Data for the models have been reviewed and selected for use in example calculations. Special consideration has been given to data for inadvertent ingestion of dirt and inhalation of contaminated dusts, since these were found to be wide ranging and thus could contribute significantly to uncertainties. Data have been selected for application to the 58 scenarios and applied to unit activity concentrations of a range of relevant radionuclides assumed to be present in 1 m length cores brought to the surface and contacted and examined by the drillers or geologists for one hour. A complete set of these normalised results for all the radionuclides (including their radioactive progeny) has been prepared and is made available in a separate excel spreadsheet. Example results have been presented and discussed.

These normalised results can be used in specific assessments in which concentrations of radionuclides in waste, the near field and/or the geosphere have been separately determined. It is a simple matter to multiple the relevant normalised results by the assessed concentrations in corresponding media.

Assessment of doses arising from contamination left at the drill site is proposed to be assessed on the basis of existing contaminated land assessment methods. This is to avoid duplication of effort and the introduction of arbitrary differences in details, as well as to support a consistent approach to safety assessment of contaminated land in the short and long term. Within this approach, account still needs to be taken of how widespread the contamination is and this has to be considered in relation to the assumptions for human behaviour on the contaminated land, i.e. to be consistent in terms of reasonable occupancy. The approach has been demonstrated and applied in a normalised fashion for each of the alternative drilling techniques. The range of results presented suggests that doses to those using contaminated areas left at the site after drilling has ceased would be similar or lower to those to drilling workers and geologists. Some exceptions may arise in the case of agricultural use of the site, for those radionuclides which may have very high uptake via the foodchain. In this event, it may be appropriate to consider the use of site specific data in assessment of the foodchain pathways.

All the conceptual model and data assumptions have been made on a conservative but plausible, realistic basis. These assumptions have been made clear so that implications of alternative assumptions can be readily investigated.

Illustrative results have been present for doses to drillers arising from HI into realistic HLW and ILW waste inventories. Results have been presented for human intrusion at a range of times after disposal from 100 to 100,000 years. These illustrations have not taken account of possible radionuclide migration prior to HI, only radioactive decay and ingrowth. Therefore they do not represent the full assessment picture and only serve to illustrate the use of the normalised results.

HI while institutional control is effective would not occur; hence the presentation of doses no earlier than 100 y. Longer institutional control periods may be considered viable, possibly supported by studies of information conservation and retrieval. The likelihood of human intrusion has not been part of this study, however it can be readily seen that vertical as opposed to horizontal displacement of waste in a repository would reduce the chance of a borehole intersecting waste.

The methods and data described are considered to be consistent with assessment requirements arising out of current international recommendations and guidance on deep geological disposal.

1 INTRODUCTION

1.1 Background

Human intrusion (HI) has been considered an issue in post-closure safety of solid radioactive disposal for many years [NEA, 1989]. The issue is problematic because of the difficulty of justifying assumptions about human behaviour over relevantly long periods of time. Risk assessment typically includes consideration of the likelihood of radiation exposure as well as the probability of harm arising as a result of that exposure, itself a function of the size of the dose[1] and the likelihood of harm arising from that level of dose [NRPB, 1983]. Site selection away from natural resources may reduce the probability, but it is not obvious what will be considered as a resource in the future. Thus, it has been concluded that the likelihood that HI occurs should not be ignored in reaching an informed decision on radioactive waste management, but it is necessary to recognise the illustrative nature of long-term probability estimates [Smith et al, 1998].

Accordingly, over the last decade or so, the development of protection objectives with respect to HI has focussed upon the level of radiation exposure rather than an attempt at estimating the risks. ICRP Publication 81 recommendations on solid waste disposal [ICRP, 2000] note the difficulties of estimating probabilities of HI, but that its occurrence cannot be entirely ruled out. ICRP therefore recommends (paragraph 62) that "*one or more typical plausible stylised* {HI} *scenarios*" should be considered by the decision-maker to evaluate the resilience of a repository to postulated HI events or scenarios[2].

The IAEA requirements on disposal of radioactive waste [IAEA, 2011a] set out recent international guidance on criteria relating to HI. The key text which relates to HI is as follows:

- The dose limit for members of the public for doses from all planned exposure situations is an effective dose of 1 mSv in a year. This and its risk equivalent are considered criteria that are not to be exceeded in the future.
- To comply with this dose limit, a disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person who might be exposed in the future as a result of possible natural processes affecting the disposal facility does not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year.
- In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.
- If human intrusion were expected to lead to a possible annual dose of more than 20 mSv per year, to those living around the site, then alternative options for

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[1] Dose is taken in this report to mean effective dose, and for the purpose of comparison with annual dose limits, is the sum of external effective dose received in a year and the committed effective dose from intakes in that year, as defined in ICRP [2007].

[2] Similar guidance is proposed in the ICRP's consultation document [ICRP, 2011] which is a draft update of ICRP Publication 81 [ICRP, 2001]. See further discussion below.

waste disposal are to be considered; for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.

- If annual doses in the range 1 – 20 mSv are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimisation of the facility's design.

These IAEA criteria allow a higher dose for inadvertent HI than the dose (or its risk equivalent) for scenarios due to natural processes. According to the IAEA, these dose criteria for HI apply only to "*those living around the site*". They do not apply, for example, to geological investigators who may be exposed through their work while not actually living around the site. In the absence of any explanation, the exclusion of this exposure situation may be hard to understand given the significance of this scenario in the history of HI studies, e.g. NEA [1989, and 1995].

ICRP Publication 101 [ICRP, 2006] states that guidance on protection of future individuals in the case of disposal of long-lived radioactive waste, as provided in ICRP Publication 81 [ICRP, 2000], remains valid. Although not yet finalised at the time of this study, it is useful to note the content of an ICRP consultation document, issued in July 2011 [ICRP, 2011]. When finalised, this will update ICRP Publication 81, and takes a broadly similar approach to it and to IAEA [2011a]. At paragraph 58, it says, '*the consequences of one of more plausible stylised intrusion scenarios should be considered.*', and goes on to say, '*... the Commission continues to consider* {it} *not appropriate to include the probabilities of such events in a quantitative performance assessment.*' The consideration of the assumed possibility of human intrusion and how to reduce it, by design etc., is, however, still appropriate. (See discussion in paragraph 57 of the consultation document.)

Regarding exposure situations, at paragraph 56 ICRP [2011] says, '*inadvertent human intrusion could bring waste material to the surface and hence lead to direct exposure of the intruder and nearby populations*', which implies a wider consideration of exposures within the stylised scenarios than required by IAEA in [IAEA, 2011a].

Intentional intrusion is recommended to excluded from consideration of safety and safety assessment in ICRP Publication 81 and in the consultation document, as it is considered out of scope of the current generation to protect a deliberate intruder. This appears to ignore any responsibility to protect third parties who might be impacted by some deliberate, e.g. malicious, act. However, placement in a geological disposal facility is regarded as providing long term passive nuclear security [IAEA, 2011a].

Another relevant publication is the IAEA safety guide on Geological Disposal Facilities for Radioactive Waste [IAEA, 2011b]. It does not discuss safety assessment in great detail but the following extract is relevant to HI assessment:

- "Active institutional controls such as monitoring may also be applied for a period after closure of a geological disposal facility, for example, to address public concerns and licensing requirements or as protection against human intrusion."

- "The safety assessment should include some stylized calculations of the consequences of inadvertent human intrusion into the closed disposal facility."

Consistent with the above international guidance and recommendations, various examples of national regulatory guidance recognize that the possibility of HI presents a special case for setting of criteria and for assessment, but clearly indicate that it needs to be considered alongside other safety considerations. As an example, regulatory guidance developed within the UK suggests that the developer/operator of a deep geological repository should assess the potential consequences of HI for the time after the period of authorisation [Environment Agency of England and Wales, Scottish Environment Protection Agency and Department of the Environment for Northern Ireland, 2009]. Prior to these 2009 requirements, a risk criterion was applied, involving assessment of the dose, the probability of a serious health effect arising from the dose and the probability of the dose occurring. The 2009 guidance includes no quantitative criterion for HI into the repository[3]; however, it does require assessment of HI scenarios based on human actions that use technology and practices similar to those that currently take place, or that have historically taken place, in similar geological and geographical settings anywhere in the world. This implies inclusion of those involved in the HI process, not only those living at the site after intrusion has occurred. Other examples of national regulatory guidance are considered in Appendix A, alongside summary information on some relevant previous HI assessments.

For near-surface disposal, approaches to assessment of HI have been developed through international cooperation within the IAEA's ISAM programme [IAEA, 2004a and 2004b]. Comparable international cooperation to develop an approach to HI assessment for deep geological disposal has not taken place and so this forms the focus of the current study.

1.2 Objectives and scope

Noting the points in Section 1.1, the project described in this report was designed with the objectives to:

- examine the technical aspects of why and how HI into deep geological repositories might occur;
- consider how and to what degree radiation exposure would arise to the people involved in such intrusion;
- identify the processes which constrain the uncertainties; and hence
- develop and document an approach for evaluation of the human intruder doses.

The scope of the study includes:

- Land-based deep geological disposal of all kinds of radioactive waste which may be so disposed, taking into account generically relevant wastes, waste forms and packaging, near field engineered barrier systems (EBS) and geological environments. Deep disposal is taken to mean disposal at greater than 50 m.

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[3] For drilling intrusion into the geosphere, e.g. into a contaminated aquifer away from the repository, a risk criterion still applies, i.e. as for natural releases from the repository.

- Dose consequences to those directly involved in the intrusion and to those directly affected by contaminated material brought to the surface.

Scenarios relating to deliberate human intrusion into a disposal facility not included within the scope of this project.

1.3 Structure of report

Following this introduction, Section 2 reviews how and why HI into a deep repository might occur and thereby identifies a range on HI scenarios. Section 3 identifies the radionuclides of interest. Section 4 describes the assessment of annual individual doses to humans following exposure to unit activity concentration of a range of relevant radionuclides in unit amount of material brought to the surface through the various HI scenarios. Separate consideration is given to exposure of those involved in the HI process and exposures of others arising from residual activity being left at the intrusion site. Section 5 illustrates how those results might be applied to a specific repository containing a particular inventory. Section 6 provides conclusions and discussion of the issues raised in Section 1. References are provided in Section 7. Appendix A gives summary information on examples human intrusion assessments. Appendix B tabulates with references examples of data relevant to dust inhalation and inadvertent ingestion.

2 WHY AND HOW DEEP GEOLOGICAL INTRUSION MIGHT OCCUR

A review of previous studies relating to inadvertent human intrusion into radioactive waste facilities located at depths of 50 m or more below ground has been undertaken. For this purpose, the definition of HI given by NEA [1989] has been adopted, such that HI relates to any inadvertent human activity that results in significant damage to the natural or engineered barriers of a waste facility or otherwise impairs the containment offered by these barriers.

Information relating to the waste types, forms and packaging, EBSs and geological environments has been collated. A technical overview of the different forms and mechanisms for sub-surface investigation at the depths of interest is also presented.

2.1 Review of previous human intrusion studies

In 1989, a workshop was held by the NEA on the risks associated with human intrusion at radioactive waste disposal sites [NEA, 1989]. When considering human intrusion, the focus had been largely focussed on the consequences to the intruders themselves. However, it has been highlighted both as a result of the NEA workshop and by Charles and McEwen [1991] that consideration should also be given to consequences in terms of changes to the groundwater flow system, and thus those potentially exposed at the end of the groundwater migration pathway. Charles and McEwen [1991] also identified the following that may affect the migration of radioactivity from a disposal facility following an intrusion event:

- The potential for a direct permeable flow path such as a borehole from the deep geosphere to the near surface to be generated; and
- The potential for drilling fluids to alter groundwater chemistry, and hence alter radionuclide behaviour.

Review of information on the various scenarios that have been considered in relation to HI events indicates a general consensus on the mechanisms by which intrusion could occur. Differences of note relate largely to site geology, for example, whether a facility is constructed in hard rocks like granite, argillaceous rocks, or salt formations. Accordingly, information on previous human intrusion studies has been categorised according to these geologies.

Unless otherwise stated, the information presented below has been derived from the proceedings of the NEA workshop on human intrusion [NEA, 1989]. More detailed information on specific scenarios considered at the national level, including additional references, is provided in Appendix A.

2.1.1 Disposal facilities in hard rocks

Credible human intrusion scenarios that could result in significant changes to the performance of the EBS of waste disposal facilities constructed in hard rock are primarily based on deep geological drilling, although some alternative scenarios have been considered. Drilling is assumed to occur due to prospecting for mineral or water resources once knowledge of the repository has been lost. Although it has been argued that such scenarios are highly unlikely due to the strict siting criteria for repositories, it has been acknowledged [Charles and McEwen, 1991] that it is difficult to predict what resources could be considered economically exploitable in the future, or of research interest. For example, it may be noted that investigations by deep drilling into apparently uninteresting rocks have taken place to investigate the viability of radioactive waste disposal.

Where differences in the type of scenario (i.e. alternatives to deep drilling) have been considered, these are largely a consequence of specifics relating to the depth and location of the facility. Also, it is plausible that deep underground activities would be preceded by some drilling program to check the properties of the rock prior to major exploration and/or excavation. Therefore, intrusion by deep drilling is a reasonable scenario to evaluate, and such an event would likely result in the identification of abnormalities such as unusual levels of radioactivity.

Deep geological drilling

In identifying plausible scenarios, use has typically been made of knowledge of current economic needs and technology and the anticipated pattern and frequency of resource exploitation.

The following sub-scenarios have been considered in relation to deep geological drilling:

- A drill penetrates a waste canister and waste is brought to the surface in the drill core. For such a scenario, in evaluation of the dose consequences, no credit is taken for technical drilling techniques and developments, such as in situ monitoring resulting identification of a hazard and avoidance of any radiation exposure.
    - The exposure pathways that have been taken into account include:
        - Handling of drill core and exposure to any contaminated air or debris at site by the drill crew, including possible superficial examination of returns from the coring process, and then,
        - In situ detailed (including intrusive) examination of unusual cores by geologists; and,
        - Detailed laboratory analysis of cores.
    - Inspection and analysis of the core material is assumed to give rise to radiation exposure via external irradiation, inhalation of dust and inadvertent ingestion.
    - The dose implications from different drill flushing techniques have also been considered in some assessments (see for example Charles and McEwen [1991]). Both water and air flushing techniques were taken into account, which could result in radioactive material being transported to the surface environment with the latter technique potentially giving rise to radioactive material that could be inhaled by drill operators.

  - In [Nirex, 2003] specific consideration was given to the inhalation of radon emanating from the core due to the radioactive decay of the parent radionuclide, radium-226.
  - In some assessments, consideration has been given to future occupants of the drill site that has been contaminated by drilling spoil, once operations have ceased and the site is made available for alternative use. Under such a scenario, occupants are assumed to produce food on the contaminated land and internal and external exposure pathways are considered.
- A borehole is drilled into the contaminated near field or far field, i.e. without direct intersection by the drill with waste canisters or packages. Similar radiation exposure pathways to those considered for the direct intersection have been considered. Pessimistic assumptions have generally been applied such that waste canisters fail soon after emplacement and closure of the facility, leading to contaminated of the EBS and geosphere. In some instances, no account was taken of radioactive decay prior to the intrusion event, which appears unnecessarily pessimistic.
- A borehole is drilled into an aquifer in the bedrock close to the facility.
  - Two exposure pathways have been considered:
    - Groundwater is extracted from the contaminated aquifer for human consumption and agriculture (irrigation and drinking water for cattle).
    - The borehole gives rise to a preferential pathway for the transfer of contaminated groundwater to the biosphere.
  - Abstraction of contaminated groundwater is commonly considered as a mechanism for transfer of radionuclides across the geosphere-biosphere interface (GBI) and, as such, is not considered by some as human intrusion. This is reflected in the criteria applied to this situation, e.g. in Environment Agency of England and Wales, Scottish Environment Protection Agency and Department of the Environment for Northern Ireland [2009], the risk guidance level for natural releases is applied to this situation; HI criteria are only applied to direct intrusion into the underground disposal facility and its immediate surroundings.

Mining

Where disposal facilities are to be appropriately sited in relation to both location and depth, consideration has been given to the dose implications arising from cavern excavation. The drivers for the excavation have been argued to be the exploitation of mineral resources or the construction of road tunnels [van Dorp and Vigfusson, 1989].

2.1.2 Salt formations

The disposal of radioactive waste in facilities constructed in salt formations has been considered or implemented by a number of countries, including Germany, the Netherlands and the USA [NEA, 1989]. Similar drilling scenarios to those described above have been considered in relation to inadvertent HI, although some differences are of note. One difference is that the presence of metals and waste materials in a salt formation would be very unexpected and quickly recognized as artificial, and so it is plausible that the hazard would be quickly recognized and responded to appropriately. Additional scenarios have also been described in relation to solution and conventional mining.

Drilling scenarios

Salt formations may be associated with pockets of pressurised brine. Several scenarios have been considered in relation to drills penetrating pockets such that, where the drill makes contact with waste packages, a direct path between the pressurised brine and radioactive material could be formed. Plugging of the borehole would allow dissolution of radionuclides into the brine. Over time, pressure within the borehole is assumed to increase such that the borehole plug is breached and a preferential flow path to groundwater above the facility is formed. This groundwater is subsequently extracted for use, resulting in human exposure.

An alternative scenario considered involves the removal of contaminated material in drilling fluid following the penetration of a waste canister. Contaminated drilling fluid is then collected in settling ponds. Human exposure may occur due to surface water transport of the contamination to local habitations or as a result of aerial transport of dust once the settling ponds have dried.

Solution mining

Solution mining is a process whereby soluble minerals (e.g. salt) are extracted through the injection of fluid. The process can be used to create caverns (e.g. for the storage of oil or gas) or for the exploitation of salt, which may be used for human consumption. During the mining process, non-soluble material collects in sumps at the base of the excavated area.

Where the intention is the creation of a storage cavern, it is estimated that mining activity would take place over a period of around one year with a subsequent operational period of several decades. Scenarios have largely considered that, during cavern construction, defective waste packages are dislodged from their storage location, falling into the sump area where radioactive material is released. Brine within the sump area further corrodes waste packages resulting in relatively high activity concentrations within the brine during the construction and operation phases of the storage cavern. Following the operational phase, oil or gas is replaced with either brine or water leading to diffusion of radioactivity from the sump area into the wider cavern. Increasing salt pressure over time then results in the cavern seal being breached such that contamination migrates into groundwater above the facility. Human exposure pathways consider the extraction of contaminated groundwater for human consumption or irrigation of agricultural land.

The salt exploitation scenario considers that, during the salt dissolution process, radionuclides also dissolve and are extracted along with salt from the salt formation. Defective waste canisters falling into the sump area have also been considered as a source of salt contamination. The mining process would be extended over a number of decades should salt extraction be the objective such that radioactive material would have the opportunity to migrate from the damaged waste container to contaminate salt. Human exposure may then occur through the consumption of contaminated salt and/or inhalation of contaminated salt dust within salt factories.

Conventional mining

Conventional mining has not been considered for salt formations to the same degree as solution mining. Nonetheless, human intrusion scenarios have been developed. These primarily consider mining to construct a gallery which could be used for storage, discussed above. Should waste be contacted, it is assumed that the activity would cease. However, assessments have considered the possibility that the gallery is constructed close to a borehole containing high level waste (HLW), but that the presence of the waste goes unnoticed by those working within the gallery.

2.2 Technical overview of different forms and mechanisms for geological investigation

2.2.1 Review of why and how deep geological intrusion might occur

Human intrusion by geological drilling

Potential drivers for shallow and deep drilling in different geological formations are detailed in Table 1. In summary, they are identified as related to interest in mining, geothermic energy, oil and gas exploration and exploitation, and geological investigations for scientific research and special constructions such as future waste disposals. Although the siting of repositories would generally be restricted to geological formations which would be less likely to attract interest, it cannot not be ruled out that in the future the same formations could have a new interest or could have changed in characteristics – for example, hydrogeological dynamics of the area could be altered in response to climate change.

New technologies could allow the exploitation of resources that are not currently viable for exploitation on an economic basis. It is also difficult to predict the raw materials that will be used in the future such that some raw materials, currently of no commercial interest, could become of greater interest for future generations. However, even in this case, the repository host rock volume is likely to be part of a large rock mass of similar type and so inadvertent selection of the repository site for investigation is no more likely than other parts of the rock mass.

Besides the direct interaction of the drill with the repository area, it should be noted that some drilling works, although not in the exact area of the repository, could result in changes in groundwater flow dynamics at a regional level that could interact with the repository, causing mobilisation of radionuclides from the contaminated near field. Activities that could result in such occurrences include drilling for the purposes of geothermal works and CO2 storage. Groundwater extraction could also affect flow dynamics.

Table 1. *Reasons for human intrusion into a repository associated with drilling depths and geological formations.*

Human actions	Depth	Formations to drill
Mining exploration / exploitation	Shallow and deep	Crystalline rocks or sedimentary environments
Water supply	Normally only up to about 100 m	Fractured rocks or porous rocks/formations
Geothermal energy exploration/ exploitation	Deep	Sedimentary and crystalline rocks (fractured or not)
Hydrocarbon exploration	Deep	Fractured or porous rock formations with lower permeability formations (reservoirs)
Future waste disposals location (toxics and/or radioactive)	Shallow and deep	Not fractured crystalline rocks and sedimentary formations with low permeability.
Oil/gas exploration and exploitation	Shallow and deep	Rock formations
Oil/gas underground storage	Shallow and deep	Sedimentary formations (mainly old caverns in evaporates) and crystalline rocks
CO_2 storage	Deep	Sedimentary formations
Scientific research	Shallow and deep	General
Building and construction	Generally less than 50 m, apart from very exceptional examples, such as deep tunnels and secure facilities	General
Brine injection wells (mining industry)	Shallow to intermediate. Generally less than 100 m	Fractured Rocks or porous rocks/formations

If one takes into account the geological media described in Table 1, it can be seen that some of these would not be likely candidate sites for the emplacement of radioactive waste, such as formations for water supplies, brine wells or CO2 storage. Even so, it should be noted that the aquifers or exploitable media might be located below a confining layer of clays or in a fractured zone of granite which had no fracturing above. In those cases, it would be possible that the location of the repository would be in the upper formations and that, during drilling, it would be affected.

In the case of drilling for water supplies, for domestic or other use, shallow drilling is commonly practised. However, due to increasing contamination of aquifers, deeper drilling for water supplies may be necessary in the future and is already increasingly common.

Overall, drilling at depths greater than 50 m is much less common than less deep drilling. Deep drilling is also expensive, thus execution will likely be preceded by non-invasive investigations (such as geophysics), which may detect a geophysical anomaly and alert investigators to the presence of the repository. It also suggests there would be more likelihood of review of literature which could reveal the presence of a repository. In addition, deep drilling usually requires a more technically competent driller, which means that there is greater likelihood of following good practices during and after drilling.

If urban development takes place above the disposal site, such as a small town, the geomagnetic signature of the repository location could be lost. In fact, it is possible that the detection of a geophysical anomaly detected would not have an opposite effect, with the geological anomaly creating greater interest such that drilling proceeds for archaeological or mining research purposes. In this case the repository horizon is the deliberate drilling target, cores from this depth would be specifically examined, and it is plausible that the nature of the hazard would be recognized and responded to appropriately. However, until that recognition occurs, the investigators would be at risk of exposure, both from any core material brought to the surface, and to contaminated drilling fluids coming to the surface.

Drilling intrusion scenarios

Three scenarios can be envisaged in relation to HI events involving drilling: drilling directly into a waste package; drilling into the EBS, e.g. bentonite or concrete buffer or other backfill; or drilling into the adjacent rock. These are illustrated in Figure 1 and basic features of each scenario are specified below.

Drilling into a waste canister / package

In this scenario, the drill penetrates the EBS including the waste canister or other waste container. Depending on the type of rock adjacent to the repository and the drilling method, a change induced by the gallery materials could be noted during drilling; alternatively, the steel or metal of the waste package might be detected, involving a stop in drilling. A possibility is that the drill bit would just chew through the buffer so fast it would be like dropping and would be noted by crew. Still, with non-recoverable core drilling and the use of drilling mud, the presence of the waste may not be detected or only some time after drilling.

Cessation of drilling might be followed by a more detailed investigation of the area to look for the origin of the material change. In the event that the radiation hazard was not detected, a sample might be taken from that depth or drilling could continue with the objective of gaining more information.

If a sample of the waste materials is brought to the surface, it is likely that man-made materials would be identified. The presence of radioactive material may not, however, be identified immediately, such that exposure to radioactive material could occur at the drill location during inspection and possibly during more detailed analysis following transfer to a laboratory.

Drilling into bentonite or concrete buffer or backfill

This scenario becomes relevant in the case where radioactive material has been released from a waste canister or package, in which case the bentonite or concrete buffer or backfill could be contaminated with radioactivity, and the removal of drilling materials to the surface would involve exposure to this contamination.

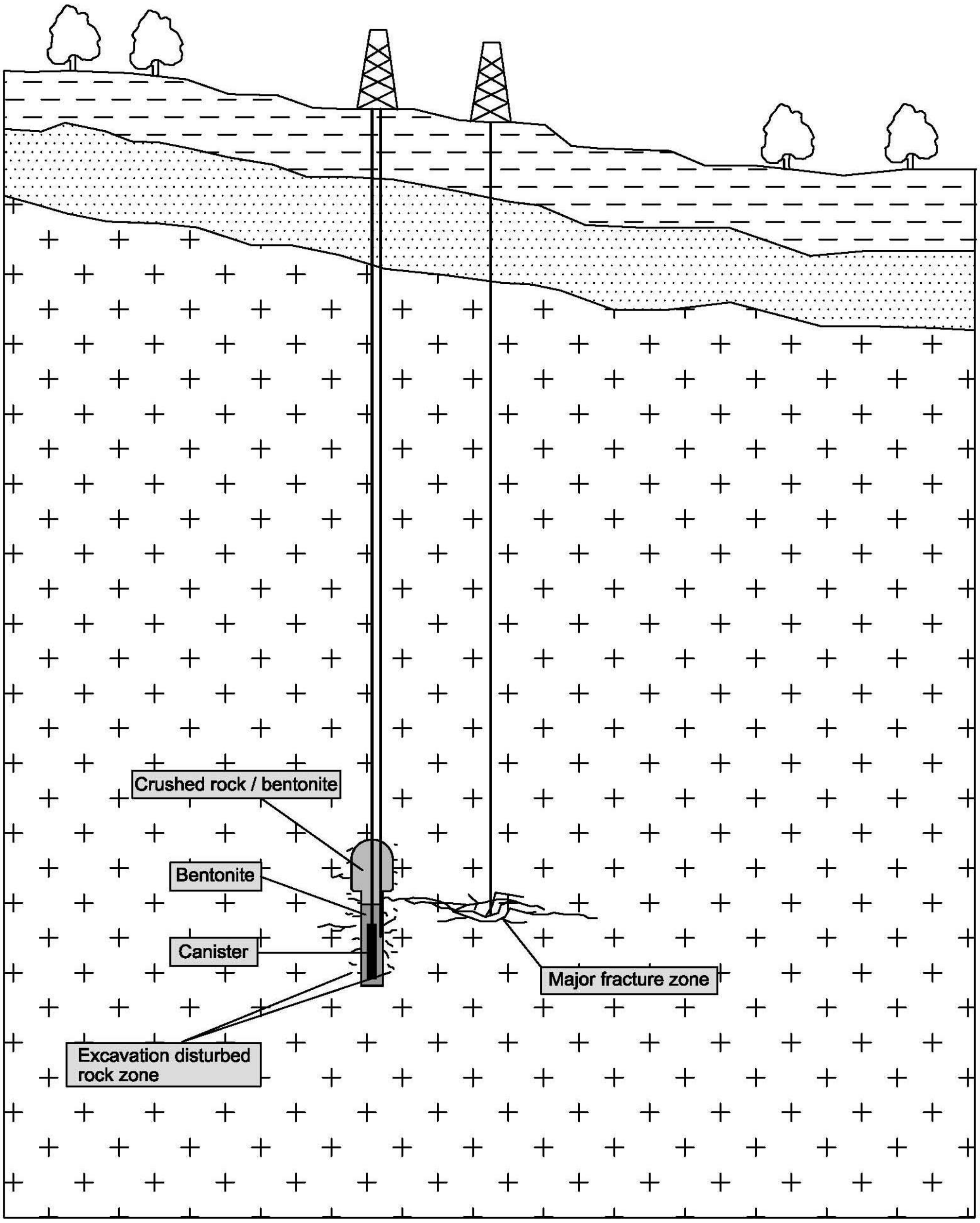

Figure 1. *Basic scheme of the three scenarios considered as potential human intrusion resulting from drilling.*

A bentonite or concrete buffer or backfill might not be detected during non-recoverable core drilling because the contrast with mechanical properties with the adjacent rock is unlikely to be high. The presence of bentonite or concrete buffer or backfill is more likely to be detected with diamond core drilling.

By penetrating into the buffer or backfill, and continuing with drilling, a preferential path for radionuclide release to the normally accessible biosphere would be created, which could result in new pathways for groundwater or gas release.

The surface material removed during the drilling could be detected as man-made material in the case of diamond core drilling; or it might be seen as a geological change. In both cases, the presence of radioactivity is unlikely to be identified immediately, resulting in exposure to the drilling personnel and, potentially, laboratory staff.

Drilling into adjacent rock

Although the probability of drilling in this area is higher than in previous scenarios as it presents a larger area, the scenario need only be taken into account at times once the near field containment system is assessed to have failed, which is likely to be only after considerable delay. The contamination levels in the far field geosphere would be likely to be much lower than in the near field or the waste packages themselves.

The rock samples taken from the drilling would be treated as normal rock samples, without detecting radioactive contamination. Samples may also be transported to a laboratory or other facility, according to the purpose of the drilling activity.

2.2.2 Review of how the intrusion results in exposure of drilling workers and those who contact material brought to surface

Drilling methods

To assess the doses associated with HI, the drilling method and the possible implications for exposure should be kept in mind. Future engineering developments may be expected, but methods that have not yet been conceived cannot be taken into account, and it is reasonable to assume that the basic mechanics of the drilling system will maintain a certain similarity with current drilling techniques. The characteristics of the current drilling methods commonly used nowadays are detailed in Table 2. Other drilling methods aside from those detailed are available, such as auger drilling, which is used for surface drillings (less than 20 m depths). Such methods have been excluded on the basis of limited depth.

Table 2. *Characteristics of current drilling techniques.*

Method	Depth	Materials applied to:
Cable tool	< 600 m	Unconsolidated formations: mud, sand, gravel. Semi-consolidated soft and few compact materials: clay, loam, limestone, etc. Compact materials: fractured or karstic.
Rotary drilling	< 12000 m	Semi-consolidated and consolidated formations, from soft to hard and abrasive.
Reverse circulation	< 500 m	Semi-consolidated and consolidated formations, from soft to hard and abrasive
Percussion rotary	< 1500 m	Hard rocks, compact and abrasive
Diamond core	< 1800 m	All kinds of formations.

A repository is likely to be located in a low-permeability formation, in materials with some degree of consolidation and with no fractures or karstification. One of the favourable media is an un-fractured plutonic rock (granite). This implies that, in the situation of drilling in this type of media, rotary drilling (Figure 2) percussion rotary drilling (Figure 3) or diamond core drilling (Figure 4) would be employed. The former can reach to great depths and in all kinds of rocks, whereas percussion rotary drilling has the advantage that it is the fastest way to drill hard rocks and the cheapest if there are no unexpected problems. Diamond core drilling is a widely used method of research that is very useful for core logging, especially in hard rock; it is however the most expensive of the three methods.

Figure 2. *Image of rotary drilling.*

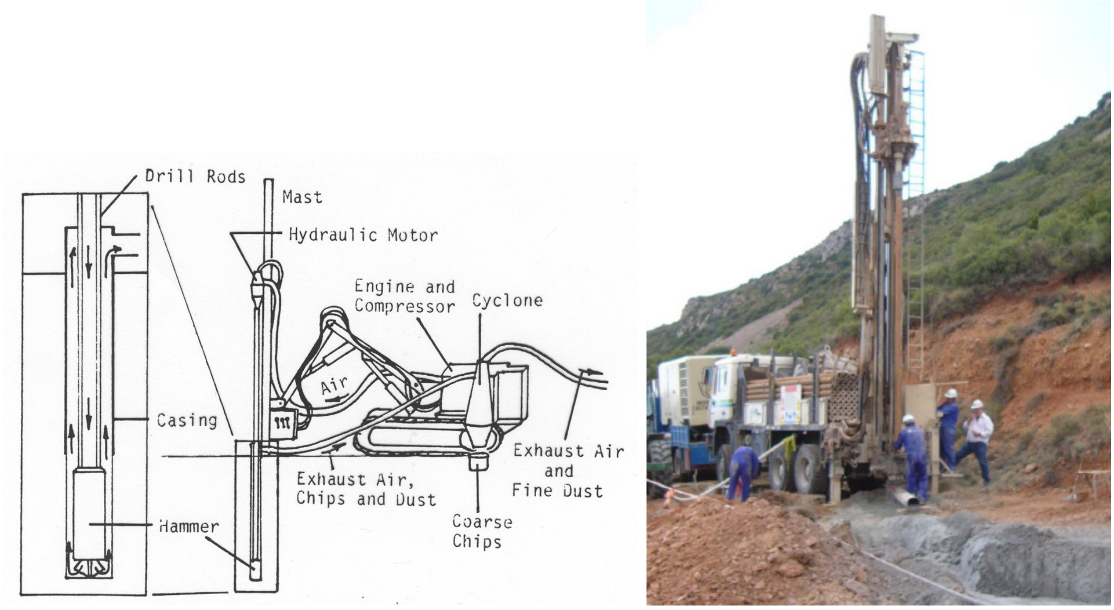

Figure 3. *Basic operation scheme (left) and image (right) of percussion rotary drilling.*

Figure 4. *Images of diamond core drilling (top), core extraction (bottom left) and core tray (bottom right).*

Percussion rotary drilling is commonly used in crystalline rocks, as problems may be encountered in drilling plastic clay formations. As such, for this technique, drilling through a bentonite zone of a repository may well be noticed as anomalous.

Clays and evaporite media are alternative formations considered for the location of repositories. It is understood that low permeable media are characterised by some degree of consolidation. The most commonly used drilling methods for these media are rotary drilling, reverse circulation drilling (Figure 5) and diamond core drilling.

In some cases diamond rigs can be part of a multi-combination rig, with a dual setup rig capable of operating in either a reverse circulation (RC) or diamond drilling role. The rig would initially be set up to drill as an RC rig and, once the desired depth is drilled, the rig would be set up for diamond drilling. This is very useful for helping in the characterisation of the ground at specific depths.

Cable tool drilling (Figure 6) is a very effective and reliable method that has been used generally for the first few hundred meters. However, it is used less frequently at present times due to technological advances in other drilling techniques.

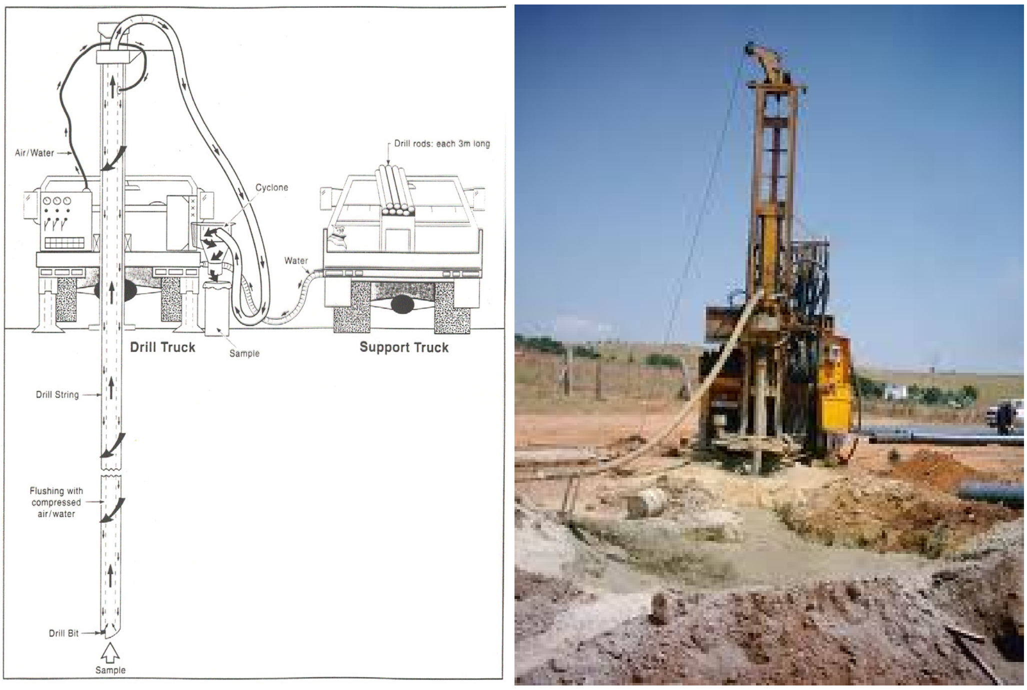

Figure 5. *Basic operation scheme (left) and image (right) of reverse circulation drilling.*

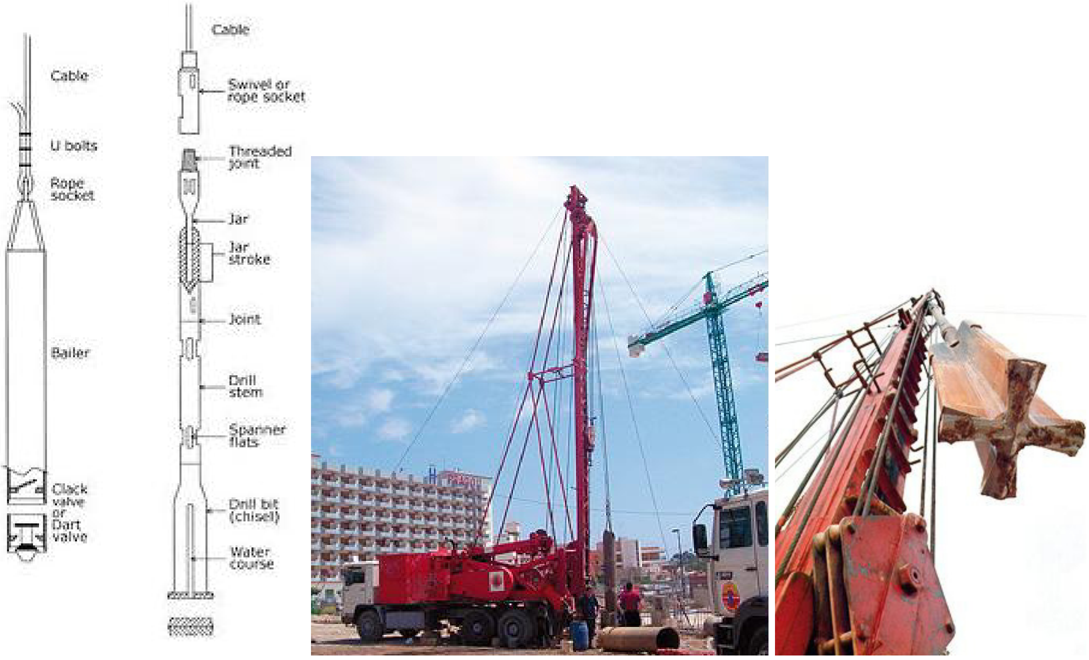

Figure 6. *Basic scheme (left) and images (middle and right) of cable tool drilling.*

Classification of drilling methods

Drilling methods can be classified according to the techniques employed for the destruction of the rock, the detritus rising to the surface and the maintenance of the drill walls. For the present study, removal of core samples or detritus and their appearance at the surface are among the most important characteristics in determining the exposure to the personnel involved in the drilling activities.

The evacuation of the drilling detritus can be done in two ways:

- Mechanically using bailers, helical screws or with a core barrel ("lifter tube").
    - The removal of detritus using bailers is the method used in the drilling cable. This consists of periodically removing the drill string from the borehole and extracting the drill cuttings with a bailer. In removal with helical screws the drilling cuttings are lifted to the surface by the blade of the screw, continuously along the perforation. In the removal with a core barrel, a hollow drill rod impregnated with an annular diamond drill is used to cut a cylindrical core of solid rock and remove it from the hole. Water is sometimes used to make the extraction easier.
- Hydraulically with the injection and circulation of fluids.
    - The fluid may be either air or bentonitic mud (with water), and the injection may be done by direct or reverse circulation according to the direction of the fluid within the drill. Direct circulation is used in the rotary drilling methods, where the drill cuttings are removed by injection of the fluid inside the rods and they are returned to the surface via the annular area. In the surface they are collected in a settling pond (Figure 7). Reverse circulation is similar to direct circulation, but in the opposite direction: the fluid is injected into the drill via the annular area and the drill cuttings are swept up the inner tube to the surface (into a settling pond).

Rotary percussion drills can use both methods of circulation.

Figure 7. *Image of the settling pond used for fluids circulation during drilling.*

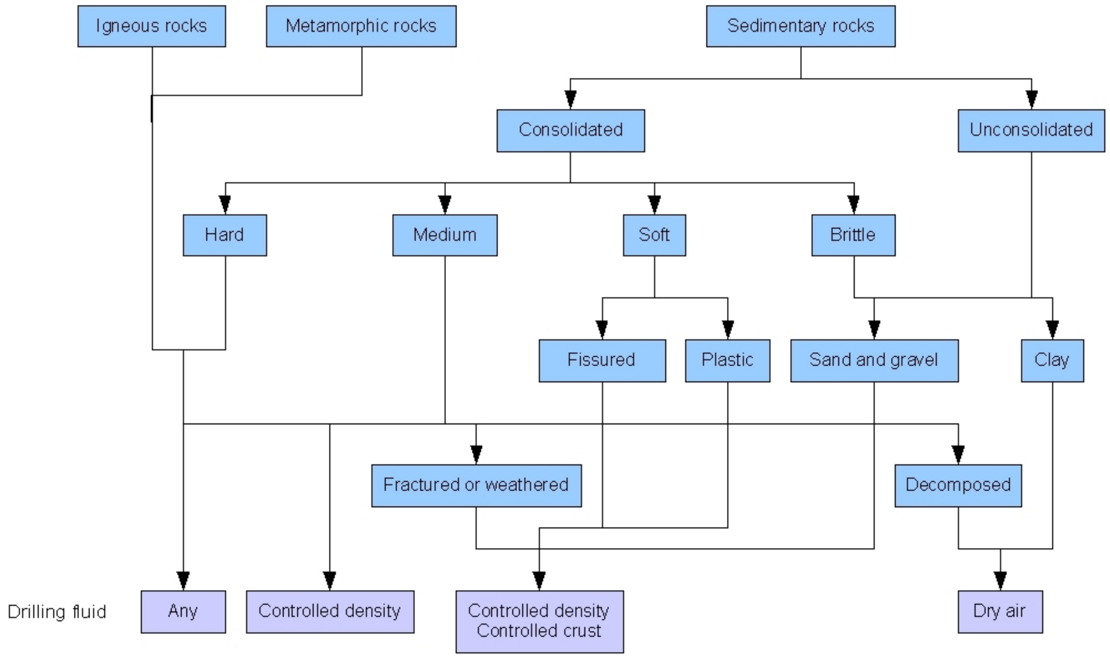

Figure 8. *Diagram of drilling fluids.*

Note that, in some mechanical methods, water can be used during drilling to help well development and refrigeration. According to the injection flow and the type of geologic material, this water can also go up the borehole sweeping fine drilling materials to the surface.

Figure 8 shows the types of fluids used depending on the geological material being drilled.

Air is used as a fluid for drilling unconsolidated clayey sedimentary rocks, brittle or decomposed consolidated rocks and igneous or metamorphic hard rocks; although in the latter mud can also be used. For all other formations drilling mud (water-based or oil-based fluid) is used with controlled density. Air is not a current practice for drilling through salt formations; in this case mud is used.

Radiation exposure pathways to drilling personnel will depend upon the method of detritus removal or drilling sample extraction. By removing detritus or samples mechanically, they will normally appear dry on the surface, such that exposure by inhalation of airborne material should be taken into account. However, if drilling fluids are used, the fluids will tend to reduce the level of airborne contamination arising during drilling activities. Nonetheless, once drilling operations have ceased, the material remaining in the settling pond could be transported through airborne or surface-water paths. In addition, the water injected into the drill could cause contamination to the rest of materials along the borehole section. This could lead to an extension of the contamination in the ground and in groundwater.

Radiation exposure can occur from the moment that drilling material is brought to the surface. The volume of material, and hence contaminated material that could be brought to the surface during drilling, depends on the diameter of the drill bit, which may vary with the depth to be drilled and the technique employed.

Initially, it is likely that the person who receives the highest exposure to the radioactive material brought to the surface is the geologist; the person who will be closely examining samples. On the other hand, the drilling personnel should also be taken into account since they are in direct contact with the ground, the rods that could be contaminated and near the drilling fluids settling pond, if there is one.

Concerning contact with rods during drilling, it should be noted that diamond core drilling and cable tool drilling involve removing the drill string to remove detritus or samples, so with these techniques drilling personnel would have greater contact with radioactivity than with other techniques. On the other hand, it is sometimes necessary while drilling to change the drill bit because of a breakage or erosion and thus contact with the rods would also occur in the other techniques. This might occur if drilling through a repository were in some way to damage a drill head or other part of the drill system.

Those individuals or groups that may become exposed subsequent to the drilling work should also be kept in mind. This might include residents near the drilling site[4] exposed to contamination left at the site and laboratory staff, if the samples were not detected as hazardous during field inspections.

If radioactive material were to be extracted as a result of drilling, it is possible that the hazard would not be identified, at least not initially. Exposure of the geologist and workers within a geotechnical laboratory is therefore plausible. In the event that, during drilling, metal fragments or their corrosion products were removed, the origin of the materials may be easier to identify, but would also attract interest, and hence longer contact, until any hazard were to be identified. However, the greater part of the repository volume is filled with cementitious material, so it could be mistaken during initial observation for a type of natural rock. If the sample is taken from the adjacent contaminated rock, it may also be wrongly identified as ordinary uncontaminated rock.

To analyse this in more detail, the different potential exposure modes for people involved in such intrusion are described below. This is taken to include primarily drilling workers and geological investigators. Consideration is also given to those directly affected by contaminated material brought to the surface and left at the drill site.

External irradiation

Radioactive detritus, liquids or samples extracted during drilling may be dumped at the surface. For example they may be placed in a settling pond, directly on above ground surfaces, or into core trays. This process will result in external radiation exposure to the drilling personnel and the geologist, during the time at which radioactive material is removed. In general, exposure would occur at large distances (> 1 m) as compared to

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[4] IAEA [2011a] limits consideration *only* to this potentially exposed group, i.e. those living around the site.

exposure in the case of a detailed examination of the sample, but occasionally exposure can be at a shorter distance, for instance during sample retrieval practices by the driller.

It is also supposed that the geologist will perform a detailed examination of the core sample within a shorter distance (1 m). If the sample seems to be common rock adjacent to the repository it will be a routine examination (regular time), but if the sample is unusual, the sample examination will be more detailed and for an extended time (which may involve close examination).

In the event that samples are not identified as hazardous, they may be sent to a laboratory. Short-term external exposure would be expected to result from close contact with samples during their examination and longer-term, more distant radiation exposure would result from the storage of samples.

Longer term exposure might also occur to any contaminated material left at the surface, for example to people occupying or using the site for residence or other purposes.

Inadvertent ingestion

During drilling, some the extracted material could be transferred onto the body (primarily via the hands) of drilling personnel or geologists and, if it was not detected and hands not cleaned, material could be ingested through hand to mouth contact.

The drilling technique that would enhance this pathway would be diamond core drilling, because the sample is removed from the rod manually and the drilling personnel could come into contact with it. In addition, this technique involves continuous material analysis, such that a geologist would have greater exposure by examining and touching samples because there would be more material to analyse.

Ingestion could also occur in a laboratory during closer inspection of the material; the use of gloves during handling and analysis of the samples in a geotechnical laboratory is not a usual practice.

Subsequent site occupiers could also be exposed by this pathway, and also through ingestion of activity taken up into the foodchain, especially if the contamination reaches cultivated ground.

Inhalation of airborne material

Contaminated airborne material, dust and aerosols, might be inhaled by drilling personnel throughout the working day. The potential for this pathway to occur will depend on the drilling method employed. When using drilling fluids with water, dust levels would be relatively low. The presence of a settling pond near the drilling site could however lead to radioactive material becoming suspended in air, especially if the pond dries out during operations.

An on-site geologist would also be exposed to airborne material resulting from the drilling process or from a settling pond. Even so, the greatest exposure would be caused by the closer inspection and manipulation of samples, which would be much more important from a dose perspective from diamond core drilling which requires a greater analysis of all core trays.

With reference to the laboratory, inhalation of airborne material might arise as a result of sample analysis such as cutting, grinding and crushing of samples and actions related to the cleaning machine. These actions could produce contaminated material in the form of respirable dusts.

The presence of radionuclides in the atmosphere could also result in longer-term exposure of residents near the site.

It is also noted that in drilling related to geothermal exploration, drillers are exposed to risks associated with fumes, gases, water and mud at high temperatures reaching 80 degrees Celsius up the borehole. This could influence the transfer of radionuclides to the atmosphere in cases related to contaminated material. However, these jobs require extreme protective measures (gloves and special masks among others). This personal protective equipment could reduce exposure to radionuclides. Furthermore, repositories are not likely to be located at sites with geothermal activity.

2.2.3 Identification of drilling and exposure scenarios

From the information described above, different scenarios can be identified which take into account the different drilling techniques. Thus, a scenario for each of the drilling techniques identified as the most common today, combined with each relevant kind of geologic material, has been developed below. Taking these scenarios as a starting point, the exposure pathways for each drilling technology can be determined, focusing on the technique for extracting detritus, which is considered to be the most influential factor contributing to exposure.

The features used in each of the scenarios (diameter, depth, repository, etc.) are described and explained considering the following:

- Each of the drilling techniques described can reach different depths. The depth may not affect the exposure significantly, but is of interest in determining which scenarios are most pertinent to particular assessments.
- The exposure to radioactive materials depends significantly on the volume of contaminated material brought to the surface, which depends on the drill diameter and the thickness of the contaminated region of rock.
- It has been taken into account that the most common geologies of interest are granite and clay. Thus, one or other has been chosen depending on the drilling technique and the procedure for removal of detritus. For example, in percussion rotary drilling granite has been considered as the adjacent rock, since this method is not very appropriate for plastic clay media, and vice versa, reverse circulation drilling has been applied to a clayey geosphere since it cannot be applied easily to hard formations such as granite. If the drilling technique allows drilling in the two types of materials, the two technique can be used to assess exposure pathways in each geology.

- Finally, a qualitative assessment of the magnitude of each of the exposure pathways for all the scenarios has been made, during the contaminated detritus extraction, using the sign "--" for the lowest magnitude and the sign "++" for the highest one. This assessment only takes into account the detritus extraction technique and its surface treatment; it is not an assessment according to the volume of material removed.

The characteristics of each of the proposed scenarios are detailed in Table 3 below. Consideration is given separately to the drilling worker and the specialist geologist. Note that drilling worker is assumed to have normal exposure whereas the geologist receives higher exposure due to his close inspection of any contaminated materials.

Cable tool drilling

This method is for drilling depths up to 600 m, but is a technique being used less frequently. It is more likely to be relevant to repositories that are located at shallower depths. This technique involves the largest drill diameter and so results in the largest amount of contaminated material coming to the surface.

In a case where drilling penetrates directly into a waste package, due to the material change (metal, man-made material), drilling would possibly be stopped after the first or second detritus extraction. If it only drilled into buffer or backfill, it is unlikely that the material change would be detected so drilling would be continued as planned. It is also likely that the contaminated clays extracted to the surface would not be identified as hazardous material, so the drilling would continue.

The main exposure pathways might be inhalation of airborne material and external radiation, arising from dry materials deposited on the surface as they are removed. Inadvertent intake would be lower for the drilling personnel because they would only be in contact with the drill bit and the bailer during detritus removal operations. However, the geologist might contact material for closer examination occasionally, during the observation of the detritus.

Diamond core drilling

This research method can reach great depths with diameters smaller than the other techniques. In Table 3 the greatest depth and diameter are considered, in order to reflect the worst-case situation. This technique allows drilling clays and granites using either water or mud as drilling fluids.

Table 3. *Characteristics of the drilling scenarios.*

Drilling technique	Typical drilling depth (m)	Drilling diameter (mm)	Removal of detritus	Rock type	Drilling fluid	Exposure pathways according to the detritus extraction technique	
						Drillers (normal)	**Geologist (close inspection)**
Cable tool drilling	600	1200	Mechanically	Clay	Water	External radiation - Inadvertent intakes + Inhalation airborne material	External radiation + Inadvertent intakes - Inhalation airborne material
Diamond core drilling	1500	134	Mechanically	Crystalline	Water	External radiation - Inadvertent intakes + Inhalation airborne material	External radiation + Inadvertent intakes - Inhalation airborne material
				Clay	Water/ mud	External radiation - Inadvertent intakes + Inhalation airborne material	External radiation + Inadvertent intakes - Inhalation airborne material
Rotary drilling	1200	660	Hydraulically	Crystalline	Air/Mud	External radiation ---/++ Inadvertent intakes +++/-- Inhalation airborne material	External radiation --/+++ Inadvertent intakes ++/--- Inhalation airborne material
				Clay	Mud	External radiation ++ Inadvertent intakes -- Inhalation airborne material	External radiation +++ Inadvertent intakes --- Inhalation airborne material
Reverse circulation drilling	400	1800	Hydraulically	Clay	Mud	External radiation ++ Inadvertent intakes -- Inhalation airborne material	External radiation +++ Inadvertent intakes --- Inhalation airborne material
Percussion rotary drilling	1500	380	Hydraulically	Crystalline	Air	External radiation --- Inadvertent intakes +++ Inhalation airborne material	External radiation -- Inadvertent intakes ++ Inhalation airborne material

If drilling penetrates into the buffer or backfill, the material change would be noted if the adjacent rock was granite, but not if the rock was clay. Even so, it could be interpreted as a mere change of material and the drilling could continue. However, if the drilling penetrated into a waste package, the man-made material might be distinguished and the drilling would probably stop, but only after 1 or 2 meters of potentially contaminated material had already been removed. Drilling into the adjacent rock, in a contaminated volume, could be done without the detection of hazardous material and the drilling would continue.

With reference to the exposure pathways and considering that the extracted detritus would be dry, the same external irradiation and inhalation of airborne material pathways for drilling personnel as in the cable tool drilling are likely. However, due to the extraction technique used to remove the rock from the hollow drill rod (by hand and with a hammer), it is considered that the inadvertent intake exposure pathway will be higher than in the preceding scenario and, even more, in the case of clay formations (where there would be a greater fraction of material adhered to gloves and clothes). In relation to the geologist, exposure could be greater than for drilling personnel in all exposure pathways because the geologist makes a detailed examination of the core samples.

Rotary drilling

This method can be used both in clays and crystalline rocks. Clays are usually drilled with water as a drilling fluid, whereas granite that can also be drilled with compressed air. In Table 3, the greatest diameters (660 mm, oil wells) and depth are presented.

If the drilling penetrated into buffer or backfill, the material change could be noticed if the adjacent rock was granite, but it couldn't be noticed if it was clay. In case of drilling granite with compressed air, the buffer or backfill would be noted within a few meters, as would be the metal of a waste package; but the detritus removed to the surface would be crushed and mixed, so it could be difficult to detect its origin and drilling could possibly continue until the proposed depth. The same would happen if the repository were to be in clay, in which case a change of material would probably be undetected or maybe would be detected once it has been drilled a long way through. As for the drilling methods, drilling into the contaminated rock adjacent to the repository could be done without any detection and drilling would continue.

The use of one or other type of drilling fluid will affect the level of exposure. Compressed air in granite formations would result in greater inhalation of airborne material compared to water

During granite drilling with compressed air, external radiation would be similar to the other techniques, as detritus will also be deposited on the surface. Moreover, as their removal is done by the drilling fluid, there would lower contact with rods or contaminated material, such that inadvertent intake would be reduced compared with other scenarios. The exposure of the geologist could be somewhat higher because he/she would be occasionally in closer contact with the material during the analysis of the detritus. In the drilling of clay formations with the use of water (mud), the ingestion would be slightly higher than the situation exposed before, as the clay material mixed with the drilling fluid would be more likely to adhere to clothes, gloves and hands of drilling personnel and the geologist, and thus be transferred to the mouth inadvertently.

Reverse circulation drilling

This method is not commonly used in consolidated or semi-consolidated rocks, so is considered only in relation to a scenario where drilling into clay occurs. Depths of around 400 m can be reached and are associated with large diameters, as indicated in Table 3.

The exposure pathways are assumed to be similar to those for rotary drilling, noting the use of mud to drill clay formations.

Percussion rotary drilling

The use of this method in clays is problematic, so consideration is only given to the drilling of granite. This technique can reach depths of 1500 m with diameters up to 380 mm.

The drilling method is also problematic with respect to plastic formations; as such, penetration into buffer or backfill is likely to prevent the drill from advancing and drilling would likely cease. Because of this, there would be little chance to penetrate into buffer or backfill and, hence, waste packages. However, the likelihood of drilling in the contaminated adjacent rock would be the same as in the previous scenarios.
In case of granite as the adjacent rock and the use of mud as a drilling fluid, exposure pathways would be similar to those assumed in the rotary drilling in granite scenario, with the difference that inhalation of airborne material would be greatly reduced with the use of water.

Contaminated material left at the drill site

Table 3 only considers exposures relevant to the drilling workers and geological investigators.

If contaminated material were to be left on the surface at the drill site, this could lead to exposure of others who use the contaminated area after the drilling work has ceased. A very large range of exposure scenarios could arise in this case, corresponding to those which could arise from radioactively contaminated land.

The range of exposure possibilities has been examined thoroughly in the context of present day management of radioactively contaminated land in Oatway and Mobbs [2003]. These possibilities take into account use of the land for agriculture, recreation, housing, school area and industry, as well as construction activities. Each of these land uses has associated with it a range of exposure pathways. The approach is comprehensive and parallels more general assessments to support exemption and clearance levels prepared for the European Commission [EC, 2000 and 2001] and the IAEA [2005]. The significance of different assessment assumptions for the various exposure scenarios is discussed in EC [2010].

3 RADIONUCLIDES OF INTEREST IN WASTE

The following Table 4 of radionuclides has been developed from inventories for a range of proposed and actual repositories. This list is intended to be representative of all radionuclides likely to be of interest for deep geological disposal, i.e. including a full range of relevant half-lives and radiation emissions, as well as having been identified as significant in various assessments. However, it is noted that priorities can change from time to time, according to new information about inventories, radionuclides of a shorter half-life than 5 years are not included in Table 4 since they will decay to extremely low levels before intrusion is considered reasonably likely, taking into account expected periods of institutional control, as discussed in IAEA [2011b]. Radioactive progeny of those listed with half-life less than 5 years, are not listed either, but are considered below in the radiological assessments. Table 4 thus reflects the radionuclides of potential interest at the time of disposal.

Table 4. *Radionuclides of interest in waste at the time of disposal.*

Radionuclide	
H-3	Cm-246
C-14	Cm-245
Cl-36	Cm-244
Ca-41	Am-243
Co-60	Am-242m
Ni-59	Am-241
Ni-63	Pu-242
Se-79	Pu-241
Sr-90	Pu-240
Zr-93	Pu-239
Nb-93m	Pu-238
Mo-93	Np-237
Nb-94	U-238
Tc-99	U-236
Pd-107	U-235
Ag-108m	U-234
Sn-126	U-233
I-129	U-232
Ba-133	Th-232
Cs-135	Th-230
Cs-137	Th-229
Eu-152	Th-228
Eu154	Pa-231
Sm-151	Ac-227
	Ra-228
	Ra-226
	Pb-210

4 ASSESSMENT OF DOSES FOR NORMALISED EXPOSURE

Here, the assessment of doses is presented from exposure to unit activity concentration of each radionuclide identified in Section 3, in unit amount of material brought to the surface. Assessments have been made for scenarios involving direct contact with contaminated material brought to the surface (drilling workers and geologists), and others exposed due to contaminated material being left at the drill site.

4.1 Selected scenarios for quantitative dose assessment: direct contact

Assumptions for how exposure arises should be based on reasonable consideration of how drilling workers and others may have direct contact with contaminated material which is brought to the surface, taking into account mechanisms for how material gets to the surface, what would then be done with it and how that could result in exposure via inhalation, ingestion and external exposure. Because of the large range of drilling techniques, types of waste form, types of EBS and far-field geology, as demonstrated in Section 2, an envelope of representative situations has been considered quantitatively, covering:

- Typical spent fuel HLW package
- Typical cement L/ILW package

- Bentonite buffer or backfill
- Cement buffer or backfill

- Crystalline rock geosphere
- Clay geosphere

Consideration is given to workers at the drill head assumed to work normally, and to others who make close inspection of core or other extracted material, as illustrated in Figure 9.

Intrusion into each package, EBS and rock type has been considered for each radionuclide, so that the results can be applied and combined, as appropriate, to a wide range of situations.

Very simple assumptions have been used for external irradiation geometry as the number of options is enormous. The intention is not to rely on highly specific assumption which could only be applicable in those specific situations. No assumptions for shielding have been made, as these will either be negligible or unjustifiable. Similarly, simple assumptions for inhalation and ingestion have been made. Account could be taken of the physical and chemical form of the radionuclides in selecting dose coefficients, based on relevant waste form information, such as described in Anttila [2005]. However, standard default assumptions for chemical and physical form have been made here. No account has been taken of personnel protection measures beyond those normal for the relevant assumed activities.

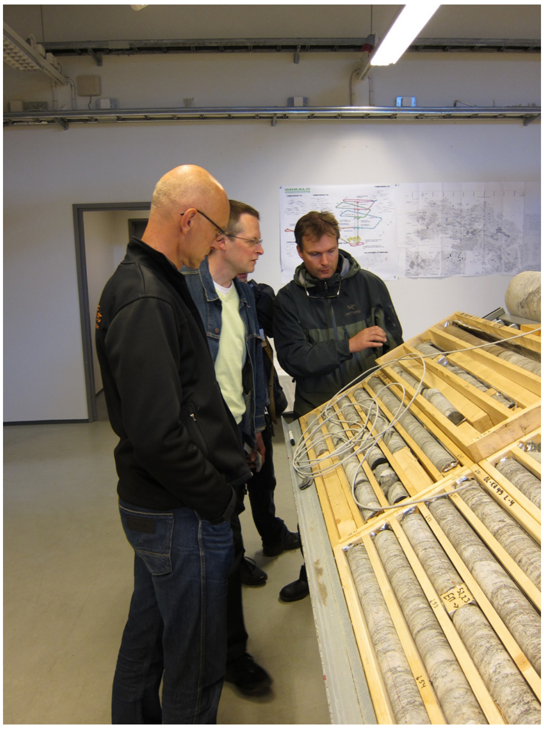


Figure 9. *Illustration of core examination.*

4.2 Quantification of direct contact exposure scenarios

Consideration is given to external irradiation of workers at the drill head and others who might be involved in inspection or evaluation of contaminated material which is brought to the surface, for example, because of its unexpected appearance or anomalous behaviour of the drill. In addition consideration is given to inhalation of dusts which might be generated from the same material and inadvertent ingestion of the same material. Parameter for the dose models values have been selected to be realistic but conservative.

4.2.1 External irradiation

The calculation is based on exposure at 1 m from a point source of the same size as the content of a 1 m length of contaminated core or drill material. Many alternative geometries can be imagined, e.g. a line source of 1 m representing a core sample, or standing over a plane source of an area contaminated by the same volume of extracted material, contaminated to some realistic but still arbitrary thickness. Given the objective is to obtain an idea of how high the dose might be, assuming typical working contacts and no protective measures, i.e. shielding etc., then the point source geometry is as reasonable as any other, and the differences for different geometries, while still assuming reasonable close contact are only a factor of a few. For examples of effects of different geometries at different energies, see Section 3 of Radioactive Substances Advisory Committee [1971], and further illustrative data and discussion in Eckerman and Ryman [1993]. This approach is also consistent with ICRP advice [ICRP, 2011] that the scenarios to be evaluated should be plausible and stylised, which is taken here to mean physically realistic but including limited details, which otherwise would be hard to justify.

The dose equation is taken from Lawson and Smith [1985] with some simple modifications for the volume of material assumed, as explained in Table 5 below.

4.2.2 Inhalation

The equation for inhalation dose is elaborated in Table 6.

4.2.3 Inadvertent ingestion

The equation for inadvertent ingestion dose is elaborated in Table 7.

Table 5. *Calculation of external irradiation dose.*

External irradiation → $D_{ext} = 1.4{\cdot}10^{-13} \cdot f_1 \cdot f_2 \cdot \frac{1}{x^2} \cdot \rho \cdot V \cdot t_{\exp} \cdot \sum_i \left(\cdot E_i \cdot S_i \right)$		Sv
D_{ext}	Effective dose equivalent from external irradiation	Sv
$1.4{\cdot}10^{-13}$	Constant relating exposure rate to source size and distance	(100R·m^2)/ (MeV·h·Bq)
f_1	Conversion factor from exposure to effective dose equivalent	Sv/100R
f_2	Self-shielding factor	-
x	Distance from the source	m
E_i	Mean gamma energy per disintegration for each radionuclide of interest	MeV
S_i	Average activity concentration of a radionuclide i in the sample	Bq/g
ρ	Density of sample	g/m^3
V	Volume of sample (m^3) where, $V = \pi \cdot r^2 \cdot h$	m^3
	r Borehole radius	m
	h Core length	m
$t_{\exp}$	Exposure time	h

Table 6. *Calculation of inhalation dose.*

Inhalation of airborne material → $D_{inh} = t_{\exp} \cdot R \cdot d \cdot \sum_i \left(I_{inh,i} \cdot S_i \right)$		Sv
D_{inh}	Effective dose equivalent from inhalation	Sv
$t_{\exp}$	Exposure time	h
R	Respiration rate	m^3/h
d	Air dust concentration, where dust is derived from drilling material	g/m^3
$I_{inh,i}$	Dose per unit intake by inhalation of each radionuclide i	Sv/Bq
S_i	Average activity concentration of a radionuclide i in the sample	Bq/g

Table 7. *Calculation of inadvertent ingestion dose.*

Inadvertent ingestion → $D_{ing} = t_{\exp} \cdot m \cdot \sum_i \left(I_{ing,i} \cdot S_i \right)$		Sv
D_{ing}	Effective dose equivalent from inadvertent ingestion	Sv
$t_{\exp}$	Exposure time	h
m	Intake by ingestion	g/h
$I_{ing,i}$	Dose per unit intake by ingestion of each radionuclide i	Sv/Bq
S_i	Average activity concentration of a radionuclide i in the sample	Bq/g

4.2.4 Radionuclide independent data assumptions

Table 8 provides radionuclide independent data assumptions for the equations above and the references upon which they are based. Two of the more problematic parameters include the assumption for dust level in the breathable atmosphere which is associated with the contaminated material, and the amount of contaminated material which might be inadvertently ingested. These parameters have the subject of further review and consideration, set out in Appendix B.

Table 8. *Radionuclide independent data.*

Parameter	Value	Comments		Reference
f_1	0.7	The conversion from absorbed dose to effective dose equivalent is energy dependent, but above 0.1 MeV the modifying factor is between 0.7 and 1. For the present calculations a factor of 0.7 has been used.		Charles and McEwen (1991)
f_2	1	No self-shielding effect has been taken into account. For the higher energy emissions the effect would be small even for core material; for irradiation from fines or sectioned core the self-shielding would be more generally small.		Charles and McEwen (1991)
x	1 m	The dose will be normalized by distance to the material (1 m) for driller and geologist		Charles and McEwen (1991)
S_i	1 Bq/g	It is assumed an initial activity of 1 Bq of each radionuclide for each gram of excavated material. To obtain the total dose for an inventory, the activity of each radionuclide is taken into account.		Normalising assumption
ρ	kg/m³	Different bulk density values depending on the material excavated:		
		Crystalline rock	**2630 kg/m^3** 2190 kg/m^3	ENRESA (2001) SKB (2006)
		Clay	2760 kg/m^3 (Opalinus) 1980 kg/m^3 (Ypresian) **2410 kg/m^3 (Callovo-Oxfordian)**	Wersin and Schwyn (2004) ONDRAF/NIRAS (2001) Zhang and Rothfuchs (2004)
		Concrete	**2400 kg/m^3**	
		Bentonite	**2700 kg/m^3 (FEBEX)** 2760 kg/m^3 (MX-80) 2000 kg/m^3 (MX-80)	ENRESA (2001) Wersin and Schwyn (2004) SKB (2006)
		Canister	**2750 kg/m^3 (conditioned waste)**	ONDRAF/NIRAS (2001)

Table 8 (cont'd). Radionuclide independent data.

Parameter	Value	Comments			Reference
r	0.07 - 0.90 m	Borehole radius values depend on the drilling technique used:			
		Cable tool	0.60 m		
		Diamond core	0.07 m		
		Rotary	0.33 m		
		Reverse circulation	0.90 m		
		Percussion rotary	0.19 m		
h	1 m	The dose will be normalized to an assumed core length of 1 m			Normalising assumption
V	0.02 – 2.54 m^3	It will be used different volume values depending on the drilling technique used:			See Table 3
		Cable tool	1.13 m^3		
		Diamond core	0.02 m^3		
		Rotary	0.34 m^3		
		Reverse circulation	2.54 m^3		
		Percussion rotary	0.11 m^3		
t_{exp}	1 h	The dose is normalized to 1 h			Normalising assumption
m	0.8 – 55 mg/h	Different intakes of sample depending on the humidity level of the sample was classified qualitatively for each technique and the operator (driller or geologist), from very low intake (---) to very high intake (+++). The corresponded values are :			See Appendix B
		---	0.8 mg/h		
		--	8 mg/h		
		-	17 mg/h		
		+	33 mg/h		
		++	42 mg/h		
		+++	55 mg/h		
		Original data is in mg/d. Working hours per day is usually around 8. But considering that workers doing field works have to change and have some procedure to get effectively working next to the excavation, it is assumed that their presence next to the excavation is reduced to 6 h/day.			
$I_{ing,i}$		See Table 10			
R	1.5 - 3 m^3/h	2 references: the inhalation rate for an adult (1 m^3/h), And, In IRSN, there are inhalation rates for adults (>18 years) depending on the sex and the type of exercise:			Charles and McEwen (1991) IRSN (2010)
			Man	Woman	
		Light exercise	1.50	1.25	
		Heavy exercise	3.0	2.7	
		It is assumed that the driller is involved in heavy exercise and the geologist, light; and male as this is conservative in dose estimation.			
d	0.001 - 10 mg/m^3	Dust concentration has been classified qualitatively for each technique and the operator (driller or geologist), from very low inhalation (---) to very high inhalation (+++). The corresponding values are :			See Appendix B
		---	0.001 mg/m^3		
		--	0.1 mg/m^3		
		-	1 mg/m^3		
		+	2 mg/m^3		
		++	5 mg/m^3		
		+++	10 mg/m^3		
$I_{inh,i}$		See Table 11			

4.2.5 Radionuclide dependent data assumptions

Treatment of the decay chains

Table 9 presents the half-lives of the radionuclides of interest and the associated radioactive progeny. Some of these progeny need to be considered dynamically in any calculation of decay and ingrowth between disposal and the intrusion event; others are assumed to be in secular equilibrium with their parents. These latter have been selected on the basis of having a half-life less than 30 days. The radiation effects of these relatively short-lived radioactive progeny are added into those of the parent. Branching ratios are also noted as these affect the summation over these chains. Data are taken from ICRP [2008].

Note that the list is longer than that in Section 3. There, the interest was in which radionuclides are important in the disposed source term. Here the interest is in which radionuclides are giving rise to the dose as a result of disposal of those radionuclides. This requires detailed consideration of the radiation effects of the radioactive progeny as set out in Tables 10, 11 and 12.

Dose coefficients for ingestion

Table 10 gives committed effective doses per unit ingestion for adults [ICRP, 1996]. Default values for workers are taken here. Knowledge of different chemical forms could allow for different assumptions to be made concerning selection of gut transfer factors. However, knowledge of chemical conditions at the time of intrusion has not been assumed here, hence the use of defaults.

Dose coefficients for inhalation

Table 11 gives committed effective doses per unit inhalation for adults [ICRP, 1996], assuming a particle size of one micron activity mean aerodynamic diameter (AMAD). The assigned inhalation class for the aerosols relates to whether absorption is considered to be fast, medium or slow (F, M or S) from respiratory tissues into body fluids. The ‘default’ class indicates the relevant absorption rate for dose calculations provisionally assumed to be relevant to HI calculations. The summation of progeny assumed to be in secular equilibrium is shown. Where progeny are considered to be present in secular equilibrium they take the same inhalation class as their parent. Additional explanatory notes are provided at the end of the table.

Table 9. *Radionuclide half-lives and treatment of shorter-lived decay chain products.*

Header radionuclide	Radioactive progeny which are modelled dynamically	Radionuclides assumed in secular equilibrium, i.e. with half-life less than 30 days	Half-life (y)	Branching ratio, where appropriate (proportion of parent decaying to this progeny)
H-3		-	12.32	-
C-14	-	-	5.70E+03	-
Cl-36	-	-	3.01E+05	-
Ca-41	-	-	1.02E5	-
Ni-59	-	-	1.01E+05	-
Ni-63	-	-	1.00E+02	-
Co-60	-	-	5.27	-
Se-79	-	-	2.95E+05	-
Sr-90		Sr-90	2.88E+01	-
		Y-90	7.31E-03	1
Zr-93	Go to Nb-93m	-	1.53E+06	-
Nb-93m	-		1.61E+01	0.975 for Zr-93 0.88 for Mo-93
Nb-94	-	-	2.03E+04	-
Mo-93	Go to Nb-93m	-	4.00E+03	-
Tc-99	-	-	2.11E+05	-
Pd-107	-	-	6.50E+06	-
Ag-108m	-	-	4.18E+02	-
Sn-126		Sn-126	2.30E+05	-
		Sb-126m	3.64E-05	1
		Sb-126	3.38E-02	0.14
I-129	-	-	1.57E+07	-
Ba-133	-	-	10.5	-
Cs-135	-	-	2.30E+06	-
Cs-137		Cs-137	3.02E+01	-
		Ba-137m	4.85E-06	0.994
Sm-151		-	9.00E+01	-
Eu-154	-	-	8.59	Gd-154 ignored on basis of extremely long half-life
Eu-152	-	-	1.35E+01	-
Pb-210		Pb-210	2.22E+01	1
		Bi-210	1.37E-02	1
		Po-210	3.79E-01	1
Ra-226		Ra-226	1.60E+03	1
		Rn-222	1.05E-02	1
		Po-218	5.89E-06	1
		Pb-214	5.10E-05	0.9998
		Bi-214	3.78E-05	1

Table 9 (cont'd). Radionuclide half-lives and treatment of shorter-lived decay chain products.

Header radionuclide	**Radioactive progeny which are modelled dynamically**	**Radionuclides assumed in secular equilibrium, i.e. with half-life less than 30 days**	**Half-life (y)**	**Branching ratio, where appropriate (proportion of parent decaying to this progeny)**
		Po-214	5.21E-12	0.9998
	Go to Pb-210			
Ra-228		Ra-228	5.75E+00	1
		Ac-228	7.02E-04	1
	Go to Th-228			
Ac-227		Ac-227	2.18E+01	1
		Th-227	5.11E-02	0.9862
		Ra-223	3.13E-02	1
		Rn-219	1.26E-07	1
		Po-215	5.64E-11	1
		Pb-211	6.86E-05	1
		Bi-211	4.07E-06	1
		Tl-207	9.07E-06	0.9972
Th-228		Th-228	1.91E+00	1
		Ra-224	1.00E-02	1
		Rn-220	1.76E-06	1
		Po-216	4.60E-09	1
		Pb-212	1.21E-03	1
		Bi-212	1.15E-04	1
		Po-212	9.48E-15	0.642
		Tl-208	5.81E-06	0.359
Th-229		Th-229	7.34E+03	1
		Ra-225	4.08E-02	1
		Ac-225	2.74E-02	1
		Fr-221	9.32E-06	1
		At-217	1.02E-09	1
		Bi-213	8.67E-05	1
		Po-213	1.33E-13	0.979
		Tl-209	4.11E-06	0.0209
		Pb-209	3.71E-04	1
Th-230	Go to Ra-226		7.54E+04	1
Th-232	Go to Ra-228	-	1.41E+10	1
Pa-231	Go to Ac-227	-	3.28E+04	1
U-232	Go to Th-228	-	6.89E+01	1
U-233	Go to Th-229	-	1.59E+05	1
U-234	Go to Th-230	-	2.46E+05	1

Table 9 (cont'd). Radionuclide half-lives and treatment of shorter-lived decay chain products.

Header radionuclide	**Radioactive progeny which are modelled dynamically**	**Radionuclides assumed in secular equilibrium, i.e. with half-life less than 30 days**	**Half-life (y)**	**Branching ratio, where appropriate (proportion of parent decaying to this progeny)**
U-235		U-235	7.04E+08	1
		Th-231	2.91E-03	1
	Go to Pa-231			
U-236	Go to Th-232	-	2.34E+07	1
U-238		U-238	4.47E+09	1
		Th-234	6.60E-02	1
		Pa-234m	2.23E-06	1
	Go to U-234			
Np-237		Np-237	2.14E+06	1
		Pa-233	7.38E-02	1
	Go to U-233			
Pu-238	Go to U-234	-	8.77E+01	1
Pu-239	Go to U-235	-	2.41E+04	1
Pu-240	Go to U-236	-	6.56E+03	1
Pu-241	Go to Am-241	-	1.44E+01	1
Pu-242	Go to U-238	-	3.75E+05	1
Am-241	Go to Np-237	-	4.32E+02	1
Am-242m		Am-242m	1.41E+02	1
		Am-242	1.83E-03	0.995
	Go to Pu-242 And Cm-242			1.73E-1 8.27E-1 Ignoring small fraction to Np-238
Am-243		Am-243	7.37E+03	1
		Np-239	6.45E-03	1
	Go to Pu-239			
Cm-244	Go to Pu-240	-	1.81E+01	1
Cm-245	Go to Pu-241		8.50E+03	1 ignoring small spontaneous fission fraction
Cm-246	Go to Pu-242	-	4.76E+03	1 ignoring small spontaneous fission fraction

Table 10. *Committed effective dose per unit ingestion for an adult.*

Parent radionuclide	Decay chain	Branching ratio	Dose per unit ingestion (Sv Bq^{-1})	Dose per unit ingestion of parent in equilibrium with listed progeny (Sv Bq^{-1})
H-3	H-3	1	1.8E-11	1.8E-11
C-14	C-14	1	5.8E-10	5.8E-10
Cl-36	Cl-36	1	9.3E-10	9.3E-10
Ca-41	Ca-41	1	1.9E-10	1.9E-10
Co-60	Co-60	1	3.4E-9	3.4E-9
Ni-59	Ni-59	1	6.3E-11	6.3E-11
Ni-63	Ni-63	1	1.5E-10	1.5E-10
Se-79	Se-79	1	2.9E-9	2.9E-9
Sr-90	Sr-90	1	2.8E-8	3.1E-8
	Y-90	1	2.7E-9	
Zr-93	Zr-93	1	1.1E-9	1.1E-9
Nb-93m	Nb-93m	1	1.2E-10	1.2E-10
Nb-94	Nb-94	1	1.7E-9	1.7E-9
Mo-93	Mo-93	1	3.1E-9	3.1E-9
Tc-99	Tc-99	1	6.4E-10	6.4E-10
Pd-107	Pd-107	1	3.7E-11	3.7E-11
Ag-108m	Ag-108m	1	2.3E-09	2.3E-09
Sn-126	Sn-126	1	4.7E-09	5.1E-09
	Sb-126m	1	3.6E-11	
	Sb-126	0.14	2.4E-09	
I-129	I-129	1	1.1E-7	1.1E-7
Ba-133	Ba-133	1	1.5E-9	1.5E-9
Cs-135	Cs-135	1	2.0E-9	2.0E-9
Cs-137	Cs-137	1	1.3E-8	1.3E-8
	Ba-137m	0.944	-	
Sm-151	Sm-151	1	9.8E-11	9.8E-11
Eu-152	Eu-152	1	1.4E-9	1.4E-9
Eu-154	Eu-154	1	2.0E-9	2.0E-9
Pb-210	Pb-210	1	6.9E-7	1.9E-6
	Bi-210	1	1.3E-9	
	Po-210	1	1.2E-6	
Ra-226	Ra-226	1	2.8E-7	2.8E-7
	Rn-222	1	-	
	Po-218	1	-	
	Pb-214	0.9998	1.4E-10	
	Bi-214	1	1.1E-10	
	Po-214	0.9998	-	
Ra-228	Ra-228	1	6.9E-7	6.9E-7
	Ac-228	1	4.3E-10	

Note: ‘-‘ indicates no dose coefficient available, but would be extremely small if assessed.

Table 10 (cont'd). Committed effective dose per unit ingestion for an adult.

Parent radionuclide	**Decay chain**	**Branching ratio**	**Dose per unit ingestion (Sv Bq^{-1})**	**Dose per unit ingestion of parent in equilibrium with listed progeny (Sv Bq^{-1})**
Ac-227	Ac-227	1	1.1E-6	1.2E-6
	Th-227	0.9862	8.7E-9	
	Ra-223	1	1.0E-7	
	Rn-219	1	-	
	Po-215	1	-	
	Pb-211	1	1.8E-10	
	Bi-211	1	-	
	Tl-207	0.9972	-	
Th-228	Th-228	1	7.2E-8	1.4E-07
	Ra-224	1	6.5E-8	
	Rn-220	1	-	
	Po-216	1	-	
	Pb-212	1	6.0E-9	
	Bi-212	1	2.6E-10	
	Po-212	0.6406	-	
	Tl-208	0.3594	-	
Th-229	Th-229	1	4.9E-7	6.1E-7
	Ra-225	1	9.9E-8	
	Ac-225	1	2.4E-8	
	Fr-221	1	-	
	At-217	1	-	
	Bi-213	0.9999	2.0E-10	
	Po-213	0.979	-	
	Tl-209	0.0209	-	
	Pb-209	0.9999	5.7E-11	
Th-230	Th-230	1	2.1E-7	2.1E-7
Th-232	Th-232	1	2.3E-7	2.3E-7
Pa-231	Pa-231	1	7.1E-7	7.1E-7
U-232	U-232	1	3.3E-7	3.3E-7
U-233	U-233	1	5.1E-8	5.1E-8
U-234	U-234	1	4.9E-8	4.9E-8
U-235	U-235	1	4.7E-8	4.7E-8
	Th-231	1	3.4E-10	
U-236	U-236	1	4.7E-8	4.7E-8
U-238	U-238	1	4.5E-8	4.8E-8
	Th-234	1	3.4E-9	
	Pa-234m	1	-	
Np-237	Np-237	1	1.1E-7	1.1E-7
	Pa-233	1	8.7E-10	
Pu-238	Pu-238	1	2.3E-7	2.3E-7

Note: ‘-‘ indicates no dose coefficient available, but would be extremely small if assessed.

Table 10 (cont'd). Committed effective dose per unit ingestion for an adult.

Parent radionuclide	Decay chain	Branching ratio	Dose per unit ingestion (Sv Bq^{-1})	Dose per unit ingestion of parent in equilibrium with listed progeny (Sv Bq^{-1})
Pu-239	Pu-239	1	2.5E-7	2.5E-7
Pu-240	Pu-240	1	2.5E-7	2.5E-7
Pu-241	Pu-241	1	4.8E-9	4.8E-9
Pu-242	Pu-242	1	2.4E-7	2.4E-7
Am-241	Am-241	1	2.0E-7	2.0E-7
Am-242m	Am-242m	1	1.9E-7	1.9E-7
	Am-242	0.995	3.0E-10	
Am-243	Am-243	1	2.0E-7	2.0E-7
	Np-239	1	8.0E-10	
Cm-244	Cm-244	1	1.2E-7	1.2E-7
Cm-245	Cm-245	1	2.1E-7	2.1E-7
Cm-246	Cm-246	1	2.1E-7	2.1E-7

Note: ‘-‘ indicates no dose coefficient available, but would be extremely small if assessed.

Table 11. *Committed effective dose per unit inhalation for an adult.*

Parent radionuclide	Decay chain, assumed in equilibrium with parent	Branching ratio	Default inhalation class	Dose per unit inhalation (Sv Bq^{-1})	Dose per unit inhalation of parent in equilibrium with listed progeny (Sv Bq^{-1})
H-3	H-3	1	M	4.5E-11	4.5E-11
C-14	C-14	1	M	2.0E-9	2.0E-9
Cl-36	Cl-36 [1]	1	M	7.3E-9	7.3E-9
Ca-41	Ca-41	1	M	9.5E-11	9.5E-11
Ni-59	Ni-59	1	M	1.3E-10	1.3E-10
Ni-63	Ni-63	1	M	4.8E-10	4.8E-10
Co-60	Co-60	1	M	1.0E-8	1.0E-8
Se-79	Se-79	1	F	1.1E-9	1.1E-9
Sr-90	Sr-90	1	M	3.6E-8	3.70E-08
	Y-90 [2]	1	-	1.4E-9 (M)	
Zr-93	Zr-93	1	M	1.0E-8	1.0E-8
Nb-93m	Nb-93m	1	M	5.1E-10	5.1E-10
Nb-94	Nb-94	1	M	1.1E-8	1.1E-8
Mo-93	Mo-93	1	M	5.9E-10	5.9E-10
Tc-99	Tc-99	1	M	4.0E-9	4.0E-9

Notes: ‘-‘ indicates no default inhalation class and/or no dose coefficient available. Where no default inhalation class is given, the medium class is used.

1 Most common compounds are F or M, but M has the larger dose factors.
2 Not needed as treated in chain.
3 Default, but modified to conform to the parent radionuclide.
4 Applies to all common compounds.
5 Applies to all common compounds, but modified to conform to parent radionuclide.

Table 11 (cont'd). Committed effective dose per unit inhalation for an adult.

Parent radionuclide	**Decay chain, assumed in equilibrium with parent**	**Branching ratio**	**Default inhalation class**	**Dose per unit inhalation (Sv Bq^{-1})**	**Dose per unit inhalation of parent in equilibrium with listed progeny (Sv Bq^{-1})**
Pd-107	Pd-107	1	-	2.54E-11 (F) 8.50E-11 (M) 5.87E-10 (S)	8.50E-11
Ag-108m	Ag-108m	1	M	7.4E-9	7.4E-9
Sn-126	Sn-126 [1]	1	M	2.8E-8	2.9E-8
	Sb-126m	1	M	1.9E-11	
	Sb-126	0.14	M	2.4E-9	
I-129	I-129	1	F	3.6E-8	3.6E-8
Ba-133	Ba-133	1	M	3.1E-9	3.1E-9
Cs-135	Cs-135	1	F	6.9E-10	6.9E-10
Cs-137	Cs-137	1	F	4.6E-9	4.6E-9
	Ba-137m [3]	0.944	F	-	
Sm-151	Sm-151 [4]	1	M	4.0E-9	4.0E-9
Eu-154	Eu-154 [4]	1	M	5.3E-8	5.3E-8
Eu-152	Eu-152 [4]	1	M	4.2E-8	4.2E-8
Pb-210	Pb-210	1	M	1.1E-6	4.5E-6
	Bi-210, assumed S as no default	1	-	1.07E-09 (F), 9.30E-08 (M), 1.33E-07 (S)	
	Po-210	1	M	3.3E-06	
Ra-226	Ra-226	1	M	3.5E-6	3.5E-6
	Rn-222 [2]	1	-	-	
	Po-218	1	M	-	
	Pb-214	0.9998	M	1.36E-08	
	Bi-214, assumed S as no default lung class	1	-	7.23E-09 (F), 1.46E-08 (M), 1.54E-08 (S)	
	Po-214	0.9998	M	-	
Ra-228	Ra-228	1	M	2.6E-6	2.6E-6
	Ac-228	1, assumed S as no default lung class	-	1.19E-08 (F), 1.19E-08 (M), 1.46E-08 (S)	

Notes: '-' indicates no default inhalation class and/or no dose coefficient available. Where no default inhalation class is given, the medium class is used.

1 Most common compounds are F or M, but M has the larger dose factors.
2 Not needed as treated in chain.
3 Default, but modified to conform to the parent radionuclide.
4 Applies to all common compounds.
5 Applies to all common compounds, but modified to conform to parent radionuclide.

Table 11 (cont'd). Committed effective dose per unit inhalation for an adult.

Parent radionuclide	**Decay chain, assumed in equilibrium with parent**	**Branching ratio**	**Default inhalation class**	**Dose per unit inhalation ($Sv\ Bq^{-1}$)**	**Dose per unit inhalation of parent in equilibrium with listed progeny ($Sv\ Bq^{-1}$)**
Ac-227, assumed F as no default lung class and this is most conservative	Ac-227	1	S	5.5E-4	5.7E-4
	Th-227 [3]	0.9862	S	9.9E-6	
	Ra-223	1	M	7.4E-06	
	Rn-219 [2]	1	-	-	
	Po-215	1	M	-	
	Pb-211	1	M	1.11E-08	
	Bi-211 [2]	1	-	-	
	Tl-207 [4]	0.9972	F	-	
Th-228	Th-228	1	S	4.0E-5	4.3E-05
	Ra-224 [3]	1	M	3.0E-6	
	Rn-220 [2]	1	-	-	
	Po-216 [3]	1	M	-	
	Pb-212 [3]	1	M	1.7E-7	
	Bi-212 [2], assumed S as no default lung class	1	-	9.0E-9 (F), 3.1E-8 (M), 3.3E-8 (S)	
	Po-212 [3]	0.6406	M	-	
	Tl-208 [3]	0.3594	F	-	
Th-229	Th-229	1	S	7.1E-5	8.6E-05
	Ra-225 [3]	1	M	6.3E-6	
	Ac-225, , assumed S as no default lung class	1	-	7.97E-07 (F), 7.39E-06 (M), 8.49E-06 (S)	
	Fr-221 [5]	1	F	-	
	At-217	1	-	-	
	Bi-213, assumed S as no default lung class	0.9999	-	1.05E-08 (F), 2.98E-08 (M), 3.20E-08 (S)	
	Po-213 [3]	0.979	M	-	
	Tl-209 [3]	0.0209	F	-	
	Pb-209 [3]	0.9999	M	5.6E-11	

Notes: '-' indicates no default inhalation class and/or no dose coefficient available. Where no default inhalation class is given, the medium class is used.

1 Most common compounds are F or M, but M has the larger dose factors.
2 Not needed as treated in chain.
3 Default, but modified to conform to the parent radionuclide.
4 Applies to all common compounds.
5 Applies to all common compounds, but modified to conform to parent radionuclide.

Table 11 (cont'd). Committed effective dose per unit inhalation for an adult.

Parent radionuclide	**Decay chain, assumed in equilibrium with parent**	**Branching ratio**	**Default inhalation class**	**Dose per unit inhalation (Sv Bq^{-1})**	**Dose per unit inhalation of parent in equilibrium with listed progeny (Sv Bq^{-1})**
Th-230	Th-230	1	S	1.4E-5	1.4E-5
Th-232	Th-232	1	S	2.5E-5	2.5E-5
Pa-231, lung class M adopted as for lanthanides and higher actinides	Pa-231	1	M	1.4E-4	1.4E-4
U-232	U-232	1	M	7.8E-6	7.8E-6
U-233	U-233	1	M	3.6E-6	3.6E-6
U-234	U-234	1	M	3.5E-6	3.5E-6
U-235	U-235	1	M	3.1E-6	3.1E-6
	Th-231 [3]	1	S	3.3E-10	
U-236	U-236	1	M	3.2E-6	3.2E-6
U-238	U-238	1	M	2.9E-6	2.9E-6
	Th-234	1	S	7.7E-9	
	Pa-234m	1	-	-	
Np-237	Np-237	1	M	2.3E-5	2.3E-5
	Pa-233,	1	-	1.03E-09 (F). 3.33E-09 (M), 3.86E-09 (S)	
Pu-238	Pu-238	1	M	4.6E-5	4.6E-5
Pu-239	Pu-239	1	M	5.0E-5	5.0E-5
Pu-240	Pu-240	1	M	5.0E-5	5.0E-5
Pu-241	Pu-241	1	M	9.0E-7	9.0E-7
Pu-242	Pu-242	1	M	4.8E-5	4.8E-5
Am-241	Am-241	1	M	4.2E-5	4.2E-5
Am-242m					
Am-243	Am-243	1	M	4.1E-5	4.1E-5
	Np-239	1	M	9.3E-10	
Am-242m	Am-242m	1		3.5E-5	3.5E-5
	Am-242	0.995		1.6E-8	
Cm-244	Cm-244	1	M	2.7E-5	2.7E-5
Cm-245	Cm-245	1	M	4.0E-5	4.0E-5
Cm-246	Cm-246	1	M	4.0E-5	4.0E-5

Notes: ‘-‘ indicates no default inhalation class and/or no dose coefficient available. Where no default inhalation class is given, the medium class is used.

1 Most common compounds are F or M, but M has the larger dose factors.
2 Not needed as treated in chain.
3 Default, but modified to conform to the parent radionuclide.
4 Applies to all common compounds.
5 Applies to all common compounds, but modified to conform to parent radionuclide.

Concerning values of dose coefficients, it may be noted that the values given in ICRP [1996] are based on the ICRP Publication 60 [ICRP, 1991] definition of dose, and thus are due to be updated to take account of the ICRP Publication 103 definition of dose [ICRP, 2007] and the new assumptions for anatomical data given in ICRP Publication 89 [ICRP, 2001]. In addition, while there is no intention to address the uncertainties in dose coefficients in this study, the following quotation from the Report of the Committee Examining Radiation Risks of Internal Emitters [CERRIE, 2004] gives some idea of the uncertainties, viz:

> *"Committee members agreed that insufficient attention has been paid in the past to uncertainties in dose and risk estimates for internal emitters. Reliable quantitative estimates of uncertainties in dose coefficients for a range of radionuclides are not yet available. Uncertainties in estimating equivalent dose, which combine the uncertainties in estimating both absorbed dose and RBE, are always likely to be significant, and probably vary in magnitude from around a factor of 2 or 3 above and below the central estimate in the most favourable cases (i.e. where good data are available) to well over a factor of ten in unfavourable ones (where they are not)."*

This conclusion is relevant to attempts at precision in other assessment parameters, see discussion in Section 5.2.

The mean gamma energy per disintegration for each parent radionuclide considered, including the contributions from short-lived progeny which are assumed to be in equilibrium with the header radionuclide are given Table 12. Note that the emissions from even the very short lived radionuclides need to be considered. The formula for external irradiation dose is strictly correct for 1 MeV photons, but is reasonably accurate between 0.1 and 2 MeV. Photons with energy less than 50 keV do not contribute significantly to effective dose and so have been omitted. Data have been taken from Browne and Firestone (1986) since ICRP Publication 107 [ICRP, 2008] does not indicate the proportion of emissions below 50 keV.

Table 12. *Mean gamma energy per disintegration emitted above 50 keV.*

Parent	**Decay chain (equilibrium progeny only)**	**Branching ratio**	**Mean gamma energy per disintegration, MeV, emitted above 50 keV**	**Total for decay of parent in equilibrium with listed progeny, MeV**
H-3	-	1	0	0
C-14	-	1	1.36E-6	1.36E-6
Cl-36	-	1	1.52E-4	1.52E-4
Ca-41	-	1	1.08E-5	1.08E-5
Co-60	-	1	2.5	2.5
Ni-59	-	1	2.99E-4	2.99E-4
Ni-63	-	1	0	0
Se-79	-	1	2.16E-6	2.16E-6

Table 12 (cont'd). Mean gamma energy per disintegration emitted above 50 keV.

Parent	**Decay chain (equilibrium progeny only)**	**Branching ratio**	**Mean gamma energy per disintegration, MeV, emitted above 50 keV**	**Total for decay of parent in equilibrium with listed progeny, MeV**
Sr-90	Sr-90	1	8.86E-5	1.91E-3
	Y-90	1	1.91E-3	
Zr-93	-	1	4.80E-9	4.80E-9
Nb-93m	-	1	0	0
Nb-94	-	1	1.57	1.57
Mo-93	-	1	6.61E-6	6.61E-6
Tc-99	-	1	1.12E-5	1.12E-5
Pd-107	-	1	0	0
Ag-108m	-	1	1.61	1.61
Sn-126	Sn-126	1	6.40E-6	1.88
	Sb-126m	1	1.55	
	Sb-126	0.14	2.33	
I-129	-	1	1.27E-6	1.27E-6
Cs-135	-	1	3.68E-6	3.68E-6
Cs-137	Cs-137	1	9.03E-5	5.60E-1
	Ba-137m	0.944	5.94E-1	
Sm-151	-	1	3.20E-5	3.20E-5
Eu-154	-	1	1.21	1.21
Eu-152	-	1	1.11	1.11
Pb-210	Pb-210	1	8.50E-10	3.9E-4
	Bi-210	1	3.87E-4	
	Po-210	1	8.50E-6	
Ra-226	Ra-226	1	6.74E-3	1.73
	Rn-222	1	3.98E-4	
	Po-218	1	9.12E-6	
	Pb-214	0.9998	2.7E-1	
	Bi-214	1	1.46	
	Po-214	0.9998	8.35E-5	
Ra-228	Ra-228	1	0	9.25E-1
	Ac-228	1	9.25E-1	
Ac-227	Ac-227	1	1.24E-4	3.84E-1
	Th-227	0.9862	1.00E-1	
	Ra-223	1	1.30E-1	
	Rn-219	1	5.58E-2	
	Po-215	1	1.76E-4	
	Pb-211	1	5.03E-2	
	Bi-211	1	4.65E-2	
	Tl-207	0.9972	2.20E-3	

Table 12 (cont'd). Mean gamma energy per disintegration emitted above 50 keV.

Parent	Decay chain (equilibrium progeny only)	Branching ratio	Mean gamma energy per disintegration, MeV, emitted above 50 keV	Total for decay of parent in equilibrium with listed progeny, MeV
Th-228	Th-228	1	2.00E-3	1.39
	Ra-224	1	9.85E-3	
	Rn-220	1	3.85E-4	
	Po-216	1	1.69E-5	
	Pb-212	1	0	
	Bi-212	1	1.84E-1	
	Po-212	0.6406	0	
	Tl-208	0.3594	3.36	
Th-229	Th-229	1	8.34E-2	3.05E-1
	Ra-225	1	1.64E-5	
	Ac-225	1	1.56E-2	
	Fr-221	1	3.07E-2	
	At-217	1	3.08E-4	
	Bi-213	0.9999	1.33E-1	
	Po-213	0.979	0	
	Tl-209	0.0209	2.03	
	Pb-209	0.9999	9.56E-5	
Th-230	-	1	3.75E-4	3.75E-4
Th-232	-	1	1.73E-4	1.73E-4
Pa-231	-	1	3.45E-2	3.45E-2
U-232	-	1	2.52E-4	2.52E-4
U-233	-	1	2.71E-4	2.71E-4
U-234	-	1	1.19E-4	1.19E-4
U-235	U-235	1	1.5E-1	1.61E-1
	Th-231	1	1.04E-2	
U-236	-	1	2.33E-5	2.33E-5
U-238	U-238	1	2.65E-5	1.90E-2
	Th-234	1	7.81E-3	
	Pa-234m	1	1.12E-2	
Np-237	Np-237	1	2.11E-2	2.17E-1
	Pa-233	1	1.96E-1	
Pu-238	-	1	7.46E-6	7.46E-6
Pu-239	-	1	5.03E-5	5.03E-5
Pu-240	-	1	7.30E-6	7.30E-6
Pu-241	-	1	1.53E-6	1.53E-6
Pu-242	-	1	8.12E-6	8.12E-6
Am-241	-	1	2.13E-2	2.13E-2

Table 12 (cont'd). Mean gamma energy per disintegration emitted above 50 keV.

Parent	Decay chain (equilibrium progeny only)	Branching ratio	Mean gamma energy per disintegration, MeV, emitted above 50 keV	Total for decay of parent in equilibrium with listed progeny, MeV
Am-242m	Am-242m	1	2.97E-4	1.32E-2
	Am-242	0.995	1.29E-2	
Am-243	Am-243	1	5.04E-2	2.17E-1
	Np-239	1	1.63E-1	
Cm-244	Cm-244	1	0	0
Cm-245	Cm-245	1	9.60E-2	9.60E-2
Cm-246	Cm-246	1	2.00E-3	2.00E-3

4.3 Normalised results for direct contact exposure scenarios

The logistically appropriate combination of drilling techniques and contaminated materials leads to consideration of a wide range of possible scenarios. The dose calculation has been done for each technique (cable tool, diamond core, rotary, reverse circulation and percussion rotary), material (clay, bentonite, crystalline rock, concrete and canister) and worker (driller and geologist). This generates 58 scenarios which take into account the corresponding parameters (see second table below). The materials have been divided into two groups depending of their consistency:

- Soft materials: clay and bentonite
- Hard materials: crystalline rock, concrete and canister.

The full set of normalised dose results for each pathway for each radionuclide is provided in a separate excel sheet provided as an annex to this report. Normalised here means assuming 1 Bq/g in the contaminated material hit by the drill; drilling into a 1 m length of contaminated material, and exposure for one hour.

The selection of other parameters in the exposure models is synthesised in Table 13. These data and results enable straightforward calculations of doses for any alternative inventory and assumptions for time of exposure and length of core extracted.

As an example of normalised results, Table 14 shows the doses assessed for the drilling worker, exposed for one hour to a one meter core extracted using diamond core technique into crystalline rock material contaminated at a level of 1Bq/g each.

The significance of the different features of the scenarios is explored below.

Table 13. *Parameters values of all drilling scenarios in different types of rock (*Bent. *for bentonite,* Conc. *for concrete,* Cryst. r. *for crystalline rock,* Can. *for canister).*

		Exposure pathways according to the detritus extraction technique					
		Normal inspection			**Closer inspection**		
Drilling scenario	**Rock type**	**External radiation** $D_{ext} = f(\rho, V)$	**Inadvertent intakes** $D_{ing} = f(m)$	**Inhalation airborne material** $D_{inh} = f(R, d)$	**External radiation** $D_{ext} = f(\rho, V)$	**Inadvertent intakes** $D_{ing} = f(m)$	**Inhalation airborne material** $D_{inh} = f(R, d)$
Cable tool drilling (Humid) (CT)	Clay	Dext = f(2410, 1.13)	Ding = f(17)	Dinh = f(3, 2)	Dext = f(2410, 1.13)	Ding = f(33)	Dinh = f(1.5, 1)
	Bent.	Dext = f(2700, 1.13)			Dext = f(2700, 1.13)		
	Conc.	Dext = f(2400, 1.13)	Ding = f(8)	Dinh = f(3, 5)	Dext = f(2400, 1.13)	Ding = f(17)	Dinh = f(1.5, 2)
	Can.	Dext = f(2750, 1.13)			Dext = f(2750, 1.13)		
Diamond core drilling (Water) (DCW)	Bent.	Dext = f(2700, 0.02)	Ding = f(33)	Dinh = f(3, 1)	Dext = f(2700, 0.02)	Ding = f(42)	Dinh = f(1.5, 5)
	Cryst. r.	Dext = f(2630, 0.02)	Ding = f(17)	Dinh = f(3, 2)	Dext = f(2630, 0.02)	Ding = f(33)	Dinh = f(1.5, 1)
	Conc.	Dext = f(2400, 0.02)			Dext = f(2400, 0.02)		
	Can.	Dext = f(2750, 0.02)			Dext = f(2750, 0.02)		
Diamond core drilling (Humid) (DC)	Clay	Dext = f(2410, 0.02)	Ding = f(17)	Dinh = f(3, 2)	Dext = f(2410, 0.02)	+ Ding = f(33)	- Dinh = f(1.5, 1)
	Bent.	Dext = f(2700, 0.02)			Dext = f(2700, 0.02)		
	Conc.	Dext = f(2400, 0.02)	Ding = f(8)	Dinh = f(3, 5)	Dext = f(2400, 0.02)	- Ding = f(17)	+ Dinh = f(1.5, 2)
	Can.	Dext = f(2750, 0.02)			Dext = f(2750, 0.02)		

*Table 13 (cont'd). Parameters values of all drilling scenarios in different types of rock (*Bent. *for bentonite,* Conc. *for concrete,* Cryst. r. *for crystalline rock,* Can. *for canister).*

		Exposure pathways according to the detritus extraction technique					
		Normal inspection			Closer inspection		
Drilling scenario	Rock type	External radiation $D_{ext} = f(\rho,V)$	Inadvertent intakes $D_{ing} = f(m)$	Inhalation airborne material $D_{inh} = f(R,d)$	External radiation $D_{ext} = f(\rho,V)$	Inadvertent intakes $D_{ing} = f(m)$	Inhalation airborne material $D_{inh} = f(R,d)$
Rotary drilling (Air) (RA)	Bent.	D_{ext} = f(2700, 0.34)	D_{ing} = f(5)	D_{inh} = f(3,7.5)	D_{ext} = f(2700, 0.34)	D_{ing} = f(25)	D_{inh} = f(1.5,7.5)
	Cryst r	D_{ext} = f(2630, 0.34)	D_{ing} = f(1)	D_{inh} = f(3,10)	D_{ext} = f(2630, 0.34)	D_{ing} = f(5)	D_{inh} = f(1.5,10)
	Conc.	D_{ext} = f(2400, 0.34)			D_{ext} = f(2400, 0.34)		
	Can.	D_{ext} = f(2750, 0.34)			D_{ext} = f(2750, 0.34)		
Rotary drilling (Mud) (RM)	Clay	D_{ext} = f(2410, 0.34)	D_{ing} = f(50)	D_{inh} = f(3,0.1)	D_{ext} = f(2410, 0.34)	D_{ing} = f(75)	D_{inh} = f(1.5,0.1)
	Bent.	D_{ext} = f(2700, 0.34)			D_{ext} = f(2700, 0.34)		
	Conc.	D_{ext} = f(2400, 0.34)	D_{ing} = f(25)	D_{inh} = f(3,1)	D_{ext} = f(2400, 0.34)	D_{ing} = f(50)	D_{inh} = f(1.5,1)
	Can.	D_{ext} = f(2750, 0.34)			D_{ext} = f(2750, 0.34)		
Reverse circulation drilling (RC)	Clay	D_{ext} = f(2410, 2.54)	D_{ing} = f(50)	D_{inh} = f(3,0.1)	D_{ext} = f(2410, 2.54)	D_{ing} = f(75)	D_{inh} = f(1.5,0.1)
	Bent.	D_{ext} = f(2700, 2.54)			D_{ext} = f(2700, 2.54)		
	Conc.	D_{ext} = f(2400, 2.54)	D_{ing} = f(25)	D_{inh} = f(3,1)	D_{ext} = f(2400, 2.54)	D_{ing} = f(50)	D_{inh} = f(1.5,1)
	Can.	D_{ext} = f(2750, 2.54)			D_{ext} = f(2750, 2.54)		

*Table 13 (cont'd). Parameters values of all drilling scenarios in different types of rock (*Bent. *for bentonite,* Conc. *for concrete,* Cryst. r. *for crystalline rock,* Can. *for canister).*

		Exposure pathways according to the detritus extraction technique					
		Normal inspection			Closer inspection		
Drilling scenario	**Rock type**	**External radiation** $D_{ext} = f(\rho,V)$	**Inadvertent intakes** $D_{ing} = f(m)$	**Inhalation airborne material** $D_{inh} = f(R,d)$	**External radiation** $D_{ext} = f(\rho,V)$	**Inadvertent intakes** $D_{ing} = f(m)$	**Inhalation airborne material** $D_{inh} = f(R,d)$
Percussion rotary drilling (PR)	Bent.	D_{ext} = f(2700, 0.11)	D_{ing} = f(50)	D_{inh} = f(3,0.1)	D_{ext} = f(2700, 0.11)	D_{ing} = f(75)	D_{inh} = f(1.5,0.1)
	Cryst r	D_{ext} = f(2630, 0.11)	D_{ing} = f(25)	D_{inh} = f(3,1)	D_{ext} = f(2630, 0.11)	D_{ing} = f(50)	D_{inh} = f(1.5,1)
	Conc.	D_{ext} = f(2400, 0.11)			D_{ext} = f(2400, 0.11)		
	Can.	D_{ext} = f(2750, 0.11)			D_{ext} = f(2750, 0.11)		

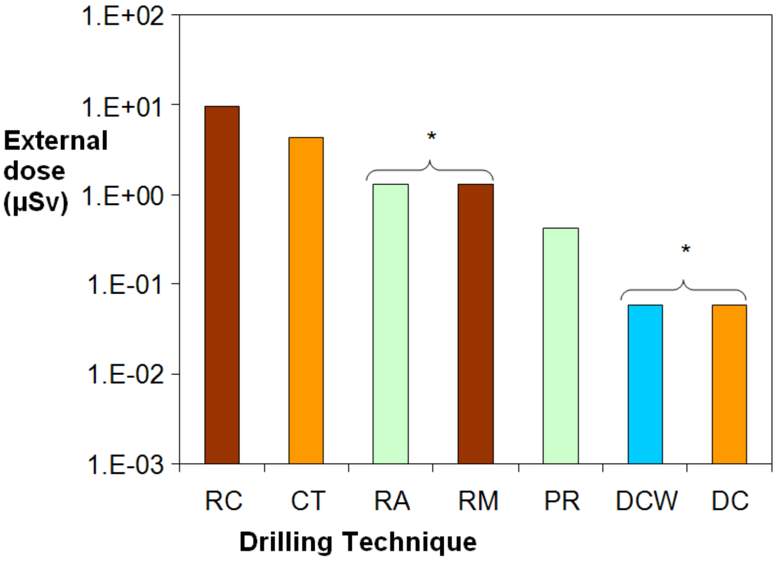
Table 14. *Normalised doses to the driller using the diamond core technique in crystalline rock.*

Nuclide	D ext (µSv)	D ing (µSv)	D inh (µSv)	D total (µSv)
H-3	0.0E+00	3.1E-07	2.7E-07	5.8E-07
C-14	5.4E-09	9.9E-06	1.2E-05	2.2E-05
Cl-36	6.0E-07	1.6E-05	4.4E-05	6.0E-05
Ca-41	4.3E-08	3.2E-06	5.7E-07	3.8E-06
Ni-59	1.2E-06	1.1E-06	7.8E-07	3.0E-06
Ni-63	0.0E+00	2.6E-06	2.9E-06	5.4E-06
Co-60	9.9E-03	5.8E-05	6.0E-05	1.0E-02
Se-79	8.6E-09	4.9E-05	6.6E-06	5.6E-05
Sr-90	7.6E-06	5.3E-04	2.2E-04	7.6E-04
Zr-93	1.9E-11	1.9E-05	6.0E-05	7.9E-05
Nb-93m	0.0E+00	2.0E-06	3.1E-06	5.1E-06
Nb-94	6.2E-03	2.9E-05	6.6E-05	6.3E-03
Mo-93	2.6E-08	5.3E-05	3.5E-06	5.6E-05
Tc-99	4.4E-08	1.1E-05	2.4E-05	3.5E-05
Pd-107	0.0E+00	6.3E-07	5.1E-07	1.1E-06
Ag-108m	6.4E-03	3.9E-05	4.4E-05	6.5E-03
Sn-126	7.5E-03	8.8E-05	1.7E-04	7.7E-03
I-129	5.0E-09	1.9E-03	2.2E-04	2.1E-03
Ba-133	0.0E+00	2.6E-05	1.9E-05	4.4E-05
Cs-135	1.5E-08	3.4E-05	4.1E-06	3.8E-05
Cs-137	2.2E-03	2.2E-04	2.8E-05	2.5E-03
Sm-151	1.3E-07	1.7E-06	2.4E-05	2.6E-05
Eu-152	4.4E-03	2.4E-05	2.5E-04	4.7E-03
Eu-154	4.8E-03	3.4E-05	3.2E-04	5.2E-03
Pb-210	1.5E-06	1.2E-02	7.2E-03	1.9E-02
Po-210	3.4E-08	2.0E-02	2.0E-02	4.0E-02
Ra-226	6.9E-03	4.8E-03	2.1E-02	3.3E-02
Ra-228	3.7E-03	1.2E-02	1.6E-02	3.1E-02
Ac-227	1.5E-03	2.0E-02	3.4E+00	3.4E+00
Th-228	5.5E-03	2.4E-03	2.6E-01	2.7E-01
Th-229	1.2E-03	1.0E-02	5.2E-01	5.3E-01
Th-230	1.5E-06	3.6E-03	8.4E-02	8.8E-02
Th-232	6.9E-07	3.9E-03	1.5E-01	1.5E-01
Pa-231	1.4E-04	1.2E-02	8.4E-01	8.5E-01
U-232	1.0E-06	5.6E-03	4.7E-02	5.2E-02
U-233	1.1E-06	8.7E-04	2.2E-02	2.2E-02
U-234	4.7E-07	8.3E-04	2.1E-02	2.2E-02
U-235	6.4E-04	8.0E-04	1.9E-02	2.0E-02
U-236	9.2E-08	8.0E-04	1.9E-02	2.0E-02
U-238	7.5E-05	8.2E-04	1.7E-02	1.8E-02
Np237	8.6E-04	1.9E-03	1.4E-01	1.4E-01
Pu-238	3.0E-08	3.9E-03	2.8E-01	2.8E-01
Pu-239	2.0E-07	4.3E-03	3.0E-01	3.0E-01
Pu-240	2.9E-08	4.3E-03	3.0E-01	3.0E-01

Table 14 (cont'd). Normalised doses to the driller using the diamond core technique in crystalline rock.

Nuclide	D ext (µSv)	D ing (µSv)	D inh (µSv)	D total (µSv)
Pu-241	6.1E-09	8.2E-05	5.4E-03	5.5E-03
Pu-242	3.2E-08	4.1E-03	2.9E-01	2.9E-01
Am-241	8.5E-05	3.4E-03	2.5E-01	2.6E-01
Am-243	8.6E-04	3.4E-03	2.5E-01	2.5E-01
Cm-244	0.0E+00	2.1E-03	1.6E-01	1.6E-01
Am-242m	5.2E-05	3.2E-03	2.2E-01	2.3E-01
Cm-245	4.3E-04	3.6E-03	2.2E-01	2.3E-01
Cm-246	2.0E-05	3.6E-03	2.2E-01	2.3E-01

External dose is not influenced significantly by the material that is drilled. This dose is influenced by the quantity of material extracted, which depends on the diameter of the drill and the density of the material. However, the variation of latter is negligible (between 2400 and 2750 kg/m³). As core diameter is variable, the volume of 1 meter long core varies of two orders of magnitude (between 0.02 and 2.54 m³). Therefore the external dose varies from two orders of magnitude depending on the technique used. Figure 10 illustrates this for the sum of normalised external doses; the value of the doses has no absolute significance.



* Both of them are the same technique so the external dose, which mainly depends on the technique, is the same. The difference between them is the used fluid which has no effect on the external dose

Figure 10. *Variation of the external dose in function of the technique of drilling.*

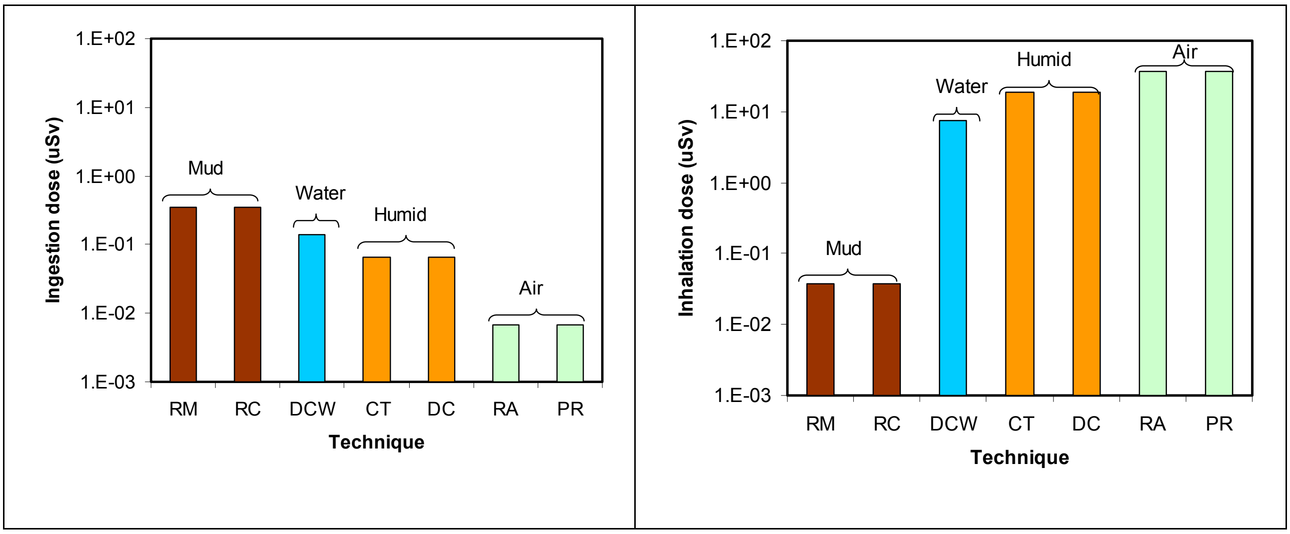


Figure 11. *Variation of ingestion (left) and inhalation (right) dose depending of the fluid used and the drilling technique. (extraction of 1 m core of concrete by the driller).*

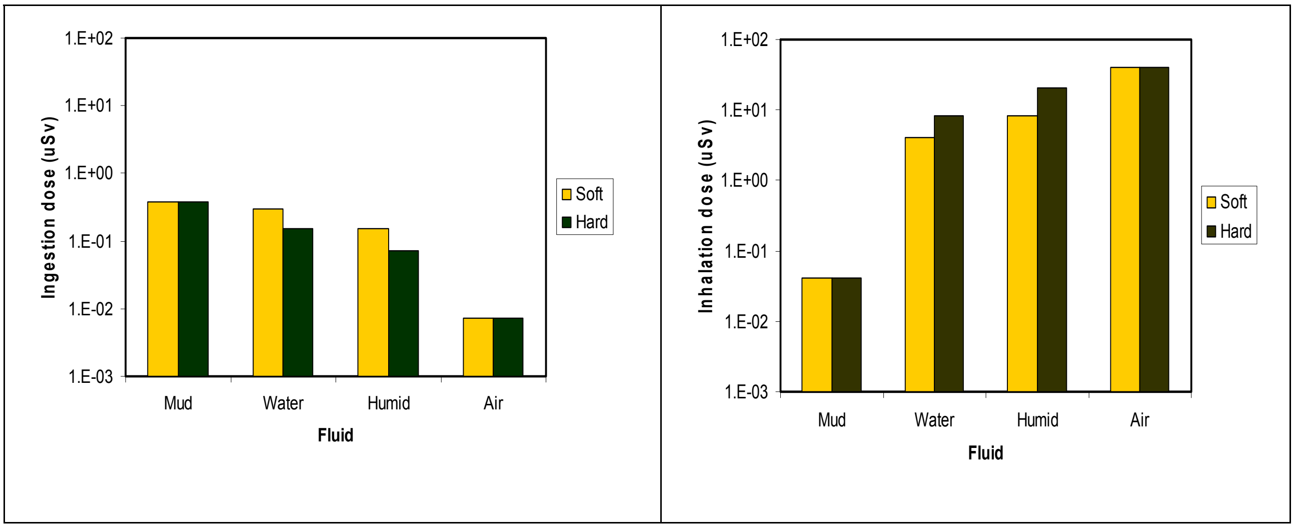


Figure 12. *Variation of ingestion (left) and inhalation (right) dose depending on the hardness of the extracted material and drilling fluid. (extraction of 1 m core by the driller using rotary drilling technique).*

Ingestion and inhalation doses are dependent of the fluid used in the drilling techniques. The wetter the fluid, the sticker is the material, the higher is the ingestion and the lower is the dust production. As a consequence, techniques that use mud as fluid have the highest ingestion dose and the lowest inhalation dose, and vice versa for the techniques using air as fluid. The doses vary by several orders of magnitude as a result, see Figure 11, for the sum of normalised external doses; again, the value of the doses has no absolute significance.

Also, ingestion and inhalation doses may be influenced by the hardness of extracted material. Bentonite and clay are considered as soft material, and crystalline rock, concrete and the canister as hard material. The harder the excavated material, the less sticky is the material, the lower is the ingestion and the higher is the dust production. As a consequence, soft materials have the highest ingestion dose and the lowest inhalation dose, on the opposite to hard materials, see Figure 12.

4.4 Calculation of doses from residual radioactivity left at the drill site

4.4.1 Methodology

The approach used here is to take advantage of existing assessment work on doses arising from various land uses where that land is assumed to be contaminated at a given radionuclide specific level. The advantage is that this avoids re-inventing or adding to existing versions of calculations already developed in this and related contexts, such as exemption and/or clearance of radioactive material from regulatory supervision. It also provides a consistent basis for assessment of doses arising now and in the future.

The main reference used here to assess doses to people at the site after drilling operations cease is Oatway and Mobbs [2003], a methodology for estimating the doses to members of the public from the future use of land previously contaminated with radioactivity. This includes consideration of different land uses and activities, specifically: agriculture, recreation, construction, school, industrial use, and housing. The results are presented for a range of radionuclides and for a range of different spatial distributions of contamination, including uniform, patchy and partly buried contamination. A full range of dose results is presented for each radionuclide, all the land use scenarios and contamination distributions, for adults, children and infants.

Here, uniform unburied contamination is taken as the most suitable case, as being the most simple to apply, and there being no obvious basis for an alternative selection.

The most significant doses for all radionuclides for uniform unburied contamination arise from the agriculture and construction scenarios, in most cases, to adults. Variation in doses between adults, children and infants has been considered in ICRP Publication 101 [ICRP, 2006] and found to be generally less than a factor of 3 (paragraph 80). In the context of assessment of radioactive waste disposal assessment this is considered to be a small uncertainty so that only adult exposure need be considered. This view was already extant in ICRP Publication 81 [ICRP, 2000]. The results used here for the agriculture and construction scenarios are the highest dose results provided in Oatway and Mobbs [2003], whether adult, child or infant, but this has little impact on the conclusions, given the wider uncertainties.

It is also significant that results in Oatway and Mobbs [2003] suggest that effective dose is, with very limited exception, always the critical dose, e.g. compared with skin exposure.

A further consideration is that Oatway and Mobbs [2003] selected parameter values to be realistic but conservative, which is consistent with the approach adopted here for assessment of doses from direct contact with drilling extracted material, Section 4.2.

4.4.2 Further assumptions and results for normalised inventory

In order to apply the Oatway and Mobbs [2003] results is necessary to take account of mixing of contaminated drilling materials left at the site with material assumed to be contaminated according to the scenarios in Oatway and Mobbs [2003].

For the agricultural scenario Oatway and Mobbs [2003] assumed 2.5E5 m^2. This was based on realistic modern farming logistics, and corresponding assumptions for occupancy of the contaminated area, and consumption by the farmer and his family of crops grown in it. The presented dose includes exposure via inhalation, external irradiation and the dose from consumption of the food type giving the highest dose. Noting the assessment examples and assumptions made in Appendix A, a small farmer/ could also be considered, using an area of 1E4 m^2, and this is assumed here, but with other assumptions held the same[5]. Thus the occupancy is the same, but within a smaller area, which is overall, more conservative than Oatway and Mobbs [2003] but consistent with other assessment practice in the current context.

For the construction scenario, the area is not specified in Oatway and Mobbs [2003]; rather it is simply assumed to be large enough to involve construction work to be on-going for a full working year. Here we assume small scale construction involving considerable contact of the construction worker with contaminated material (as in Oatway and Mobbs [2003]), involving an area of 30 m x 30 m = 900 m^2. This might correspond to someone taking a year to build their own home on just the contaminated area.

The uniform contamination assumed in Oatway and Mobbs [2003] is to a depth of 1 m, so the volume of contaminated material involved in the scenarios and contaminated at 1 Bq/g is 1E4 m^3 and 900 m^3 for agriculture and construction respectively.

The volume of contaminated material brought to the surface for the normalised drilling cases is 1 m length multiplied by area presented by the boring tool, which varies from technique to technique. Based on the diameters presented in Table 3, these volumes range from 0.056 m^3 for diamond core drilling to 10.18 m^3 for reverse circulation drilling. The activity in these volumes is then assumed to be fully mixed in the 1E4 m^3 and 900 m^3 for agriculture and construction scenarios given above.

Normalised doses from residual radioactivity left at the drill site (i.e. for contamination at 1 Bq/g,1 m length and 1 h exposure) are presented in Table 15 for the diamond core and reverse circulation drilling. These are set alongside the source data from Oatway and Mobbs [2003].

In cases where the radionuclides were not considered in Oatway and Mobbs [2003], suggestions are made for values which might be adopted in that absence. For cases where is says ‘assume as’, this is based on the fact that the same values for the respective radionuclides were recommended in relation to exemption and clearance in IAEA [2005]. IAEA [2005] was likewise based on a wide range of exposure scenarios,

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[5] 1E4 m^2 could, for example, produce roughly enough potatoes and field vegetables to sustain about 10 persons, assuming about half their nutritional demand is satisfied by eating potatoes and field vegetables.

and so the recommendation is a) properly supported and b) consistent with generic assessments made to support management of radioactive material.

It may be noted that IAEA [2005] results are rounded to order of magnitude values, which is consistent with the uncertainties about the values of parameter values. For some radionuclides, IAEA [2005] does not offer a value either, or there is no relevant listed radionuclide with the appropriate order of magnitude value to compare with. In these cases, a suggestion is made of the form 'similar value to', based on consideration of radionuclide properties and the results for direct exposure scenarios discussed in Section 4.2.

Inspection of Table 15 allows some general observations. Firstly, both the agriculture and construction scenarios can be dominant, depending on the radionuclide. For example, agriculture is more important for Ni-63, and construction for Co-60. The normalised doses for reverse circulation are higher than for diamond core drilling, simply because of the larger diameter borehole and therefore larger volume of material brought up and assumed to be left at the surface. The results for the two drilling techniques reflect the largest difference in bore diameter, i.e. the results include the range of normalised doses from residual radioactivity left at the drill site for all of the alternative drilling techniques.

Comparison of the normalised diamond core drilling doses for the driller (Table 14) with those from residual activity (Table 15) shows that for most radionuclides, the doses from direct contact by the driller are similar or larger. This is consistent with the notion that residual activity is likely to give rise to longer exposures, but the degree of spreading and dilution consistent with high occupancy implies a corresponding reduction in the radionuclide concentration, the net effect resulting in similar or smaller doses. The same general conclusion arises for other drilling techniques.

A few exception exceptions may arise where uptake via the foodchain can be very high, as is the case with Tc-99 according to the assumptions made in Oatway and Mobbs [2003]. In such cases, it may be appropriate to take account of the local site conditions, so as to address radionuclide specific model and parameter uncertainties. This can be particularly important for the foodchain for some radionuclides, e.g. see Smith et al [2012] in relation to Se-79.

The above conclusions rely on the assumptions about the area into which residual activity is spread and the nature of activities carried out in the relevant area. It may always be possible to envisage very unusual or extreme behaviour which would give rise to higher doses, but the same could be said for direct exposure

The application above methodology and normalised results are discussed further in the following Section.

Table 15. Normalised doses from residual radioactivity left at the drill site.

Radio-nuclide	**As no data, then** [1]	**Dose data from Oatway and Mobbs [2003], μSv/y per Bq/g** [2]		**Normalised doses, diamond core drilling, μSv in a year**		**Normalised doses, reverse circulation drilling, μSv in a year**	
		Agriculture	**Construction**	**Agriculture**	**Construction**	**Agriculture**	**Construction**
H-3	-	3.00E-00	2.36E-06	1.69E-05	1.48E-10	3.05E-03	2.67E-8
C-14	assume as Sr-90						
Cl-36	assume as Sr-90						
Ca-41	similar value to Ni-63						
Ni-59	assume as Ni-63						
Ni-63		3.86E-01	2.33E-03	2.18E-06	1.46E-07	3.93E-04	2.63E-05
Co-60	-	1.15E+02	1.11E+03	6.49E-04	6.96E-02	1.17E-01	1.26E+01
Se-79	similar value to Tc-99						
Sr-90	-	9.04E+02	3.06E+00	5.10E-03	1.92E-04	9.20E-01	3.46E-02
Zr-93	similar value to Tc-99						
Nb-93m	similar value to Tc-99						
Nb-94	assume as Co-60						
Mo-93	similar value to Ni-63						
Tc-99	-	4.99E+03	[3]	2.81E-02	[3]	5.08E+00	[3]
Pd-107	similar value to Ni-63						
Ag-108m	assume as Co-60						
Sn-126	similar value to Co-60						

[1] For justification, see main text.

[2] Data for μSv/y per Bq/g of soil of each radionuclide in the agriculture and construction scenarios taken from Oatway and Mobbs [2003]. The values for tritium in Oatway and Mobbs [2003] are in units of Sv/y per Bq/l of soil water. These have been converted to per Bq/g of soil here, assuming a soil wet porosity of 20% and a bulk soil density of 1 t/m^3.

[3] The Tc-99 result is dominated by skin exposure in Oatway and Mobbs [2003].

Table 15 (cont'd). Normalised doses from residual radioactivity left at the drill site.

Radio-nuclide	As no data, then [1]	Dose data from Oatway and Mobbs [2003], μSv/y per Bq/g [2]		Normalised doses, diamond core drilling, μSv in a year		Normalised doses, reverse circulation drilling, μSv in a year	
		Agriculture	Construction	Agriculture	Construction	Agriculture	Construction
I-129	similar value to Sr-90						
Ba-133	similar value to Sr-90						
Cs-135	similar value to Sr-90						
Cs-137	-	5.83E+01	2.41E+02	3.29E-04	1.51E-02	5.93E-02	2.73E+00
Sm-151	-	9.22E+00	1.05E-02	5.20E-05	6.58E-07	9.38E-03	1.19E-04
Eu-152	assume as Co-60						
Eu-154	-	5.28E+01	5.19E+02	2.98E-04	3.25E-02	5.37E-02	5.87E+00
Pb-210[4]	-	1.84E+03	6.46E+00	1.04E-02	4.05E-04	1.87E+00	7.31E-02
Po-210	-	1.58E+02	1.37E+01	8.91E-04	8.59E-04	1.61E-01	1.55E-01
Ra-226	-	3.01E+02	7.58E+02	1.70E-03	4.75E-02	3.06E-01	8.57E+00
Ra-228	-	1.37E+03	4.11E+02	7.73E-03	2.58E-02	1.39E+00	4.65E+00
Ac-227	-	4.16E+02	1.44E+03	2.35E-03	9.02E-02	4.23E-01	1.63E+01
Th-228	-	2.64E+02	7.78E+02	1.49E-03	4.88E-02	2.69E-01	8.80E+00
Th-229	-	1.92E+02	2.84E+02	1.08E-03	1.78E-02	1.95E-01	3.21E+00
Th-230	-	2.45E+01	3.35E+01	1.38E-04	2.10E-03	2.49E-02	3.79E-01
Th-232	-	3.05E+01	5.89E+01	1.72E-04	3.69E-03	3.10E-02	6.66E-01
Pa-231	-	3.76E+03	3.39E+02	2.12E-02	2.12E-02	3.83E+00	3.83E+00

[1] For justification, see main text.

[2] Data for μSv/y per Bq/g of soil of each radionuclide in the agriculture and construction scenarios taken from Oatway and Mobbs [2003]. The values for tritium in Oatway and Mobbs [2003] are in units of Sv/y per Bq/l of soil water. These have been converted to per Bq/g of soil here, assuming a soil wet porosity of 20% and a bulk soil density of 1 t/m^3.

[3] The Tc-99 result is dominated by skin exposure in Oatway and Mobbs [2003].

Table 15 (cont'd). Normalised doses from residual radioactivity left at the drill site.

Radio-nuclide	As no data, then [1]	Dose data from Oatway and Mobbs [2003], µSv/y per Bq/g [2]		Normalised doses, diamond core drilling, µSv in a year		Normalised doses, reverse circulation drilling, µSv in a year	
		Agriculture	Construction	Agriculture	Construction	Agriculture	Construction
U-232	assume as Pu-239						
U-233	-	9.35E+00	8.65E+00	5.27E-05	5.42E-04	9.52E-03	9.78E-02
U-234	-	8.99E+00	8.36E+00	5.07E-05	5.24E-04	9.15E-03	9.45E-02
U-235	-	1.31E+01	5.28E+01	7.39E-05	3.31E-03	1.33E-02	5.97E-01
U-236	-	8.57E+00	7.64E+00	4.83E-05	4.79E-04	8.72E-03	8.64E-02
U-238	-	9.55E+00	1.79E+01	5.39E-05	1.12E-03	9.72E-03	2.02E-01
Np237	-	4.11E+01	1.23E+02	2.32E-04	7.71E-03	4.18E-02	1.39E+00
Pu-238	-	2.50E+01	1.07E+02	1.41E-04	6.71E-03	2.54E-02	1.21E+00
Pu-239	-	2.71E+01	1.17E+02	1.53E-04	7.33E-03	2.76E-02	1.32E+00
Pu-240	-	2.71E+01	1.17E+02	1.53E-04	7.33E-03	2.76E-02	1.32E+00
Pu-241	-	4.98E-01	2.10E+00	2.81E-06	1.32E-04	5.07E-04	2.37E-02
Pu-242	assume as Pu-239						
Am-241	-	3.00E+01	1.01E+02	1.69E-04	6.33E-03	3.05E-02	1.14E+00
Am-243	assume as Am-241						
Cm-244	assume as Sr-90						
Am-242m	assume as Am-241						
Cm-245	assume as Pu-239						
Cm-246	assume as Pu-239						

[1] For justification, see main text.

[2] Data for µSv/y per Bq/g of soil of each radionuclide in the agriculture and construction scenarios taken from Oatway and Mobbs [2003]. The values for tritium in Oatway and Mobbs [2003] are in units of Sv/y per Bq/l of soil water. These have been converted to per Bq/g of soil here, assuming a soil wet porosity of 20% and a bulk soil density of 1 t/m^3.

[3] The Tc-99 result is dominated by skin exposure in Oatway and Mobbs [2003].

5 ASSESSMENT OF DOSES FOR EXAMPLE REALISTIC INVENTORIES

Two realistic disposal situations have been considered, one for high level waste (HLW) and one for intermediate level waste (ILW). The initial radionuclide inventories in the waste have been taken from Anttila [2005] for HLW and from Almkvist and Gordon [2007] for ILW. See Table 16 for the inventory data for an example set of relevant radionuclides. These have been selected to illustrate the implications for HI doses of different radionuclides exhibiting different half-lives and radiation emissions, as well as being of realistic potential interest.

For HLW, HI is assumed to occur via the drilling core technique using water, which is among the more likely techniques for crystalline rock disposal at great depth (see Table 3). For ILW, the rotary drilling technique using air is assumed, which is likely to give rise to the highest doses via inhalation.

Table 17 shows scenarios and techniques. Parameters data are defined in Section 4.2, but the data used for each type of waste and each scenario in these illustrations are presented here for convenience.

The evolution of the waste inventory has been calculated out to 100,000 y using the AMBER software [Quintessa, 2011]. At each of a range of relevant times taken to be from 1E2 to 1E5 y, the normalised results corresponding to the selected scenario have been multiplied by the calculated inventory concentration in the extracted material, assuming no leakage from the waste form, only radioactive decay and ingrowth. Results are presented in Figure 13, for inhalation, ingestion and external irradiation and for the sum over these pathways. Note that the contribution from ingrowth of radioactive progeny has been taken into account.

The results are indicative of the significance of different radionuclides over time, but are presented for illustrative purposes only. For example, not account has been taken of any possible leakage from the waste form prior to intrusion.

The potential range of doses for alternative drilling assumptions and different assumptions for exposure are discussed in Section 4.2. The implications for different normalised doses apply just the same once the normalised results are applied to a realistic assessment. For the illustrations here, important considerations could include the assumptions for dust levels and selection of dose coefficients for inhaled material.

Table 16. *Initial radionuclide inventories.*

Radionuclide	ILW Activity (Bq in whole silo waste, of mass 7E10 g)	HLW Activity, Bq/g
Sr-90	7.5E13	3.56E9
Ag-108m	6.4E11	-
Sn-126	-	2.18E4
Cs-137	7.8E14	4.72E9
Pu-239	6.2E10	1.04E7
Am-241	3.4E12	5.34E6
Np-237	9.0E8	1.21E4
U-238	7.2E7	1.16E4

***Table 17.** Data used in illustrative calculations.*

Parameter	Unit	Scenario	
		LLW (RA_CA_D)	**HLW (DCW_CA_D)**
Technique		Rotary air (given rise to the highest inhalation dose, as a consequence to the highest dose)	Diamond core drilling (the most widely used technique)
Fluid used		Air	Water
Worker		Driller	
Material excavated		Container of ILW	Canister with HLW
External irradiation → $D_{ext} = 1.4 \cdot 10^{-13} \cdot f_1 \cdot f_2 \cdot \frac{1}{x^2} \cdot \rho \cdot V \cdot t_{\exp} \cdot \sum_i \left(\cdot E_i \cdot S_i \right)$			
f_1	Sv/Gy	0.7	
f_2	–	1	
x	m	1	
ρ	kg/m³	Canister: 2750	
V	m³	RA:0.34	DCW: 0.02
$t_{\exp}$	h	1	
E_i	MeV	Radionuclide dependent	
S_i	Bq/g	Inventory LLW	Inventory HLW
Inadvertent ingestion → $D_{ing} = t_{\exp} \cdot m \cdot \sum_i \left(I_{ing,i} \cdot S_i \right)$			
$t_{\exp}$	h	1	
m	g/h	8.0E-04	1.7E-02
$I_{ing,i}$	Sv/Bq	Radionuclide dependent	
S_i	Bq/g	Inventory LLW	Inventory HLW
Inhalation of airborne material → $D_{inh} = t_{\exp} \cdot R \cdot d \cdot \sum_i \left(I_{inh,i} \cdot S_i \right)$			
$t_{\exp}$	h	1	
R	m³/h	3	
d	g/m³	1.0E-2	2.0E-03
$I_{inh,i}$	Sv/Bq	Radionuclide dependent	
S_i	Bq/g	Inventory LLW	Inventory HLW

Based on the normalised results presented and discussed in section 4, doses to those using the site after drilling work has ceased would probably be lower or similar to those presented Figure 13.

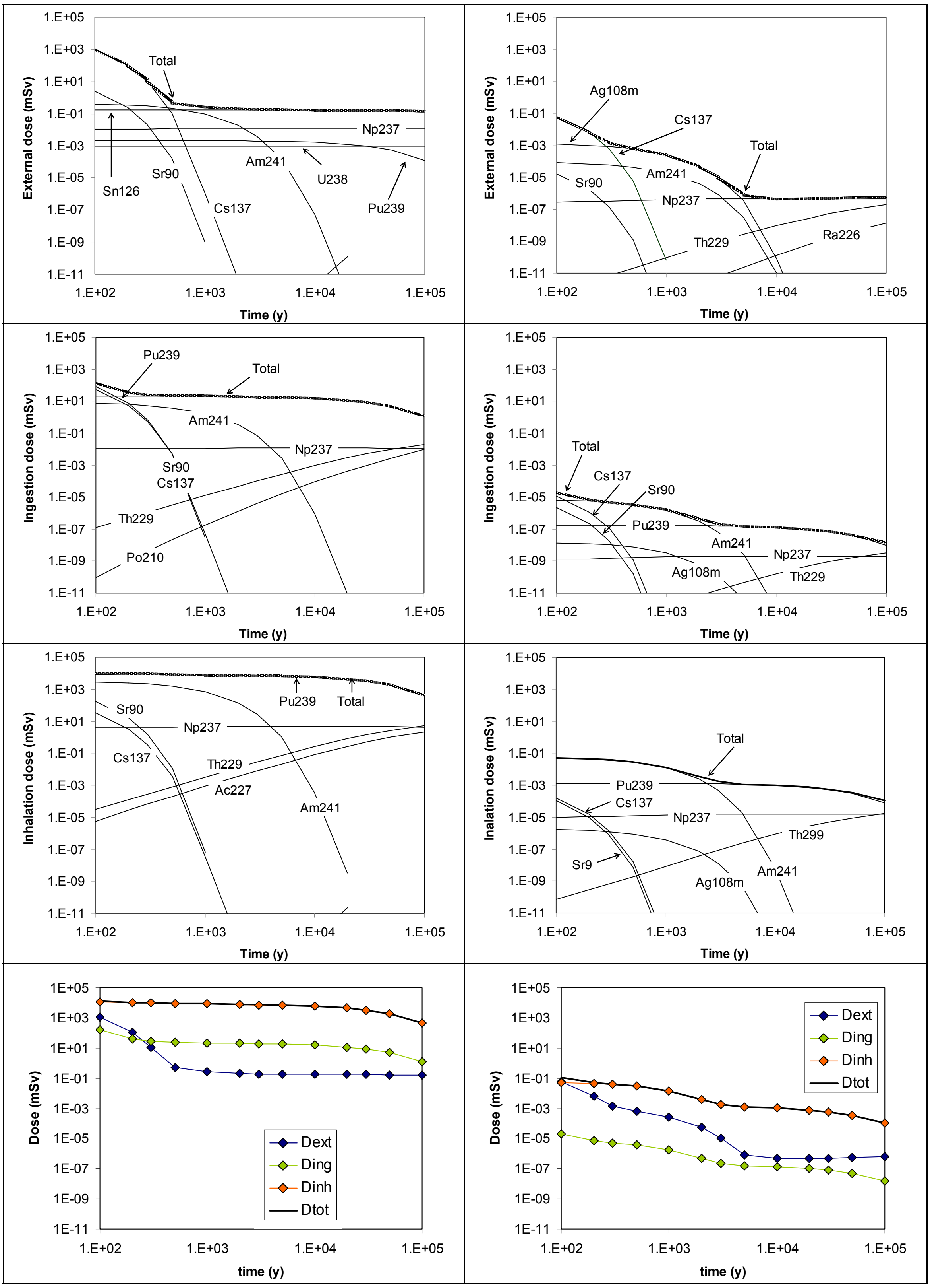

Figure 13. *External, ingestion, inhalation and total dose (from top to bottom) for the HLW Situation (left) and LLW Situation (right).*

6 DISCUSSION AND CONCLUSIONS

Based on consideration of international recommendations and examples of national application, an approach has been developed for assessing doses arising directly from inadvertent HI.

The most likely mechanisms for HI into deep geological disposal facilities have been reviewed based on previous assessment experience and from further consideration of possible interest in deep geological investigation. It is concluded that deep borehole drilling is the most likely mechanism.

The range of available technologies for deep drilling has been reviewed and described in terms relevant to their application in different geologies and to their potential for bringing contaminated material to the surface where it may give rise to radiation exposure. Such contaminated material could include waste itself, or contaminated near field material, or contaminated wider geosphere material, the latter two being relevant only after some release from the waste form.

Consideration has been given to exposure of drilling workers and geologists involved in the drilling activity, and also to others who might be exposed to contaminated material left at the site after drilling work has ceased.

Models for radiation exposure of the drilling workers and geologists have been developed and described, taking into account relevant combinations of drilling technique, geological formation and repository material. The models have been designed to be simple and stylised, in accordance with international recommendations. The set of combinations comprises 58 different scenarios which cover a very wide range of HI possibilities via deep drilling.

Data for the models have been reviewed and selected for use in example calculations. Special consideration has been given to data for inadvertent ingestion of dirt and inhalation of contaminated dusts, since these were found to be wide ranging and thus could contribute significantly to uncertainties. Data have been selected for application to the 58 scenarios and applied to unit activity concentrations of a range of relevant radionuclides assumed to be present in 1 m length cores brought to the surface and contacted and examined by the drillers or geologists for one hour. A complete set of these normalised results for all the radionuclides (including their radioactive progeny) has been prepared and is made available in a separate excel spreadsheet. Example results have been presented and discussed.

These normalised results can be used in specific assessments in which concentrations of radionuclides in waste, the near field and/or the geosphere have been separately determined. It is a simple matter to multiple the relevant normalised results by the assessed concentrations in corresponding media. It may also be appropriate to multiply by the relevant contaminated core length. Alternative assumptions for exposure time could also be adopted. Other parameters, such as dusts levels could also be applied, and the basis for making alternative selections has been provided.

Assessment of doses arising from contamination left at the drill site is proposed to be assessed on the basis of existing contaminated land assessment methods. This is to avoid duplication of effort and the introduction of arbitrary differences in details, as well as to support a consistent approach to safety assessment of contaminated land in the short and long term. Within this approach, account still needs to be taken of how widespread the contamination is and this has to be considered in relation to the assumptions for human behaviour on the contaminated land, i.e. to be consistent in terms of reasonable occupancy. The method has been developed for use in the HI assessment context, based on an existing comprehensive assessment of contaminated land which has taken into account a wide range of land uses. The method has been demonstrated and applied in a normalised fashion for each of the alternative drilling techniques. The range of results presented suggests that doses to those using contaminated areas left at the site after drilling has ceased would be similar or lower to those to drilling workers and geologists. Some exceptions may arise in the case of agricultural use of the site, for those radionuclides which may have very high uptake via the foodchain. In this event, it may be appropriate to consider the use of site specific data in assessment of the foodchain pathways.

All the conceptual model and data assumptions have been made on a conservative but plausible, realistic basis. These assumptions have been made clear so that implications of alternative assumptions can be readily investigated.

Illustrative results have been present for doses to drillers arising from HI into realistic HLW and ILW waste inventories. Results have been presented for HI at a range of times after disposal from 100 to 100,000 years. These illustrations have not taken account of possible radionuclide migration prior to HI, only radioactive decay and ingrowth. Therefore they do not represent the full assessment picture and only serve to illustrate the use of the normalised results.

HI while institutional control is effective would not occur; hence the presentation of doses no earlier than 100 y. Longer institutional control periods may be considered viable, possibly supported by studies of information conservation and retrieval, e.g. see Jensen et al [1992]. The likelihood of HI has not been part of this study, however it can be readily seen that vertical as opposed to horizontal displacement of waste in a repository would reduce the chance of a borehole intersecting waste.

The methods and data described are considered to be consistent with assessment requirements arising out of current international recommendations and guidance on deep geological disposal.

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APPENDIX A: HUMAN INTRUSION ASSESSMENT EXAMPLES

Examples of assessment of inadvertent human intrusion into deep geological disposal facilities are summarised in this Appendix. The intention is to draw on relevant experience and apply it in the current study rather than to provide a comprehensive compilation of previous work. Where information has been presented on scenarios that were initially considered, but then screened from further assessment due to the low probability of occurrence, this information, inclusive of reasoning where provided, is outlined.

A.1 Canada

OPG's Deep Geologic Repository for Low and Intermediate Level Waste

OPG's proposed facility is located at 680 m depth in an argillaceous limestone formation. The groundwater is highly saline below about 200 m, and the rock formations are underpressured (relative to hydrostatic) around the repository horizon and overpressured below it. Consistent with the regional geology and its history, there is no significant gas and oil in the area of the repository, but these do occur a few 100 km distant. The facility is not backfilled, and is expected to be mostly dry and contain gas at around hydrostatic pressure due to degradation of wastes.

An inadvertent human intrusion scenario is considered, based on an exploratory borehole intercepting waste packages within the repository [Quintessa and SENES, 2011]. Intrusion is assumed possible after 300 years. The likelihood of intrusion is low, and an indicative estimate of $10^{-10}/m^2/yr$ is suggested, based in part on historical deep drilling rates and on a notional estimate of 1 deep borehole per 10 km x 10 km area per 100 years.

The following exposure routes were considered:

- direct release to the surface of pressurised gas by drill crew and nearby resident;
- retrieval and examination of core containing waste by core technician;
- exposure to drill core debris left on site by drill crew and by a future site resident;
- the long-term release of contaminated water from the repository into the permeable geosphere horizons via the exploration borehole.

For the drilling personnel, the following exposure pathways were considered:

- inhalation of released gas;
- external irradiation from soil contaminated by drill core debris left on site;
- inadvertent soil ingestion; and
- inhalation of suspended dust.

For a site resident, exposure pathways considered were:

- inhalation of released gas;

- external irradiation from soil contaminated by drill core debris left on site;
- inadvertent soil ingestion;
- consumption of vegetables grown on contaminated soil; and
- inhalation of suspended dust.

The calculated peak dose was around 1 mSv for drill crew or nearby resident. However it was noted that the likelihood of the site occupancy scenario is very low since it assumes that drilling slurry is not managed to current drilling standards and that the soil is used for farming immediately after the intrusion event.

Under likely circumstances (borehole stopped at repository horizon), there would be little water transport through the borehole and no long term groundwater contamination or exposure due to the under-pressure and low permeability of the host rock formation. In order for there to be significant long-term dose (indicated as tens of mSv), the borehole would have to be extended 120 m to the pressurized Cambrian formation below the repository horizon and not sealed. This allows for water flow through the repository to surface groundwaters.

C-14 and Nb-94 were the dominant dose contributors, so the potential intrusion dose becomes less than 1 mSv on 10-100 ka time frame due to their decay.

Third Case Study for Used Fuel

NWMO evaluated various aspects of a repository for used CANDU fuel at a hypothetical site in the Canadian Shield in its Third Case Study [Gierszewski et al. 2004]. The study considered an inadvertent human intrusion scenario based on an exploration borehole intercepting a container. Exposure to the drill crew, a lab technician examining core, a construction worker subsequently working on the site in contaminated soil, and a future resident living near site and growing a garden in contaminated soil. The various exposure probabilities were estimated using an event tree approach, but the resulting exposures were presented from both a risk and a dose/likelihood perspective. NWMO is currently updating this safety case in its Fourth Case Study. This will include an inadvertent human intrusion scenario, although with more simplified and stylized exposures.

A.2 UK

In the UK, the disposal of intermediate level waste (ILW) and that of low level waste (LLW) not suitable for disposal to a near surface facility falls within the remit of the Nuclear Decommissioning Authority Radioactive Waste Management Directorate (NDA RWMD), formerly UK Nirex Ltd (Nirex). No site has yet been selected for the disposal of such wastes and, as such, studies undertaken by NDA RWMD in relation to the disposal concept are generic in relation to both location and geology. Nonetheless, consideration has been given to the potential consequences to members of the public arising from inadvertent human intrusion into a deep geological disposal facility as part of a generic post-closure performance assessment [Nirex, 2003].

The performance assessment is based around a scenario whereby the potentially exposed group is comprised of a farming community which makes maximal use of local resources and is located in the area with the highest release of radionuclides to the biosphere. All water requirements are met through the abstraction of groundwater from a well that is drilled within the local aquifer. Variant scenarios are then assumed to take account of uncertainties concerning future human action, including inadvertent intrusion into the disposal facility.

The inadvertent direct human intrusion scenarios considered are those that were considered plausible based on current economic needs and technology, the current pattern of resource exploitation and an evaluation of frequencies of human activities observed in the recent past. The mode of intrusion assumed was exploratory drilling for natural resources following loss of knowledge of the location of the facility and/or its purpose. Drilling activity was assumed to penetrate the EBS with radioactive waste material being brought to the surface. The frequency of intrusion into the repository was based on the area of the facility and the frequency of drilling that could occur based on current practise in coal, hydrocarbon and mineral extraction industries. No prior loss of activity from the facility was assumed to occur as a result of radionuclide transport, although radioactive decay was taken into account.

Two exposure scenarios were considered – exposure of geotechnical workers and site occupiers – based on the assumption that the nature of the material brought to the surface is not recognised. The impacts of intrusion events on the integrity of the EBS were not considered.

Exposure of geotechnical workers occurs as a result of laboratory work on the drill core, leading to: external exposure during short-term working in close proximity to the core and longer term irradiation at a greater distance; inadvertent ingestion following handling of the core; and, inhalation of dust generated as a result of laboratory analysis techniques and radon generated from the presence of Ra-226 within the core. Results of the scenario were presented in terms of individual risk with a peak risk, corresponding to an intrusion event occurring at 100 years post closure, was calculated to be 6.6E-9 per year, risk being the product of the dose, the risk per unit dose and the probability in a year of the dose occurring. The latter was based on the area of interest and a midrange value for the drilling frequency, 10^{-10} holes per m^2 per year, which is said to be an appropriate average for mineral exploration in the UK in low-relief, hard rock areas.

The site occupier scenario assumes that radioactive material from drilling spoil is dispersed around the site of the exploratory borehole, which is subsequently inhabited and land used for agriculture. The size of the resource area (that used as arable land) was assumed to be 10,000 m^2. Exposure pathways considered include external exposure to contaminated material in surface soil, ingestion of foodstuffs grown in contaminated soil, and inhalation of dust derived from contaminated soil and of radon generated as a result of the presence of parent material. Risk to site occupiers is cumulative such that as time progresses, the likelihood of exposure is increased due to drilling events in previous years. The peak risk was calculated to be 9.3E-7 per year, occurring 200,000 years following repository closure. Here the probability of the dose is relatively high because of the possibilities for intrusion in previous years prior to the year of exposure, and the relatively long residence time in soil for at least some of the radionuclides brought to the surface. Thus, while the risk is higher, the dose is not higher than for the laboratory worker.

More recently, the NDA RWMD issued a generic post-closure performance assessment [NDA, 2010], which considers the potential for inadvertent HI into a disposal facility through the presentation of an example scenario which is formulated around the potential exposure of a geotechnical worker through drilling into the facility. Consistent with the change in regulatory guidance discussed in section 1.1, the assessment endpoint was dose rather than risk. Doses in the range up to 50 Sv were indicated for the most active waste types (spent fuel) for HI from early times after disposal up to about 1000 years. Am-241 and Pu isotopes were the dominant radionuclides. Once a site is selected, NDA [2010] state a commitment to assess a number of scenarios that would include:

- Description of the systematic approach followed to identify potential scenarios.
- Technical analysis: identification of human actions that may impact on the safety functions of a disposal facility with justification of the actions in technical terms.
- Analysis of societal factors and future human actions that can affect the radiological safety of a facility, such as: population change, technological advances and political stability.
- Choice of representative scenarios. The results of the technical and societal analysis will be combined and one or several illustrative cases of future human activities chosen.
- Scenario description and consequence analysis of the chosen cases.
- The screening of those scenarios and justification of choices, to identify those modelled in detail.
- An assessment of the likelihood (probability) of each scenario that is modelled in detail, which may be quantified for some scenarios, or for those scenarios which are impossible to quantify, the arguments for considering the probability to be low would be presented.

Note that discussion of probability is considered relevant, even if quantitative assessment is problematic.

A.3 Finland

In Finland, spent nuclear fuel is to be disposed of in a deep geological facility, the construction and operation of which is the responsibility of Posiva. Posiva in their 2008 safety case plan [Posiva, 2008] outline an approach centred around a base scenario with variant scenarios then being used to evaluate uncertainty and potential disruptive events such as human intrusion. The development of scenarios, including those relating to inadvertent human intrusion, is in line with regulatory guidance issued by STUK [STUK, 2001]. Human intrusion scenarios that are identified include the drilling of a deep well into an aquifer in the locality of the disposal facility and core drilling which results in penetration of the EBS and a spent fuel canister (i.e. effects on multiple barriers). Intrusion is not assumed to occur for the first 200 years post-closure as a result of institutional control and the preservation of information. Development of calculation cases for human intrusion scenarios are under development and will be included in the safety assessment supporting the construction license application of the disposal facility to be submitted by [Posiva, 2010].

Nordman and Vieno [1989] also considered the potential consequences of inadvertent intrusion by drilling into a radioactive waste disposal facility in Finland. In their assessment, it was estimated that the probability of an inadvertent hit on a disposal canister of HLW would be of the order 2×10^{-8} per year based on the regional history of deep drilling rates. Such an assumption was considered conservative since it did not take into account the saturation of the ground area with boreholes. The external exposure resulting from handling a drill core from a direct hit with a canister was calculated to represent the maximum level of individual exposure. The intrusion event was assumed to occur 100 years post closure.

In the case of repositories for LLW and ILW, a scenario whereby a domestic well is drilled into the bedrock in the vicinity of the facility has been considered [Nordman and Vieno, 1989]. It was not considered feasible for exposure to occur as a result of drilling a drinking water well into the repository itself on the grounds that the water would be unpalatable due to its chemical content. The use of the drinking water well scenario is intended to be representative of a range of intrusion events that may encompass the drilling of a new borehole, a failure in the sealing of an old investigation borehole and/or the use of an intentional monitoring borehole, the purpose of which has been forgotten.

A.4 Germany

In Germany, consideration has been given to the potential consequences of inadvertent human intrusion into a repository for HLW situated in a salt dome [Hirsekorn, 1989]. Intrusion was presumed to occur 1000 years post-closure. Three scenarios have been considered – conventional mining, borehole drilling and solution mining.

Conventional mining

Intrusion into the HLW facility could arise, following loss of knowledge of the facility, from mining activities undertaken for the exploitation of salt or for the construction of storage facilities for resources such as oil or for the final isolation of hazardous chemical or radioactive waste. However, it is unlikely that, upon contact with the HLW facility, it would not be recognised as such because it would be so unexpected and clearly artificial in salt. Thus this form of intrusion was screened out from further assessment.

Borehole drilling

A scenario was considered whereby exploratory drilling resulted in contact with a HLW canister. In striking the canister, drill action would be affected that would not go unnoticed and could lead to closer examination of the resultant core and/or fines and, hence radiation exposure to a geologist or drilling worker. Once recognised as a HLW facility it was assumed that the borehole would be carefully sealed. Alternatively the borehole could be abandoned which would allow water ingress into the facility that could leach radioactive material from the waste package.

An alternative scenario considered that, rather than striking a waste package, the drill could make contact with a contaminated brine inclusion whereby up to 1 m^3 of brine could be brought to the surface. It is possible that contamination of the brine could go unnoticed leading to biosphere exposure pathways.

Solution mining

Solution mining is a process whereby soluble minerals (e.g. salt) are extracted from sub-surface strata by the injection of fluid and subsequent controlled extraction of the resultant mineral-laden solution. The process can be used both for the exploitation of salt (e.g. for human consumption) or as a means of create caverns within salt formations for the storage of oil or gas.

Hirsekom [1989] considered a scenario whereby defective waste canisters become dislodged as a result of solution mining, falling into the excavated area and becoming buried in the sump of insoluble material at the base of the cavern where radionuclides are subsequently released.

If solution mining is undertaken as a means of generating a storage cavern, the short time required for cavern excavation (of the order of 1 year) and low temperatures would result in a very low rate of leaching from the waste canister such that brine contamination during the excavation period would be minimal. However, over prolonged periods (i.e. during the operational phase of the storage cavern), continued corrosion of the defective canisters could lead to relatively high levels of radionuclide contamination of the brine within the sump region of the cavern. Subsequent to the operational phase, stored oil or gas is likely to be replaced with brine or water at which point contamination within the sump would diffuse into the wider cavern area. The assumption is then made that the cavern seal is breached due to increasing salt pressure over time. This leads to a pathway to the overburden where contamination of groundwater occurs.

As an alternative to solution mining being employed to form a storage cavern, the technique could be used to exploit salt. Under such a scenario, the mining process could extend for a number of decades. Consequences in terms of human dose could be of relevance if the mined salt were produced for human consumption in which case both ingestion of salt and inhalation of salt dust by salt factory workers would require evaluation. Similar scenarios have also been considered by Jacquier and Raimbault [1989] in France, and by Prij and Glasbergen [1989] in the Netherlands.

Recent considerations

ATW [2008] provides an updated position on how to address HI based on considerations of a working group on ‘scenario development’ that was set up in 1997.

On the basis of documentation preserved within German archives on mining, the working group considered that HI will only occur from periods of 500 years or more post-closure. The working group also concluded that it is not possible to quantify consequences associated with HI due to the lack of predictability of boundary conditions and other parameters and, as such, consequences of HI should not be evaluated by means of radiological limit values. Finally, the working group recommended that the range of scenarios that should be considered for HI be limited to, for example, exploratory drilling in the host salt rock, construction of a mine and solution mining of caverns, which is consistent with previous considerations (e.g. Hirsekorn et al [1989]).

A.5 Netherlands

Prij and Glasbergen [1989] considered a number of scenarios in relation to a HLW facility in a salt formation that largely mirror those considered for the German facility described above. However, in relation to conventional mining a slightly altered exposure scenario was considered whereby a gallery could be mined close to a HLW containing borehole such that the walls of the gallery showed no signs of the presence of radioactivity. Gallery workers would then be subject to potentially prolonged external exposure.

A.6 Sweden

An assessment of the radiological consequences of inadvertent intrusion into such a KBS3 type HLW repository was undertaken by Charles and McEwen [1991]. In evaluating consequences, a reasonably representative set of scenarios was required and following review of the activities that may give rise to intrusion events, a scenario around drilling a borehole into the facility was developed. It was assumed that the objective of the activities was to prospect for mineral resources. Exploitation of mineral resources was considered very unlikely due to strict siting criteria that would prevent a repository from being constructed in a geology that has exploitable resources. Nonetheless, it was acknowledged that it is difficult to predict what resources could be judged in the future to be exploitable on an economic basis. The analysis considered that a deep hole is drilled into the geological region of the repository and that drilling personnel and associated workers are directly affected as a result of their proximity to radioactive material brought to the surface.

Engineering judgement was applied to identify the likely methods that could be applied to exploratory drilling in deep geologies and to determine those situations where drilling personnel and associated workers may become exposed and thus to evaluate the magnitude of such exposure.

The calculations were performed assuming that a single cylindrical canister of HLW (spent fuel) is impacted by the drilling activity. The canister itself is comprised of copper of 10 cm thickness and filled with either molten lead or copper powder. The canister is surrounded by compacted sodium bentonite. In performing calculations, no credit was taken for technical drilling developments (i.e. in situ radiation monitoring).

Two drilling techniques were considered – water flushing or air flushing, the latter of which could give rise to respirable material reaching the surface. Further pathways for exposure considered were:

- Superficial examination of returns from the coring process by geologists;
- More detailed examination of unusual returns within a laboratory;
- Exposure to core logging operators (for which short-term close contact and longer-term more distant exposure were considered);
- Inhalation and external exposure (including contamination of equipment, clothing and skin) resulting from in situ sampling of unusual cores; and
- Inhalation, inadvertent ingestion and external exposure arising from detailed laboratory analysis of cores. It was considered that the potential for inhalation/ingestion of contaminated material in the laboratory would be reduced from that occurring as a result of in situ analysis due the availability of more refined laboratory analysis techniques, but that external exposure would be increased.

It was noted that the HLW would still be heat generating after several hundred years and this may arouse interest in cores, even if there is no unusual appearance; however it was considered uncertain as to whether this would increase or decrease the exposure of drilling personnel through greater interest or avoidance respectively.

Recent considerations

Concerning recent work, the following is noted from SKB [2011]. In the General Guidance to their Regulations, SSM recommends the inclusion of direct intrusion by means of drilling as well as examples of activities that indirectly may affect the safety functions in the safety assessment [SSM 2008a]. They also recommend basing the future human activity scenarios on current habits and technical practise. Regarding the consequences, SSM [2008a] state that only doses due to the impaired repository function need to be calculated, whereas the consequences for the individuals performing the intrusion need not to be assessed. However, SSM [2008b] states that cases to illustrate impacts on humans intruding into the repository should be included. The need of a stylised calculation of impacts to humans who intrude into the repository was also pointed out by the authorities in their review of the SR-Can study [Dverstorp and Strömberg, 2008] and this approach has been followed in the analyses of Future Human Actions scenarios in SR-Site [SKB, 2011].

Following an analysis of a list of future human actions (see listing below) which might impact a closed repository, it was concluded [SKB, 2011] that “Drill in the rock” (deep drilling) was the only one that could directly lead to penetration of the copper canister and breach of waste containment, while at the same time being inadvertent, technically possible, practically feasible and plausible. The construction of a rock facility at shallow depth or a mine in the vicinity of the Forsmark site was also considered worth consideration.

Table A1. *Human actions that may impact repository safety [SKB, 2011].*

Category	Action
Thermal impact	T1: Build heat store*
	T2: Build heat pump system*
	T3: Extract geothermal energy (geothermics)*
	T4: Build plant that generates heating/cooling on the surface above the repository
Hydrological impact	H1: Construct well*
	H2: Build dam
	H3: Change the course or extent of surface water bodies (streams, lakes, sea) and their
	connections with other surface water bodies
	H4: Build hydropower plant*
	H5: Build drainage system
	H6: Build infiltration system
	H7: Build irrigation system*
	H8: Change conditions for groundwater recharge by changes in land use
Mechanical impact:	M1: Mechanical impact M1: Drill in the rock*
	M2: Build rock cavern, tunnel, shaft, etc*
	M3: Excavate open-cast mine or quarry*
	M4: Construct dump or landfill
	M5: Bomb or blast on the surface above the repository
	M6: Subsurface bomb or blast*
Chemical impact	C1: Store/dispose hazardous waste in the rock*
	C2: Construct sanitary landfill (refuse tip)
	C3: Acidify air, soil and bedrock
	C4: Sterilise soil
	C5: Cause accident resulting in chemical contamination

* Includes or may include drilling and/or construction of rock cavern.

A.7 Switzerland

Several assessments have previously been carried out by Nagra and the Swiss Nuclear Safety Inspectorate (HSK) on the consequences of human actions on both LLW/ILW and HLW repositories including both direct and indirect effects [van Dorp and Vigfusson, 1989]. A range of possible human actions have been identified that may have implications for the function of repositories, including:

- Borehole drilling for exploration and production of drinking water, mineral resources, hydrocarbons, geothermal energy and/or for storage and waste injection purposes; and
- Cavern excavation for the exploitation of mineral resources, for storage, road tunnel and/or military or industrial purposes.

Whether or not these actions should be considered for a particular scenario is dependent upon the site location and the depth of the facility.

It was considered that, in order to evaluate the consequences of human activities, consideration would need to be given to the following:

- The potential for contaminated material to be extracted either directly from the disposal facility or from the surrounding contaminated geosphere;
- Exposure resulting from the extraction of contaminated groundwater from the repository, host rock or a more distant contaminated aquifer; and

- The effects of changes in barrier properties and/or hydrogeology on radionuclide transport.

A.8 USA

Yucca Mountain Assessment Requirements

The US DoE required, in relation to the proposed Yucca Mountain facility, that effects of human intrusion events focus on credible scenarios including exploratory drilling, groundwater withdrawal and mining and mine-dewatering [Rickertsen and Alexander, 1989]. The most credible human intrusion scenarios were considered to involve exploratory drilling and two scenarios have been developed by the US DoE that vary according to the scale of drilling:

- Small scale drilling involving three or less boreholes per square kilometre per ten thousand years; and
- Large scale drilling which may give rise to between three and thirty boreholes per square kilometre per ten thousand years.

Drilling is considered to either result in the penetration of a waste package leading to the migration of radioactivity from the waste package to the surface in drilling fluid, or result in the penetration of an aquifer beneath the repository that leads to the creation of a preferential pathway for the transfer of radionuclides to the biosphere.

The release rate of radionuclides from a waste package is estimated from the groundwater flow rate, the solubility limits for individual radionuclides and the waste form. Travel time to the biosphere is a function of flow rate and both chemical and mechanical retardation properties of the transported radionuclides.

Waste Isolation Pilot Plant

Anderson et al [1989] describes scenarios that were considered in relation to inadvertent human intrusion events relating to the WIPP, including drilling and mining activities.

In the case of drilling, a number of scenarios have been identified that could result in radionuclides being transported to the biosphere.

- Drilling could result in penetration of a reservoir of pressurised brine below the WIPP with both then being connected. Following drilling, the resultant borehole would be plugged, but the assumption made that the plug degrades over time leading to the release of pressurised brine, which has been in contact with radioactive material, to groundwater above the WIPP and subsequent flow to a well.
- Drilling leads to penetration of a repository panel which results in contact between drilling fluid and the waste material. Radioactivity could be transported to the surface either as eroded material in drilling fluid or as cuttings. Cuttings may be examined by a geologist who is the maximally exposed individual. Drilling fluid is deposited in a settling pond which, following cessation of drilling activities, dries due to the arid climate, with radioactivity then being

transported as airborne particles downwind to where a hypothetical farming family is located.

- Alternatively, multiple boreholes could result in a pathway for gravity driven flow of radioactive material from the facility to the surface environment.

In all cases considered, a conservative approach was taken to consequence analysis by assuming that no radioactive decay had occurred prior to drilling activities occurring.

APPENDIX B: DATA AND ASSUMPTIONS FOR DUST INHALATION AND INADVERTENT INGESTION

The following tables provide comments on references and data for assumptions about dust inhalation and the amount of non-food material which can be inadvertently consumed in various circumstances. It may be noted that these references are not themselves necessarily original sources, but they do include consideration of the health assessment problem in the selection of a suitable parameter value.

Table B1. *Dust inhalation information.*

Reference	Dust value (mg/m^3)	Type of dust	Scenario/Comments		
			Activity	Receptor	Rock type/material
Office of the Queensland Parliamentary Counsel (2010). Mining and Quarrying Safety and Health Act 1999. Mining and Quarrying Safety and Health Regulation 2001. Reprint No. 3B	10 5	Inspirable Respirable	Mining activities	Worker	
BIOPROTA (2005). Modelling the Inhalation Exposure Pathway. A report prepared within the international collaborative project BIOPROTA: Key Issues in Biosphere Aspects of Assessment of the Long-term Impact of Contaminant Releases Associated with Radioactive Waste Management. Main Contributors: M Wasiolek (Task Leader), A Aguero, A Albrecht, U Bergstrom, H Grogan, G M Smith, M C Thorne, S M Willans and H Yoshida. Published on behalf of the BIOPROTA Steering Committee by Nexia Solutions Ltd, UK.	- 5	Respirable	0.1 for normal activity 5 for hard activity in dry conditions	Agricultural community adopting modern practices, exposure due to the inhalation of dust re-suspended from soil contaminated via irrigation with polluted aquifer water	Cultivable soil
Good practices in controlling quartz dust exposure http://www.ufa.se/publikationer/OSHD4/4good.html	0.1 - 5	Respirable (quartz levels)	Mining: 0.1-2 Granite: 0.6-1.5 Construction: 4.35		
Peters, S. et al (2009) Personal Exposure to Inhalable Cement Dust among Construction Workers. Journal of Physics: Conference Series 151 (2009) 012054	0.05 - 34 Mean = 1 current German exposure limit for inhalable dust :	Inspirable	construction site (cement and concrete production)	Construction workers	Cement/concrete
Nuclear Regulatory Commission (2006) Environmental Impact Statement for the Proposed American Centrifuge Plant in Piketon, Ohio. Final Report. NUREG-1834, Volume 2.	0.3 mg/m^3			Worker	Industrial activity with uranium

Table B1 (cont'd). Dust inhalation information.

Reference	Dust value (mg/m^3)	Type of dust	Scenario/Comments		
			Activity	Receptor	Rock type/material
Kennedy Jr, W. E. and Aaberg, R. L. (1991). Dose and Risk Assessment for Intrusion into Mixed Waste Disposal Sites. PNL-SA—20032, DE92 004503	Range: 0.001 - 10 Drilling Selected: 0.1 Excavation: Selected: 5	Respirable	Drilling, construction	Operator Excavator	Drilling: Involve penetrating the waste layer Excavation: characterize, clean up or build a structure (clean layer removed)
van der Steen J, Timmermans, C W M, van Weers A W, Degrange J-P, Lefoure C and Shaw P V. (2004) SMOPIE final report. Annex 2: Work Package 2, Case studies with industrial partners. NRG Report 20790/04.60901/P	3.81 - 5.56 0.28 - 0.67 (both measurements)	Inspirable Respirable	Thermal phosphorus industry (NORM)	Worker	
van der Steen J, Timmermans, C W M, van Weers A W, Degrange J-P, Lefoure C, Shaw P V and Witschger O (2004) SMOPIE final report. Annex 1: Work Package 1, EU NORM Industries, Review of number of exposed workers and magnitude of internal doses. NRG Report 20790/04.60901/P.	0.06 - 10	activity mean aerodynamic diameter: 1 - 5 µm	NORM industry	Worker	Processing of minerals
Fiche 9. Chute de solutions visqueuses et de boues (stimulant). BADIMIS Version 3.0, 2000. An IRSN database.	4 - 147 calculated	<10 µm	Experiment	Worker	Sludge
MinEx (2008). Guidelines for the control of dust and associated hazards in surface mines and quarries. Minex Technologies Ltd, Somerset, UK. *Note: Respirable dust is said to consist of small particles (< 10 microns)*	0.2 10 3	Respirable silica Inspirable particulates <1% silica Respirable particulates <1% silica and respirable coal	Exposure limits mining, drilling	Worker	

Table B1 (cont'd). Dust inhalation information.

Reference	**Dust value (mg/m^3)**	**Type of dust**	**Scenario/Comments**		
			Activity	**Receptor**	**Rock type/material**
Oatway W B and Mobbs S F (2003). Methodology for estimating the doses to members of the public from the future use of land previously contaminated with radioactivity. NRPB-W36. National Radiological Protection Board, Chilton, UK.	5 0.5	Enhanced outside dust loading Ambient dust loading	Construction: site being developed for future industrial use or housing. Mechanical disturbance of soil	Construction worker (adult)	Contaminated land
IAEA (2005) Derivation of Activity Concentration Values for Exclusion, Exemption and Clearance. Safety Reports Series. No. 44	0.5 realistic 1 low probability	Not specified	Worker on landfill or in a facility (other than foundry)	Worker	
Penfold J S S, Mobbs, S F, Degrange J P and Schneider T (1999). Radiation Protection 107. Establishment of reference levels for regulatory control of workplaces where materials are processed which contain enhanced levels of naturally-occurring radionuclides. European Commission.	1 - 5 5 - 10	Respirable	Normal / unlikely assumptions Stockpile scenario Scales and residues scenario	Worker Worker	Processing of minerals
Conclusion: The range of reviewed values is very large, from 0.001 to 10 mg/m^3.					

Table B2. *Inadvertent ingestion information.*

Reference	Ingestion value (mg per day or shift)	Scenario/Comments	
		Activity	**Receptor**
Walke R, Bath A, Bond A, Calder N, Humphreys P, King F, Little R., Metcalfe R, Penfold J, Rees J, Savage D, Towler G and Walsh R (2009). Deep Geologic Repository for OPG's Low & Intermediate Level Waste. Postclosure Safety Assessment (V1): Data. NWMO DGR-TR-2009-08.	330	Farming, fishing, recreation and dwelling	A local group has been identified for assessment in the scenario, which is exposed via a wide range of pathways
Oatway W B and Mobbs S F (2003). Methodology for estimating the doses to members of the public from the future use of land previously contaminated with radioactivity. NRPB-W36. National Radiological Protection Board, Chilton, UK.	5	Construction: site being developed for future industrial use or housing. Mechanical disturbance of soil	Construction worker (adult)
Klein, A.K. and Valoppi, L. (1992) Office of the science advisor guidance. Chapter 1. Default exposure parameters.	50 100	Commercial industrial Agricultural/residential	Worker Public
New Zealand Government (2010) Draft Methodology for Deriving Soil Guideline Values Protective of Human Health. ME 979	50-100	Commercial/industrial	Outdoor worker
EPA (1989). Exposure factors handbook. Volume 1 – General Factors, Chapter 4 – Soil Ingestion and Pica. US Environmental Protection Agency. Hawley J K (1985). Assessment of health risk from exposure to contaminated soil. Risk Anal. 5, pp. 289-302. Calabrese E J, Kostecki P T, Gilbert C E (1987). How much soil do children eat? An emerging consideration for environmental health risk assessment. Comments Toxicol. 1, pp 229-241, 1987.	480 (Hawley, 1985) 1 - 100 (Calabrese et al., 1987) 50 (EPA) 100 (EPA) 50 (their recommendation)	Outdoor, yard work or other physical activity Industrial Residential and agricultural	Public Worker
EPA (2003) Comments of the General Electric Company in the U.S. Environmental Protection Agency's Human Health Risk Assessment for the Housatonic River site – Rest of river. Attachment E. Selection of Soil Ingestion Rates	100/50 (general) 200/100 (farmers, agricultural) 330/100 (utility worker)	Reasonable Maximum Exposure / Central Tendency Exposure	Public, worker

Table B2 (cont'd). Inadvertent ingestion information.

<table>
<tr><th rowspan="2">Reference</th><th rowspan="2">Ingestion value
(mg per day or shift)</th><th colspan="2">Scenario/Comments</th></tr>
<tr><th>Activity</th><th>Receptor</th></tr>
<tr><td>NMED (2009) Technical background document for development of soil screening levels. Revision 5.0. New Mexico Environment Department.</td><td>100
330</td><td>Commercial/industrial (outdoor works: maintenance, ground keeping)
Construction worker (excavation, maintenance, building: intrusive operations)</td><td>Worker</td></tr>
<tr><td>Environment Agency of England and Wales (2011) RLCEA. The Radioactively Contaminated Land Exposure Assessment Methodology – Technical Report. CLR-14, Version 1.2. A report prepared fot the Department for Environment, Food and Rural Affairs, UK.</td><td>9200 mg/y
230d/y → 40 mg/d</td><td>Commercial/Industrial</td><td>Worker</td></tr>
<tr><td>EPA (2002) Supplemental guidance for developing souls screening levels for superfund sites. OSWER 9355.4-24. Environmental Protection Agency.</td><td>100
330 (New value selected by EPA, instead of 480. The last one based on theoretical calculations. This one based on the 95th percentile value for adult soil intake rates)</td><td>Commercial/Industrial (moderate digging, landscaping)
Construction</td><td>Outdoor worker
Worker</td></tr>
<tr><td>IAEA (2005) Derivation of Activity Concentration Values for Exclusion, Exemption and Clearance. Safety Reports Series. No. 44. International Atomic Energy Agency, Vienna.</td><td>10 / 50 g/y
450/1800 h/y
<table>
<tr><td colspan="2" rowspan="2">Data in mg/h</td><td colspan="2">h/y</td></tr>
<tr><td>450</td><td>1800</td></tr>
<tr><td rowspan="2">g/y</td><td>10</td><td>22</td><td>5</td></tr>
<tr><td>50</td><td>111</td><td>28</td></tr>
</table></td><td>WL: worker on landfill or in other facility (other than foundry)
Values: realistic / low probability</td><td>Worker</td></tr>
<tr><td>Penfold, J.S.S., et al. (1999) Radiation Protection 107. Establishment of reference levels for regulatory control of workplaces where materials are processed which contain enhanced levels of naturally-occurring radionuclides. European Commission.</td><td>1.25 / 3.75 mg/h
2.5 / 5 mg/h</td><td>Normal / unlikely assumptions
Various work scenarios
Working with scales and residues and grinding samples</td><td>Worker
Worker</td></tr>
</table>

Table B2 (cont'd). Inadvertent ingestion information.

Reference	Ingestion value (mg per day or shift)	Scenario/Comments	
		Activity	Receptor
Charles D and McEwen T J (1991). Radiological Consequences of Drilling Intrusion into a Deep Repository for High Level Waste. A study made for the Swedish National Institute for Radiation Protection, Intera Sciences, I2446-1, Henley, UK.	25 mg over period of working with contaminated drilling material, based on review of data from Los Alamos, lead in urban atmospheric dust, and inhalation exposure data for the environment near Sellafield.	Various	Various
Conclusion: Most of ingestion intakes for workers are estimated for light digging or excavation exercises for construction purposes. Ingestion intake for deep drilling is not commonly assessed. The minimum assumed of ingestion for a worker is 5 mg/d [Oatways and Mobbs, 2003] due to mechanical disturbance of soil for construction purposes. The maximum ingestion daily ingestion rate for a worker is 330 mg/d [EPA, 2002; EPA, 2003; Walke et al, 2009] for construction or light activities such as fishing, recreational and dwelling. A higher rate of 111 mg/h [IAEA, 2005] can be derived from a combination of the worst scenario for a worker on landfill which includes the low probability assumption of inadvertent ingestion (50 g/y) and the realistic one for exposure time (450 h/y). The latter illustrates that it is always possible for someone to swallow quite a lot of dirt even if it is not considered normal.			