IAEA TECDOC SERIES

IAEA-TECDOC-1824

IAEA-TECDOC-1824

# Generic Post-closure Safety Assessment for Disposal of Disused Sealed Radioactive Sources in Narrow Diameter Boreholes

IAEA
International Atomic Energy Agency

# IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

## IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Information on the IAEA's safety standards programme is available on the IAEA Internet site

http://www-ns.iaea.org/standards/

The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at: Vienna International Centre, PO Box 100, 1400 Vienna, Austria.

All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to Official.Mail@iaea.org.

## RELATED PUBLICATIONS

The IAEA provides for the application of the standards and, under the terms of Articles III and VIII.C of its Statute, makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety in nuclear activities are issued as **Safety Reports**, which provide practical examples and detailed methods that can be used in support of the safety standards.

Other safety related IAEA publications are issued as **Emergency Preparedness and Response** publications, **Radiological Assessment Reports**, the International Nuclear Safety Group's **INSAG Reports**, **Technical Reports** and **TECDOCs**. The IAEA also issues reports on radiological accidents, training manuals and practical manuals, and other special safety related publications.

Security related publications are issued in the **IAEA Nuclear Security Series**.

The **IAEA Nuclear Energy Series** comprises informational publications to encourage and assist research on, and the development and practical application of, nuclear energy for peaceful purposes. It includes reports and guides on the status of and advances in technology, and on experience, good practices and practical examples in the areas of nuclear power, the nuclear fuel cycle, radioactive waste management and decommissioning.

# GENERIC POST-CLOSURE SAFETY ASSESSMENT FOR DISPOSAL OF DISUSED SEALED RADIOACTIVE SOURCES IN NARROW DIAMETER BOREHOLES

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-1824

# GENERIC POST-CLOSURE SAFETY ASSESSMENT FOR DISPOSAL OF DISUSED SEALED RADIOACTIVE SOURCES IN NARROW DIAMETER BOREHOLES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

## COPYRIGHT NOTICE

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

For further information on this publication, please contact:

Waste and Environmental Safety Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
September 2017

**IAEA Library Cataloguing in Publication Data**

Names: International Atomic Energy Agency.
Title: Generic post-closure safety assessment for disposal of disused sealed radioactive sources in narrow diameter boreholes / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2017. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1824 | Includes bibliographical references.
Identifiers: IAEAL 17-01112 | ISBN 978–92–0–107117–0 (paperback : alk. paper)
Subjects: LCSH: Radioactive waste disposal in the ground. | Radioactive waste — Safety measures. | Radioactive waste repositories.

# FOREWORD

The beneficial applications of radioactive sources in nuclear research and in industrial and medical areas have been a genuine breakthrough in modern scientific endeavours. However, the use of radioactive sources can generate small volumes of radioactive waste once the sources, some of which are potentially highly radioactive, become disused. Compared with waste from the nuclear fuel cycle and nuclear power generation, less consideration has been given in some countries to the management of disused sealed radioactive sources. Consequently, accidents have ensued from the misuse of such sources, particularly in countries with no suitable disposal options.

These accidents show a growing need for the international community to develop and implement safe and practical disposal solutions for disused sealed radioactive sources. Disposal in borehole facilities has in recent years been recognized as an effective solution for the disposal of disused sealed radioactive sources. IAEA Safety Standards Series No. SSG-1, Borehole Disposal Facilities for Radioactive Waste, provides specific guidance on the design, construction, operation and closure of borehole disposal facilities, mainly focusing on boreholes no wider than a few hundred millimetres at a depth beyond a few tens of metres and up to a few hundred metres. In light of initial work by the South African Nuclear Energy Corporation (NECSA), the IAEA has further developed the borehole disposal concept in an effort to assist Member States in the management of disused sealed radioactive sources.

In accordance with the relevant IAEA safety standards, this publication is intended to complement SSG-1 by presenting a generic post-closure safety assessment for the IAEA borehole disposal concept for the disposal of disused sealed radioactive sources in narrow boreholes. All the steps required to conduct such an assessment are covered by providing safety elements to be considered to ensure safety at borehole disposal sites. This publication identifies the key safety features, under varying disposal system conditions, in order to support the design and licensing processes of the borehole disposal concept, and facilitate its site specific implementation. This publication is primarily intended for those involved in developing or regulating the disposal of disused sealed radioactive sources to borehole facilities, and will be of particular interest to States that have disused sealed radioactive sources but no suitable disposal options at present.

The IAEA wishes to express its gratitude to all those who assisted in the drafting and review of this publication. The IAEA officers responsible for this publication were D. Bennett, P. Metcalf and G. Bruno of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

*This publication has been prepared from the original material as submitted by the contributors and has not been edited by the editorial staff of the IAEA. The views expressed remain the responsibility of the contributors and do not necessarily represent the views of the IAEA or its Member States.*

*Neither the IAEA nor its Member States assume any responsibility for consequences which may arise from the use of this publication. This publication does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any person.*

*The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.*

*The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.*

*The authors are responsible for having obtained the necessary permission for the IAEA to reproduce, translate or use material from sources already protected by copyrights.*

*The IAEA has no responsibility for the persistence or accuracy of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.*

## CONTENTS

# 1. INTRODUCTION

## 1.1. BACKGROUND

The application of radioactive sources in medicine, research, industry, agricultural and consumer products is a worldwide phenomenon. Consequently, many countries now have sources that need to be managed and disposed of carefully and in a safe and secure manner. These sources contain different radionuclides in highly variable quantities. In some cases, the activity of a source decays to a level below which the source is no longer suitable for its original purpose, in others the associated equipment may become obsolete, worn out, or damaged, and in others the source may develop a leak and so is no longer used. In all these circumstances, the radioactive sources are referred to as 'disused' or 'spent'[1], even though their activity could still be very high [1].

The majority of sources are small in physical size (e.g. Ra-226 needles), with the only items of significant size being some industrial radiography units and commercial irradiators. Despite their predominately small physical size, radioactive sources can contain very high activities, with typical levels in the MBq ($10^6$ Bq) to PBq ($10^{15}$ Bq) range [2]. Therefore, if they are not managed properly, radioactive sources can represent a significant hazard to human health and the environment, which is evident from the number of accidents that have taken place worldwide as a result of the mismanagement of such sources [3]. Some sources can be returned to their manufacturers and recycled, but for many users of sources it is impractical or uneconomical to recycle all sources, and many sources end up being stored for long periods of time [4]. Storage in a secure facility can be considered as an adequate final management option for sources containing quantities of short lived radionuclides, which decay to harmless levels within a few years. However, for most other sources a suitable disposal option is required. The IAEA has developed and published requirements and guidance on radioactive waste disposal [5], [6], [7].

Many countries have existing or proposed near surface radioactive waste disposal facilities [7]. However, the specific activity of many disused sealed radioactive sources exceeds the waste acceptance criteria for such facilities since the source constitutes a high, localized concentration in the facility and could give rise to unacceptable radiation doses in the event of human intrusion or other causes of facility disruption. Safety cases for many near surface disposal facilities assume a period of institutional control (typically a few tens to hundreds of years) during which disruption of the waste is assumed to be unlikely. However, even within these, and particularly for longer timeframes, it is possible that such control will no longer be fully in place and thus disruption of the waste cannot be ruled out. Consequently, disused sources that will not decay to negligible levels within a few tens to hundreds of years need to be disposed of in facilities that will provide higher levels of isolation than provided by surface storage or near surface facilities.

Deep geological disposal [6] offers the highest level of isolation available within disposal concepts currently actively considered. Such facilities are under consideration for the disposal of spent nuclear fuel, high level waste and intermediate level waste in a number of countries. However, they are expensive to develop and only viable for countries with extensive nuclear power programmes. It is unlikely that such an option will become available in many countries since they have no nuclear power programme requiring such resources. In particular, some countries in Africa, Asia, South America, and the former Soviet Union have limited infrastructure or administrative capability to manage or dispose radioactive waste in their country. Therefore increasing attention has been given in recent years to the disposal of disused sources in narrow diameter (a few tens of centimetres) borehole facilities with a view to providing a safe disposal option for limited amounts of highly active radioactive waste including disused sources [4], [8].

---

[1] According to Ref. [1], subtle differences can be noted between the terms 'spent' and 'disused'. A disused source differs from a spent source in that it may still be capable of performing its function, even though it is no longer used for that purpose. To be consistent, the broader 'disused' term is used in this document.

## 1.2. OBJECTIVE

The objective of this TECDOC is to document a GSA for this borehole disposal concept, with the purpose of identifying the concept's key safety features, under varying disposal system conditions, in order to support the concept design and licensing processes, and facilitate its site specific implementation.

## 1.3. SCOPE

The focus of the work described in this publication is the post-closure, radiological safety assessment of the disposal of disused sealed radioactive sources. The publication considers exposure of humans due to natural processes and human intrusion, but excludes intrusion that can be considered as deliberate (i.e. intrusion by a human when the intruder knows that the facility is a radioactive waste disposal facility). Consistent with Ref. [8], the impact of deliberate human intrusion is considered to be the responsibility of those intruding and is beyond the scope of the current assessment, as are malicious acts that might arise from deliberate human intrusion.

A variety of borehole designs have been used for the disposal of radioactive waste with differing depths (a few metres to several hundred metres) and diameters (a few tens of centimetres to several metres) (see Ref. [4] for details). The design evaluated in the GSA is based on the narrow diameter (0.26 m) design developed under the IAEA's AFRA project [9] since this design has been developed specifically for the disposal of disused sealed radioactive sources and uses borehole drilling technology that is readily available in all countries. The design can accommodate disused sources of less than 110 mm in length and 15 mm in diameter. This means that the design is applicable to a wide range of sources; Table 1 provides some examples taken from Ref. [10]. It is assumed that the sources are disposed at least 30 m from the ground surface. The geological, hydrogeological and geochemical conditions considered in this TECDOC have been selected to represent a broad spectrum of site conditions.

It is considered that the reference activity values derived are applicable to situations in which the inventory, design and site conditions fall within the envelope of assumptions and data used in the GSA. For situations falling outside the envelope defined by the GSA, the GSA could be used to guide and support the development of the site specific assessment. Furthermore, the derived generic reference activity values could be used as a benchmark against which to compare values derived from the site specific assessment.

It is recognized that, whilst radiological safety is of key importance, it is still only part of a broader range of issues that need to be considered in a safety case such as planning, financial, economic and social issues, and non-radiological safety [11]. However, these issues are not specifically covered in this TECDOC. They need to be considered as part of the wider safety case documentation to be developed to support any site specific implementation of the borehole disposal concept. Separate guidance will be developed by the IAEA on the development of safety case documentation.

## 1.4. STRUCTURE

The GSA has been undertaken using an approach that is consistent with best international practice. Specifically, the approach developed by the Coordinated Research Project of the International Atomic Energy Agency (IAEA) on Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities (the ISAM Safety Assessment Approach) [12] (Fig. 1) has been used, with the aim of ensuring that the assessment is undertaken and documented in a consistent, logical and transparent manner.

TABLE 1. EXAMPLE SOURCES SUITABLE FOR DISPOSAL IN THE NARROW DIAMETER BOREHOLE CONSIDERED IN THE GSA

| Source | Typical Dimensions | | Typical Activity When New (Bq) | Application |
|---|---|---|---|---|
| | Diameter | Length | | |
| Industrial gamma radiography sources | Up to 7 mm | Up to 15 mm | Co-60: 3.7E+12<br>Se-75: 2.9E+12<br>Cs-137: 3.7E+11<br>Yb-169: 7.4E+11<br>Ir-192: 5.5E+12 | Industrial radiography |
| Brachytherapy sources | Modern Ir-192 sources: 3 mm<br>Older Co-60 sources: 3 mm sphere | Modern Ir-192 sources: 15 mm | Co-60: up to 1.5E+9<br>Cs-137: 1.5E+9<br>Ir-192: 3.7E+11 | Medical therapy |
| High energy gamma industrial gauging sources | 3 to 12 mm | 5 to 15 mm | Co-60: 3.7E+7 to 3.7E+10<br>Cs-137: 3.7E+8 to 3.7E+11 | Industrial gauging and soil density gauging |
| Neutron industrial gauging sources | 8 to 20 mm | 12 to 30 mm | Am-241: 1.85E+9 to 1.85E+11<br>Cf-252: 7.2E+7 to 7.2E+9 | Industrial gauging and soil moisture gauging |
| Gamma oil well logging sources | 8 to 20 mm | 12 to 30 mm | Cs-137: 3.7E+10 to 1.11E+11 | Oil exploration and production |
| Low energy fixed industrial gauging sources | 10 to 50 mm | 7 to 15 mm | Kr-85: 3.7E+8 to 7.4E+9<br>Sr-90: 3.7E+8 to 7.4E+9<br>Am-241: 3.7E+8 to 7.4E+10 | Industrial gauging |
| Low energy gamma analytical sources | 3 to 15 mm | 7 to 10 mm | Cd-109: 3.7E+8 to 1.85E+9<br>Am-241: 3.7E+8 to 1.85E+9 | Industrial gauging |
| Calibration and reference sources | Wide variations | Wide variations | Wide range of isotopes up to 3.7E+7 | Instrument calibration |

The ISAM Safety Assessment Approach consists of the following key steps:

- The specification of the assessment context;
- The description of the disposal system;
- The development and justification of scenarios;
- The formulation and implementation of models; and
- The presentation and analysis of results.

These steps are presented in Sections 2 to 6. Initial guidance on the use of the GSA and its results is provided in Section 7. Finally, overall conclusions are presented in Section 8, whilst supporting information is provided in Appendices I to XIII.

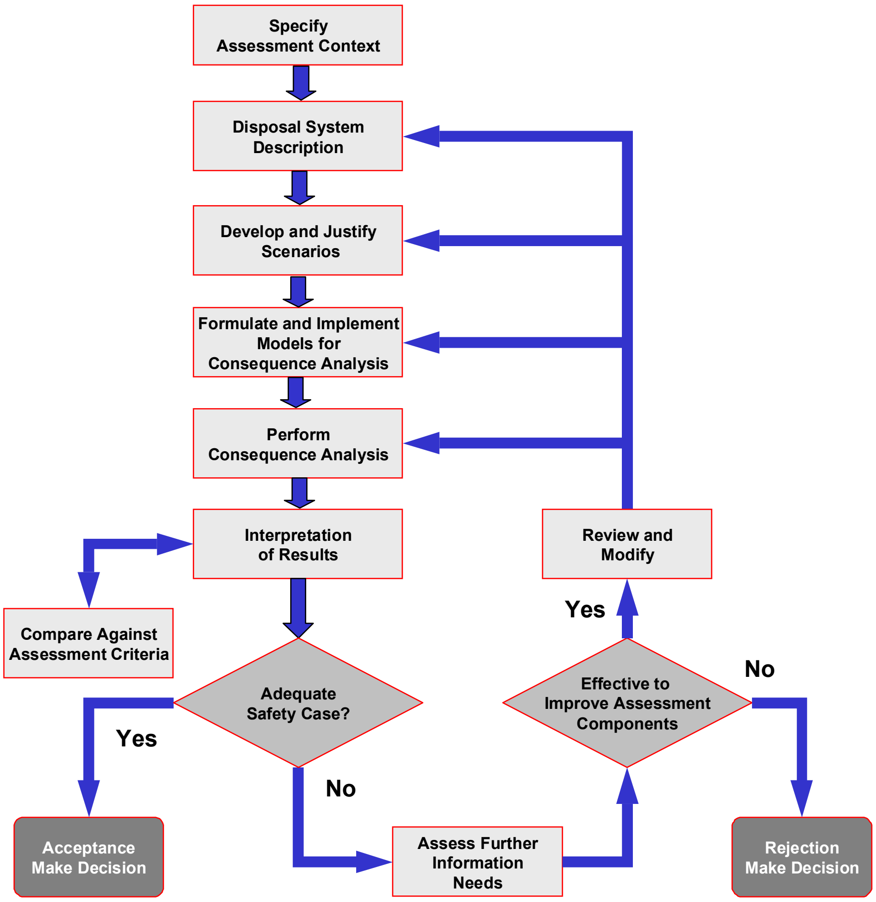


*FIG. 1. ISAM safety assessment approach (reproduced from Ref. [12])* .

# 2. SPECIFICATION OF ASSESSMENT CONTEXT

## 2.1. BACKGROUND

The assessment context defines the scope and content of the safety assessment. Specifically, it specifies the assessment's:

- Purpose and scope (Section 2.1);
- Target audience (Section 2.2);
- Regulatory framework (Section 2.3);
- End-points (Section 2.4);
- Philosophy (Section 2.5); and
- Timeframes (Section 2.6).

## 2.2 PURPOSE AND SCOPE

The GSA has the following main purposes:

1. To demonstrate and build confidence in the use of narrow diameter boreholes as a safe disposal concept for disused sealed radioactive sources of less than 110 mm in length and 15 mm in diameter.
2. To produce a GSA for an envelope of disposal system conditions and assumptions against which a specific disposal system can be compared by identifying:
    - Inventories suitable for disposal using the borehole disposal concept;
    - Suitable levels of engineering;
    - Suitable site characteristics;
    - The need for and duration of the institutional control period required to provide adequate safety; and
    - The half-life around which there is no practical limit for disposal from a post-closure perspective.
3. To identify the key parameters that need to be characterized for a specific site.

The GSA's scope is the assessment of the post-closure (i.e. once the waste has been emplaced and the borehole backfilled and closed) radiological impacts on humans arising from the disposal of disused sealed radioactive sources at least 30 m below the ground surface in a narrow diameter borehole.

## 2.3. TARGET AUDIENCE

This publication is a technical report and as such is written primarily for a technical audience whose prime interest is in the regulation and implementation of safe radioactive waste disposal[2]. The publication is considered to be of particular interest to those countries that have disused sealed radioactive sources and no suitable disposal options at present.

Two main technical audiences can be identified.

- 'Developers' including those individuals and organizations that have a direct interest in the disposal of disused sealed radioactive sources to borehole facilities. This group could include not only any organization directly involved in pursuing a disposal facility development programme, but also other nuclear industry organizations and radioactive waste producers.
- 'Regulators' including those organizations who would have a direct responsibility to decide whether to grant a 'licence to operate' a borehole disposal facility. In addition, there could be a wider range of organizations, such as local authority and other governmental organizations, which would need to be consulted if a borehole facility were to be developed for the disposal of disused sources.

Included in both these groups are the scientists who would provide technical support to the developers and regulators.

It is recognized that there is a range of other audiences that could be interested in the borehole disposal of disused sources (for example the media, politicians, and the public). However, given its technical focus, this publication is not specifically aimed at these audiences. It is recognized that additional publications will have to be developed that is tailored to the specific interests and needs of these other audiences.

## 2.4. REGULATORY FRAMEWORK

The assessment is not related to any specific site, organization or country, and so it is considered inappropriate to use a particular country's regulatory framework. Furthermore, few countries have national requirements for the safe disposal of disused sealed radioactive sources that can be used as regulatory framework for the assessment, and where frameworks do exist, for example in South Africa [13], guidance provided related to issues influencing the post-closure safety of a borehole disposal facility is relatively limited. Given this, it is considered appropriate to use the recommendations of the IAEA Specific Safety Guide [8]. This Specific Safety Guide provides post-closure protection objectives and criteria which in turn are based on the recommendations of the IAEA and the ICRP [14], [15], [16].

Consistent with Ref. [8], the GSA adopts an individual effective dose constraint of 0.3 mSv/y for adult[3] members of the public for all potential future exposures other than those arising from human intrusion.

---

[2] The report assumes that the reader is familiar with the technical terms used in safety assessment. Key technical terms are defined in Ref. [1].

[3] Doses to children and infants could also be calculated, especially if there was a need to demonstrate consideration of a wide range of calculation end points. However, various post-closure assessment studies, such as Refs [17], [18], have demonstrated that the differences between adult, child and infant doses are usually less than a factor of two. Therefore, for the purposes of the GSA, consideration will be limited to adult doses as an indicator of impacts.

## 2.5. END POINTS

In most post-closure safety assessments, some measure of impact on humans or the environment is the calculation end point. The waste activity concentrations and total activity levels (i.e. the facility inventory) are usually the starting points of the assessment. In contrast, in this publication, the calculation end points are the reference activity levels for disposal to a borehole, which can be expressed as total activity values and per waste package activity values for each radionuclide, and the measure of impact (the annual individual effective dose), can be seen as the starting point of this calculation. However, in practice, the calculation of reference activity levels first requires a unit inventory for a borehole (1 TBq of each radionuclide per waste package in a borehole) to be assumed for which the dose is calculated. Assuming a linear relationship between the inventory and the dose[4], total and per waste package activity levels that meet the appropriate radiological protection criteria can then be derived for each radionuclide disposed in the borehole. Further details concerning the calculation of reference activity levels are provided in Section 5.3.

Radiological impacts on non-human biota are not considered in this publication since it is assumed that if individual humans are shown to be adequately protected, then non-human biota will also be protected, at least at the species level [19]. The basis of this assumption is currently being investigated by various international organizations such as the International Commission on Radiological Protection (ICRP), the IAEA and the European Commission (see for example Refs [16], [20], [21]). However, in the absence of any, as yet, clear consensus and guidance on the assessment of radiological impacts on non-human biota, the recommendations of ICRP Publication 60 [19] are adopted.

Non-radiological impacts, which might arise from the content of chemically or biologically toxic materials in the waste (for example beryllium in some Am-241 sources) or engineered barrier materials, are considered to be beyond the scope of the GSA given its emphasis on radiological impacts.

## 2.6. PHILOSOPHY

Different approaches can be applied to the assessment of the end points discussed in Section 2.5. Whilst the nature of the end points may have been clearly defined, the nature of the approach used to calculate the end points also needs to be made clear. From this perspective, the assessment philosophy is an expression of the approach that is applied to the assessment.

Consistent with best international practice, the ISAM Safety Assessment Approach (Fig. 1) is used to undertake the assessment with the aim of ensuring that the assessment is undertaken and documented in a consistent, logical and transparent manner.

### 2.6.1. Nature of assumptions adopted

In undertaking an assessment, various assumptions have to be adopted. Assumptions are often categorized as 'realistic'[5] or 'conservative'[6], although, care needs to be taken when using such terms.

---

[4] The limitations of this assumption are discussed in Section 5.3.

[5] Realism can be defined as "*the representation of an element of the system (scenario, model or data), made in light of the current state of system knowledge and associated uncertainties, such that the safety assessment incorporates all that is known about the element under consideration and leads to an estimate of the expected performance of the system attributable to that element*".

[6] Conservatism can be defined as *"the conscious decision, made in light of the current state of system knowledge and associated uncertainties, to represent an element of the system (scenario, model or data) such that it provides an under-estimate of system performance attributable to that element and thereby an over-estimate of the associated radiological impact (i.e. dose or risk)"*.

A mixture between a realistic and a conservative approach is applied to the GSA. The key issue is to document and justify the nature of each assumption in the assessment. Typically, realistic assumptions are used where information is available and the associated uncertainty is relatively well known, whilst conservative assumptions are used where the information is highly uncertain.

### 2.6.2. Data availability

The assessment is not related to any specific location and, consequently, is carried out using well-justified values for the defined disposal systems derived from a range of national and international literature. All data sources are documented. The near field conditions are based on parameter values obtained as part of the development of the borehole disposal concept under the IAEA's AFRA project [9], supplemented by generic data available from literature where necessary.

Since the assessment is generic, no site characterization studies were undertaken to supplement existing available information.

### 2.6.3. Treatment of uncertainties

The treatment of uncertainty is a key component of any assessment to establish the safety of a radioactive waste disposal facility. Uncertainties require consideration in a variety of ways and assimilation into the structure of the assessment as appropriate. They arise from three main sources [22]:

- Uncertainty in the evolution of the disposal system over the timescales of interest (scenario uncertainty);
- Uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour and evolution of the disposal system (e.g. Owing to the inability of models to represent the system completely, and to approximations used in solving the model equations); and
- Uncertainty in the data and parameters used as inputs in the modelling.

In addition, Ref. [12] suggests that a further type of uncertainty, subjective uncertainty (uncertainty due to reliance on expert judgement), is also linked with the above sources of uncertainty.

The uncertainty in the future evolution of the site is treated using a transparent and comprehensive scenario development and justification methodology (Section 4). Data and parameter uncertainty that exist are treated using a deterministic sensitivity analysis, whilst model uncertainties are treated using alternative conceptualizations and mathematical representations of the system (Section 6). Subjective uncertainties can be managed by using a systematic and transparent assessment approach, which allows subjective judgements to be document, justified and quantified (as far as possible).

## 2.7. TIMEFRAMES

Table 2 summarizes the timeframes for the various activities associated with the construction, operation, closure and subsequent release of the borehole from institutional control. It is assumed that following construction of the borehole, waste is disposed for a maximum period of one year since the volume of waste packages to be disposed is small (less than 0.2 m$^3$) and, from an operational (and post-closure safety) perspective, it is best for this to be disposed over a relatively short period of time. It is assumed that following the disposal of the disused sources, the site is closed immediately and the institutional control period starts. During this period, surveillance of the site might be undertaken for the purpose of public assurance (active institutional control). Local/national government records and planning authority restrictions may be maintained to prevent unauthorized use of the land and inadvertent human intrusion (passive institutional control). For the illustrative purposes of the GSA (and consistent with the lower end of the range considered in Ref. [23]), the duration of the institutional control period is assumed to last 30 years. During the institutional control period, it is assumed that members of the public do not have access to the land in the immediate vicinity of the borehole and that inadvertent human intrusion into the facility does not occur.

TABLE 2. TIMEFRAMES FOR THE VARIOUS ACTIVITIES ASSOCIATED WITH THE CONSTRUCTION, OPERATION, CLOSURE AND SUBSEQUENT RELEASE OF THE BOREHOLE FROM INSTITUTIONAL CONTROL

| Activity | Timeframe |
|---|---|
| Borehole construction and waste emplacement | About one year<br>(at a maximum) |
| Site closure | Immediately following the waste disposal operation |
| Institutional control period (e.g. surveillance, local/national government records, planning authority restrictions, site marked on official maps) | Illustrative period of 30 years |
| No control (neither active nor passive) – all records/knowledge conservatively assumed to be lost | From 30 years onwards |

In terms of the cut off time for calculations, the generic regulatory framework adopted for the assessment does not impose any explicit limit on the timescale for assessment. Therefore, calculations presented in the GSA are undertaken out to a time when it can be demonstrated that the peak value of the primary safety indicator (dose) has been passed for the radionuclide and disposal system of interest. It is important to recognize that uncertainties associated with these estimates will increase as the timescales become longer.

# 3. DESCRIPTION OF DISPOSAL SYSTEMS

Together with the assessment context, the disposal system description provides the necessary basis to develop a well-justified set of exposure scenarios (Section 4). The disposal system can be divided into:

- The near field - the waste, the disposal zone, the engineered barriers of the borehole plus the disturbed zone of the natural barriers that surround the borehole.
- The geosphere - the rock and unconsolidated material that lies between the near field and the biosphere. It can consist of both the unsaturated or vadose zone (which is above the groundwater table) and the saturated zone (which is below the groundwater table).
- The biosphere - the physical media (atmosphere, soil, sediments and surface waters) and the living organisms (including humans) that interact with them.

These descriptions are provided in Sections 3.1 to 3.3. The near field, geosphere and biosphere characteristics are then combined in Section 3.4 and resulting disposal systems identified.

## 3.1. NEAR FIELD

For the purposes of the GSA calculations presented in Section 6, it is assumed that there is a single disposal borehole and that the design assessed is based on the narrow diameter borehole design developed under the IAEA's AFRA project [9]. Alternative borehole designs could be considered (see for example Ref. [4]), but these would have to be evaluated using a separate, design-specific safety assessment.

It is assumed that the disposal zone in the borehole is at least 30 m from the ground surface thereby significantly reducing the probability of the waste being disturbed by human intrusion or other disruptive events and processes [4]. The disposal zone could extend down to around 100 m, although depths of several hundred metres could be considered if geological conditions were found to be more appropriate at such depths [4].

### 3.1.1. Inventory

Since the 1940s, there has been a considerable increase in the number of disused sealed radioactive sources, the range of radionuclides that they contain and the diversity of their application in medicine, research, industry, agricultural and consumer products. The application of sources in these sectors, the range of radionuclides that they contain, their expected maximum activity and the application associated with the maximum activity are summarized in various publications such as Refs [2], [4], [9].

In order to identify an inventory for assessment in the GSA, the IAEA's Net Enabled Waste Management Database (NEWMDB) [24] was consulted. Only countries that do not have a nuclear power programme were considered, since these are the countries that are more likely to implement the borehole disposal option. The countries considered were: Belarus, Chile, Costa Rica, Cuba, Ecuador, Estonia, Guatemala, Indonesia, Ireland, Kuwait, Luxembourg, Madagascar, Morocco, Paraguay, Peru, Philippines, Singapore, Thailand and Tunisia. Additional data, available from the AFRA project (for Algeria, Egypt and Ghana) and from other IAEA projects (for Bolivia and Nicaragua) was also considered. The list of the radionuclides that were found in sources from more than one country is given in Table 3. Note that NEWMDB and other data sources do not always contain information on the dimensions of the sources, so not all the sources listed might be suitable for disposal in a narrow diameter borehole. Nevertheless, the list of radionuclides is considered to be a representative estimate of the radionuclides that might need to be disposed.

TABLE 3. RADIONUCLIDES CONSIDERED IN THE GENERIC SAFETY ASSESSMENT

| | | | |
|---|---|---|---|
| **H-3** | Se-75 | Sm-151 | **Pb-210** |
| Na-22 | **Kr-85** | Eu-152 | Po-210 |
| Mn-54 | Y-88 | Gd-153 | **Ra-226** |
| Fe-55 | **Sr-90** | Yb-169 | **Pu-238** |
| Co-57 | Cd-109 | Ir-192 | **Pu-239** |
| **Co-60** | Ba-133 | Au-195 | **Am-241** |
| **Ni-63** | **Cs-137** | Hg-203 | Cf-252 |
| Zn-65 | Pm-147 | Tl-204 | |

**Note:** Emboldened radionuclides are those considered in detail in the GSA.

For reasons of practicality, it is desirable to screen out any radionuclides that, due to their half-life, maximum activity, and/or radiotoxicity, will not result in significant post-closure impacts. For the purposes of radionuclide screening, the GSA dose constraint of 0.3 mSv/y is applied (Section 2.4). Radionuclide screening has been undertaken in two simple steps described in Appendix I.

1. Preliminary screening – doses associated with direct exposure via ingestion, inhalation and external irradiation to a single disused source following a 30 year institutional control period are calculated.
2. Main screening – for those radionuclides remaining after Step 1, a simple assessment of doses associated with the groundwater and gas pathways is undertaken.

The screening process has resulted in the identification of 11 radionuclides for detailed consideration in the GSA. These radionuclides are emboldened in Table 3. For the purpose of the activity level calculations presented in Section 6, it is assumed that a unit inventory of 1 TBq per waste package of each of the radionuclides in Table 3 is disposed in the borehole. For those 20 radionuclides that have been screened out from consideration (i.e. those that are not emboldened in Table 3), it is considered that their presence in disused sealed radioactive sources at the activity levels identified in Appendix I (see Table 30) does not result in significant post-closure impacts. Borehole disposal could be considered for such radionuclides. However, other management options might be more appropriate such as surface storage or disposal in a near surface disposal facility.

### 3.1.2. Engineering

Based on the narrow diameter design developed under the IAEA's AFRA project [9], the reference design for the near field evaluated in the GSA is assumed to comprise a series of engineered components which are described below, illustrated in Figs 2 to 4, and summarized, together with their post-closure safety related functions, in Table 4. Alternative dimensions to those given below are considered in the variant calculations presented in Section 6.2.

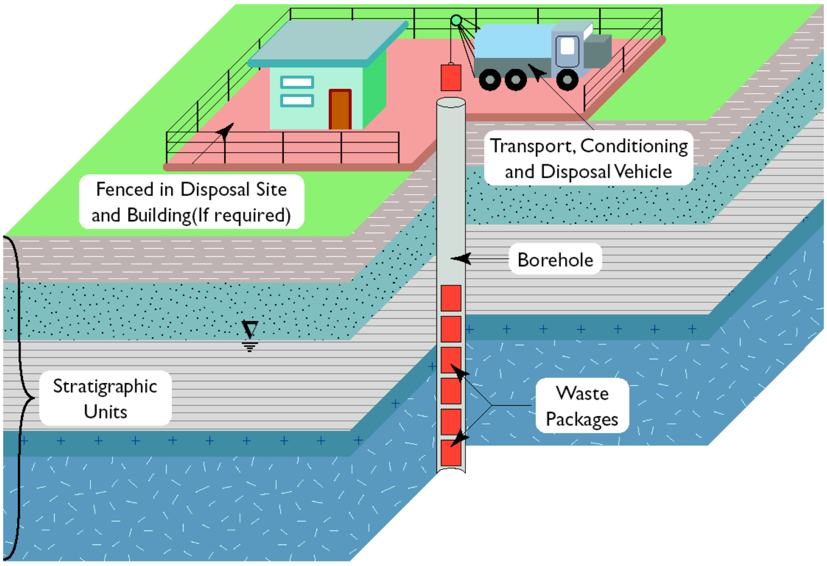


*FIG. 2. Schematic representation of the borehole site. Reproduced courtesy of Van Blerk [25].*

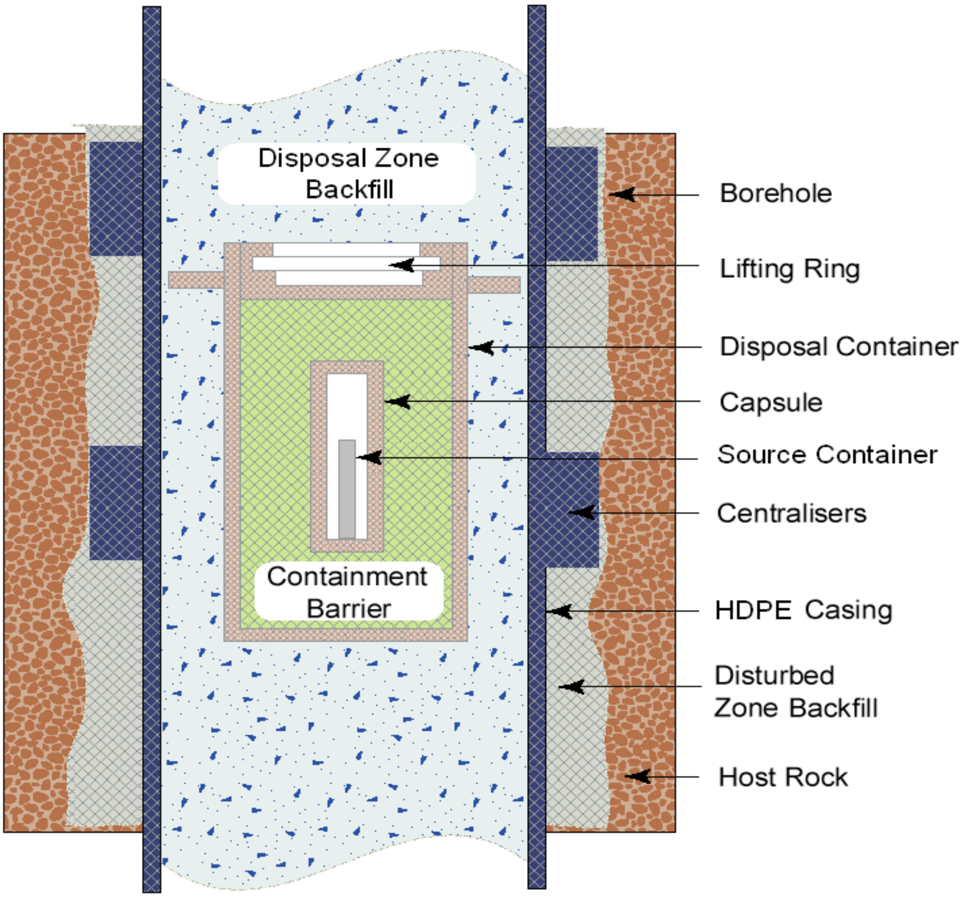


*FIG. 3. Cross-section through the disposal borehole for the reference design evaluated in the GSA. Reproduced from Ref. [8].*

TABLE 4. NEAR FIELD COMPONENTS FOR THE REFERENCE DESIGN EVALUATED IN THE GSA AND THEIR POST-CLOSURE SAFETY RELATED FUNCTIONS

| Near field Component | Description | Post-closure Safety Related Functions |
|---|---|---|
| Source and its container | Source and its container within which the source material is sealed | • No safety function since it is assumed that the source container will have failed prior to disposal. |
| Capsule | Standard stainless steel (Type 304) capsule containing the source container | • Until breached, isolates source from water, animals and humans;<br>• Until breached, prevents escape of gas from source;<br>• Once breached, limits release of radionuclides available for release from the capsule until it has been corroded. |
| Containment barrier | Space between the capsule and the disposal container is backfilled with sulphate-resistant cement grout | • Physical barrier – can inhibit disruption of the disused source by surface erosion, human intrusion, and biotic intrusion;<br>• Physical barrier – once the disposal container has been breached, can limit flow of water around the capsule due to low permeability;<br>• Physical barrier – once the capsule has been breached, can act as low permeability barrier to the migration of radionuclides from the borehole in liquid and gaseous phases;<br>• Cement can passivate corrosion of stainless steel capsule and reduce chloride levels in water through formation of calcium chloride;<br>• Chemical barrier – once the capsule has been breached, can act as sorption barrier for radionuclides released;<br>• Chemical barrier – once the capsule has been breached, can act to regulate the availability of radionuclides for release into water through its impact on the solubility of radionuclides . |
| Disposal container | Type 316 L stainless steel | • Until breached, isolates source container, capsule and containment barrier from water, animals and humans;<br>• Once it and the capsule are both breached, the disposal container can limit the fraction of radionuclides available for release into the borehole until the entire container has been corroded. |
| Disposal zone backfill | Sulphate-resistant cement grout used to separate disposal containers in vertical dimension from one another, and in the horizontal dimension from the borehole casing | • Physical barrier – can inhibit disruption of the disused source by surface erosion, human intrusion, and biotic intrusion;<br>• Physical barrier – can limit the flow of water around the disposal container due to low permeability;<br>• Physical barrier – once the disposal container and capsule have been breached, can act as low permeability barrier to the migration of radionuclides from the borehole in liquid and gaseous phases;<br>• Cement can passivate corrosion of stainless steel capsule and reduce chloride levels in water through formation of calcium chloride;<br>• Chemical barrier – once the disposal container and capsule have been breached, can act as sorption barrier for radionuclides released;<br>• Chemical barrier – once the capsule has been breached, can act to regulate the availability of radionuclides for release into water through its impact on the solubility of radionuclides. |
| Disposal zone plug | Sulphate-resistant cement grout plug at base of borehole | For unsaturated systems:<br>• Physical barrier – once the disposal container and capsule have been breached, can act as low permeability barrier to the migration of radionuclides from the borehole in liquid phase;<br>• Chemical barrier – once the disposal container and capsule have been breached, can act as sorption barrier for radionuclides released;<br>• Chemical barrier – once the disposal container and capsule has been breached, can act to regulate the availability of radionuclides for release into water through its impact on the solubility of radionuclides.<br>For saturated systems:<br>• Physical barrier – until the casing starts to degrade will limit the flow of water up into borehole due to low permeability. |

TABLE 4. NEAR FIELD COMPONENTS FOR THE REFERENCE DESIGN EVALUATED IN THE GSA AND THEIR POST-CLOSURE SAFETY RELATED FUNCTIONS (cont.)

| Near field Component | Description | Post-closure Safety Related Functions |
|---|---|---|
| Casing | High-density polyethylene (HDPE) casing emplaced at time of drilling. Top sections withdrawn at closure of borehole down to 1 m of the disposal zone | • Until degraded, restricts the flow of water into the disposal zone in saturated systems. |
| Disturbed zone backfill | Sulphate-resistant cement grout used to fill the gap between the casing and the host rock and any voids/cracks in the host rock immediately adjacent to the borehole | • Physical barrier – limits the flow of water into the borehole due to low permeability;<br>• Physical barrier – once the disposal container and capsule have been breached, can act as low permeability barrier to the migration of radionuclides from the borehole in liquid and gaseous phases;<br>• Chemical barrier – once the disposal container and capsule have been breached, can act as sorption barrier for radionuclides released from the borehole;<br>• Chemical barrier – once the capsule has been breached, can act to regulate the availability of radionuclides for release into water through its impact on the solubility of radionuclides;<br>• Cement can passivate corrosion of stainless steel capsule and reduce chloride levels in water through formation of calcium chloride. |
| Closure zone backfill | Assume that the first 5 m from the ground surface is native soil/crushed rock and the remainder is sulphate-resistant cement grout | • Physical barrier – limits the flow of water into the borehole due to low permeability;<br>• Physical barrier – inhibits disruption of the disused source by surface erosion, human intrusion, and biotic intrusion;<br>• Physical barrier – once the disposal container and capsule have been breached, can act as low permeability barrier to the migration of radionuclides from the borehole in liquid and gaseous phases;<br>• Chemical barrier – once the disposal container and capsule have been breached, can act as sorption barrier for radionuclides released from the borehole;<br>• Chemical barrier – once the capsule has been breached, can act to regulate the availability of radionuclides for release into water through its impact on the solubility of radionuclides;<br>• Cement can help maintain high pH conditions which then passivate corrosion of stainless steel capsule and reduce chloride levels in water through formation of calcium chloride. |

#### *3.1.2.1. Waste Package*

The waste package used for the disposal of disused sealed radioactive sources in the borehole disposal concept comprises the following components (see Fig. 3). It is assumed for the purposes of the derivation of the reference activity levels presented in Section 6 that a total of 50 waste packages are disposed in the borehole.

- The **source and its container** – the radioactive source material and its container (for example, the radium needles containing the radium salt, or the Pyrex tubes containing tritium gas or tritium oxide). The dimensions of the reference capsule (Table 5) limit the source and its container to be less than 110 mm in length and 15 mm in diameter.
- The **capsule** – assumed to be a standard stainless steel capsule (Type 304)[7]. The disused source and its associated container are emplaced in the capsule and sealed. No backfill material is used,

---

[7] Stainless steels are chromiun-containing steels where the Cr provides resistance to corrosion through the formation of a protective (‘passive’) Cr(III) oxide or hydroxide film. There are various classes of stainless steel, a common class being the so-called 300-series austenitic alloys. Two of these alloys have been selected for the waste capsule and disposal container.

which means that apart from the disused source and its container, the capsule is empty. The dimensions for the capsule are presented in Table 5 (alternative dimensions are considered in variant calculations presented in Section 6.2).

- The **containment barrier** – assumed to be a backfill comprising sulphate-resistant cement grout and filling the void between the capsule and the disposal container. The dimensions for the containment barrier are presented in Table 5.
- The **disposal container** – assumed to be manufactured from Type 316 L stainless steel with the reference dimensions given in Table 5. Alternative dimensions for the disposal container are considered in variant calculations presented in Section 6.2. These would allow the disposal of source containers of less than 160 mm in length and 140 mm in diameter directly into the disposal container (i.e. with no capsule). As shown in Fig. 3, the container is equipped with a lifting ring to facilitate waste emplacement in the borehole. There are also three centralisers that help to ensure that the container is emplaced centrally and vertically. The centralisers are thin (<10 mm) and do not inhibit the flow of cement grout past the top of the disposal container.

TABLE 5. DIMENSIONS OF THE CAPSULE, CONTAINMENT BARRIER AND DISPOSAL CONTAINER FOR THE REFERENCE DESIGN EVALUATED IN THE GSA

| Waste package component | Length (mm) | Inside diameter (mm) | Outside diameter (mm) | Thickness[8] (mm) |
|---|---|---|---|---|
| Capsule | 110 | 15 | 21 | 3 |
| Containment barrier | 186 | 21 | 103 | 41 |
| Disposal container | 250 | 103 | 115 | 6 |

### *3.1.2.2. Disposal Borehole*

The disposal borehole is 260 mm in diameter and is drilled to a depth of over 80 m. The borehole is fitted with a high-density polyethylene (HDPE) casing for the reference design evaluated in the GSA, although potentially more durable alternative casings such as steel could be considered if it was considered necessary to introduce an additional longer-term isolation barrier. The inner and outer diameters of the casing are 140 mm and 160 mm, respectively, giving a casing thickness of 10 mm.

Three distinct zones can be defined in the disposal borehole (see Fig. 4).

---

Type 304 stainless steel has the nominal composition 18-20 wt.%Cr, 8-10.5 wt.%Ni, 1 wt.%Si, 2 wt.%Mn, 0.08 wt.%C, 0.045 wt.%P, and 0.03 wt.%S. Type 316L stainless steel has the nominal composition 16-18 wt.%Cr, 10-14 wt.%Ni, 1 wt.%Si, 2 wt.%Mn, 0.03 wt.%C, 0.045 wt.%P, 0.03 wt.%S, and 2-3 wt.% Mo, where the addition of Mo improves the resistance to localized corrosion and the reduced C content improves resistance to intergranular attack.

[8] As used here thickness refers to the wall thickness of the capsule and disposal containers as well as the thickness of the containment barrier.

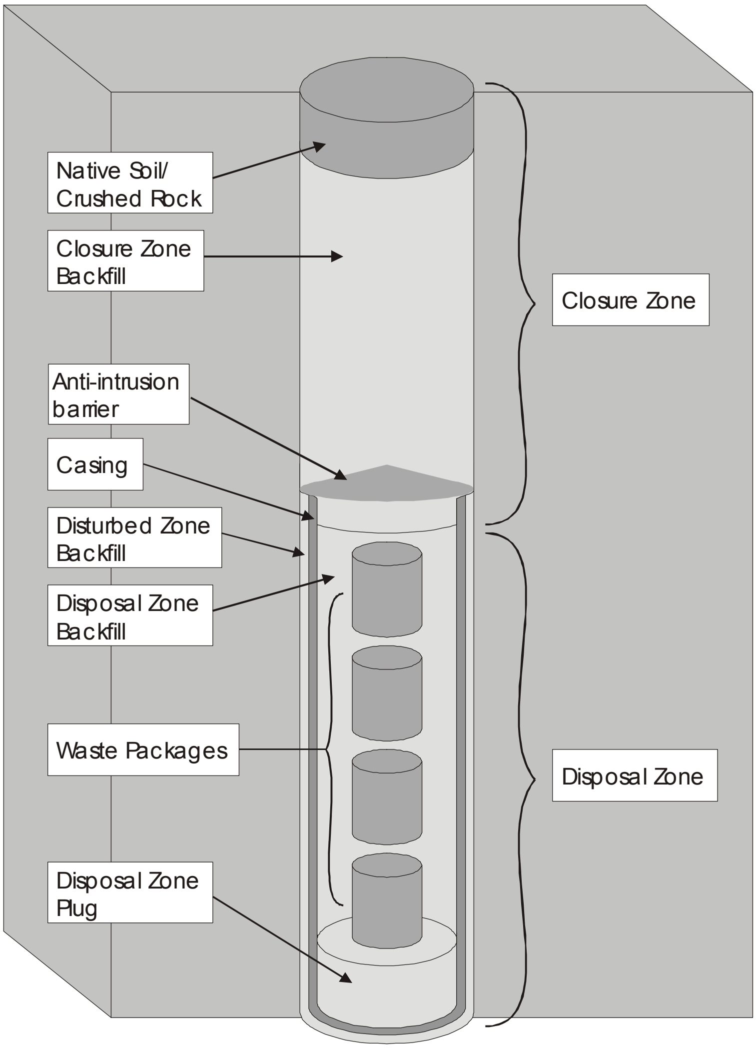


*FIG. 4. Illustration of the borehole zones for the reference design evaluated in the GSA.*

- The **disposal zone** – the zone inside the casing in which the waste packages are disposed. The base of the disposal zone is assumed to be at least 80 m from the ground surface. A 0.5 m thick 'plug' of backfill slurry is emplaced at the base of the borehole. The borehole backfill slurry is assumed to be sulphate-resistant cement grout. Once the plug material is set, the waste packages are lowered into the borehole, one at a time. After the emplacement of each waste package, backfill material is poured over the waste packages to fill the 12.5 mm thick void between the waste package and the casing wall, as well as a volume on top of the waste package. The layer of backfill on top of the waste package is on the order of 700 mm to 800 mm deep. Together with the waste package, this constitutes a pitch height of about 1 m per waste package. Given that it is assumed that there are 50 waste packages to be disposed, the total thickness of the disposal zone is about 50 m.
- The **closure zone** – the zone between the disposal zone and the ground surface. Once the waste packages have been emplaced in the borehole, it is assumed that the casing in the closure zone is withdrawn from the borehole from a depth 1 m above the disposal zone. This removes a potential fast transit pathway to and from the disposal zone which might arise once the casing has degraded. An anti-intrusion barrier (for example a metallic 'drill deflector') is placed above

the disposal zone in order to deter/prevent human intrusion. The closure zone is then backfilled to a depth 5 m below the ground surface with the same backfill material used for the disposal zone. The final 5 m of the closure zone is then backfilled with native soil and/or crushed rock to the ground surface. It is assumed that the total depth of the closure zone is at least 30 m, which is considered to be a depth beyond which human intrusion is limited to drilling [8].

- The **disturbed zone** – the zone between the casing and the wall of the borehole. Voids and cracks in the host geology immediately adjacent to the borehole are assumed to be grouted and sealed during the drilling process with the same slurry used for the backfilling of the disposal and closure zones. In addition, an average gap of 50 mm between the casing and the borehole wall is backfilled with the slurry using a pressure grouting technique [9]. As shown in Fig. 3, the casing is fitted with centralisers to ensure that the casing is in the middle of the borehole. These centralisers are made of thin mild steel plates inserted vertically to ensure that they do not hamper the flow of the backfill slurry.

The design of the borehole disposal concept is a final disposal concept that is not designed to facilitate the retrieval of waste packages once disposed since, once each waste package has been lowered into the borehole, it is backfilled into the borehole with sulphate-resistant cement grout. Following the emplacement of the final waste package, the closure zone above the waste package is also backfilled with sulphate-resistant cement grout. This greatly reduces the possibility of sabotage or theft of the disposed disused sealed radioactive sources.

### 3.1.3. Hydrology and chemistry

Disposal in either saturated or unsaturated conditions is considered in the GSA. However, conditions where the disposal zone is in both the saturated and unsaturated zones are not considered in the GSA and to be avoided for a number of reasons. The waste may undergo cyclical changes in chemical, hydraulic, and microbiological environments due to fluctuating groundwater levels. Such cyclical changes could enhance releases from waste packages, compared to less dynamic conditions. These dynamic conditions could enhance degradation of engineered barriers in the borehole, which would tend to further aggravate the tendency to increase release rates from the borehole. Also, this dynamic system would be difficult to evaluate from a safety assessment perspective. Rather than using a long term average hydraulic system, on which transport analyses are conducted, one would have to evaluate the influences of short-term dynamic processes on release and transport phenomena. For a real site, it is considered that it could be both difficult and costly to develop a robust and defensible assessment of such a system.

Geochemical conditions in the borehole will be determined by the interaction of the borehole engineering and the host groundwater. A range of geochemical conditions is identified in Section 3.2 for analysis. Their impact on near field geochemistry is considered in Section 5.2.

## 3.2. GEOSPHERE

The geosphere has a number of safety related functions; these are summarized in Table 6.

For a site specific assessment, site specific data relating to the geosphere can be collected and collated. However, for a site-generic assessment, it can be helpful to consider a range of ‘synthesised’ geospheres, which are not based on specific geospheres. Instead, the synthesised geospheres are representative of potential conditions that might be found in reality, thereby helping to ensure that the GSA and its findings are relevant to realistic geosphere conditions. By considering more than one synthesised geosphere, the performance of the borehole can be evaluated under a range of geosphere conditions thereby helping to define the envelope of site conditions for which the GSA and its results are applicable.

TABLE 6. GEOSPHERE COMPONENTS AND THEIR SAFETY RELATED FUNCTIONS

| System component | Post-closure safety related functions |
|---|---|
| Unsaturated zone | • Physical barrier for disposal in the unsaturated zone – can delay the migration of radionuclides from the near field to the saturated zone due to slow percolation rate and/or thick unsaturated zone. This will cause greater radionuclide decay in the unsaturated zone and so lower concentrations reaching the watertable.<br>• Physical barrier for disposal in the unsaturated zone – lower radionuclide concentrations in percolating water due to dispersion and diffusion.<br>• Physical barrier for disposal in the unsaturated and saturated zones – can isolate the waste from intrusion (human and animal) and geomorphological processes such as surface erosion.<br>• Chemical barrier for disposal in the unsaturated zone – can retard the migration of radionuclides from the near field to the saturated zone due to sorption of radionuclides. This will cause greater radionuclide decay in the unsaturated zone and so lower concentrations reaching the watertable. |
| Saturated zone | • Physical barrier for disposal in the unsaturated and saturated zones – can delay the migration of radionuclides to the geosphere-biosphere interface (assumed to be a water abstraction borehole for the GSA) due to slow travel times (in turn determined by hydraulic conductivity, hydraulic gradient and porosity of the saturated zone, and the distance to the geosphere-biosphere interface). This will cause greater radionuclide decay in the saturated zone and so lower concentrations reaching the abstraction borehole.<br>• Physical barrier for disposal in the unsaturated and saturated zones – lower radionuclide concentrations in groundwater due to dispersion and diffusion.<br>• Physical barrier for disposal in the saturated zone – can isolate the waste from intrusion (human and animal) and geomorphological processes such as surface erosion.<br>• Chemical barrier for disposal in the unsaturated and saturated zones – can retard the migration of radionuclides to the geosphere-biosphere interface (assumed to be a water abstraction borehole for the GSA) due to sorption of radionuclides. This will cause greater radionuclide decay in the unsaturated zone and so lower concentrations reaching the watertable.<br>• Dilution for disposal in the unsaturated and saturated zones – groundwater flow in the saturated zone will dilute the concentration of radionuclides leaving the near field/unsaturated zone by mixing and dispersion. In low flow groundwater systems dilution might also occur due to blending of contaminated groundwater with groundwater abstracted from uncontaminated horizons. |

Before specifying reference conditions for disposal in the unsaturated zone (Section 3.2.1) and saturated zone (Section 3.2.2), consideration needs to be given to a number of common issues.

- **Variability in the geosphere characteristics** – for the GSA, it is assumed that, consistent with the recommendations of the IAEA Specific Safety Guide for the disposal of radioactive waste in borehole facilities [8], there is an absence of geological complexity in the synthetic geosphere (for example alternating aquitards and confined aquifers). This does not mean that the geology in each reference geosphere and its hydrological and geochemical characteristics are homogeneous; there can be variation. However, it is assumed that, for any given geosphere, this variation can be adequately represented through the use of averaged hydrological and geochemical parameter values for the geosphere.

- **Nature of water flow** – reflecting the variation seen in reality, consideration is given to flow in both porous and fractured systems. In porous systems, different pore geometries and flow fields exist on microscopic scales but the existence of a representative elementary volume (REV) over which such microscopic variations can be averaged is assumed. In fractured systems, flow is considered to be confined to well-defined fractures or fracture zones. The intervening blocks are often considered to be impermeable or contain only static water in pore spaces.

- **Nature of the Geosphere-Biosphere Interface (GBI)** – a range of potential GBIs could be considered for the GSA (for example a terrestrial or marine water body and/or its associated sediment, and/or soil). The nature of GBI will affect the amount of dilution that occurs at the GBI. For the purpose of the GSA, it is assumed that the GBI is a borehole, which is used to abstract water to meet a demand of 266 $m^3$/y (see Section 3.3). This is considered to be a conservative assumption since dilution at this GBI is small compared with other potential GBIs, such as a river[9], and it allows a short distance to be specified between the disposal borehole and the GBI.

- **Geochemistry** – a range of geochemical conditions are considered. These are discussed in Appendix II.
- **Geological stability** – it is assumed that the disposal borehole is located in an area which is geologically stable and is believed to have no, or extremely limited, tectonic and seismic activity, and limited regional and local surface erosion and deposition which could disturb the disposal borehole (see Section 3.3).
- **Natural resources** – it is assumed that the disposal borehole is located in an area that has no natural resources requiring excavation by extensive surface excavation or underground mining. There are assumed to be no significant sources of geothermal heat or gas in the vicinity of the disposal borehole.

When considering the migration of radionuclides in water through the unsaturated and/or saturated zones, it is helpful to consider a number of inter-related parameters (see for example Ref. [26]).

- **Flux of water through the near field**. This influences the release rate of radionuclides from the near field into the geosphere. If the disposal zone is in the unsaturated zone, this is determined by the cross-sectional area of water flow through the near field and the percolation rate through the near field (which in turn depends on factors such as: the infiltration rate of rainwater into the unsaturated zone and near field; the hydraulic conductivity of the unsaturated zone and near field; and moisture content of the unsaturated zone and near field). If the disposal zone is in the saturated zone, it is determined by the cross-sectional area of groundwater flow through near field, plus the hydraulic gradient, hydraulic conductivity, and porosity of the saturated zone and near field.
- **Travel time of a conservative (non-sorbed) contaminant through the geosphere**, from its interface with the near field to its interface with the biosphere (the GBI). This, together with a radionuclide's half-life and sorption coefficient (see below), determines the amount of radioactive decay that occurs during transport through the geosphere, which in turn will influence the concentration of the radionuclide in geosphere water. In the unsaturated zone, the travel time is determined by the depth of the unsaturated zone beneath the disposal borehole and the percolation rate through the unsaturated zone. In the saturated zone, it is determined by the hydraulic gradient, hydraulic conductivity, porosity and distance to the GBI.
- **Distance to the GBI**. This will affect not only the geosphere travel time, but also the amount of dispersion and hence lowering in radionuclide concentrations in the geosphere.
- **Flux of water in the geosphere**, especially at the GBI. This influences the dilution of radionuclides released into the biosphere. If the disposal zone is in the unsaturated zone, dilution in the unsaturated zone is determined by: the cross-sectional area of the unsaturated zone through which the radionuclides are transported; and the percolation rate through the unsaturated zone (which in turn depends on factors such as: the infiltration rate of rainwater into the unsaturated zone; the hydraulic conductivity of the unsaturated zone; and moisture content of the unsaturated zone). In the saturated zone, it is determined by: the cross-sectional area of

---

[9] By comparison, a small stream with a cross-sectional area of 0.5 $m^2$ and a flow rate of 0.1 m $s^{-1}$ would have a discharge of more than 1.5E6 $m^3$ /y resulting in a dilution factor more than three orders of magnitude greater than the water abstraction borehole.

the saturated zone through which the radionuclides are transported; the hydraulic gradient; and the hydraulic conductivity.

- **Sorption coefficients of the radionuclides in the geosphere**, which determine the extent to which radionuclides are retarded within the geosphere, resulting in increased decay and lowering of concentrations in geosphere water. Sorption coefficients can vary according to the nature of the unconsolidated and consolidated materials that form the geosphere, and the geochemical conditions in the geosphere.

For the GSA, consideration is given to a range of synthetic geospheres with differing averaged values for the key parameters identified above. These are summarized in Tables 7 and 8, and discussed below for disposal in the unsaturated zone (Section 3.2.1) and for disposal in the saturated zone (Section 3.2.2). Alternative values for the parameters used are considered in the variant calculations presented in Section 6.2.

### 3.2.1. Disposal in the unsaturated zone

#### *3.2.1.1. Unsaturated zone characteristics*

For the case with a disposal zone in the unsaturated zone, an unsaturated zone of 10 m below the base of the disposal borehole is assumed, giving a total depth of unsaturated zone of 90 m (30 m closure zone, 50 m disposal zone and 10 m of unsaturated zone below the disposal borehole). Such depths to groundwater can be found in arid and semi-arid zones but are uncommon in humid zones. A reference percolation rate of 5E-2 m/y and an associated water-filled porosity of 5E-2 are assumed (these are considered to be values that are consistent with an unsaturated zone depth of 90 m, a total porosity of 1.5E-1 and degree of saturation of 3.3E-1), resulting in an unsaturated zone travel time of 10 years for a conservative (non-sorbed) contaminant from the base of the borehole to the watertable. Assuming that the flux is not limited by the engineered barriers of the near field[10], this results in a flux through the near field of about 3E-3 $m^3$/y.

The geochemical parameters for the water percolating into the borehole are based on water No. 1 presented in Appendix II. This is considered representative of an oxidising, meteoric water with a low pH. Selecting a low pH is conservative in that it will promote corrosion of the steel containers and the enhanced degradation of the cement grout.

#### *3.2.1.2. Saturated zone characteristics*

On reaching the saturated zone, it is assumed that the radionuclides migrate through the saturated geosphere to the water abstraction borehole. An illustrative travel distance of 100 m to the abstraction borehole is considered. Alternative distances are considered in the variant calculations in Section 6.2. Four different sets of reference travel times, groundwater fluxes and associated hydraulic parameter values are considered (see Table 7). These have been selected to represent saturated porous geospheres with high, medium and low flow rates and a fractured geosphere with a high flow rate in the fractures. These are considered to represent a realistic range of conditions that might be found in the field. For the medium and low flow geospheres, the rate of flow of contaminated water into the abstraction borehole is less than the demand and so it is assumed that the additional water required is abstracted from uncontaminated horizons that the abstraction borehole also intercepts.

Geochemical parameters for the porewater in the saturated zone are summarized in Table 8. For the high and medium flow systems, the parameter values are based on water No. 5 presented in Appendix II, which is considered to be representative of fresh groundwater with a relatively short residence time

---

[10] Account is taken of the effect of engineered barriers on water flux through the near field in the mathematical model presented in Appendix XI.

in the geosphere. For the low flow system, they are based on water No. 6 presented in Appendix II, which is representative of groundwater with a relatively long residence time.

### 3.2.2. Disposal in the saturated zone

For disposal in the saturated zone, explicit consideration does not need to be given to the unsaturated zone, other than recognizing its role in isolating waste from intrusion and providing recharge to the saturated zone. The characteristics of the saturated zone are generally the same as the saturated geosphere assumed for disposal in the unsaturated zone (see Section 3.2.1 and Tables 7 and 8). However, an allowance is made for the cross-sectional area of contaminated flow being greater since it is conservatively assumed that the water abstraction borehole intercepts the contaminated plume along the full length of the disposal zone (50 m).

## 3.3. BIOSPHERE

For a site specific assessment, site specific data relating to the biosphere can be collected and collated. However, for a site-generic assessment, a range of 'synthesised' biospheres could be considered or a single biosphere system could be developed applicable to a wide range of differing biosphere conditions. In order to keep the number of calculations to a manageable level, the approach of using a single biosphere has been adopted for the GSA. This reference biosphere assumes the use of contaminated water direct from the abstraction borehole for domestic (drinking) and agricultural purposes (watering of cattle and irrigation of green and root vegetables), resulting in a water abstraction rate of $2.66 \times 10^2$ $m^3/y$ (see Table 82 in Appendix XII). It is recognized that additional/alternative uses of the water could be envisaged and so these are considered in the variant calculations in Section 6.2. BIOMASS recommended that, when describing a biosphere system, it is important to consider: climate; surface water bodies; human activity; biota; near surface lithostratigraphy; topography; geographical extent; and location [27]. A brief description of each of these features is given below for the reference biosphere considered in the GSA.

TABLE 7. HYDROGEOLOGICAL PARAMETER VALUES FOR THE REFERENCE GEOSPHERES' SATURATED ZONE

| | Distance to abstraction borehole (m) | Hydraulic conductivity (m/y) | Hydraulic gradient (-) | Water-filled porosity (-) | Cross-sectional Area of contaminated plume ($m^2$) | Water flux in which contaminated plume is mixed ($m^3/y$)[f] | Travel time in saturated geosphere to abstraction borehole (y)[g] | Fraction of water demand supplied by contaminated water (-)[h] |
|---|---|---|---|---|---|---|---|---|
| *Disposal in unsaturated zone* | | | | | | | | |
| High flow rate system: porous system | 1E+2 | 1E+3 | 1E-2 | 1E-1 | 1E+0[b] | 1E+1 | 1E+0 | 3.76E-2 |
| High flow rate system: fractured system | 1E+2 | 1E+3 | 1E-2 | 1E-1[a] | 1E+0[c] | 1E+1 | 1E+0 | 3.76E-2 |
| Medium flow rate system | 1E+2 | 1E+1 | 1E-2 | 1E-1 | 1E+0[b] | 1E-1 | 1E+2 | 3.76E-4 |
| Low flow rate system | 1E+2 | 1E-2 | 1E-2 | 1E-2 | 1E+0[b] | 1E-4 | 1E+4 | 3.76E-7 |
| *Disposal in saturated zone* | | | | | | | | |
| High flow rate system: porous system | 1E+2 | 1E+3 | 1E-2 | 1E-1 | 5E+1[d] | 5E+2 | 1E+0 | 1.00E+0 |
| High flow rate system: fractured system | 1E+2 | 1E+3 | 1E-2 | 1E-1[a] | 5E+1[e] | 5E+2 | 1E+0 | 1.00E+0 |
| Medium flow rate system | 1E+2 | 1E+1 | 1E-2 | 1E-1 | 5E+1[d] | 5E+0 | 1E+2 | 1.88E-2 |
| Low flow rate system | 1E+2 | 1E-2 | 1E-2 | 1E-2 | 5E+1[d] | 5E-3 | 1E+4 | 1.88E-5 |

**Notes:**

[a] Water-filled porosity in fracture in saturated zone (matrix porosity is given in Table 78).

[b] For disposal in the unsaturated zone, it is assumed that the radionuclides enter the saturated zone and then are horizontally and vertically dispersed. The degree of horizontal and vertical dispersion is assumed to be 1% of the distance to the abstraction borehole, consistent with Ref. [28], resulting in a plume cross-sectional area of 1 $m^2$.

[c] It is assumed that there is a fracture zone 0.1 m deep within the top 1 m of the saturated zone along which the contaminated water travels. The degree of transverse dispersion is assumed to be 10% of the distance to the abstraction borehole (as opposed to the 1% value used for the porous system; reflecting the more open nature of the fracture), resulting in a plume cross-sectional area of 1 $m^2$.

[d] For disposal in the saturated zone, it is assumed that the radionuclides enter the saturated zone over the entire length of the disposal zone (50 m) and then are dispersed transverse to the direction of flow. The degree of transverse dispersion is assumed to be 1% of the distance to the abstraction borehole, consistent with Ref. [29], resulting in a plume cross-sectional area of 50 $m^2$.

[e] It is assumed that 10% of the disposal zone length (i.e. 5 m) is intersected by fractures along which contaminated groundwater flows from the disposal borehole to the abstraction borehole. The degree of transverse dispersion is assumed to be 10% of the distance to the abstraction borehole (as opposed to the 1% value used for the porous system; reflecting the more open nature of the fracture), resulting in a plume cross-sectional area of 50 $m^2$.

[f] Derived by multiplying the cross-sectional area of the plume by the hydraulic gradient and hydraulic conductivity.

[g] Travel time for a non-sorbed radionuclide. Derived by multiplying the distance to the abstraction borehole by the water-filled porosity and dividing by product of the hydraulic gradient and hydraulic conductivity.

[h] The minimum value of unity and the result of dividing the water flux, in which the contaminated plume is mixed, by the assumed abstraction rate (266 $m^3/y$).

TABLE 8. GEOCHEMICAL PARAMETERS FOR POREWATER FROM UNSATURATED AND SATURATED ZONES FOR THE REFERENCE GEOSPHERES

| Determinand | Units | Reference water for unsaturated system[a] | Reference water for high and medium flow saturated systems[b] | Reference water for low flow saturated systems[c] |
|---|---|---|---|---|
| pH | pH | 4.1 | 8.46 | 7.95 |
| Eh | mV | 996 | -281 | -303 |
| Dissolved $O_2$ | mg $l^{-1}$ | 12.0 | - | - |
| Na | mg $l^{-1}$ | 0.11 | 81.61 | 14185 |
| K | mg $l^{-1}$ | 0.08 | 2.40 | 414.5 |
| Mg | mg $l^{-1}$ | 0.05 | 1.22 | 6.05 |
| Ca | mg $l^{-1}$ | 0.16 | 4.37 | 13.39 |
| Si | mg $l^{-1}$ | - | 9.52 | 8.29 |
| Al | mg $l^{-1}$ | - | 0.01 | 0.0001 |
| Fe | mg $l^{-1}$ | - | 0.0001 | 0.0022 |
| Mn | mg $l^{-1}$ | - | - | - |
| Cl | mg $l^{-1}$ | 0.53 | 0.52 | 20917 |
| $SO_4$ | mg $l^{-1}$ | 2.88 | 10.66 | 2891 |
| $H_2S$ | mg $l^{-1}$ | - | - | - |
| N | mg $l^{-1}$ | 0.34 | 0.32 | 72.13 |
| TIC | mg $l^{-1}$ | 0.23 | 42.52 | 415.58 |

**Notes:** [a] Values for water No. 1 presented in Appendix II.

[b] Values for water No. 5 presented in Appendix II.

[c] Values for water No. 6 presented in Appendix II.

- **Climate** – it is assumed that the climate is consistent with the assumption of self-sufficient agriculture land use (see below) and with the assumed geosphere characteristics (see Section 3.2). It is only in extreme climates (intense heat or cold) that self-sufficient agriculture cannot be practiced for at least part of the year and that the geosphere characteristics are inconsistent with those assumed in Section 3.2 (e.g. permafrost, glaciation, high salinity). Therefore, it is considered that the generic biosphere is applicable to the majority of climates.
- **Surface water bodies** – it is assumed that there are no significant surface water bodies in the vicinity, consistent with the use of the abstraction borehole as a source of water.
- **Human activity** – it is assumed that the abstraction borehole is drilled at the end of the institutional control period (assumed to be 30 years – see Section 2.7) and that the abstracted water is used for domestic (drinking) and agricultural purposes (watering of cattle and irrigation of green and root vegetables). It is assumed that the land is used for self-sufficient agriculture. In the variant calculations in Section 6.2, consideration is given to other uses of the contaminated water and land. It is also assumed that a dwelling can be constructed above the disposal borehole at the end of the institutional control period. Consistent with the recommendations of ICRP [12], no consideration is given to the development of new societal structures and technologies.
- **Biota** – it is assumed that cattle are raised and root and green vegetables grown, consistent with the assumption of self-sufficient agriculture. Alternative livestock and crops are considered in the variant calculations in Section 6.2.

- **Near surface lithostratigraphy** – it is assumed that there is a soil cover that is capable of supporting the growth of root and green vegetables.
- **Topography** – it is assumed that the topography is 'subdued'[11] and so is not subjected to significant erosive or depositional processes that might affect the ability of the disposal system to isolate the waste. This assumption is also consistent with the assumption that the hydraulic gradient in the saturated geosphere is relatively shallow (1 in 100) (see Table 7) and that the biosphere is used for self-sufficient agriculture. A surface erosion rate of $3 \times 10^{-4}$ m/y is assumed [16], consistent with the subdued topography of the site, which would result in the disposal zone being uncovered by erosion after 100 000 years (assuming a disposal zone depth of 30 m – see Section 3.1.2). The effect of alternative assumptions for surface erosion rates is considered in the variant calculations in Section 6.2.
- **Geographical extent** – it is assumed that the area of interest is limited to the area in the immediate vicinity of the disposal and water abstraction boreholes, and the land used for raising crops and animals.
- **Location** – it is assumed that the borehole disposal facility is not located in an area of significant geomorphological activity (including flooding). Furthermore, it is assumed that the site is located in a position that will not be susceptible to coastal processes and possible future sea level rises.

## 3.4. DISPOSAL SYSTEMS OF INTEREST

The reference near field, geosphere and biosphere characteristics for the GSA have been described in Sections 3.1, 3.2 and 3.3, respectively. Further relevant information is provided in Appendix X for use in the mathematical models used to represent each component of the disposal system in the GSA calculations that are identified in Section 5. Note that information and calculations for variant characteristics for the near field, geosphere and biosphere are presented in Section 6.2.

For certain near field and geosphere characteristics, more than one reference option is considered in order to allow the results of the GSA to be applicable to a range of conditions. The various options are:

- Disposal in either the unsaturated or saturated geosphere;
- The assumption of either low, medium or high flow rates in the saturated geosphere; and
- The assumption of either porous or fracture flow in the saturated (and unsaturated) geosphere.

Therefore eight potential disposal systems can be identified (Table 9).

---

[11] Used to imply that the land immediately in the vicinity of the disposal borehole is relatively flat, although there are some slopes (it could also be described as gently undulating or rolling). Thus the land does not have steep slopes nor, on the other hand, is it totally flat. The term is taken from the BIOMASS Theme 1 landform category described in Ref.[13] (the other categories are 'plain' and 'marked slope').

TABLE 9. DIFFERING CHARACTERISTICS OF DISPOSAL SYSTEMS CONSIDERED

| Near field | Saturated geosphere | |
|---|---|---|
| Disposal zone | Flow rate | Flow type |
| Unsaturated | High | Porous |
| | | Fractured |
| | Medium | Porous |
| | Low | Porous |
| Unsaturated | High | Porous |
| | | Fractured |
| | Medium | Porous |
| | Low | Porous |

# 4. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

As used in this TECDOC, a scenario is a hypothetical sequence of processes and events, and is one of a set devised for the purpose of illustrating the range of future behaviours and states of a disposal system, for the purposes of evaluating a safety case [12]. Scenarios handle future uncertainties associated with the processes and events by describing alternative future evolutions of the disposal system and allow for a mixture of quantitative analysis and qualitative judgements. The purpose of scenario development is not to try to predict the future; rather, it is to use scientifically informed expert judgement to guide the development of descriptions of possible future evolution of the disposal system to assist in making safety related decisions.

## 4.1. APPROACH

The approach to scenario development and justification used for the GSA is shown in Fig. 5 and described in Appendix III. Using information relating to the assessment context (Section 2), the system description (Section 3) and the status of scenario-generating external factors[12], a 'Design Scenario' was identified. The scenario represents how the disposal system can be expected to evolve assuming the boreholes design functions as planned and it provides a benchmark against which alternative scenarios can be compared.

Alternative scenarios were then identified by considering possible alternative conditions for the scenario-generating external factors, consistent with the assessment context and system description (Table 10). The following four alternative scenarios were identified.

- 'The Defect Scenario' – it is assumed that not all components of the near field perform as envisaged in the Design Scenario due to either defective manufacturing of waste packages (e.g. welding defects), or defective implementation in the borehole (e.g. improper emplacement of cement grout). This results in the earlier release of radionuclides from the near field.

---

[12] Sub-divided into repository factors, geological processes and events, climate processes and events, and future human actions and behaviours.

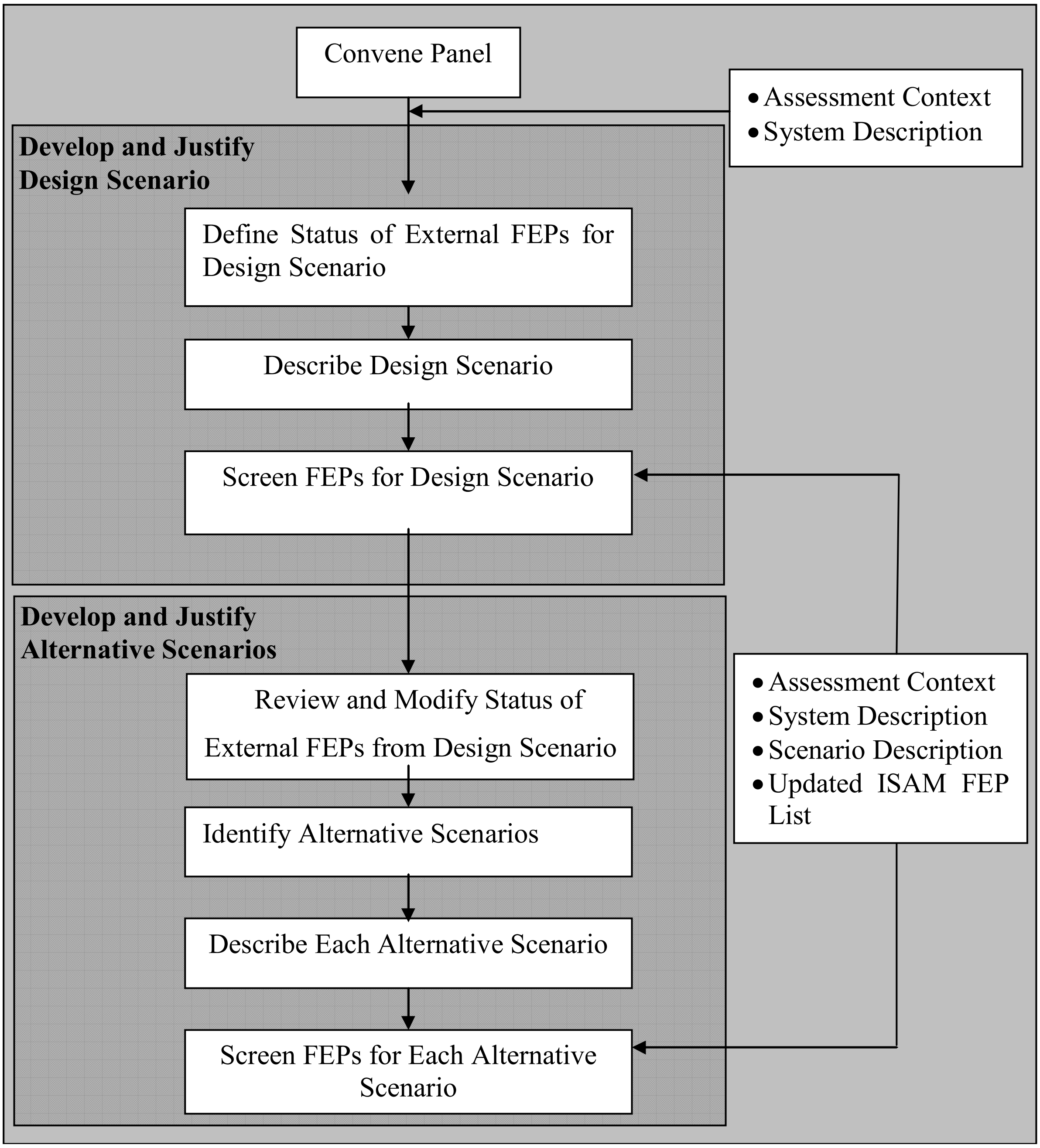


*FIG. 5. Scenario development and justification approach used.*

TABLE 10. STATUS OF EXTERNAL FACTORS FOR ALTERNATIVE SCENARIOS

| External factors | Alternative scenarios | | | |
|---|---|---|---|---|
| | Defect | Unexpected geological characteristics | Changing environmental conditions | Borehole disturbance |
| Repository factors | *Not all near field components perform as envisaged in the Design Scenario* | Borehole constructed, operated and closed as designed and planned | Borehole constructed, operated and closed as designed and planned | Borehole constructed, operated and closed as designed and planned |
| Geological processes and events | No unexpected features, processes or events | *Unexpected features, processes or events* | No unexpected features, processes or events | No unexpected features, processes or events |
| Climate processes and events | Constant climate conditions with continuous, gradual surface erosion | Constant climate conditions with continuous, gradual surface erosion | *Changing climate conditions with more rapid surface erosion* | Constant climate conditions with continuous, gradual surface erosion |
| Future human actions and behaviours | Domestic and agricultural use of water from an abstraction borehole sunk at the end of the institutional control period. Construction of a dwelling above the disposal borehole at the end of the institutional control period | Domestic and agricultural use of water from an abstraction borehole sunk at the end of the institutional control period. Construction of a dwelling above the disposal borehole at the end of the institutional control period | Domestic and agricultural use of water from an abstraction borehole sunk at the end of the institutional control period. Construction of a dwelling above the disposal borehole at the end of the institutional control period | *Disturbance of the disposal borehole by human intrusion at the end of the institutional control period. Domestic and agricultural use of water from an abstraction borehole sunk immediately adjacent to the disturbed disposal borehole. Construction of a dwelling above the disturbed disposal borehole.* |

**Note:** External factors in italic bold differ from those assumed for the Design Scenario.

- 'The Unexpected Geological Characteristics Scenario' – it is assumed that the actual performance of the geosphere from a safety perspective is worse than the expected performance (e.g. the geosphere is subjected to an unexpected seismic event resulting in the reactivation of high permeability fractures and modification of associated sorption properties).
- 'The Changing Environmental Conditions Scenario' – it is assumed that the disposal system is affected by climate change resulting in modifications to certain geosphere characteristics (e.g. groundwater recharge rates) and biosphere characteristics (e.g. water demand, surface erosion rates).
- 'The Borehole Disturbance Scenario' – it is assumed that drilling of a water abstraction borehole immediately adjacent to the disposal borehole results in the disturbance of the disposal borehole and the earlier release of radionuclides from the near field and subsequent exposure of humans to radionuclides (e.g. due to the use of contaminated water from the abstraction borehole).

On the basis of information provided in the assessment context and system description, and in light of the assumed status of the External Features, Events and Processes (External FEPs, or EFEPs), each of the above basic scenario descriptions is developed further in the following sub-sections.

## 4.2. DESIGN SCENARIO

### 4.2.1. Description

The first stage in the further development of the Design Scenario description is to consider the temporal evolution of the disposal system (i.e. the near field, geosphere and biosphere). Each component of the disposal system is considered in turn.

The near field has been sub-divided into a series of components based on the system description (Table 4) and the temporal evolution of each component considered. The temporal evolution of each near field component is documented in Table 11 together with the associated assumptions.

For the geosphere component of the disposal system, it is assumed that there is no evolution over the assessment period. Geologically, this means that the site is located in a geologically stable area with no or extremely limited tectonic and seismic activity (see Section 3.2).

For the biosphere component of the disposal system, it is recognized that certain changes might occur due, in the short term, to the effects of global warming and, in the longer term, due to global glacial/inter-glacial cycling. However, it is considered that such changes will not have significant impacts on the water uses considered in the GSA since they are applicable to a wide range of climatic conditions (see Section 3.3). Consistent with the recommendations of ICRP [14], no consideration is given to the development of new societal structures and technologies. Furthermore, it is assumed that the borehole disposal facility is not located in an area of significant geomorphological activity (including flooding), although a constant rate of surface erosion is assumed (Section 3.3).

Consistent with the above discussion and the information in the assessment context and system description, the following description of the Design Scenario can be developed.

#### *4.2.1.1. Construction, operation and closure periods*

The current assessment only assesses post-closure safety. This section is included to clarify the status of the facility following construction, operation and closure. It is assumed that the borehole is constructed, operated and closed as designed and planned (see Section 3.1.2) with appropriate quality assurance and no accidents or unplanned events.

During operations, measures are assumed to be taken to ensure that the waste packages are emplaced in a dry environment, even if the disposal zone is below the watertable and that shrinkage cracks in the backfill are minimized. The whole site area is controlled to prevent animal and unauthorized human access. All site investigation activities are managed with the intention to ensure that there are no adverse effects on post-closure safety.

#### *4.2.1.2. Institutional control period*

During the institutional control period, the emphasis is on passive rather than active control measures. However, a limited level of environmental monitoring may be performed for the purpose of public assurance. All monitoring activities are managed with the intention to ensure that there are no adverse effects on post-closure performance.

At closure, it is assumed that no markers, which might encourage deliberate human intrusion, are fixed at the site to reveal the location of a radioactive waste disposal facility. However, a detailed record of the disposal site as well as the disposal facility and its content is available at the local authority. This means that during the institutional control period certain land use controls are enforced. These land use controls are related to the erection of buildings at the site and drilling of boreholes. After the institutional control period (assumed to last 30 years for the Design Scenario – see Table 2), all societal memory of the site is assumed to be lost.

Following construction, it is assumed that moisture starts to enter the borehole from above and/or below and some corrosion of the stainless steel disposal containers begins. Nevertheless, the containers remain intact and ensure that water does not come into contact with the source. They also ensure that there are no releases of gases for a period of at least 30 years.

TABLE 11. TEMPORAL EVOLUTION OF THE NEAR FIELD COMPONENTS FOR THE DESIGN SCENARIO

| Near field component | Temporal evolution |
|---|---|
| Source container | In many cases the source container will still be intact at the time of disposal, due to proper quality control and quality assurance procedures during the conditioning of the sources. However, this cannot be guaranteed, nor can the longevity of the source container be guaranteed. Consequently, it is assumed that the source container will have failed prior to disposal. It is assumed that the radionuclides in the source container are available for potential release only once the capsule that surrounds the source container is breached. |
| Capsule | A number of different types of corrosion can occur including general and localized (e.g. pitting and crevice). These mechanisms can be enhanced by high chloride concentrations in water and oxidising conditions. More rapid breaching of the capsule can be expected to result from localized corrosion in unsaturated conditons. Corrosion of capsule is assumed to start only once the disposal container and the associated containment barrier has been breached by water (see below). |
| Containment barrier | Physical and chemical degradation of the cement grout will start only once the disposal container has been breached and the cement grout is contacted by water. Initially the hydraulic conductivity might decrease due to carbonation, however with time it will increase due to the physical (e.g. cracking) and chemical (e.g. calcium leaching and sulphate attack) degradation of the cement grout due to contact with flowing water. Chemical degradation generally results in a decrease in the cement grout's sorption capacity. |
| Disposal container | See discussion concerning capsule for corrosion mechanisms. Corrosion of disposal container is assumed to start before the corrosion of the capsule. |
| Disposal zone backfill | It is assumed that any shrinkage or jointing cracks that might form in the cement grout backfill do not act as significant water flow or radionuclide migration pathways. Initially the hydraulic conductivity might decrease due to carbonation, however with time it will increase due to the physical (e.g. cracking) and chemical (e.g. calcium leaching and sulphate attack) degradation of the cement grout due to contact with flowing water, especially once the borehole casing starts to fail (see below). Chemical degradation generally results in a decrease in the sorption capacity of the cement grout. |
| Disposal zone plug | Assumed to behave in the same manner as the disposal zone backfill. |
| Casing | Processes such as embrittlement, cracking and biodegradation are assumed to result in the failure of the HDPE casing. References [30], [31] suggest HDPE lifetimes in the region 100 to 400 years. However, there is considerable uncertainty over lifetimes and it is therefore conservatively assumed that the casing fails immediately following closure. |
| Disturbed zone backfill | Assumed to behave in the same manner as the disposal zone backfill. |
| Closure zone backfill | The closure zone backfill will be subjected to surface erosion at an assumed rate of $3 \times 10^{-4}$ m/y. The characteristics of the native soil/crushed rock used to fill the first 5 m of the closure zone from the ground surface is assumed to remain constant. The cement grout used to fill the remainder of the closure zone is assumed to behave in the same manner as in the disposal zone. |

#### 4.2.1.3. *Post-institutional control period*

Due to the corrosion of the stainless steel disposal containers and the subsequent corrosion of the capsules, water eventually contacts the source container, which is assumed to have failed prior to disposal. The radionuclides in the source could be in a number of different physical and chemical forms (Table 12) and so release of radionuclides could occur in the liquid or gas phase.

For radionuclides released in the liquid phase, transport from the source through the various components of the near field can occur by advection, dispersion and diffusion. The relative importance of these processes depends upon the hydrogeological conditions at the site. Migration through the near field is limited by decay/in-growth and sorption of the radionuclides onto the cement grout in the near field. On leaving the near field, the radionuclides migrate through the geosphere by advection, dispersion and diffusion and are subject to decay/in-growth and retardation due to sorption onto the rocks. Flow can be through pores or fractures and diffusion can occur into stagnant water in the rock matrix depending upon the characteristics of the geosphere (Section 3.2). Again the relative importance of these geosphere processes depends on the hydrogeological conditions at the site. The groundwater is assumed to be abstracted from the geosphere via an abstraction borehole that is drilled at the start of the post-institutional control period. The borehole is assumed to be 100 m down the hydraulic gradient from the disposal borehole (Section 3.2) and used for domestic purposes (drinking) and agricultural purposes (watering of cows and irrigation of root and green vegetables) (Section 3.3). The water is not treated or stored before use. The main features of the Design Scenario for radionuclides released in the liquid phase into the unsaturated and saturated disposal zones are summarized in Figs 6 and 7, respectively.

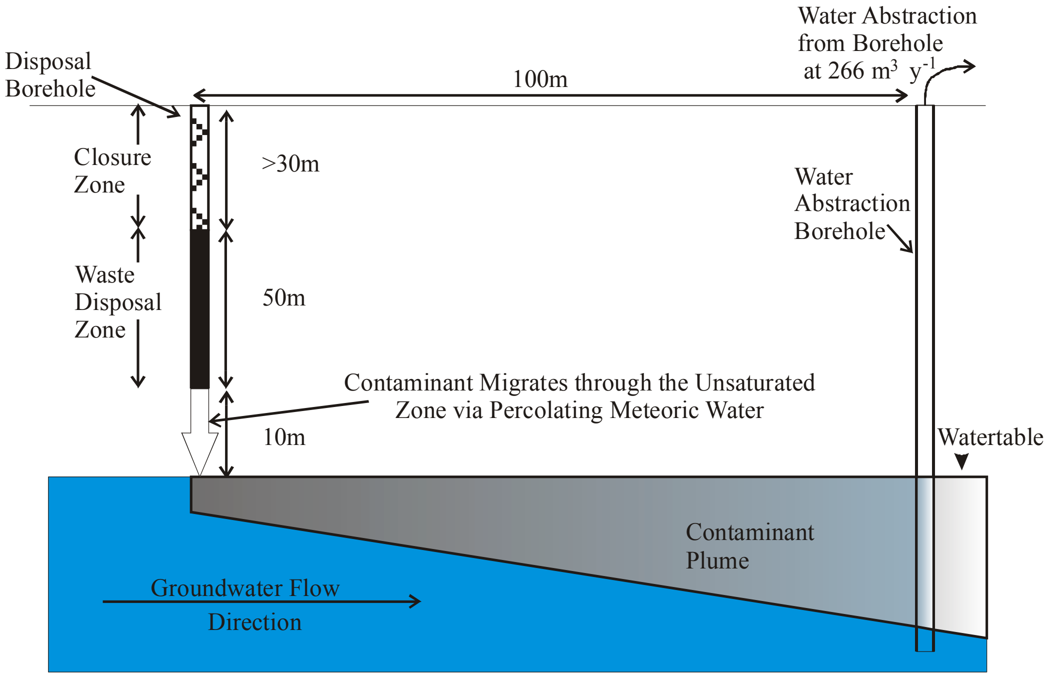


*FIG. 6. Design scenario: liquid releases for unsaturated disposal zone.*

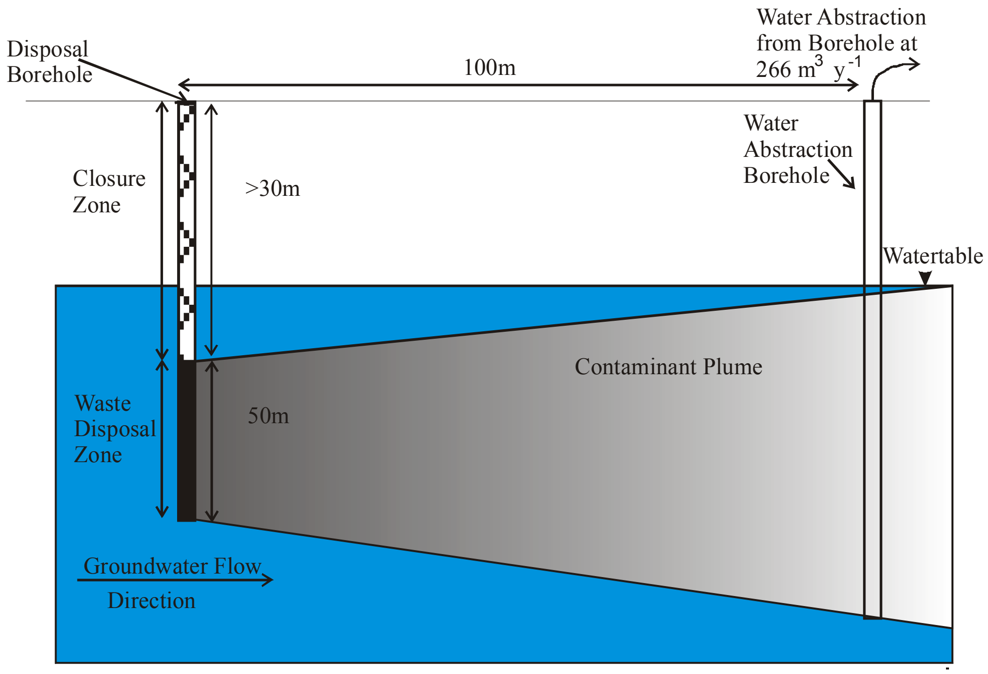


*FIG. 7. Design scenario: liquid releases for saturated disposal zone.*

TABLE 12. PHYSICAL AND CHEMICAL FORMS OF RADIONUCLIDES IN DISUSED SOURCES

| Radionuclide | Physical/chemical form |
|---|---|
| H-3 | Often tritium gas or liquid as $H_2O$ |
| Co-60 | Metallic form in thin discs or small cylindrical pellets. Very low solubility. |
| Ni-63 | Solid, electrical deposition on metal foil. |
| Kr-85 | Gas. |
| Sr-90 | Oxide or titanate form. |
| | Often silver plated for medical applications. |
| | Ceramic or glass bead or rolled silver foil for other applications. |
| Cs-137 | Only used as a salt (often caesium chloride). |
| | Sometimes ceramic form for weak sources (very low solubility). |
| Pb-210 | Solid, mainly carbonate and sulphate. |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble. |
| Pu-238 (+ Rn gas)<br>Pu-239 | Used in RTGs, and for neutron generators and calibration. Sources typically have Pu oxide in ceramic. |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used. |
| | For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form. |
| | Sometimes in sintered form. |

The failure of the containers and capsules allows radioactive gases to be released, which are assumed to migrate up the borehole through the closure zone into the biosphere. It is conservatively assumed that a dwelling is constructed on top of the borehole (without intruding into the disposal zone of the borehole) at the start of the post-institutional control period, resulting in the gases migrating directly into the dwelling and being inhaled by the occupants. The main features of the Design Scenario for radionuclides released in the gas phase into the unsaturated and saturated disposal zones are summarized in Figs 8 and 9, respectively.

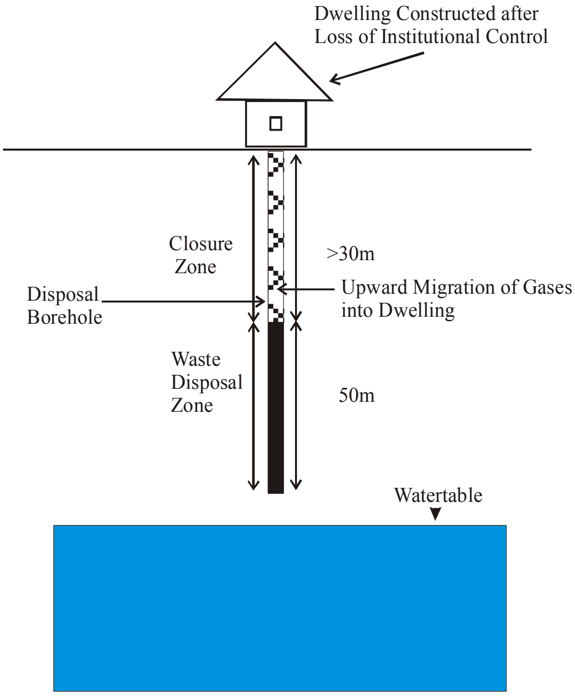


*FIG. 8. Design scenario: gas releases for unsaturated disposal zone.*

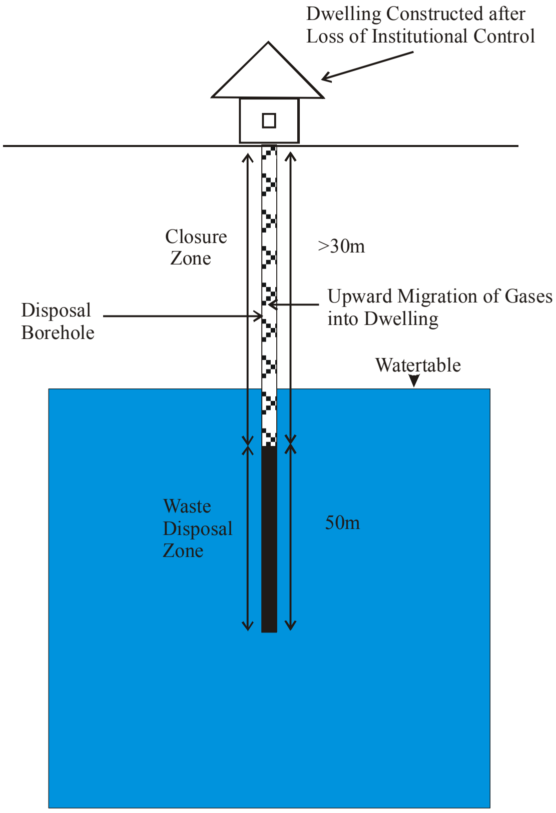


*FIG. 9. Design scenario: gas releases for saturated disposal zone.*

The combination of the assumed surface erosion rate ($3 \times 10^{-4}$ m/y – see Section 3.3) and the depth of the disposal zone from the ground surface (30 m – see Section 3.1.2) results in the waste being uncovered after 100 000 years. The main features of the Design Scenario for radionuclides released in the solid phase are summarized in Fig. 10.

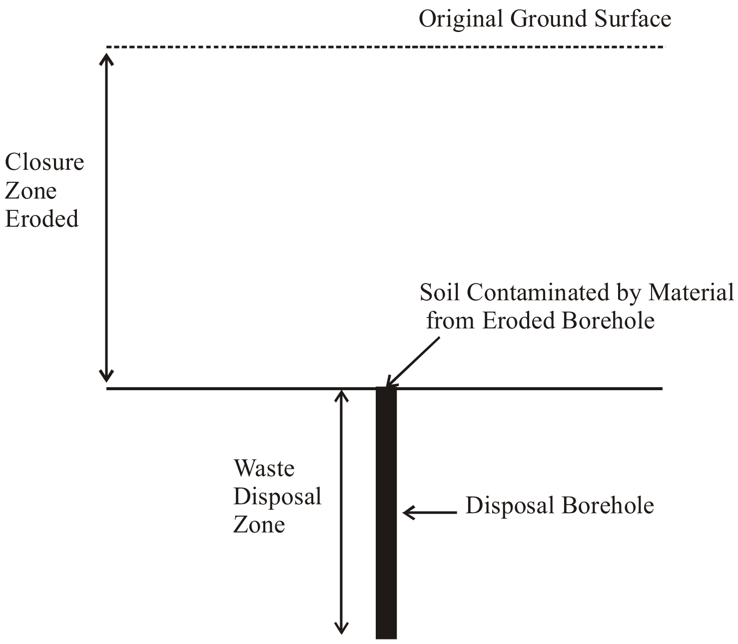


*FIG. 10. Design scenario: solid releases.*

### 4.2.2. FEP Screening

As a check to ensure that all potentially relevant Features, Events and Processes (FEPs) have been considered in the scenario, a list of potentially relevant FEPs has been selected and screened for the scenario, on the basis of information provided in the assessment context, system description and the scenario description. A FEPs list based on that developed in the ISAM programme [12] and subsequently updated has been used. The screened FEP list for the Design Scenario is presented in Appendix IV. Text is provided to explain why each FEP has been included (indicated by a 'Yes') or excluded (indicated by a 'No') from consideration in the Design Scenario based on information from the assessment context, system description and/or scenario description.

Since the near field (i.e. waste, waste form and engineered features) is a significant component of the borehole disposal system, the relevant FEPs identified in the FEP list (i.e. FEP 2.1.1 to 2.1.5) have been further broken down into 53 FEPs. These are presented and screened in Appendix V.

## 4.3. DEFECT SCENARIO

### 4.3.1. Description

The scenario assumes that a properly qualified team applies appropriate quality assurance and quality control (QA/QC) to the construction, operation and closure activities. For example, radiographic and other post-weld inspection procedures are expected to be part of the waste capsule and container fabrication process. This assumption of appropriate QA/QC limits the extent of the defects that might arise. However, as in any engineering system, some defects may arise despite best efforts to eliminate them. Furthermore, maintaining quality during field welding, as is envisaged for the borehole disposal concept, is generally more challenging than during shop welding.

Therefore the scenario assumes that not all components of the near field perform as envisaged in the Design Scenario, resulting in the earlier release of radionuclides from the near field.

A range of possible defects involving one or more of the near field barriers (i.e. capsule, containment barrier, disposal container, disposal and disturbed zone backfill and casing) can be identified. These are summarized and screened in Table 13. Four Defect Scenario variants are identified:

- D1: all welds are satifactory due to QA/QC except for the closure weld in one 316 L **disposal container**. All other near field barriers as per Design Scenario.
- D2: All welds are satifactory due to QA/QC except for the closure weld in one 304 **waste capsule**. All other near field barriers as per Design Scenario.
- D3: degraded/incomplete **disposal/disturbed zone cement grout**. All other near field barriers as per Design Scenario.
- D4: all welds are satifactory due to QA/QC except for the closure weld in one 316 L **disposal container** and one 304 **waste capsule**. The faulty capsule is in the faulty container. All other near field barriers as per Design Scenario.

### 4.3.2. FEP screening

The screened FEP list for the Defect Scenario is presented in Appendix VI. Text is provided to explain why each FEP has been included (indicated by a ‘Yes’) or excluded (indicated by a ‘No’) from consideration in the Defect Scenario based on information from the assessment context, system description and/or scenario description. In addition the detailed near field FEPs are presented and screened in Appendix V.

TABLE 13. POSSIBLE DEFECTS CONSIDERED

| Description | Considered in defect scenario calculations (variant number) | Justification |
|---|---|---|
| All welds okay due to QA/QC except for the closure weld in one 316 L **disposal container**.<br>All other near field barriers as per Design Scenario. | Yes (D1) | Cannot be ruled out.<br>For the mass production of welded structures under strict QA/QC procedures, the probability of an individual undetected, through-wall defect is of the order of $10^{-3}$ to $10^{-4}$ [32]. Because of the potential for more challenging conditions for welding and inspecting the disposal container, the higher end of this range ($10^{-3}$) is assumed for the GSA. The probability that the weld on 1 of the 50 disposal containers in the borehole contains a defect can be estimated based on a binomial distribution, and is found to be 0.05 for an individual probability of $10^{-3}$. The probability that 2 out of the 50 disposal containers in a borehole will contain defects is 0.0012 and is considered to be too small to be of concern here. |
| All welds okay due to QA/QC except for the closure weld in one 304 **waste capsule**.<br>All other near field barriers as per Design Scenario. | Yes (D2) | Feasible, although considered to be lower consequence than D1. A similar probability for an individual defect (i.e. $10^{-3}$) is assumed, and for the probability that only 1 out of the 50 waste capsules will contain a defect. |
| Missing/degraded/incomplete **containment barrier cement grout**.<br>All other near field barriers as per Design Scenario. | No, but missing cement grout is covered by a 'What-if' calculation presented separately from the Defect Scenario results | It is considered that the absence of cement grout would be noted due to the reduced weight of the container and the rattling of the capsule in the container (so multiple incompetence would be required for this case to arise).<br>Degraded/incomplete grout is feasible but considered to be low consequence in comparison to D3. |
| Missing/degraded/incomplete **disposal/disturbed zone cement grout**.<br>All other near field barriers as per Design Scenario. | Yes (D3) | Cannot be ruled out. Probability assumed to be c. 1%.<br>Consider more rapid chemical and physical degradation of cement grout than for Design Scenario.<br>Case of missing cement grout is covered under 'What-if' calculation presented separately from the Defect Scenario results. |
| Missing **casing**.<br>All other near field barriers as per Design Scenario. | No | No credit is taken for the casing in the Design Scenario. |
| **All engineered barriers** are missing. | No, but to be covered by 'What-if' calculations presented separately from the Defect Scenario results | Very low probability. |
| All welds okay due to QA/QC except for the closure weld in one 316 L **disposal container** and one 304 **waste capsule**. The faulty capsule is in the faulty container.<br>All other near field barriers as per Design Scenario. | Yes (D4) | Based on probabilities of $10^{-3}$ for individual weld defects and of 0.05 that 1 out of the 50 disposal containers and waste capsules contain a defect, the probability that the defected waste capsule is inside the defected disposal container is $0.05 \times 0.05 \div 50 = 5 \times 10^{-5}$. Although of low probability, the consequences of this scenario could be high (since there could be immediate release from the waste package) and warrants analysis.<br>This is considered to be the most likely two-barrier failure scenario. |
| All welds okay due to QA/QC except for the closure weld in one 316 L **disposal container** and degraded/incomplete **disposal/disturbed zone cement grout**.<br>All other near field barriers as per Design Scenario. | No, but covered by 'What-if' calculations presented separately from the Defect Scenario results | Considered to be low probability since it requires two independent failure events. |

## 4.4. UNEXPECTED GEOLOGICAL CHARACTERISTICS SCENARIO

This scenario assumes that the actual performance of the geosphere from a safety perspective is worse than its expected performance, resulting in the more rapid transport of radionuclides through the geosphere. This could be due to a number of factors such as: higher hydraulic conductivities than anticipated; lower geosphere sorption coefficients than anticipated; the presence of undetected high permeability zone(s); and the reactivation of high permeability zone(s) due, for example, to unexpected seismic activity.

It is not necessary to develop a separate scenario, as the range of geosphere characteristics (considered in Section 3.2) combined with the additional geosphere parameter sensitivity analysis (presented in Section 6.2) bound the consequences of this scenario. For example, Table 7 shows that a four order of magnitude range of geosphere travel times is considered. Results from a previous GSA, that did consider a seismic event scenario [32], further support the screening out of the scenario.

## 4.5. CHANGING ENVIRONMENTAL CONDITIONS SCENARIO

This scenario assumes that the disposal system is affected by climate changes caused by the effects of global warming in the short term, and global glacial/inter-glacial cycling in the longer term. These changes will result in modifications to certain geosphere characteristics (e.g. groundwater recharge rates) and biosphere characteristics (e.g. water demand, surface erosion rates).

It is not necessary to develop a separate scenario, as the range of geosphere characteristics (considered in Section 3.2) combined with the additional geosphere and biosphere parameter sensitivity analysis (presented in Section 6.2) bound the consequences of this scenario. Furthermore, such changes will not have significant impacts on the water uses considered in the GSA since they are applicable to a wide range of differing climatic conditions (see Section 3.3). Results from a previous GSA, that did consider an environmental change scenario [32], further support the screening out of this scenario.

## 4.6. BOREHOLE DISTURBANCE SCENARIO

The impact of deliberate human intrusion is considered to be beyond the scope of the GSA (see Section 1.3).

The depth of the disposal zone (at least 30 m from the ground surface), the small footprint of the disposal borehole, and its location in an area that has no natural resources requiring excavation by extensive surface excavation or underground mining (Section 3.2), all mean that the likelihood of inadvertent human intrusion directly affecting the disposal borehole is extremely low. Even if the site were to be developed, given the disposal borehole's narrow cross-sectional area (about 5E-2 $m^2$) and a site investigation borehole density of 1 per 1000 $m^2$ [33], the likelihood of an investigation borehole being within the footprint of the disposal borehole is around 1 in 20 000. Furthermore, even if the investigation borehole were to be within the footprint of the disposal borehole, the various components of the near field, such as the steel of the disposal container and the capsule and the anti-intrusion barrier above the disposal zone (see Section 3.1.2), could be expected to deter direct intrusion into the disposal zone. Due to these reasons, further consideration is not given to the borehole disturbance scenario.

# 5. FORMULATION AND IMPLEMENTATION OF MODELS

## 5.1.APPROACH

The model formulation and implementation process is shown in Fig. 11. Information from the assessment context, system description and scenario development steps of the safety assessment approach can be used to help generate conceptual models of the disposal system for the scenarios to be assessed (i.e. the Design and Defect Scenarios). These conceptual models and their associated processes are represented in mathematical models that are then implemented in computer codes. Throughout this process, data are used to help develop the conceptual and mathematical models and as input to the computer codes.

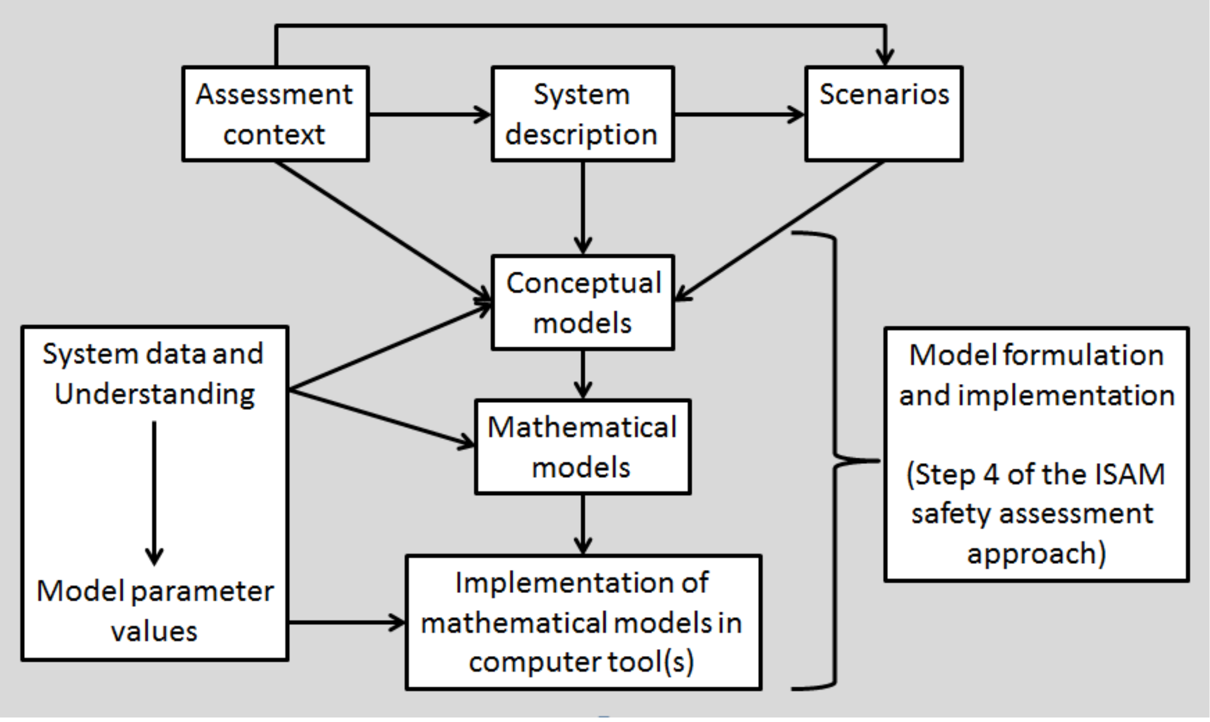


*FIG. 11. Model formulation and implementation process used.*

## 5.2.CONCEPTUAL MODELS

The Interaction Matrix approach has been used to help identify the main components of the disposal system and the processes that result in the release and migration of radionuclides through the system (Appendix VII). The conceptual model for each of the system's main components (near field, geosphere and biosphere) is summarized below.

### 5.2.1. Near field

The near field is comprised of a series of engineered barriers. Working from the outside inwards, these comprise (see Fig. 3):

- The disturbed zone cement grout backfill;
- The hdpe casing;
- The disposal zone cement grout backfill;
- The stainless steel disposal container;

- The cement grout containment barrier inside the disposal container;
- The stainless steel capsule; and
- The source container.

The HDPE casing and source container are assumed to have failed by the time of closure of the borehole (Table 11). Therefore, the migration of radionuclides from the near field is controlled by the degradation of the cement grout and stainless steel barriers and the release of radionuclides from the source into the borehole. The models for cement grout and stainless steel degradation adopted for the GSA are described in detail in Appendices VIII and IX, respectively, and summarized below. The release and transport models are also presented below. Further information concerning the role of specific near field FEPs is provided in Appendix V.

#### 5.2.1.1. *Cement grout degradation*

The various alteration processes discussed in Appendices V and VIII (e.g. chloride binding, carbonation, ettringite precipitation, expansion caused by corrosion) will affect the chemical and physical degradation of the cement grout. Four stages of degradation are considered based on the work reported in Refs [34], [35].

- Stage 1 – porewater pH is around 13.5, owing to the presence of significant NaOH and KOH and such high pHs can persist during flushing by about 100 pore volumes of water. It is assumed that the values for chemical and physical parameters such as sorption coefficient, porosity and hydraulic conductivity are comparable with those for undegraded cement grout.
- Stage 2 – porewater pH has fallen slightly to about 12.5, owing to buffering by $Ca(OH)_2$ and this pH can persist during flushing by an additional 900 pore volumes. Although pH has declined slightly, it is assumed that the chemical and physical parameter values are the same as for Stage 1.
- Stage 3 – porewater pH diminishes steadily from 12.5 to about background groundwater pH, owing to buffering with C-S-H phases having progressively decreasing Ca/Si ratios. This stage can persist during flushing by approximately an additional 4000 to 9000 pore volumes. There is significant chemical and physical degradation of the cement grout resulting in changes in chemical and physical parameter values. It is assumed that there is a linear change during Stage 3 in parameter values from the start value (i.e. value for undegraded conditions) to the end value (i.e. value for degraded conditions).
- Stage 4 – porewater pH has returned to that of the background waters and the cement grout is fully degraded. The chemical and physical parameter values are the same as those at the end of Stage 3 (i.e. degraded values).

As discussed in Appendix VIII, the exact duration of each stage depends on the composition of groundwater (in particular groundwater pH), the rate of groundwater flow (the higher the flow, the more rapid the pore flushes and the more rapid the degradation) and the nature of the scenario assessed. Shorter stages are assumed for the Defect Scenario Variant D3 (incomplete or degraded disposal zone cement grout) (see Section 4.3).

#### 5.2.1.2. *Stainless steel corrosion*

A review of the literature indicates that, for the expected environmental conditions, Types 304 and 316L stainless steel will be subject to general corrosion and, under aerobic conditions only, localized corrosion in the form of crevice corrosion or pitting, the probability of which increases as near field pH decreases. Although stress corrosion cracking (SCC) is also possible in aerobic environments, it occurs under more aggressive conditions than localized corrosion and, as such, will be preceded by localized attack. Therefore, failure by SCC is not explicitly included in the corrosion model. Microbiologically influenced corrosion (MIC) of stainless steel is also possible in natural groundwaters, but because of the conditioning of the near field pH by the cementitious materials, microbial activity will be limited until such time that the near field pH drops below ~pH 10. Since the majority of containers are calculated to have failed by general corrosion before the pH drops below this value, MIC has not been explicitly included in the corrosion model developed for the GSA.

For the corrosion model, a four-stage time-dependent evolution of the near field chemistry has been used. The evolution of the cement grout porewater pH is assumed to evolve through the stages defined above. Table 14 provides a summary of the corrosion processes included in the model for each stage in the evolution of the environment and for both aerobic and anaerobic groundwaters (details are provided in Appendix I). Since general corrosion dominates in all conditions, the corrosion model assumes instantaneous complete failure of the containers rather than gradual failure. It is also assumed that internal corrosion of the disposal containers and capsules is not significant and is therefore not considered.

The corrosion model assumes that the corrosion rate is a function of not only pH but also chloride concentration and redox potential (reducing and low chloride conditions give lower corrosion rates than oxidising and high chloride conditions) (Appendix I). The porewater chloride concentration and redox potential are assumed to be spatially and temporally constant and to be determined by the groundwater properties.

The four Defect Scenario variants identified in Section 4.3 will reduce the lifetimes of the affected containers due to the earlier onset of corrosion, although the processes will be the same as the Design Scenario (see Appendix I). Variant D3 (incomplete or degraded disposal and disturbed zone cement grout) compromises the ability of the cement grout to condition the near field pH and can result in substantially shorter lifetimes in aerobic environments because of the possibility of rapid localized corrosion failure of the disposal container.

TABLE 14. SUMMARY OF THE GSA CORROSION MODEL

| pH | Aerobic conditions | Anaerobic conditions |
|---|---|---|
| Stage 1 (pH 13.5) | General corrosion only | General corrosion only |
| Stage 2 (pH 12.5) | General corrosion only | General corrosion only |
| Stage 3(a) ($pH_{CRIT} < pH < 12.5$) | General corrosion only | General corrosion only |
| Stage 3(b) ($pH_{GW} < pH \leq pH_{CRIT}$) | General and localized corrosion | General corrosion only |
| Stage 4 ($pH_{GW}$) | General and localized corrosion | General corrosion only |

Note: $pH_{CRIT}$ is defined as pH 10 for Type 316 stainless steel and pH 11 for Type 304 (see Appendix I).

Anaerobic corrosion of steel is accompanied by the generation of hydrogen gas. The most aggressive rates of general corrosion are predicted in aerobic waters, in which corrosion is supported by the cathodic reduction of $O_2$ and does not lead to $H_2$ generation. In contrast, the rates of anaerobic corrosion are lower and are estimated to be in the range 0.01-1 μm/y, the lower end of the range corresponding to fresh, high-pH conditions and the upper end of the range to saline, near-neutral pH waters. Because the disposal containers tend to fail prior to the establishment of near-neutral pH conditions, the predicted maximum rate of $H_2$ generation is of the order of 4-8 ml/y per disposal container, or 200-400 ml/y per borehole. Following failure of the disposal containers, the rate of gas production will decrease by a factor of ~12 (for the same corrosion rate), as the surface area of the waste capsule is much smaller than that of the disposal container. It is likely that $H_2$ generated at these rates will be transported away from the borehole and that a separate gaseous $H_2$ phase is unlikely to develop within the borehole.

#### *5.2.1.3. Release of radionuclides*

Due to the corrosion of the stainless steel disposal containers and the subsequent corrosion of the capsules, water eventually contacts the waste in source container, which is assumed to have failed prior to disposal. The radionuclides in the source container could be in a number of different physical and chemical forms and release of radionuclides could occur on breaching of the waste capsule due to the following mechanisms (Table 15).

- Instantaneous release of gas for radionuclides that are in gaseous form (H-3 and Kr-85) or which have gas phase progeny (Rn-222 for Ra-226 and Pu-238).
- Instantaneous dissolution of radionuclides that are in a form that would result in immediate release to water (e.g. liquid, soluble solid, surface contamination) (H-3, Ni-63, Sr-90, Cs-137, Pb-210, Ra-226 and Am-241).
- Congruent release of radionuclides that are in a form that would result in slow release to water (e.g. solid with low solubility) (Co-60, Pu-238 and Pu-239).

It is recognized that the instantaneous dissolution and congruent release mechanisms could, under certain circumstances, be solubility limited (see Table 15 and Appendix X). No solubility limitation is considered for the reference case calculations (a conservative assumption).

#### *5.2.1.4. Migration of radionuclides*

For radionuclides released in the liquid phase, transport from the source container through the various components of the near field can occur by advection, dispersion and diffusion. The relative importance of these processes depends upon the hydrogeological conditions at the site. Migration through the near field is limited by decay/in-growth and sorption of the radionuclides onto the cement grout in the near field. It is assumed that the migration is not solubility limited (see Appendix X).

For radionuclides released in the gas phase, it is assumed that, if the disposal zone is in the saturated zone, H-3 gas is dissolved in the groundwater, whilst Kr-85 and Rn-222 remain in the gas phase. It is conservatively assumed that the Kr-85 will migrate directly up into the unsaturated zone and then into the biosphere via the closure zone. The very short half-life of Rn-222 (around 3 days) means that there likely to be significant decay within the saturated zone, although some will reach the unsaturated zone and might eventually discharge into the biosphere via the closure zone. If the disposal zone is in the unsaturated zone, it is assumed that the H-3, Kr-85 and Rn-222 gases remain in the gas phase and migrate up the borehole through the closure zone and into the biosphere.

For radionuclides released in the solid phase due to erosion of the closure zone, it is assumed that the radionuclide in the topmost container is transferred directly into the soil.

The associated near field migration processes are summarized in the yellow boxes in Figs 12 and 13 for the saturated and unsaturated zones, respectively. Note that the processes considered for the Defect Scenario are the same as those for the Design Scenario since the faster degradation rates, earlier failure times, and faster radionuclide migration times of the Defect Scenario can be accounted for by modifying the associated parameters in the mathematical model (e.g. container degradation rates) rather than considering different processes. For release in the liquid phase, it is assumed that the defective capsule/container is at the base of the disposal zone for disposal in the unsaturated zone, thereby minimizing the travel distance to the saturated zone. For disposal in the saturated zone, the position of the defective capsule/container is not important since the flow from the disposal borehole to the abstraction borehole is assumed to be horizontal. For gas releases, it is assumed that the defective capsule/container is at the top of the borehole for disposals in both the unsaturated and saturated zones.

TABLE 15. PHYSICAL AND CHEMICAL FORMS OF RADIONUCLIDES IN DISUSED SOURCES

| Radionuclide | Physical/chemical form | Release mechanism<br>(release only occurs once capsule is breached | Scope for solubility limitation in cement-buffered porewater (based on calculation results in Appendix X) | Scope for solubility limitation in groundwater (based on calculation results in Appendix X) |
|---|---|---|---|---|
| H-3 | Often tritium gas or liquid as $H_2O$ | Instantaneous release to air or water (depending upon form of H-3) | No | No |
| Co-60 | Metallic form in thin discs or small cylindrical pellets. Very low solubility | Congruent release (slow rate of release due to low solubility and metallic form) | No | No |
| Ni-63 | Solid, electrical deposition on metal foil | Conservatively assume instantaneous release to groundwater since the Ni-63 is on the surface of the metal foil | Yes | Yes |
| Kr-85 | Gas | Instantaneous release to air | No | No |
| Sr-90 | Oxide or titanate form<br>Often silver plated for medical applications<br>Ceramic or glass bead or rolled silver foil for other applications | The oxide is likely to be soluble in all waters. There is less information concerning the titanate form, but this is likely to be much less soluble than the oxide<br>Conservatively assume soluble and instantaneous release to groundwater | Yes | Yes |
| Cs-137 | Only used as a salt (often caesium chloride)<br>Sometimes ceramic form for weak sources (very low solubility) | Conservatively assume instantaneous release to groundwater | No | No |
| Pb-210 | Solid, mainly carbonate and sulphate | Depending upon the water composition the carbonate and sulphate could be very soluble or poorly soluble<br>Conservatively assume soluble and instantaneous release to groundwater | Yes | Yes |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble | Instantaneous release to groundwater. Instantaneous release of radon gas to air | Yes | Yes |
| Pu-238 (+ Rn gas)<br>Pu-239 | Used in RTGs, and for neutron generators and calibration. Sources typically have Pu oxide in ceramic | $PuO_2$ is only poorly soluble<br>Assume a congruent release with a slow rate of release to groundwater | Yes | Yes |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used<br>For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form<br>Sometimes in sintered form | $AmO_2$ is very soluble<br>Consequently, it is conservative to assume instantaneous release to groundwater<br>Under high pH, oxidising conditions Am-241 could have low solubility and so a congruent release with a slow rate of release to groundwater would be appropriate | Yes | Yes |

### 5.2.2. Geosphere

On leaving the near field, the radionuclides in groundwater migrate through the geosphere by advection, dispersion and diffusion and are subject to decay/in-growth and retardation due to sorption onto the rocks. Depending upon the characteristics of the geosphere, flow can be through pores or fractures and diffusion can occur into the rock matrix. The relative importance of these geosphere processes depends on the hydrogeological conditions at the site (Section 3.2). The groundwater is assumed to be abstracted from the geosphere via an abstraction borehole that is drilled 100 m down the hydraulic gradient from the disposal borehole once institution controls are assumed to be no longer effective (i.e. 30 years after closure). The associated geosphere migration processes are summarized in the blue boxes in Figs 12 and 13 for the saturated and unsaturated zones, respectively.

### 5.2.3. Biosphere

The groundwater abstraction borehole is assumed to be used for domestic purposes (drinking) and agricultural purposes (watering of cows and irrigation of root and green vegetables) (Section 3.3). The water is not treated or stored before use. Humans are exposed via ingestion of water, animal products and crops, inadvertent ingestion of soil, external irradiation from soil, and inhalation of dust.

For radionuclides released from the disposal borehole in the gas phase, it is conservatively assumed that a dwelling is constructed on top of the disposal borehole (without intruding into the disposal zone of the borehole) once institution controls are assumed to be no longer effective (i.e. 30 years after closure). Radioactive gases are assumed to migrate directly into the dwelling and be inhaled by the occupants.

For radionuclides released in the solid phase due to erosion of the closure zone, it is assumed that the contaminated soil is used for the growing of vegetables by a site dweller. Humans are exposed via ingestion of vegetables, inadvertent ingestion of soil, external irradiation from soil, and inhalation of dust.

The associated biosphere migration processes are summarized in the green boxes in Figs 12 and 13 for the saturated and unsaturated zones, respectively.

| | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***A*** | Source (degradation, gas release, dissolution, decay) | Advection<br>Dispersion<br>Diffusion<br>Gas migration (once capsule breached) | | | | | | Transfer into soil due to erosion of closure zone | | | | | |
| ***B*** | Groundwater flow (only once capsule is breached) | Containment Barrier (degradation, sorption, decay) | Advection<br>Dispersion<br>Diffusion<br>Gas migration | | | | | | | | | | |
| ***C*** | | Groundwater flow (only once disposal container is breached) | Disposal Zone (degradation, sorption, decay) | Diffusion<br>Gas migration | Advection<br>Dispersion<br>Diffusion | | | | | | | | |
| ***D*** | | | | Closure Zone (degradation, sorption, decay) | Advection<br>Dispersion<br>Diffusion | | | | Gas migration | | | | |
| ***E*** | | | Groundwater flow | | Disturbed Zone and Plug (degradation, sorption, decay) | | Advection<br>Dispersion Diffusion | | | | | | |
| ***F*** | | | | | | Unsaturated Zone | Recharge | | | | | | |
| ***G*** | | | | | Groundwater flow | | Saturated Zone (advection, dispersion, diffusion, sorption, decay) | Irrigation | | Irrigation | Ingestion | Ingestion | Advection<br>Dispersion<br>Diffusion |
| ***H*** | | | | | | Percolation | | Soil (sorption, decay) | Suspension | Root uptake | | External irradiation<br>Ingestion | Erosion<br>Percolation |
| ***I*** | | | | | | | | Precipitation<br>Deposition | Atmosphere | Deposition | | Inhalation | Dispersion |
| ***J*** | | | | | | | | Death and decay | | Crops (translocation) | | Ingestion | Food preparation losses |
| ***K*** | | | | | | | | Excretion<br>Bioturbation | | | Animals | Ingestion | |
| ***L*** | | | | | | | Abstraction | Ploughing | | Cultivation<br>Harvesting | Rearing | Humans | Excretion |
| ***M*** | | | | | | | | | | | | | Elsewhere (decay) |

*FIG. 12. Interaction matrix for the saturated disposal zone.*

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **A** | Source<br>(degradation,<br>gas release, dissolution,<br>decay) | Advection<br>Dispersion<br>Diffusion<br>Gas migration<br>(once capsule breached) |  |  |  |  |  | Transfer into soil<br>due to erosion of<br>closure zone |  |  |  |  |  |
| **B** | Percolation<br>(only once capsule is<br>breached) | Containment Barrier<br>(degradation, sorption,<br>decay) | Advection<br>Dispersion<br>Diffusion<br>Gas migration |  |  |  |  |  |  |  |  |  |  |
| **C** |  | Percolation<br>(only once disposal<br>container is breached) | Disposal Zone<br>(degradation,<br>sorption, decay) | Gas migration | Advection<br>Dispersion<br>Diffusion |  |  |  |  |  |  |  |  |
| **D** |  |  | Percolation | Closure Zone<br>(degradation,<br>decay) | Percolation |  |  |  | Gas migration |  |  |  |  |
| **E** |  |  |  | Percolation | Disturbed Zone<br>and Plug (degradation,<br>sorption, decay) | Advection<br>Dispersion<br>Diffusion |  |  |  |  |  |  |  |
| **F** |  |  |  |  | Percolation | Unsaturated<br>Zone<br>(sorption, decay) | Advection<br>Dispersion<br>Diffusion |  |  |  |  |  |  |
| **G** |  |  |  |  |  |  | Saturated Zone<br>(advection,<br>dispersion, diffusion,<br>sorption, decay) | Irrigation |  | Irrigation | Ingestion | Ingestion | Advection<br>Dispersion<br>Diffusion |
| **H** |  |  |  |  |  | Percolation |  | Soil<br>(sorption, decay) | Suspension | Root uptake |  | External<br>irradiation<br>Ingestion | Erosion<br>Percolation |
| **I** |  |  |  | Precipitation |  |  |  | Precipitation<br>Deposition | Atmosphere | Deposition |  | Inhalation | Dispersion |
| **J** |  |  |  |  |  |  |  | Death and decay |  | Crops<br>(translocation) |  | Ingestion | Food<br>preparation<br>losses |
| **K** |  |  |  |  |  |  |  | Excretion<br>Bioturbation |  |  | Animals | Ingestion |  |
| **L** |  |  |  |  |  |  | Abstraction | Ploughing |  | Cultivation<br>Harvesting | Rearing | Humans | Excretion |
| **M** |  |  |  |  |  |  |  |  |  |  |  |  | Elsewhere<br>(decay) |

FIG. 13. Interaction matrix for the unsaturated disposal zone.

## 5.3.MATHEMATICAL MODELS

Mathematical models translate the assumptions of a conceptual model into the formalism of mathematics, usually sets of coupled algebraic, differential and/or integral equations with appropriate initial and boundary conditions in a specified domain. These equations are solved by computer software to give the temporal and spatial dependence of the quantities of interest (such as radionuclide concentrations and doses to humans).

For the GSA, an assessment model has been developed to allow the calculation of the end points identified in Section 2.5. In addition, two supporting models have been developed to represent the degradation of the cement grout and the corrosion of the containers in detail and to provide associated input into the assessment model. The assessment and supporting models are discussed in turn below.

### 5.3.1. Assessment model

It was decided to implement the assessment model in the most recent version of the AMBER software tool (version 5) [36] since it is a suitable tool in which to implement the conceptual models developed in Section 5.2. Furthermore, AMBER has been used to develop models for a wide range of safety assessments (for example Refs [23], [37]), including a previous assessment of the borehole disposal concept for disused sealed radioactive sources [32]. AMBER uses a compartment model approach to represent the migration and fate of contaminants in the disposal system. The use of AMBER places two main conditions on the mathematical representation of a disposal system.

The first condition is that the system has to be discretized into a series of compartments. Using the compartment modelling approach, a disposal system may be represented by discretizing it into compartments that can correspond to the components identified in the conceptual model. It is assumed that either uniform mixing occurs over the timescales of interest, or the distribution of the contaminant within the compartment is not important so that a uniform concentration over the whole compartment can be used either for subsequent transport or for deriving end points of interest. Therefore each compartment is to be chosen to represent a system component for which one or other of these assumptions is reasonable.

The second condition is that processes resulting in the transfer of contaminants from one compartment (the donor compartment) to another (the receptor compartment) need to be expressed as transfer coefficients that represent the fraction of the activity in a particular compartment transferred from the donor compartment to the receptor compartment per unit time. The mathematical representation of the inter-compartmental transfer processes takes the form of a matrix of transfer coefficients that allow the compartmental amounts to be represented as a set of first order linear differential equations. For the *i*th compartment, the rate at which the inventory of radionuclides in a compartment changes with time is given by:

$$\frac{dN_i}{dt} = \left( \sum_{j \neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t) \right) - \left( \sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right) \tag{1}$$

where:

*i* and *j* indicate compartments;

*N* and *M* are the amounts (Bq) of radionuclides *N* and *M* in a compartment (*M* is the precursor of *N* in a decay chain);

*S(t)* is a time dependent external source of radionuclide *N* (Bq/y).

Transfer and loss rates are represented by $\lambda$;

$\lambda_N$ is the decay constant for radionuclide *N* (/y);

$\lambda_{ji}$ and $\lambda_{ij}$ are transfer coefficients (/y) representing the gain and loss of radionuclide *N* from compartments *i* and *j*.

For simplicity, the above equation assumes a single parent and daughter. However, AMBER allows the representation of multiple parents and daughters.

The solution of the matrix of equations given above provides the time-dependent inventory of each compartment. Assumptions for compartment sizes then result in estimates of concentrations in the corresponding media from which doses/intakes can be estimated.

The mathematical equations used to represent the release and migration processes and the exposure mechanisms identified in the Interaction Matrices are described in Appendix XI. Two further equations are used for the activity limit calculations. A total activity limit is derived based on:

$$At_i = \frac{Dose_{\lim} \cdot A_i \cdot N_p}{MaxDose_i} \tag{2}$$

where:

$At_i$ is the total activity limit of radionuclide $i$ for the scenario (Bq);

$Dose_{lim}$ is the relevant dose limit for the scenario (Sv/y) (assumed to be 0.3 mSv/y see Section 2.4);

$A_i$ is the initial activity of radionuclide $i$ in each waste package (Bq) (assumed to be 1 TBq – see Section 2.5);

$N_p$ is the number of packages in the borehole (assumed to be 50 – see Section 3.1.2);

$MaxDose_i$ is the peak dose resulting from the total activity of radionuclide $i$ in the waste (Sv/y).

A per package activity limit is derived based on:

$$Ap_i = \frac{At_i}{N_p} \tag{3}$$

where $Ap_i$ is the per package activity limit of radionuclide $i$ for the scenario (Bq).

Equations 2 and 3 assume that there is a linear relationship between dose and the radionuclide inventory disposed in the borehole. This is not the case when the release of radionuclides is solubility limited. However, for the reference calculations in Section 6.1, it is conservatively assumed that the liquid release is not solubility limited (resulting in a more restrictive reference activity level for the liquid release).

For the calculation of the activity levels presented in Section 6, the radionuclides have been considered independently of each other (except for the decay chains), i.e. as only one radionuclide was present in the disused sealed radioactive sources. When managing a spectrum of several radionuclides, as it is most often the case for inventories of disused sealed radioactive sources, it is necessary to combine the impacts of the various radionuclides using a summation rule in order to ensure that the dose constraint is not exceeded for any given scenario. This is achieved by the following limiting condition:

$$\sum_i \frac{Q_i}{Q_{i,l}} \leq 1 \tag{4}$$

where:

$Q_i$ is the actual activity of radionuclide $i$ to be disposed (Bq);

$Q_{i,l}$ is the activity limit for radionuclide $i$ from the limiting scenario, assuming radionuclide $i$ is the only radionuclide disposed (Bq).

Application of this summation rule is conservative. It could be appropriate to recognize the time dependent nature of the impacts (i.e. peak doses for the different radionuclides do not all occur at the same time).

### 5.3.2. Supporting models

As noted above, two supporting model have been developed to provide input data for use in the assessment model.

The first has been developed in an Excel spreadsheet and has been used to calculate the duration of each of the cement grout degration stages identified in Section 5.2.1 for the various hydrogeological and geochemical conditions considered in the GSA. The model, as applied to the three reference groundwaters (waters Nos 1, 5 and 6), is described in Appendix VIII.

The second supporting model has also been developed in an Excel spreadsheet and used to calculate the failure times of the disposal container and the waste capsule for the various hydrogeological, geochemical and cement grout degradation conditions considered in the GSA. The model is described in Appendix I.

## 5.4.REFERENCE CALCULATION CASES

The cases for which reference calculations need to be undertaken using the assessment model have to be identified (variant calculations are identified in Section 6.2 in light of the results obtained for the reference calculations). In defining the reference calculation cases, it is necessary to consider the range of disposal systems and range of scenarios of interest.

- Disposal systems: as noted in Section 3.4, a total of 8 different disposal systems can be identified (see Table 9).
- Scenarios: from consideration of the scenarios considered in Section 4, 15 calculations need to be considered (liquid, gas and solid releases for the Design Scenario and the four Design Scenario variants).

Thus there could be a potential total of 120 reference calculation cases. However, this number can be reduced because:

- The gas release calculations are independent of the geosphere since it is assumed that the gas is released up the borehole from the disposal zone into the closure zone and then into a house built above the borehole;
- The solid release calculations are independent of the geosphere since it is assumed that the rate of erosion is the same for all geospheres;
- Only one calculation case (based on the unsaturated disposal zone) needs to be undertaken for the gas release calculations for each scenario since this is considered to be the more restrictive case (i.e. The case that gives rise to the highest impacts) and can conservatively be applied to the saturated disposal zone; and
- The solid release calculations for the design and defect scenarios are the same (since the same surface erosion rate is assumed for both scenarios) and only one calculation case (based on the unsaturated disposal zone) needs to be undertaken since, by definition, the disposal zone will be in the unsaturated zone at the time that the exposure arises.

Thus, in total, there are 46 reference calculation cases to be considered. These are identified in Table 16.

## 5.5. DATA

The tables in Appendix XII provide data for each of the parameters of the assessment model described in Appendix XI. Data relating to the inventory, borehole and its design and the associated geosphere and biosphere characteristics have been drawn from the system description (Section 3). Other radionuclide/element dependent and independent data have been drawn from a number of relevant sources such as previous safety assessments (e.g. Ref. [32], [37]) and data compilations (e.g. Ref. [38]). Source references are given at the end of each table in Appendix XII.

## 5.6.IMPLEMENTATION

As mentioned in Section 5.3, the AMBER software tool was used to implement the assessment model. The mathematical model and data described in Appendix XII and XI were encoded directly into AMBER and quality assurance checks undertaken to ensure that the implementation was correctly performed. The time dependent solution method used by AMBER is described in Refs [39], [40]. The verification of the solution is discussed in Ref. [38].

In implementing the models and data in AMBER, the aim was to minimise the number of input files that needed to be created and thereby reduce input error, facilitate checking and updating, and avoid the replication of data needed by all or most calculation cases (e.g. decay rates and dose coefficients). This was achieved through the use of a series of 'literal' parameters as switches to allow variant cases to be easily set up from a common 'source' file. Literal parameters used include:

- TypeScenario – can be set to 'Design', 'DefectD1', 'DefectD2', 'DefectD3' or 'DefectD4'; and
- TypeGeosphere – can be set to 'LowFlowRate', 'MediumFlowRate', 'HighFlowRatePorous' or 'HighFlowRateFractured'.

Given that different conceptual models were developed for unsaturated and saturated conditions (Section 5.2), two separate AMBER 'source' files were developed:

- Unsat_Casev4.cse – for unsaturated cases; and
- Sat_Casev4.cse – for saturated cases.

The same saturated geosphere was used for the two source files, but different near fields were implemented. The data that were common were copied and pasted from one file into the other.

By changing the value taken by each literal parameter, all case files for all scenarios could be directly created in batch mode from the two Unsat_Casev4.cse and Sat_Casev4.cse 'source' files.

TABLE 16. REFERENCE CALCULATION CASES CONSIDERED

| Scenario | Exposure group | Release phase | Near field | Saturated geosphere | |
|---|---|---|---|---|---|
| | | | Disposal zone | Flow rate | Flow type |
| Design | Farmer | Liquid | Unsaturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | | | Saturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | House dweller | Gas | Unsaturated | Not relevant | Not relevant |
| | Site dweller | Solid | Unsaturated | Not relevant | Not relevant |

TABLE 16. REFERENCE CALCULATION CASES CONSIDERED (cont.)

| Scenario | Exposure group | Release phase | Near field | Saturated geosphere | |
|---|---|---|---|---|---|
| | | | Disposal zone | Flow rate | Flow type |
| Defect Variant D1 | Farmer | Liquid | Unsaturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | | | Saturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | House dweller | Gas | Unsaturated | Not relevant | Not relevant |
| Defect Variant D2 | Farmer | Liquid | Unsaturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | | | Saturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | House dweller | Gas | Unsaturated | Not relevant | Not relevant |
| Defect Variant D3 | Farmer | Liquid | Unsaturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | | | Saturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | House dweller | Gas | Unsaturated | Not relevant | Not relevant |
| Defect Variant D4 | Farmer | Liquid | Unsaturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | | | Saturated | High | Porous |
| | | | | | Fractured |
| | | | | Medium | Porous |
| | | | | Low | Porous |
| | House dweller | Gas | Unsaturated | Not relevant | Not relevant |

## 6. PRESENTATION AND ANALYSIS OF RESULTS

Before presenting and analysing the results of the GSA, it is important to summarise the main assumptions that have been adopted. This ensures that the reader is aware of these assumptions and can consider their appropriateness when comparing the GSA and its results to a specific disposal system.

The main assumptions are summarized in the first column of Table 17 (those appearing in italics relate to parameters that are site specific). These assumptions have been identified by reviewing each step of the approach used in the GSA (i.e. the specification of the assessment context (Section 2), the description of the disposal system (Section 3), the development and justification of the scenarios (Section 4), and the formulation and implementation of models (Section 5)). Where appropriate, each assumption has been classified (in the second and third columns) as to whether it is considered to be conservative or realistic, consistent with the definitions of these terms provided in Section 2.6.2. The sections of this TECDOC that provide the justification for each assumption are listed in the fourth column.

TABLE 17. KEY ASSUMPTIONS MADE IN THE GSA

| Assumption | Conservative | Realistic | Justification |
|---|---|---|---|
| | Assessment context | | |
| 1. Narrow diameter borehole (up to 50 cm) and so small diameter sources (up to 15 mm) | n.a. | n.a. | Sections 1.3 and 2.1 |
| 2. Disused sealed radioactive sources | n.a. | n.a. | Sections 1.3, 2.1 and 2.1 |
| 3. Only consider post-closure issues | n.a. | n.a. | Sections 1.3 and 2.1 |
| 4. Exclude deliberate human intrusion | n.a. | n.a. | Section 1.3 |
| 5. *Depth of cover at least 30 m* | n.a. | n.a. | Sections 1.3 and 2.1 |
| 6. Assume that the derived reference activity values are total values applicable to an entire site | Yes | - | Section 2.2 |
| 7. Only consider radiological impacts on humans | n.a. | n.a. | Section 2.2 |
| 8. Regulatory framework and associated end points | n.a. | n.a. | Sections 2.4 and 2.5 |
| 9. No explicit consideration of radiolysis, criticality and thermal effects | No | No | Such effects are considered to be insignificant for the typical inventories to be disposed |
| 10. Borehole operated only for one year and then closed | - | Yes | Section 2.7 |
| 11. Period of institutional control | - | Yes | Section 2.7 |
| 12. No cut-off time for calculation of dose | n.a. | n.a. | Section 2.7 |
| | System Description | | |
| 1. The selected radionuclides are representative of those that can be found in disused sealed radioactive sources | - | Yes | Section 3.1.1 and Appendix I |
| 2. Sources have been appropriately conditioned prior to disposal | - | Yes | Section 3.1.2 |

TABLE 17. KEY ASSUMPTIONS MADE IN THE GSA (cont.)

| | | | | |
|---|---|---|---|---|
| System Description | | | | |
| 3. | Using borehole disposal concept design and materials broadly similar to that defined in Section 3.1 | n.a. | n.a. | Section 3.1 |
| 4. | 50 waste packages | n.a. | n.a. | Section 3.1.2 |
| *5.* | *Borehole located in either unsaturated or saturated zone but not straddling the two zones* | n.a. | n.a. | Section 3.1.3 |
| *6.* | *Geological complexity and variability. Can be treated by averaging* | n.a. | n.a. | Section 3.2 |
| *7.* | *Water abstraction borehole as GBI (drilled at end of institutional control period)* | Yes | - | Section 3.2 |
| *8.* | *Geological stability (tectonic and seismic)* | n.a. | n.a. | Section 3.2 |
| *9.* | *No natural resources requiring excavation* | n.a. | n.a. | Section 3.2 |
| *10.* | *Flux and travel time through geosphere and distance to GBI* | n.a. | n.a. | Sections 3.2.1 and 3.2.2 |
| *11.* | *Sorption coefficients* | n.a. | n.a. | Sections 3.3.1 and 3.3.2 |
| *12.* | *Climatic conditions* | n.a. | n.a. | Section 3.3 |
| *13.* | *Soils capable of supporting crops* | n.a. | n.a. | Section 3.3 |
| *14.* | *Subdued relief* | n.a. | n.a. | Section 3.3 |
| *15.* | *Limited geomorphological activity (e.g. no coastal processes)* | n.a. | n.a. | Section 3.3 |
| Scenarios | | | | |
| *1.* | *Identified scenarios adequately illustrate the range of future behaviours and states of the disposal system* | - | Yes | Section 4 |
| 2. | Unexpected geological conditions and environmental change scenarios are adequately covered by the other scenarios and associated variant calculations | - | Yes | Sections 4.4 and 4.5 |
| Models | | | | |
| 1. | Use of the compartment modelling approach is appropriate for the problem | - | Yes | Section 5.3 |
| 2. | Linear relationship between activity and dose | Yes (for liquid release of certain solubility limited radionuclides) | Yes (for most radionuclides and releases) | Section 5.3 |
| 3. | Activity levels derived by considering radionuclides independently | No | - | Section 5.3 |
| 4. | Assume that the data used are appropriate | Some | Some | Section 5.5 |

## 6.1. RESULTS FOR THE REFERENCE CALCULATIONS

### 6.1.1. Design scenario

The assessment results for ***liquid releases*** for the Design Scenario are presented in Table 18 in terms of the maximum activity of a given radionuclide that can be disposed without the dose criterion of 0.3 mSv/y being exceeded for each geosphere considered (per package activity limits are provided in Table 87). For all radionuclides, other than those with long lived daughters (i.e. Pu-238, Pu-239 and Am-241), the total inventory that can safely be exposed exceeds 1 x$10^{18}$ Bq. For these radionuclides a specific disposal limit has not been given, only an indication that the limit exceeds 1 x$10^{18}$ Bq [13].

Total activity limits for Pu-238, Pu-239 and Am-241 are summarized in Fig. 14 for liquid releases. They show that disposal in the unsaturated zone generally allows disposal of higher activity levels (by more than an order of magnitude as compared to disposal in the saturated zone for the high flow systems). This is due to the increased travel time to the geosphere-biosphere interface (the water abstraction borehole).

Similarly, the low flow saturated geosphere increases travel time and so allows disposal of higher activity levels by up to five orders of magnitude compared to the high flow systems. The higher activity levels for the fractured high flow system compared to the porous high flow system are a consequence of matrix diffusion which results in additional retardation of radionuclides.

Total activity results for ***gas releases*** are provided in Table 19 (per package activity limits are provided in Table 89). They show that the release of gaseous radionuclides, either disposed or in-grown in-situ, does not impose any radionuclide disposal limits.

Total activity results for ***solid releases*** are provided in Table 20 (per package activity limits are provided in Table 91). They show that for all radionuclides, other than those with long lived daughters (i.e. Pu-238, Pu-239 and Am-241), the total inventory that can safely be exposed exceeds 1 x$10^{18}$ Bq.

---

[13] This value has been chosen for a number of reasons. At such high activities, worker doses will become an issue. Furthermore, it is at least three orders of magnitude higher than the maximum inventory available for disposal of any given radionuclide (see Appendix I).

TABLE 18. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR THE DESIGN SCENARIO

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow Rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 9E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 x$10^{18}$ Bq.

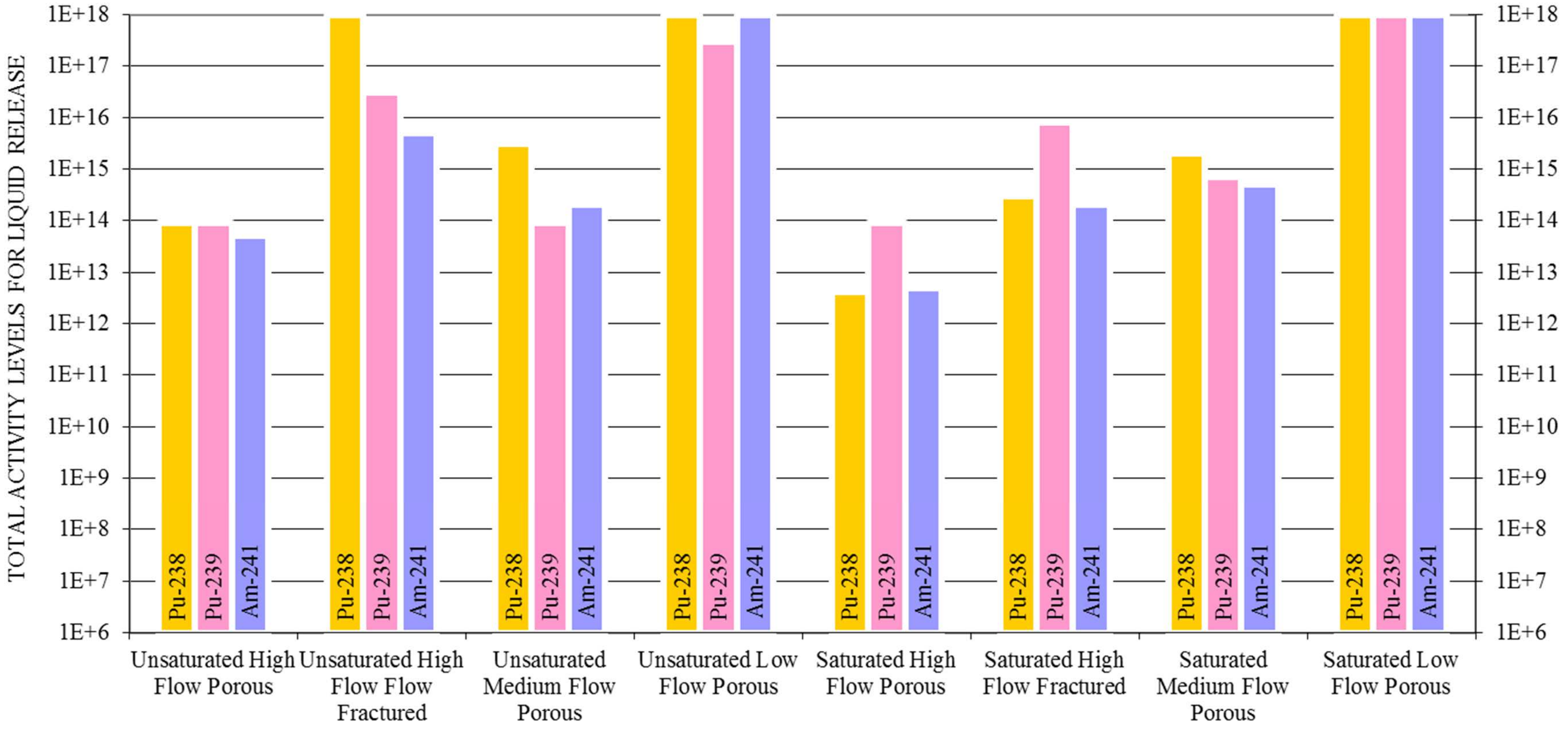


*FIG. 14. Pu-238, Pu-239 and Am-241 total activity levels for the design scenario: liquid releases.*

TABLE 19. TOTAL ACTIVITY LEVELS FOR GASEOUS RELEASE FOR THE DESIGN SCENARIO

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | n.a. | n.a. | * | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a total activity level that is greater than 1 x$10^{18}$ Bq.

TABLE 20. TOTAL ACTIVITY LEVELS FOR SOLID RELEASE FOR THE DESIGN SCENARIO

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |

* denotes a total activity level that is greater than 1 x$10^{18}$ Bq.

The results for the Design Scenario show that if the system performs to its design specification, then the chemical and physical barriers provided by the near field engineering are such that limits on the total activity which can be disposed are only required for those radionuclides with long lived daughters, i.e. Pu-238, Pu-239 and Am-241.

### 6.1.2. Defect scenario

The results for ***liquid releases*** for the Defect Scenario are presented in Figs 15 to 17 in terms of the maximum activity of Pu-238, Pu-239 and Am-241 that can be disposed for each scenario variant without exceeding the dose constraint. All other radionuclides have a maximum activity of greater than 1 $x10^{18}$ Bq except for Defect Scenario D4 (which involves a failed waste capsule being within a failed disposal container) for which H-3, Sr-90, Cs-137 and Ra-226 have activity limits of between 2 $x10^{12}$ Bq and 7 $x10^{17}$ Bq. Complete results are provided in Appendix XIII. Figs 15 to 17 show that there is little or no variation in the activity levels for a given radionuclide between the Design and Defect Scenario variants for a given geosphere. This emphasizes the multiple barrier nature of the near field that ensures defects in the performance of one barrier do not compromise the performance of the near field.

Results for ***gas releases*** show that the release of gaseous radionuclides, either disposed or in-grown in-situ, does not impose any radionuclide disposal limits for Defect Scenario D1, D2 and D3 since adequate containment is provided by the non-failed barriers. However, Defect Scenario D4 does result in a total activity limit of 6 $x10^{12}$ Bq for H-3 and 1 $x10^{14}$ Bq for Kr-85 (Table 21).

Results for ***solid releases*** are the same as for the Design Scenario (Table 20) since the same surface erosion rate (the key factor determining the time of release of contamination to the soil) is assumed for both scenarios.

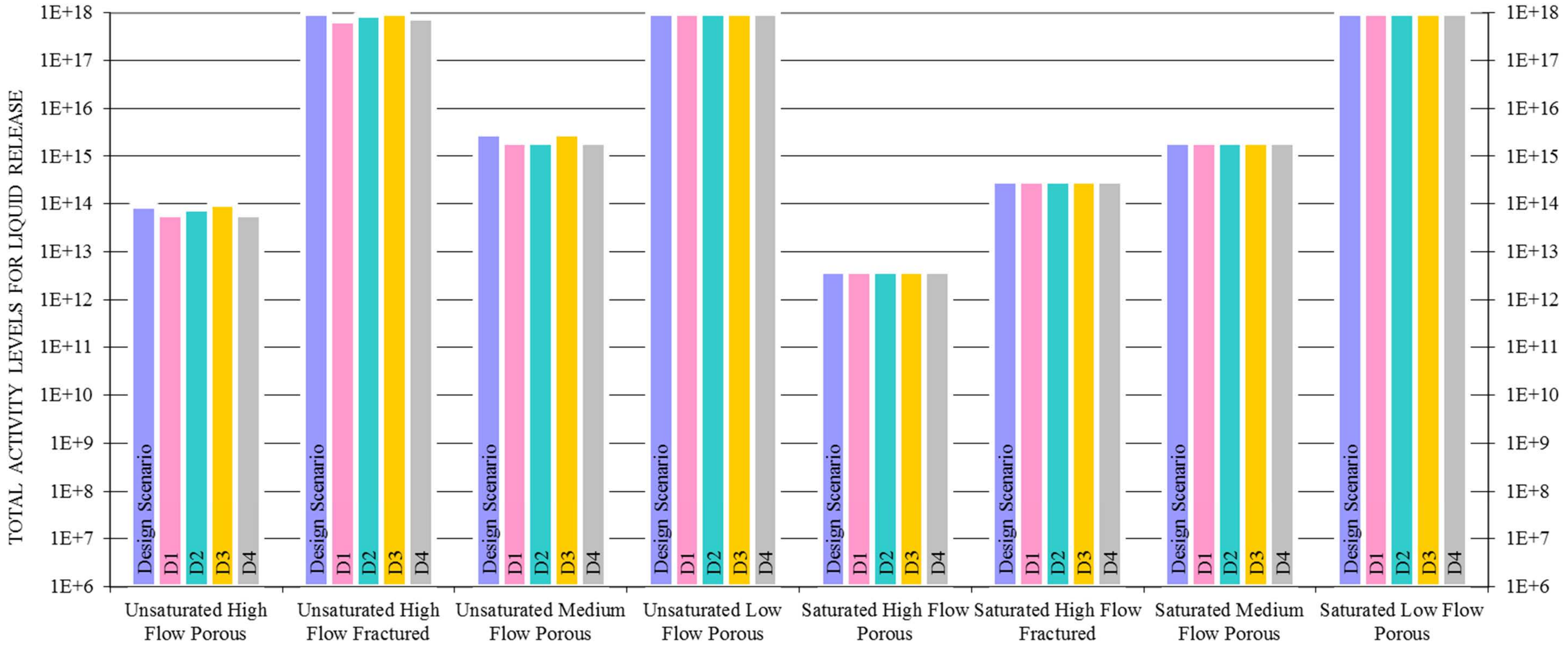


*FIG. 15. Pu-238 total activity levels for the design and defect scenarios: liquid releases.*

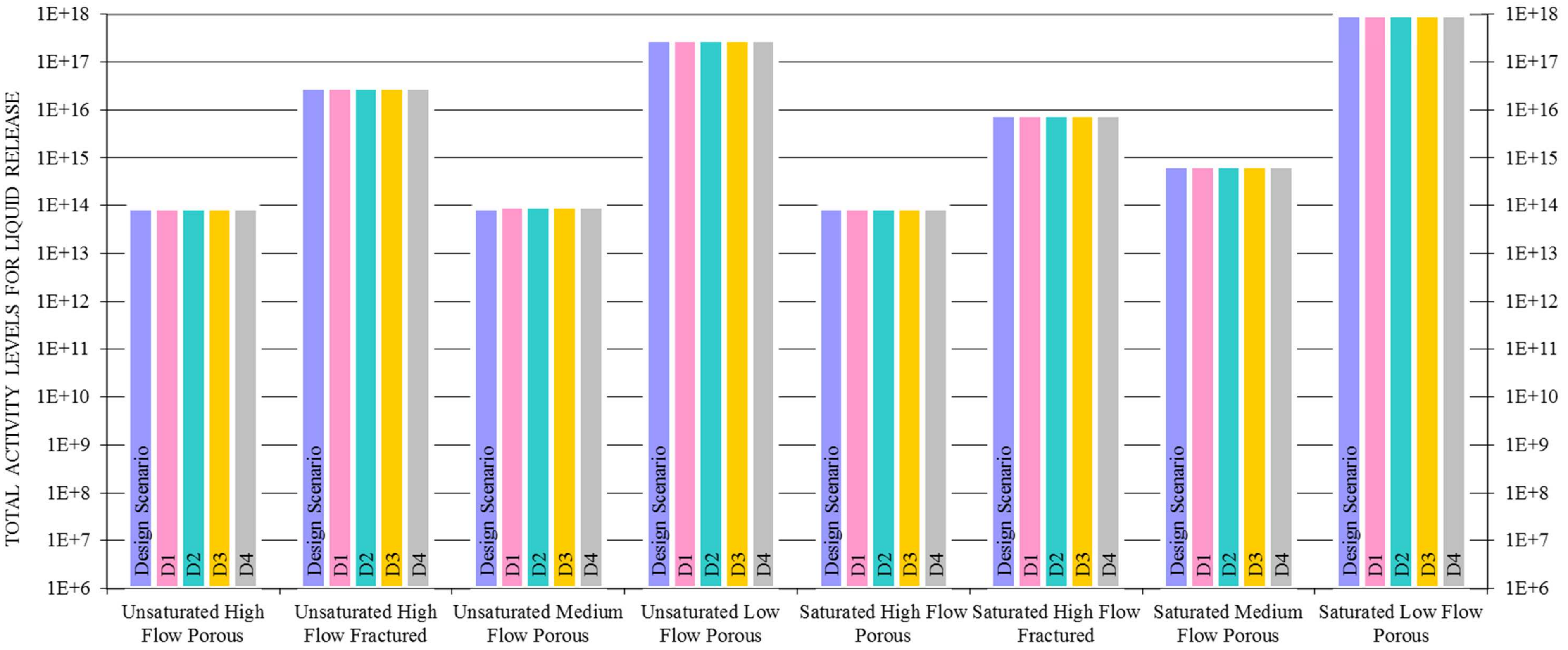


*FIG. 16. Pu-239 total activity levels for the design and defect scenarios: liquid releases.*

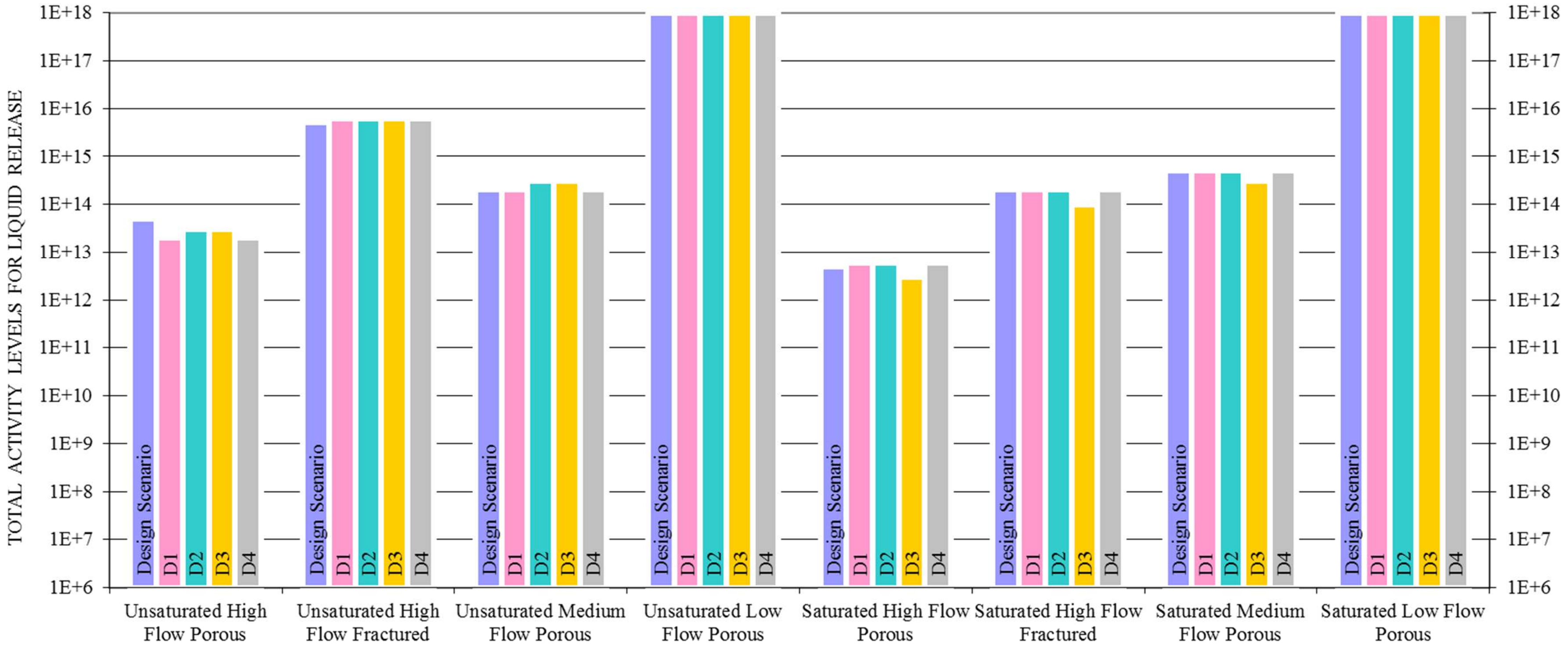


FIG. 17. Am-241 total activity levels for the design and defect scenarios: liquid releases.

TABLE 21. TOTAL ACTIVITY LEVELS FOR GASEOUS RELEASE FOR DEFECT SCENARIO D4

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| 6E+12 [14] | n.a. | n.a. | 1E+14 | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

---

[14] Only applicable to unsaturated disposal zone. H-3 in saturated disposal zone is assumed to be dissolved in the groundwater.

### 6.1.3. Disposal limits considering design and defect scenarios

The actual disposal limit is to be based on a combination of the consequences of the Design and Defect Scenarios. As noted in Table 13, in a given borehole containing 50 waste packages, there is a 5% probability that one disposal container will be defected, a 5% probability that one waste capsule will be defected, a 0.005% probability that both the waste capsule and disposal container will be defected in the same waste package, and a 90% probability that the waste packages will perform according to the Design Scenario. (The probability of two defected disposal containers or waste capsules in a borehole is 0.1%, and <0.002% for three defects in a borehole. Since the probability of multiple defects of a given kind in a borehole is small, only the case of single defects need be considered when estimating the overall disposal limit). The overall disposal limit, L, is given by:

$$L = P^{DS}L^{DS} + P_1^{D1}L^{D1} + P_1^{D2}L^{D2} + P^{D3}L^{D3} + P_1^{D4}L^{D4} \tag{5}$$

where:

$P^{DS}$, $P_1^{D1}$, $P_1^{D2}$, $P^{D3}$, and $P_1^{D4}$ are the probabilities for the Design Scenario (i.e. no defected waste packages in a borehole) and for the Defect Scenario variants (considering only a single defect for Defect Scenarios D1, D2 and D4), respectively;

$L^{DS}$, $L^{D1}$, $L^{D2}$, $L^{D3}$, and $L^{D4}$ are the corresponding radionuclide disposal limits.

Since the disposal limits for most radionuclides are similar for each of the Design and Defect Scenarios considered and since the sum of the individual probabilities equals one, the overall disposal limit can be conservatively estimated from the lowest disposal limit for a given Design or Defect Scenario. The exceptions are H-3 and Kr-85, together with Sr-90, Cs-137 and Ra-226 for certain systems, for which Defect Scenario D4 yields significantly more restrictive activities. Therefore the probability of Defect Scenario D4 (0.005% - see above) is taken into account when deriving the activities for these radionuclides.

Tables 22 and 23 summarise the limiting total and per package activities. The tables show that the borehole disposal system is potentially suitable for disposal of a wide range of radionuclides in a wide range of different geosphere environments. The multi-barrier near field engineering is such that even accounting for reduced performance of a given barrier the overall performance is little affected.

Table 24 shows the maximum sealed source inventories that the countries identified in Section 3.1.1 have for disposal and the activity limit calculated from the GSA. As noted in Section 3.1.1, NEWMDB and the other data sources used to derive the inventory do not always contain information on the dimensions of the sources, so not all the sources listed in the data sources might be suitable for disposal in a narrow diameter borehole. Therefore the inventory given in Table 24 is considered to be an upper estimate of the inventory that might need to be disposed using the borehole disposal concept. It can be seen that all the systems assessed in the GSA provide adequate capacity for all the radionuclides of interest with the exception of Pu-239 and Am-241, for which the large number of sources to be disposed distorts the value of the total activity for disposal. Even so, the calculated limits for these two radionuclides are less than a factor of four lower than maximum activity to be disposed.

Table 24 also provides information on the maximum number of sources in a country. It can be seen that the number of sources for the vast majority of radionuclides can be accommodated in a single borehole (assuming 50 sources per borehole), further underlining the practicability of the borehole disposal concept as an option for the management of disused sealed radioactive sources.

TABLE 22. TOTAL ACTIVITY LIMITS

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 2E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 3E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 23. PER PACKAGE ACTIVITY LIMITS

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 4E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |
| | Low | Porous | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 5E+10 |
| | | Fractured | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |
| | Low | Porous | * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 24. COMPARISON OF INVENTORIES FOR DISPOSAL AND CALCULATED ACTIVITY LIMITS

| Radionuclide | Maximum inventory for disposal in a country (Bq) | Calculated activity limit (Bq) | Maximum number of sources in a country |
|---|---|---|---|
| H-3 | 2.8E+14 | * | 303 |
| Na-22 | 3.4E+06 | * | 2 |
| Mn-54 | 1.0E+05 | * | |
| Fe-55 | 9.9E+09 | * | 4 |
| Co-57 | 1.7E+10 | * | 75 |
| Co-60 | 2.9E+15 | * | 158 |
| Ni-63 | 2.1E+10 | * | -[b] |
| Zn-65 | 3.7E+05 | * | 1 |
| Se-75 | 3.0E+11 | * | -[b] |
| Kr-85 | 6.3E+11 | * | 21 |
| Y-88 | 1.0E+05 | * | -[b] |
| Sr-90 | 5.3E+11 | * | 135 |
| Cd-109 | 3.1E+09 | * | 3 |
| Ba-133 | 3.3E+08 | * | 1 |
| Cs-137 | 7.5E+14 | * | 1500 |
| Pm-147 | 2.7E+11 | * | 8 |
| Sm-151 | 7.8E+09 | * | 3 |
| Eu-152 | 4.0E+08 | * | -[b] |
| Gd-153 | 1.5E+11 | * | 36 |
| Yb-169 | 2.2E+11 | * | -[b] |
| Ir-192 | 9.3E+14 | * | 29 |
| Au-195 | 4.0E+07 | * | -[b] |
| Hg-203 | 1.5E+06 | * | 1 |
| Tl-204 | 5.0E+08 | * | 9 |
| Pb-210 | 1.0E+07 | * | -[b] |
| Po-210 | 1.0E+10 | * | 4 |
| Ra-226 | 2.6E+13 | * | 912 |
| Pu-238 | 2.0E+10 | 2E+12 | 44 |
| Pu-239 | 6.7E+11 | 5E+11 | 12 918 |
| Am-241 | 1.2E+13 | 3E+12[a] | 2274 |
| Cf-252 | 4.1E+09 | * | 4 |

NOTES**:** * Denotes a total activity level that is greater than 1 × $10^{18}$ Bq (see text in Section 6.1.1).

[a] Most limiting value for the geospheres considered. Other geospheres give values that are less restrictive by about an order of magnitude.

[b] No information available.

## 6.2.RESULTS FOR VARIANT CALCULATIONS

In order to investigate the sensitivity of the results presented in Section 6.1 to conceptual model and data assumptions, eight variant cases were identified and associated calculations undertaken. The cases considered were:

- Instantaneous release instead of congruent release of Co-60, Pu-238 and Pu-239 (Section 6.2.1);
- Accelerated cement grout degradation in the near field (Section 6.2.2)
- Accelerated stainless steel corrosion (Section 6.2.3);
- Decreased and increased cement grout sorption (Section 6.2.4);
- Decreased and increased geosphere pathlength (Section 6.2.5);
- Decreased and increased geosphere sorption (Section 6.2.6);
- Alternative uses of abstracted groundwater (Section 6.2.7); and
- Decreased and increased erosion rates (Section 6.2.8).

These cases are presented and discussed below. Tables of total and per package activity levels for each variant are provided in Appendix XIII (Tables 102 to 129). The results for the key radionuclides (Pu-238, Pu-239 and Am-241) are graphically summarized for each geosphere system using a 'tornado plot' (see Figs 18 to 21). Each tornado plot shows the associated geosphere system's total activity limit for the Design Scenario for the liquid and solid releases. The total activity limit for the liquid release is shown by the solid vertical line, whilst the limit for the solid release is shown by the horizontal bar marked 'Erosion'. The total activity limits for the variant calculations are shown by the series of horizontal bars.

### 6.2.1. No congruent release

For the reference case, the physical form of the radionuclides within the disused sealed radioactive sources was taking into consideration (Section 5.2.1). It was identified that for Co-60, Pu-238 and Pu-239, the physical form of the source is such that the entire inventory would not be available once the capsule has failed and congruent release would occur. This variant examines the impact of ignoring congruent release and assuming instantaneous dissolution of the radionuclides on contact with water. The results (Tables 102 and 103) are not altered for Co-60 because its half life is so short relative to the time for failure of the capsule. For Pu-238 and Pu-239, the activity levels actually increase for the vast majority of geosphere systems by up to an order of magnitude when congruent release is ignored. The reason for this is that there is less time for decay and in-growth of more radiologically significant daughters.

### 6.2.2. Accelerated cement grout degradation

Increasing the rate at which the cement grout degrades by an order of magnitude causes the activity levels to reduce by less than a factor of two (Tables 104 and 105). This is due to the relative unimportance of the cement grout as a barrier, and the adequate performance of the other near field barriers than compensate for the more rapid degradation of the grout.

### 6.2.3. Accelerated stainless steel corrosion

Increasing the corrosion rate by an order of magnitude, has little or no effect on activity levels for disposals in the unsaturated zone since the more rapid failure of the stainless steel is compensated for by the performance of other barriers such as the unsaturated zone that retards the migration of the radionuclides (Tables 106 and 107). For disposals in the saturated zone, the increased corrosion rate decreases the activity levels that can be disposed in most geosphere systems, by an order of magnitude for Pu-238 and by two orders of magnitude for Pu-239. However, activity levels for Am-241 increase for some saturated geosphere systems since less time is available for the in-growth of radiologically significant daughters.

### 6.2.4. Decreased and increased cement grout sorption

The results are relatively insensitive to decreasing/increasing cement grout sorption values by two orders of magnitude. This is especially the case for the saturated zone due to the short (<0.25 m) horizontal travel distance through the grout meaning that the role of the grout in sorbing the radionuclides is not significant (Tables 108 to 111). For the unsaturated zone, activity levels vary by up to an order of magnitude between the values for the decreased and increased sorption cases, due to the longer (50 m) vertical travel distance through the grout.

### 6.2.5. Decreased and increased geosphere pathlength

Decreasing/increasing the pathlength through the saturated geosphere to the water abstraction well by an order of magnitude from the reference case of 100 m has a significant impact on the activity levels for most geosphere systems (Tables 112 to 115). The longer pathlength generally increases the levels due to the greater opportunity for retardation and decay, whilst the converse is true for the short pathlength. Varying the pathlength between 10 and 1000 m typically results in activity levels varying by two or three orders of magnitude.

### 6.2.6. Decreased and increased geosphere sorption

Decreasing/increasing sorption in the geosphere by two orders of magnitude has a similar effect to decreasing/increasing the geosphere pathlength, since it affects the travel time in the geosphere which in turn affect the extent of decay (Tables 116 to 119).

### 6.2.7. Alternative uses of abstracted groundwater

Calculations for the liquid release have been undertaken assuming that the abstracted water is used by humans for domestic (drinking) and agricultural purposes (watering of cattle and irrigation of green and root vegetables). It is recognized that alternative uses could be envisaged. Therefore three sets of variant calculations have been undertaken (Tables 120 to 125).

The first assumes that the water is used solely for meeting the drinking water demand of four people (2 l da/y person$^{-1}$). Results show that for the high flow saturated geospheres, the resulting activity values are up to an order of magnitude less restrictive than for the equilavent reference calculations due to the limitation of the exposure pathway to just ingestion of drinking water. However, for the saturated medium and low flow systems, and disposal in the unsaturated zone, the activity values are more restrictive by up to two orders of magnitude than for the equilavent reference calculations since there is less dilution at the GBI as a consequence of the lower abstraction rate.

The second set of calculations assumes that the water abstracted from the saturated geospheres is solely used to supply water for a fish farm. The annual individual effective dose to a human from the consumption of fish ($D_{Fish}$, in Sv/y) is given by:

$$D_{Fish} = C_W \ CF_{Fish} \ Ing_{Fish} \ DC_{Ing} \tag{6}$$

where:

$C_W$ is the radionuclide concentration in the abstracted water in which the fish are farmed (Bq m$^{-3}$) (calculated using 34);

$CF_{Fish}$ is the concentration factor for fish (m$^3$ kg$^{-1}$) (given in Table 72);

$Ing_{Fish}$ is the individual ingestion rate of fish (kg/y) (given in Table 83);

$DC_{Ing}$ is the dose coefficient for ingestion (Sv/Bq) (given in Table 65).

The results show that, in comparison with the activity levels for the equivalent reference calculations, levels increase by between one and two orders of magnitude. So consideration of fish farming does not result in more restrictive activity levels.

The third set of calculation assumes that the water abstracted from the saturated geosphere systems is used solely for bathing. The annual individual dose to a human from external irradiation from water ($D_{ExWat}$, in Sv/y) is given by:

$$D_{ExWat} = C_W \; O_{Wat} \; DC_{Extw} \tag{7}$$

where:

$C_W$ is the concentration in the water (Bq/m$^3$) (calculated using 34);

$O_{Wat}$ is the individual occupancy in the contaminated water (h/y) (given in Table 83);

$DC_{Extw}$ is the dose coefficient for external irradiation from water (Sv/h/Bq/m$^3$) (given in Table 65). The resulting activity levels are less restrictive by at least three orders of magnitude than for the reference calculation. This demonstrates the relative unimportance of this exposure pathway.

### 6.2.8. Decreased and increased erosion rates

The effect of decreasing/increasing erosion rates by an order of magnitude varies between the radionuclides considered (Tables 126 to 129). The increased rate results in the earlier exposure of the disposal zone (after 10 000 years) which in turn results in a Ra-226 activity level of $3 \times 10^{10}$ Bq. For Pu-239 there is a two order of magnitude range in the activity level with the higher erosion rate resulting in a lower activity level due to the earlier exposure of the disposal zone. The results for Pu-238 and Am-241 are affected by the in-growth of radiologically significant daughters, which means that the lower erosion rate gives a more restrictive activity level for Am-241 than the higher rate.

## 6.3. WHAT-IF CALCULATIONS

In order to investigate the role of the engineered and natural barriers in providing safety, a series of ‘what-if’ calculations have been undertaken in which various barriers have been removed from the modelled system.

### 6.3.1. No near field barriers

A series of calculation cases were undertaken that removed each near field barrier in turn, i.e.:

- No capsule but all other near field barriers in place (Tables 130, 131):
- No containment barrier but all other near field barriers in place (Tables 132, 133):
- No disposal container but all other near field barriers in place (Tables 134, 135): and
- No backfill but all other near field barriers in place (Tables 136, 137).

In addition, a further case was considered in which all near field barriers were removed (Tables 138, 139).

The results of these cases are summarized in Figs 18, 19 and 20 for Pu-238, Pu-239 and Am-241, respectively for liquid releases. They show that, for disposal of these radionuclides in the unsaturated zone, removing near field barriers has no significant effect on activity levels that can be disposed and in certain cases activity limits increase marginally due to the reduced time for the in-growth of radiologically significant daughters. More significant (order of magnitude) effects are generally seen for disposals in the saturated zone, reflecting the absence of the unsaturated zone below the disposal borehole to 'buffer' the effects of the barrier failure[15], and emphasizing the importance of the near field barriers to limit releases of radionuclides. It is important to note that not all radionuclides show a decrease in activity levels for cases with barriers removed (e.g. Pu-239 for the saturated medium flow system). This is due to the complex interplay between release mechanisms, migration times through the geosphere and the in-growth/decay of daughters. In the case of Pu-239, the release rate is assumed to be congruent (rather than instantaneous) and the medium flow geosphere provides sufficient retardation to allow the in-growth of the radiologically significant daughters. Thus, in this case, the absence of near field barriers is not significant.

Assuming that there are no near field barriers, results in significant increase in the number of radionuclides and geospheres for which the activity levels are less than $1 \times 10^{18}$ Bq (compare Table 25 with Table 18). This emphasizes the importance of the near field barriers for many of the radionuclides and geospheres considered. Fig. 21 compares the activity levels for the Design Scenario with the case with no near field barriers for H-3, Sr-90 and Ra-226 for liquid releases. The figure illustrates the significant (many orders of magnitude) reductions in activity levels for the case with no near field barriers, especially for the comparatively short lived H-3. Fig. 21 also illustrates:

- The 'buffering' effect of the unsaturated zone below the disposal borehole, especially for the longer-lived Ra-226; and
- The retarding effect of the medium and low flow geospheres which therefore allow the disposal of higher activity levels, even for the case of no near field barriers.

The absence of near field barriers also reduces the total activity levels for H-3 and Kr-85 gases from in excess of $1 \times 10^{18}$ Bq for the Design Scenario (Table 19) down to $1 \times 10^{11}$ Bq and $2 \times 10^{12}$ Bq, respectively (Table 26).

---

[15] Similar behaviour can be seen for the accelerated stainless steel corrosion variant case discussed in Section 6.2.3.

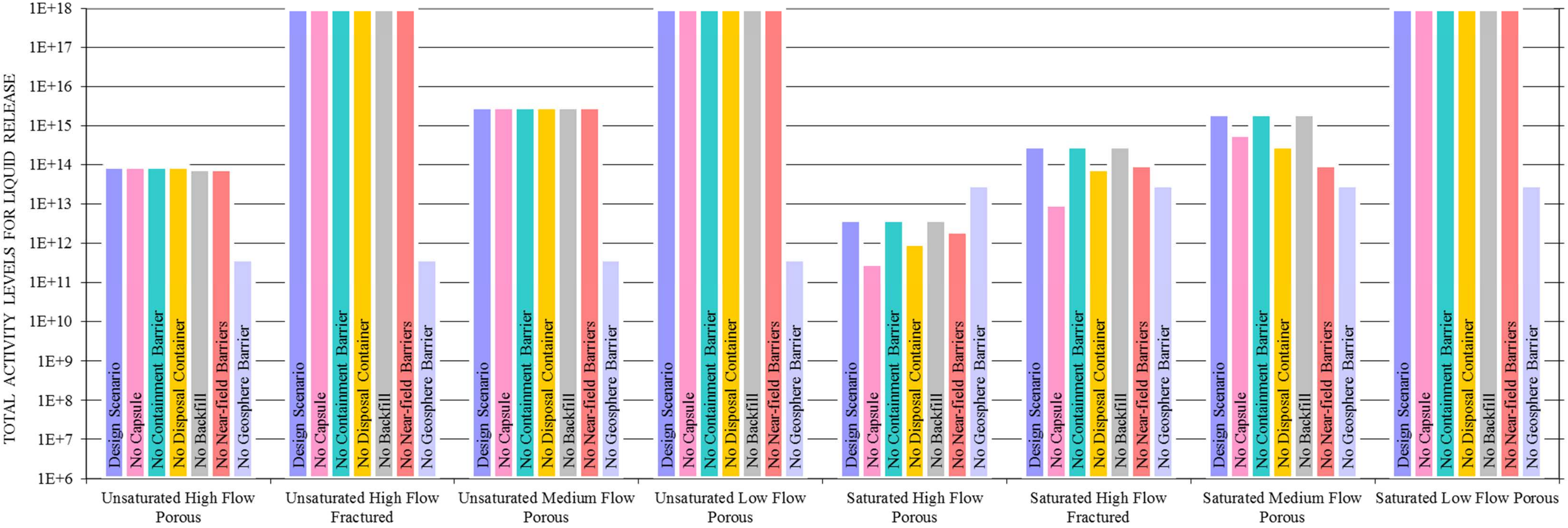


*FIG. 18. Pu-238 total activity levels for the design scenario and what-if calculations: liquid releases.*

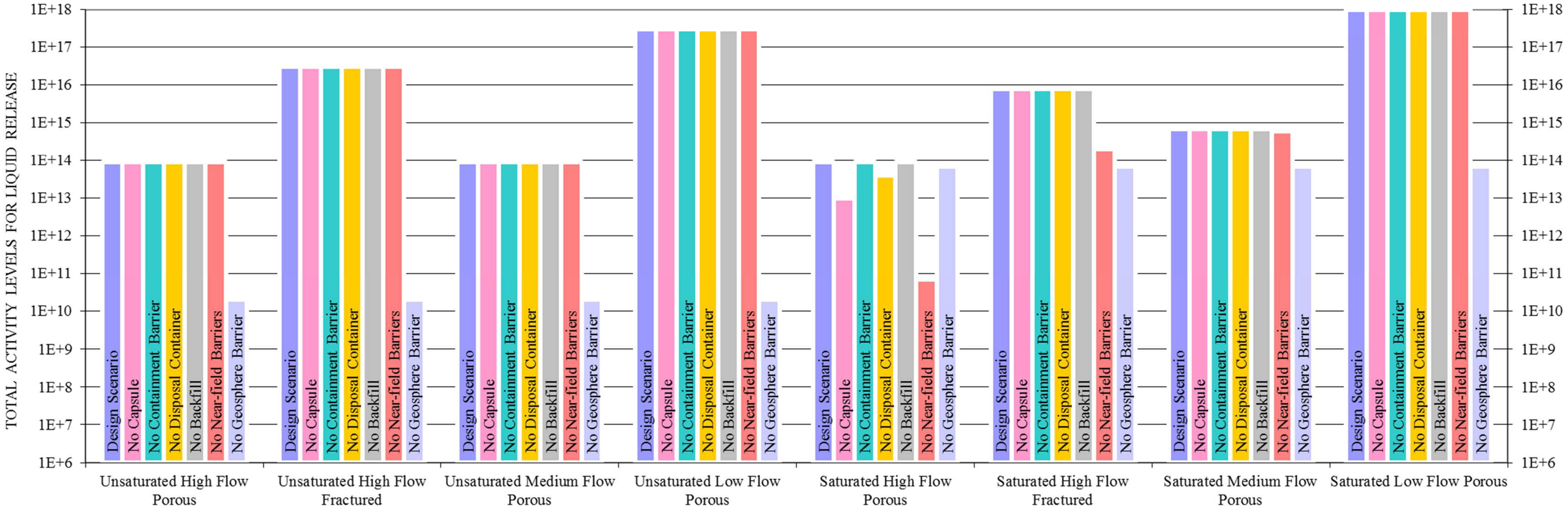


*FIG. 19. Pu-239 total activity levels for the design scenario and what-if calculations: liquid releases.*

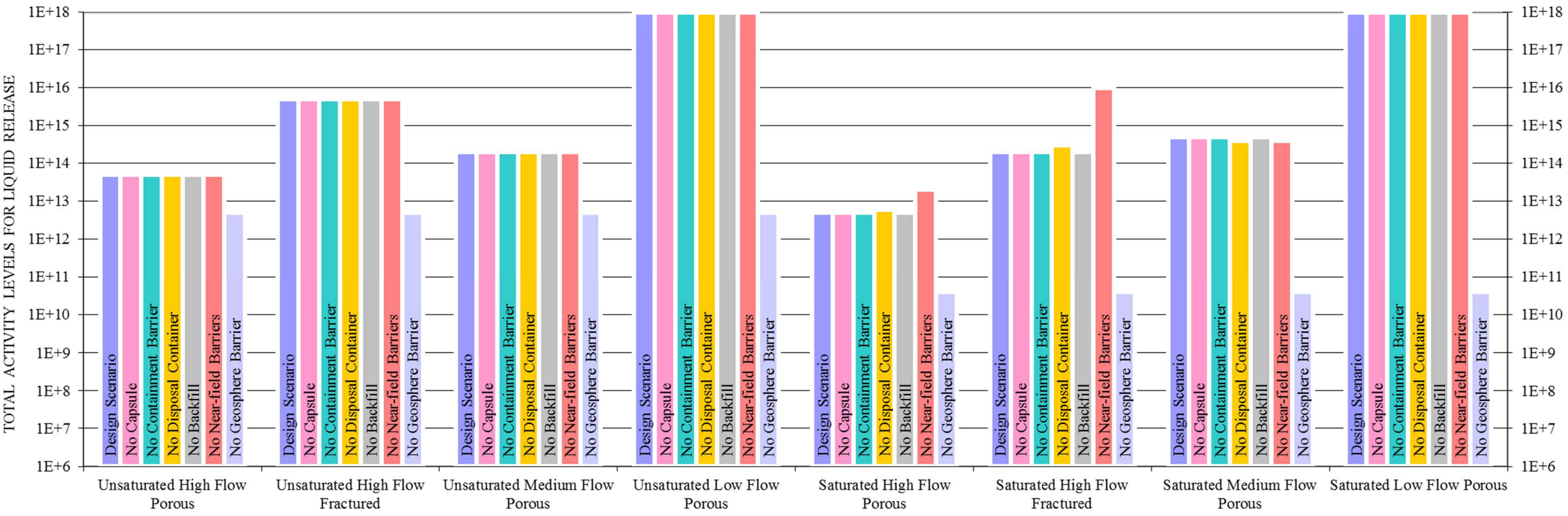


*FIG. 20. Am-241 total activity levels for the design scenario and what-if calculations: liquid releases.*

TABLE 25. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO NEAR FIELD BARRIERS

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | 2E+12 | * | * | * | 1E+17 | * | * | 9E+16 | 8E+13 | 9E+13 | 5E+13 |
| | | Fractured | 2E+12 | * | * | * | 3E+17 | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | 8E+13 | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | 2E+09 | * | 2E+14 | * | 7E+08 | 5E+12 | 3E+12 | 6E+08 | 2E+12 | 7E+10 | 2E+13 |
| | | Fractured | 2E+09 | * | 3E+14 | * | 1E+09 | 8E+13 | 3E+12 | 1E+10 | 1E+14 | 2E+14 | 1E+16 |
| | Medium | Porous | 2E+12 | * | * | * | 9E+16 | * | * | 2E+17 | 1E+14 | 6E+14 | 4E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

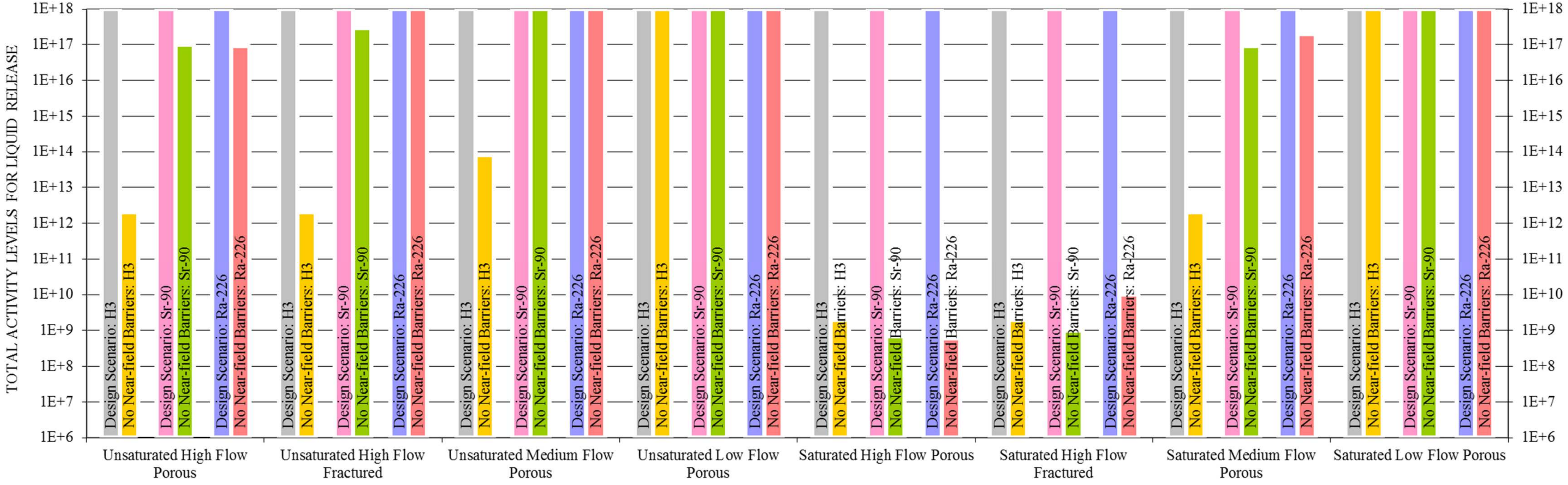


*FIG. 21. H-3, Sr-90 and Ra-226 total activity levels for the design scenario and no near field barriers calculation: liquid releases.*

TABLE 26. TOTAL ACTIVITY LEVELS FOR GASEOUS RELEASE FOR CASE WITH NO NEAR FIELD BARRIERS

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| 1E+11 [16] | n.a. | n.a. | 2E+12 | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

---

[16] Only applicable to unsaturated disposal zone. H-3 in saturated disposal zone is assumed to be dissolved in the groundwater.

### 6.3.2. No geosphere barrier

In order to quantify the contribution of the geosphere to safety, a variant case was considered in which the flux from the near field was assumed to discharge directly into the compartment from which the groundwater was abstracted (hence bypassing the geosphere). Due to the performance of the near field engineering, activity levels are above $1 \times 10^{18}$ Bq for all radionuclides except Ra-226, Pu-238, Pu-239 and Am-241 (Tables 142 and 143). For these long lived radionuclides, the activity levels are generally reduced by at least two orders of magnitude compared with the Design Scenario indicating the value of the geosphere as a natural barrier, especially in the case of disposal in the unsaturated zone and in the low flow saturated geosphere (Figs 18, 19 and 20).

## 6.4.ANALYSIS OF UNCERTAINTIES

When undertaking a long term safety assessment of a radioactive waste disposal system, it is important to be aware of and to manage, as far as possible, the various sources of uncertainty that arise, and to build confidence in the assessment and its results. Various measures have been implemented as part of the current assessment to address uncertainties and build confidence.

Uncertainties can be considered to arise from three sources:

First there is uncertainty in the evolution of the disposal system over the timescales of interest (**scenario uncertainty**). This has been accounted for in the current assessment by considering five scenarios, two of which have been evaluated quantitatively (Design and Defect Scenarios). The development and justification of these scenarios is discussed in Section 4. For a given disposal system, the range in associated activity levels for the two scenarios assessed quantitatively is generally small (much less than an order of magnitude). However, Defect Scenario D4 (which involves a failed waste capsule being within a failed disposal container) does result in a total activity limit of between $2 \times 10^{12}$ Bq and $7 \times 10^{17}$ Bq for H-3, Kr-85, Sr-90, Cs-137 and Ra-226 compared with values in excess of $1 \times 10^{18}$ Bq for the Design Scenario.

The second source of uncertainty is uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour and evolution of the disposal system (e.g. owing to the inability of models to represent the system completely and approximations used in solving the model equations) (**model uncertainty**). Various quality assurance checks have been undertaken to ensure that the mathematical model and data specified in Appendices XI and XII have been correctly implemented in the AMBER software tool and, as discussed in Section 5.6, independent verification tests for AMBER have been undertaken. Different concepts for the release of radionuclides from the near field and the use of abstracted water have been considered in Sections 6.1.2 and 6.2.7, respectively, indicating that differences of up to one to two orders of magnitude can arise compared to the reference assumptions.

The GSA considers the GBI to be a water abstraction borehole (see Section 3.2). Alternative interfaces could be considered that might result in the accumulation of certain long lived radionuclides (e.g. groundwater discharge into lake sediment). This sediment could subsequently be uncovered resulting in the exposure of humans to the accumulated radionuclides. Table 27 summarizes the peak activity of radionuclides in soil contaminated by irrigation water from the water abstraction borehole for the Design Scenario, and for lake sediment contaminated by direct groundwater discharge, for both high and low flow geospheres.

TABLE 27. PEAK ACTIVITY LEVELS FOR SOIL AND LAKE SEDIMENT

| Radionuclide | | High flow porous geosphere | | Low flow porous geosphere | |
|---|---|---|---|---|---|
| Parent | Daughter | Peak amount in soil (Bq) | Peak amount in sediment (Bq) | Peak amount in soil (Bq) | Peak amount in sediment (Bq) |
| P | | 0E+00 | 0E+00 | 0E+00 | 0E+00 |
| u | U-234 | 1E+06 | 1E+06 | 3E-09 | 6E-12 |
| - | Th-230 | 2E+06 | 5E+06 | 4E-09 | 8E-12 |
| 2 | Ra-226 | 3E+06 | 1E+07 | 7E-08 | 1E-11 |
| 3 | Pb-210 | 4E+06 | 1E+07 | 7E-08 | 1E-11 |
| 8 | Po-210 | 4E+06 | 1E+07 | 7E-08 | 1E-11 |
| Pu-239 | | 1E+01 | 2E+01 | 8E-15 | 2E-20 |
| | U-235 | 1E+06 | 9E+05 | 3E+01 | 1E+06 |
| | Pa-231 | 1E+06 | 2E+06 | 4E+01 | 1E+06 |
| | Ac-227 | 1E+06 | 2E+06 | 3E+01 | 1E+06 |
| Am-241 | | 0E+00 | 0E+00 | 0E+00 | 0E+00 |
| | Np-237 | 2E+07 | 1E+06 | 1E-05 | 9E-06 |
| | Pa-233 | 2E+07 | 1E+06 | 1E-05 | 9E-06 |
| | U-233 | 4E+07 | 3E+07 | 3E-05 | 1E-05 |
| | Th-229 | 4E+07 | 9E+07 | 3E-05 | 1E-05 |

It can be seen that activity amounts for the lake sediment are generally either lower or only marginally greater than for the soil. Given that the area affected by groundwater discharge into the lake sediment can be expected to be larger than the area of irrigated soil (361 $m^2$), it is considered that the concentration will be lower than in the soil and so the dose consequences will be lower. The only exception is for the daughters of Pu-239 discharged from the low flow geosphere, for which the peak activity is more than four orders of magnitude higher than for the soil. Activities are comparable to those for the high flow system and so disposal levels can be expected to be broadly comparable.

The third source of uncertainty is uncertainty in the data and parameters used as inputs in the modelling (**data and parameter uncertainty**). Such uncertainties can be assessed through deterministic and/or probabilistic sensitivity analysis if resources allow. The range of different near fields and geospheres considered in the current assessment allows an initial assessment of the impact of different parameter values (e.g. different corrosion and degradation rates, sorption coefficients, and hydraulic conductivities). Table 18 shows, that for liquid releases, differences of many orders of magnitude can arise in activity levels for the different systems considered due to the differences in key parameters such as sorption coefficients and travel times in the saturated zone. In addition, deterministic calculations have been reported in Section 6.2 that illustrate the sensitivity of the results to different parameter values. Differences of up to three orders of magnitude are observed for certain radionuclides for some parameters (e.g. geosphere pathlength and sorption coefficient). But for other parameters, the differences are significantly less than an order of magnitude.

In addition to the above sources of uncertainty, a further type of uncertainty, subjective uncertainty (uncertainty due to reliance on expert judgement), is also linked with the above sources of uncertainty [12]. In common with many other assessments, expert judgement has been used at many stages during the current assessment due to a variety of reasons such as a lack of knowledge concerning current and future conditions, conceptual models and data/parameter values (and distributions). Where such judgements have been made in the current assessment, they have been documented and, as far as practicable, justified – see for example Section 4 for the scenario development and justification process and Appendix XII for the data values.

## 6.5.BUILDING OF CONFIDENCE

Building confidence in the long term safety of a radioactive waste repository is an important issue [41], [42], [43]. To undertake a safety assessment and present the results is not sufficient. Confidence needs to be built in the safety assessment and its results. There is also a need to have confidence in other aspects of the long term safety of the repository in order to build confidence to the satisfaction of all stakeholders (i.e. regulators, the public, wider scientific community, political decision makers etc.). In particular, confidence in the long term safety needs to be promoted and communicated through a more broadly based ‘safety case’ e.g. [43], [44], [45]. The safety case puts the findings of the safety assessment into a broader context with other factors and considerations that are relevant to the decision making process and are important for the stakeholders involved.

Given that the focus of the current document is the safety assessment rather than the broader based safety case, the emphasis of this sub-section is on measures that have been taken to building confidence in the safety assessment and its results. Confidence in the safety assessment can be established at two levels. The first level involves establishing confidence within each stage of the safety assessment process (i.e. assessment context, system description, development and justification of scenarios, formulation and implementation of models, analysis of the results, and review, modification and subsequent iterations). The second level involves gaining an overall confidence, which involves gaining confidence in the overall safety assessment methodology, safety assessment approach and the safety assessment findings through the use of a range of techniques. The measures undertaken within the current assessment to building confidence at these two stages are summarized in Tables 28 and 29.

TABLE 28. MEASURES TAKEN TO BUILD CONFIDENCE IN EACH STAGE OF THE SAFETY ASSESSMENT

| Stage of the assessment | Confidence building measures taken in the GSA |
|---|---|
| Specification of assessment context | • The assessment context for the GSA of the borehole disposal concept is explained and justified in detail in Section 2.<br>• Each of the components of the context (purpose and scope, regulatory framework, end points, philosophy, and timeframes) is discussed in turn. |
| Description of the system | • The GSA is site generic (rather than site specific) and a wide range of differing disposal systems have been considered and are documented in Section 3.<br>• Different engineered barriers (cement grout, stainless steel, HDPE) and geospheres (unsaturated, saturated, low flow, medium flow, high flow, porous and fractured) are considered.<br>• The approach used is consistent with that used in a previous IAEA study to derive generic activity levels [23] and a previous generic safety assessment of a borehole disposal concept [32].<br>• Representative information has been taken from a range of relevant sources documented in Section 3 and Appendix XII. |
| Development and justification of scenarios | • A set of five scenarios has been developed and justified in Section 4.<br>• It is considered to be a credible and comprehensive set and to have been developed in a systematic, transparent and traceable manner using an international panel of experts with differing fields of expertise.<br>• The approach and screening criteria used to exclude or include scenarios has been justified and documented. |
| Formulation and implementation of models | • The development of conceptual models, consistent with the assessment context, the disposal systems and with the scenarios to be investigated, has been undertaken in a systematic manner consistent with best international practice (Section 5).<br>• The mathematical models used are consistent with those used in previous assessments such as [23], [32] and data are derived from a wide range of published and internationally recognized references.<br>• The software tool in which the mathematical models are encoded (AMBER) has been used in a variety of assessments (see for example Refs [23], [32], [37], [44], [45]). The verification of the time dependent solution method used by AMBER solution is discussed in Ref. [38]. The implementation of the models in the software has been audited.<br>• Consideration has been given to the use of alternative conceptual models and data. |
| Analysis of the results | • The results obtained for the wide range of disposal systems and scenarios have been presented in Sections 3 and 4 and compared against the relevant regulatory criteria.<br>• Both reference, variant and what-if calculations have been considered.<br>• Consideration has been given in Section 6.4 to the various sources of uncertainty (scenario, model and data/parameter). |
| Review, modification and subsequent iterations | • Drafts of the GSA were peer reviewed at IAEA technical meetings in 2004, 2005,2007 and in 2016 and revisions incorporated into the current version. |

TABLE 29. MEASURES TAKEN TO BUILD CONFIDENCE IN THE OVERALL SAFETY ASSESSMENT

| Confidence building measures | Application to the GSA |
|---|---|
| Use of a systematic approach | An approach based upon the internationally recognized ISAM Safety Assessment Approach [12] has been used. The approach allows the GSA and its associated assumptions to be documented in a clear manner. |
| Peer review | The GSA was peer reviewed at IAEA technical meetings in 2004, 2005, 2007 and 2016. |
| Quality assurance | The assessment has been carried out under Quintessa's Quality Management System, which is compliant with the ISO 9001:2000 standard [46]. |
| Verification, calibration and, if possible, validation of models | The verification of the time dependent solution method used by AMBER solution is discussed in Ref. [38]. Due to the generic nature of the GSA and its long timescales, validation of the models is not considered to be possible. |
| Consideration of relevant analogues | No consideration has been given to this issue in the GSA. |
| Involvement of stakeholders | IAEA staff and participants from three Member States have been involved in the development of the approach followed and the identification and justification of the scenarios for assessment. Participants from further Member States were involved in the review meetings in 2004, 2005, 2007 and 2016. |
| Consideration and treatment of uncertainties | This is discussed in Section 6.4. |
| Presentation of the assessment and its results | The results are presented in Sections 6.1, 6.2 and 6.3. The other components of the assessment are discussed in Sections 2 to 5 and the supporting appendices. |

# 7. CONCLUSIONS

This publication presents a GSA for a concept that would allow the disposal of disused sealed radioactive sources in narrow diameter boreholes. The GSA takes a design concept and, imagining it to be placed in a range of geological environments, assesses the question of post-closure safety for a variety of representative radionuclides.

The outcome of the GSA shows that, with a suitable combination of inventory, near field design and geological environment, the borehole disposal concept is capable of providing a safe solution for the disposal of both long lived and short lived radionuclides. For most radionuclides, including longer-lived radionuclides such as Ra-226, post-closure safety places no limit on the radionuclide inventory that could be disposed of in this way. Even for radionuclides with exceedingly long daughters (with half-lives in excess of 100 000 years), such as Pu-238, Pu-239 and Am-241, the concept has the potential to dispose around 1 TBq in a single borehole.

The GSA examines a series of reference geological environments. These are characterized by their geochemistry and hydrogeology. For each reference environment, the GSA derives corresponding reference activity levels of radionuclides that could, in terms of a post-closure safety, be disposed of safely. The reference inventory that is assessed in detail is limited to 11 radionuclides. However, it is considered that the borehole disposal concept is suitable for the disposal of other radionuclides of similar half-lives, mobility and radiotoxicity as demonstrated by the scoping calculations presented in Appendix I.

The GSA does not consider operational and pre-operational safety. Consequently, whilst large quantities of some radionuclides could, in principle, be disposed of using the borehole concept, the practical difficulties associated with handling large inventory sources could make it necessary to dispose of the source along with its shielding so that disposal in larger diameter boreholes might be more appropriate.

# APPENDIX I
# RADIONUCLIDE SCREENING

A total of 31 radionuclides have been identified for consideration in the GSA (see Section 3.1.1). The maximum inventory found across all the countries considered is given in Table 30, which also provides the half-life for each radionuclide. It is assumed for the purposes of the screening calculations that the total inventory is distributed evenly over the 50 capsules disposed in the borehole.

For reasons of practicality, it is desirable to screen out any radionuclides that, due to their half-life, maximum activity, or radiotoxicity, will not result in significant post-closure impacts. For the purposes of radionuclide screening, the dose constraint of 0.3 mSv/y is considered (Section 2.4).

Institutional control periods are often taken into consideration such that there is a period within which exposures are assumed not to occur. For the GSA an institutional control period of 30 years has been assumed (Section 2.7), within which exposures are considered not to occur.

Radionuclide screening has been undertaken in two simple steps:

- Preliminary screening – doses associated with direct exposure via ingestion, inhalation and external irradiation to a single disused source following a 30 year institutional control period are calculated; and
- Main screening – for those radionuclides remaining after Step 1, a simple assessment of doses associated with the groundwater and gas pathways is undertaken.

## I.1. PRELIMINARY SCREENING

The preliminary screening calculation assumes that a human is directly exposed to a single disused sealed radioactive source following the end of the institutional control period. Exposure through ingestion, inhalation and external irradiation is considered. For the inhalation pathway, Kr-85 exposure is via inhalation of the gas, for all other radionuclides exposure is due to inhalation of particulate material. The resulting doses are given in Table 31.

TABLE 30. RADIONUCLIDES CONSIDERED IN THE SCREENING CALCULATIONS

| Radionuclide | Maximum inventory (Bq) | Half life (y)[a] |
|---|---|---|
| H-3 | 2.8E+14 | 1.24E+01 |
| Na-22 | 3.4E+06 | 2.60E+00 |
| Mn-54 | 1.0E+05 | 8.56E-01 |
| Fe-55 | 9.9E+09 | 2.70E+00 |
| Co-57 | 1.7E+10 | 7.42E-01 |
| Co-60 | 2.9E+15 | 5.27E+00 |
| Ni-63 | 2.1E+10 | 9.60E+01 |
| Zn-65 | 3.7E+05 | 6.68E-01 |
| Se-75 | 3.0E+11 | 3.28E-01 |
| Kr-85 | 6.3E+11 | 1.07E+01 |
| Y-88 | 1.0E+05 | 2.92E-01 |
| Sr-90 | 5.3E+11 | 2.91E+01 |
| Cd-109 | 3.1E+09 | 1.27E+00 |
| Ba-133 | 3.3E+08 | 1.07E+01 |
| Cs-137 | 7.5E+14 | 3.00E+01 |
| Pm-147 | 2.7E+11 | 2.62E+00 |
| Sm-151 | 7.8E+09 | 9.00E+01 |
| Eu-152 | 4.0E+08 | 1.33E+01 |
| Gd-153 | 1.5E+11 | 6.63E-01 |
| Yb-169 | 2.2E+11 | 8.76E-02 |
| Ir-192 | 9.3E+14 | 2.03E-01 |
| Au-195 | 4.0E+07 | 5.01E-01 |
| Hg-203 | 1.5E+06 | 1.28E-01 |
| Tl-204 | 5.0E+08 | 3.78E+00 |
| Pb-210 | 1.0E+07 | 2.23E+01 |
| Po-210 | 1.0E+10 | 3.79E-01 |
| Ra-226 | 2.6E+13 | 1.60E+03 |
| Pu-238 | 2.0E+10 | 8.77E+01 |
| Pu-239 | 6.7E+11 | 2.41E+04 |
| Am-241 | 1.2E+13 | 4.32E+02 |
| Cf-252 | 4.1E+09 | 2.64E+00 |

**Note:** [a] Data taken from Ref. [47].

TABLE 31. PRELIMINARY SCREENING - DOSES ASSOCIATED WITH DIRECT EXPOSURE TO A DISUSED SEALED RADIOACTIVE SOURCE

| Radionuclide | Maximum inventory at 30 y (Bq) | Dose coefficients[a] | | | Ingestion dose (Sv) | Inhalation dose (Sv) | External dose (Sv)[g] |
|---|---|---|---|---|---|---|---|
| | | Ingestion (Sv/Bq)[b] | Inhalation (Sv/Bq)[b, c] | External (Sv/h per Bq)[d] | | | |
| H-3 | 1.0E+12 | 1.8E-11 | 4.5E-11 | 0.0E+00 | 1.9E+01 | 4.7E+01 | 0.0E+00 |
| Na-22 | 2.3E+01 | 3.2E-09 | 1.3E-09 | 3.1E-13 | 7.3E-08 | 3.0E-08 | 7.0E-11 |
| Mn-54 | 5.6E-08 | 7.1E-10 | 1.5E-09 | 1.2E-13 | 4.0E-17 | 8.5E-17 | 6.6E-20 |
| Fe-55 | 9.0E+04 | 3.3E-10 | 7.7E-10 | 3.4E-19 | 3.0E-05 | 6.9E-05 | 3.0E-13 |
| Co-57 | 2.3E-04 | 2.1E-10 | 5.5E-10 | 1.7E-14 | 4.8E-14 | 1.3E-13 | 3.9E-17 |
| Co-60 | 1.1E+12 | 3.4E-09 | 1.0E-08 | 3.5E-13 | 3.8E+03 | 1.1E+04 | 3.9E+00 |
| Ni-63 | 3.4E+08 | 1.5E-10 | 4.8E-10 | 0.0E+00 | 5.1E-02 | 1.6E-01 | 0.0E+00 |
| Zn-65 | 2.2E-10 | 3.9E-09 | 1.6E-09 | 8.1E-1414 | 8.7E-19 | 3.6E-19 | 1.8E-22 |
| Se-75 | 1.8E-18 | 2.6E-09 | 1.0E-09 | 5.4E-1444 | 4.6E-27 | 1.8E-27 | 9.5E-31 |
| Kr-85 | 1.8E+09 | 0.0E+00 | 9.2E-13[e] | 0.0E+00 | 0.0E+00 | 1.7E-03[f] | 0.0E+00 |
| Y-88 | 2.4E-28 | 1.3E-09 | 4.4E-09 | 3.8E-13 | 3.1E-37 | 1.0E-36 | 8.9E-40 |
| Sr-90 | 5.2E+09 | 3.1E-08 | 3.8E-08 | 2.8E-16 | 1.6E+02 | 2.0E+02 | 1.5E-05 |
| Cd-109 | 4.8E+00 | 2.0E-09 | 8.1E-09 | 4.5E-16 | 9.6E-09 | 3.9E-08 | 2.1E-14 |
| Ba-133 | 9.5E+05 | 1.5E-09 | 3.1E-09 | 5.1E-14 | 1.4E-03 | 2.9E-03 | 4.8E-07 |
| Cs-137 | 7.5E+12 | 1.3E-08 | 3.7E-08 | 7.8E-14 | 9.8E+04 | 2.8E+05 | 5.9E+00 |
| Pm-147 | 1.9E+06 | 2.6E-10 | 5.0E-09 | 4.8E-19 | 5.0E-04 | 9.6E-03 | 9.3E-12 |
| Sm-151 | 1.2E+08 | 9.8E-11 | 4.0E-09 | 4.5E-18 | 1.2E-02 | 5.0E-01 | 5.6E-09 |
| Eu-152 | 1.7E+06 | 1.4E-09 | 4.2E-08 | 1.6E-13 | 2.3E-03 | 7.0E-02 | 2.7E-06 |
| Gd-153 | 7.2E-05 | 2.7E-10 | 2.1E-09 | 7.3E-15 | 1.9E-14 | 1.5E-13 | 5.3E-18 |
| Yb-169 | 3.6E-94 | 7.1E-10 | 3.0E-09 | 3.9E-14 | 2.5E-103 | 1.1E-102 | 1.4E-106 |
| Ir-192 | 6.1E-32 | 1.4E-09 | 6.6E-09 | 1.1E-13 | 8.5E-41 | 4.0E-40 | 6.9E-44 |
| Au-195 | 7.5E-13 | 2.5E-10 | 1.7E-09 | 1.1E-14 | 1.9E-22 | 1.3E-21 | 8.3E-26 |
| Hg-203 | 8.4E-67 | 1.9E-09 | 2.4E-09 | 3.3E-14 | 1.6E-75 | 2.0E-75 | 2.8E-79 |
| Tl-204 | 4.1E+04 | 1.2E-09 | 3.9E-10 | 1.5E-16 | 4.9E-05 | 1.6E-05 | 6.0E-11 |
| Pb-210 | 7.9E+04 | 6.9E-07 | 1.2E-06 | 5.4E-17 | 5.4E-02 | 9.4E-02 | 4.3E-11 |
| Po-210 | 3.0E-16 | 1.2E-06 | 3.3E-06 | 1.2E-18 | 3.6E-22 | 9.8E-22 | 3.6E-33 |
| Ra-226 | 5.1E+11 | 2.8E-07 | 3.5E-06 | 2.4E-13 | 1.4E+05 | 1.8E+06 | 1.2E+00 |
| Pu-238 | 3.2E+08 | 2.3E-07 | 4.6E-05 | 1.0E-18 | 7.3E+01 | 1.5E+04 | 3.2E-09 |
| Pu-239 | 1.3E+10 | 2.5E-07 | 5.0E-05 | 7.0E-18 | 3.3E+03 | 6.7E+05 | 9.4E-07 |
| Am-241 | 2.3E+11 | 2.0E-07 | 4.2E-05 | 3.0E-15 | 4.6E+04 | 9.6E+06 | 6.9E-03 |
| Cf-252 | 3.1E+04 | 9.0E-08 | 2.0E-05 | 8.6E-13 | 2.8E-03 | 6.2E-01 | 2.7E-07 |

**Notes:** [a] Short lived daughters with a half life of less than 25 days are assumed to be in secular equilibrium with their parent and included in the parent's dose coefficient. A list of short lived daughters is given in Table 33.

[b] Data taken from Ref. [141] for adults.

[c] Data taken from Ref. [141] for adults, adopting the recommended default absorption class, where no recommendation is made, then the most conservative (highest) dose coefficient is adopted from the range of absorption classes reported.

[d] Dose factor for point source at a distance of 1 m calculated by multiplying mean gamma energy in MeV by 1.4E-13 Sv/h per Bq/MeV [142]. Emissions data are taken from Refs [143], [144]. Photons with individual energies below 50 keV have not been included because the equation used to calculate the dose coefficient from a point source substantially over-estimates the dose rate below this value, and the contribution to effective dose equivalent, given the existence of other exposure pathways, would in any event be very small.

[e] Units are Sv/h per Bq/m$^3$.

[f] Dose calculated assuming inventory to be in 1 m$^3$ of air and exposure duration of 1 hour.

[g] Dose calculated assuming an exposure duration of 10 hours.

The following radionuclides give a dose of less than 0.3 mSv/y following direct exposure to the disused sealed radioactive source for all three potential exposure pathways: Na-22, Mn-54, Fe-55, Co-57, Zn-65, Se-75, Y-88, Cd-109, Gd-153, Yb-169, Ir-192, Au-195, Hg-203, Tl-204 and Po-210. These radionuclides are therefore screened out.

## I.2. MAIN SCREENING

A simple exposure model has been developed for the groundwater and gas pathways using the AMBER code (as applied within the main GSA calculations – see Section 5.4). The model uses the reduced decay chains described in Tables 32 and 33, and the dose coefficients and half lives given in Table 34. The model was run for a simulation time of 1E+06 years to investigate the effects of in-growth, and in particular the generation of Rn-222 gas.

## TABLE 32. RADIONUCLIDES AND ASSOCIATED DAUGHTERS CONSIDERED IN THE MAIN SCREENING CALCULATIONS

| Disposed radionuclide | Short lived daughter(s)[a] | Daughter(s)[a] |
|---|---|---|
| H-3 | | |
| Co-60 | | |
| Ni-63 | | |
| Kr-85 | | |
| Sr-90 | * | |
| Ba-133 | | |
| Cs-137 | * | |
| Pm-147 | | |
| Sm-151 | | |
| Eu-152 | | |
| Pb-210 | * | →Po-210 |
| Ra-226 | * | →Pb-210*→ Po-210 |
| Pu-238 | | →U-234→ Th-230→ Ra-226*→ Pb-210*→ Po-210 |
| Pu-239 | | →U-235*→Pa-231→Ac-227* |
| Am-241 | | →Np-237→ Pa-233→ U-233→ Th-229* |
| Cf-252 | | → (branching ratio 0.9691)Cm-248 → (branching ratio 0.9161)Pu-244*→ Pu-240→U236→Th-232→Ra-228*→Th-228** |

**Note:** [a] * indicates a daughter with a half-life of less than 25 days (see Table 33).

## TABLE 33. SHORT LIVED DAUGHTERS WITH HALF-LIVES OF LESS THAN 25 DAYS ASSUMED TO BE IN SECULAR EQUILIBRIUM WITH THEIR PARENTS

| Parent | Short lived daughters |
|---|---|
| Sr-90 | → Y-90 |
| Cs-137 | → (branching ratio 0.946) Ba-137m |
| Pb-210 | → Bi-210 |
| Ra-226 | → Rn-222→ Po-218→ (branching ratio 0.999 8) Pb-214 → Bi-214 → (branching ratio 0.999 8) Po-214 |
| | → (branching ratio 0.000 2) At-218 → Bi-214 → (branching ratio 0.999 8) Po-214 |
| Ac-227 | → (branching ratio 0.013 8) Fr-223→(branching ratio 0.9862) Th-227 →Ra-223→Rn-219→Po-215→Pb-211 → Bi-211 |
| | → (branching ratio 0.997 2) →Tl-207→(branching ratio 0.0028) Po-211 |
| Th-229 | → Ra-225→ Ac-225→ Fr-221→ At-217→ Bi-213→ (branching ratio 0.978 4) Po-213→ Pb-209 |
| | → (branching ratio 0.021 6) Tl-209→ Pb-209 |
| Ra-228 | → Ac-228 |
| Th-228 | →Ra-224→→Rn-220→Po-216→Pb-212→→Bi-212→→(branching ratio 0.641)Po-212 |
| | →→ (branching ratio 0.359)Tl-208 |
| U-235 | → Th-231 |
| Pu-244 | → (branching ratio 0.9988)U-240→Np-240m→ (branching ratio 0.0011)Np-240 |

TABLE 34. MAIN SCREENING – DOSE COEFFICIENTS AND HALF LIVES

| Radionuclide | Dose coefficients[a] | | Half life (y)[c] |
|---|---|---|---|
| | Ingestion (Sv/Bq) | Inhalation (Sv/Bq) | |
| H-3 | 1.8E-11 | 4.5E-11<br>1.8E-11 (HTO gas) | 1.24E+01 |
| Co-60 | 3.4E-09 | 1.0E-08 | 5.27E+00 |
| Ni-63 | 1.5E-10 | 4.8E-10 | 9.60E+01 |
| Kr-85 | 0.0E+00 | 9.2E-13[b] | 1.07E+01 |
| Sr-90 | 3.1E-08 | 3.8E-08 | 2.91E+01 |
| Ba-133 | 1.5E-09 | 3.1E-09 | 1.07E+01 |
| Cs-137 | 1.3E-08 | 3.7E-08 | 3.00E+01 |
| Pm-147 | 2.6E-10 | 5.0E-09 | 2.62E+00 |
| Sm-151 | 9.8E-11 | 4.0E-09 | 9.00E+01 |
| Eu-152 | 1.4E-09 | 4.2E-08 | 1.33E+01 |
| Pb-210 | 6.9E-07 | 1.2E-06 | 2.23E+01 |
| Po-210 | 1.2E-06 | 3.3E-06 | 3.79E-01 |
| Ra-226 | 2.8E-07 | 3.5E-06<br>9.0E-09 Rn-222[b] | 1.60E+03 |
| Ra-228 | 6.9E-07 | 1.6E-05 | 5.75E+00 |
| Ac-227 | 1.2E-06 | 5.7E-04 | 2.18E+01 |
| Th-228 | 1.4E-07 | 4.4E-05 | 1.91E+00 |
| Th-229 | 6.1E-07 | 8.6E-05 | 7.34E+03 |
| Th-230 | 2.1E-07 | 1.4E-05 | 7.70E+04 |
| Th-232 | 2.3E-07 | 1.1E-04 | 1.40E+10 |
| Pa-231 | 7.1E-07 | 1.4E-04 | 3.28E+04 |
| Pa-233 | 8.7E-10 | 3.9E-09 | 7.39E-02 |
| U-233 | 5.1E-08 | 3.6E-06 | 1.59E+05 |
| U-234 | 4.9E-08 | 3.5E-06 | 2.45E+05 |
| U-235 | 4.7E-08 | 3.1E-06 | 7.04E+08 |
| U-236 | 4.7E-08 | 8.7E-06 | 2.34E+07 |
| Np-237 | 1.1E-07 | 2.3E-05 | 2.14E+06 |
| Pu-238 | 2.3E-07 | 4.6E-05 | 8.77E+01 |
| Pu-239 | 2.5E-07 | 5.0E-05 | 2.41E+04 |
| Pu-240 | 2.5E-07 | 5.0E-05 | 6.54E+03 |
| Am-241 | 2.0E-07 | 4.2E-05 | 4.32E+02 |
| Pu-244 | 2.4E-07 | 4.7E-05 | 8.26E+07 |
| Cm-248 | 7.7E-07 | 1.5E-04 | 3.39E+05 |
| Cf-252 | 9.0E-08 | 2.0E-05 | 2.64E+00 |

**Notes:** [a] Data taken from Ref. [141] for adult, except for Rn-222 gas which is taken from Ref. [144]. Short lived daughters with a half life of less than 25 days are assumed to be in secular equilibrium with their parent and included in the parent's dose coefficient. For inhalation, the recommended default absorption class given in Ref. [141] is adopted. Where no recommendation is made, then the most conservative (highest) dose coefficient is adopted from the range of absorption classes reported.

[b] Units are Sv/h per Bq/m$^3$.

[c] Data taken from Ref. [143].

For the groundwater pathway it is assumed that, following an institutional control period of 30 years, a groundwater well is sunk immediately adjacent to a disposal borehole. The well is of the same depth as the disposal borehole and is open throughout its length. It is assumed to immediately capture all the contamination released from the disposal borehole. It is assumed that water is drawn into the well from a column of radius 5 m and length 50 m, with a rock porosity of 0.3. For the purposes of calculating ingestion doses, it is assumed that the well is used to supply drinking water (assumed to be 0.6 m$^3$/y per person). For the purposes of calculating inhalation doses, it is assumed that the well is used to irrigate a small garden (4 m$^2$) and humans are exposed from inhalation of contaminated soil. External irradiation is not considered in the main scoping calculations since the preliminary scoping calculations have shown that external irradiation calculations are lower than ingestion and inhalation doses (see Table 31).

For the gas scenario, it is assumed that, following the 30 year institutional control period, a house is built directly above a disposal borehole and a resident is exposed to all the gas released from the disposed packages in the borehole. No account is taken of dilution, dispersion, or attenuation. All gas released from the borehole is assumed to enter the house, which is assumed to be continuously occupied. The house dimensions were assumed to be conservatively small (4 × 4 × 2.5 m) and a ventilation rate of 0.25 $h^{-1}$ which is typical for a well insulated building [54].

For the main screening assessment, for both the groundwater and gas pathways, it is also considered appropriate to take the engineering performance into consideration. It is assumed that 5 of the 50 packages disposed in a single disposal borehole fail after 30 years, releasing their entire inventory. The remaining 45 disposal packages are assumed to fail after 100 years releasing their entire inventories into the groundwater (for the groundwater pathway calculations) or the house (for the gas pathway calculations).

The results for the groundwater and gas pathways are presented in Tables 35 and 36, respectively. For the groundwater pathway, calculated doses for Ba-133, Pm-147, Sm-151, Eu-152 and Cf-252 are below the screening dose of 0.3 mSv/y and are therefore screening out of the GSA. The gas pathway results for all four radionuclides exceed the screening dose of 0.3 mSv/y and are therefore included in the assessment.

Following the preliminary and main screening calculations, the following 11 radionuclides are identified for inclusion in the GSA: H-3, Co-60, Ni-63, Kr-85, Sr-90, Cs-137, Pb-210, Ra-226, Pu-238, Pu-239 and Am-241.

TABLE 35. MAIN SCREENING – RESULTS FOR THE GROUNDWATER PATHWAY

| Radionuclide | Peak ingestion dose (Sv/y) | Peak inhalation dose (Sv/y)[a] |
|---|---|---|
| H-3 | 4.8E-02 | 3.5E-05 |
| Co-60 | 9.7E+00 | 8.3E-03 |
| Ni-63 | 7.8E-04 | 7.2E-07 |
| Sr-90 | 7.7E-01 | 2.8E-04 |
| Ba-133 | 3.5E-06 | 2.1E-09 |
| Cs-137 | 4.9E+02 | 4.1E-01 |
| Pm-147 | 1.3E-06 | 7.2E-09 |
| Sm-151 | 1.8E-04 | 2.1E-06 |
| Eu-152 | 6.0E-06 | 5.2E-08 |
| Pb-210 | 4.3E-04 | 3.0E-07 |
| Ra-226 | 2.7E+04 | 2.9E+01 |
| Pu-238 | 1.1E+00 | 6.2E-02 |
| Pu-239 | 8.5E+01 | 4.9E+00 |
| Am-241 | 1.0E+03 | 6.3E+01 |
| Cf-252 | 1.2E-05 | 6.8E-07 |

**Note:** [a] Calculated assuming soil depth of 0.3 m, soil porosity of 0.3, grain density of 2650 kg/$m^3$, dust loading of 1E-6 kg/$m^3$ and inhalation rate of 1.8 $m^3$/h.

TABLE 36. MAIN SCREENING – RESULTS FOR THE GAS PATHWAY

| Radionuclide (parent) | Peak inhalation dose (Sv/y) |
|---|---|
| H-3 | 9.4E+00 |
| Kr-85 | 8.3E-04 |
| Rn-222 (Ra-226) | 2.2E+04 |
| Rn-222 (Pu-238) | 3.7E-03 |

# APPENDIX II
# GEOCHEMICAL CONDITIONS CONSIDERED

## II.1. SPECIFICATIONS FOR GEOCHEMICAL CONDITIONS

The specifications for geochemical conditions need to have the following characteristics.

- Based on well-defined criteria.
- Effectively define bounding values for geochemical parameters that may affect corrosion or degradation of engineered barriers.
- Internally consistent. Note that values for many geochemical parameters are related to one another and therefore extreme (bounding) values cannot always be specified independently. For example, extremely high $CO_3^{2-}$ concentrations would not occur in groundwater with extremely low pH.
- Reasonable for the geological environments that might plausibly be chosen for borehole disposal. In other words, it is inappropriate to consider groundwater of extreme composition that would occur only in a geological environment that is unsuitable for borehole disposal according to non-geochemical criteria.

## II.2. APPROACH TO DEFINING GEOCHEMICAL CONDITIONS

It is considered that the composition of any particular groundwater will reflect primarily a combination of:

- Water/rock interactions; and
- Mixing between other compositionally distinct groundwaters and/or recharge waters.

Thus, the required bounding compositions can be based on those of:

- Groundwaters that occur in a range of different rock types;
- Surface waters that are found in a range of surface environmental conditions.

To ensure that the specified ranges of geochemical conditions are internally consistent, the compositions presented in the present publication are derived from a combination of:

- Real groundwater compositions;
- Theoretical simulations to obtain limiting values for key parameters that are consistent with these real groundwater compositions.

The real groundwater samples used have extreme compositions. An extreme composition is simply one that includes the greatest (and/or smallest) observed values for one or more determinands.

In principle, for each geochemical parameter, it would be possible to identify a groundwater composition with an extreme value. However, this approach would lead to the definition of a very large number of extreme compositions. For the present project, it is considered neither practicable nor necessary to follow this approach. Several of the chemical parameters of interest will be correlated, and will each have extreme values in the same water sample.

Note that not all such extreme groundwater compositions are ‘limiting’ compositions in the same way that mineralogical end-members are true limiting compositions of a particular solid solution. Unlike mineralogical end-members, in most real extreme groundwater compositions, one or more geochemical parameters will not be limited by any particular physical or chemical process.

Bearing in mind these points, the following steps were taken here:

- The fundamental processes that influence/control groundwater chemistry were reviewed. The database of (FEPs) used for the development and justification of scenarios (see Section 4) was used to check that no key processes had been omitted.
- These processes were screened to remove any that would occur only where conditions would be unsuitable for geological disposal, as indicated by non-geochemical criteria.
- The results of the review and screening were used to:
    - Identify theoretical limits on key parameters (e.g. Equilibrium with the atmosphere buffering the dissolved oxygen concentration);
    - Identify parameters for which theoretical limits are unlikely to be reached in nature under the pressure and temperature conditions of interest;
    - Recommend groundwater compositions with realistic extreme values for these parameters that are unlikely to be limited by natural processes.
- These groundwater compositions were used as inputs to theoretical models that calculated extreme values for process-limited parameters.
- The global distribution of the groundwater compositions that have not been screened out was determined, to demonstrate the plausibility of such compositions occurring within all countries that might consider borehole disposal.

## II.3. BOUNDING GROUNDWATER COMPOSITIONS

Table 37 tabulates 12 water compositions that effectively bound the compositional space of groundwaters that are expected to occur in all environments that are likely to be considered for borehole disposal of disused sealed radioactive sources.

However, a smaller number of water compositions is sufficient to undertake calculations that are designed to bound the degradation rates of engineered barriers. This sub-set of the water compositions was selected by identifying:

- The geochemical parameters that would influence the corrosion rate of steel and/or the degradation rate of cement grout; and
- The water compositions that have values of parameters that would result in maximum rates.

The following geochemical parameters are particularly important from the point of view of determining the rates of corrosion of metals and the degradation rates of cement grout:

- pH;
- Redox potential (Eh);
- Dissolved $O_2$ concentration;
- $SO_4^{2-}$ concentration;
- TIC concentration;
- $Cl^-$ concentration.

The screening according to the likely influence on corrosion rates places most emphasis on the redox conditions and $Cl^-$ content. Accordingly, high and low $Cl^-$ waters under both aerobic and anaerobic conditions are of most interest, leading to selection of the following compositions:

- Aerobic, high $Cl^-$: water – No. 12 (alkaline, Na-Cl-$SO_4$ brine);
- Anaerobic, high $Cl^-$ water – No. 6 (halite-saturated brine) (Nos 3, 8 and 9 also fall into this group);

- Anaerobic, but relatively oxidising, low $Cl^-$ – No. 10 (fresh, high-ph water);
- Anaerobic, but relatively reducing, low $Cl^-$ – No. 5. (fresh reducing high ph) (Nos 4 and 7 also fall into this group).

However, whereas redox state and $Cl^-$ concentrations are considered to be the primary controls on metal corrosion, pH, $SO_4^{2-}$ and TIC will be the main controls on cement grout stability. In particular, cement grout degradation will be tend to be enhanced by low pH, high $SO_4$ and high TIC. The above selection of groundwater compositions includes the highest $SO_4^{2-}$ composition among the bounding waters (groundwater No. 12). However, waters with lowest pH and highest TIC are not included. Therefore, to ensure that a conservative treatment of cement grout degradation is included among the calculations to be undertaken during this project, the following compositions are also selected:

- Low-ph meteoric water – No. 1; and
- Alkaline, Na-Cl brine with high TIC – No. 11.

Thus, of the 12 water compositions, six (Nos 1, 5, 6, 10, 11 and 12) are considered sufficient to bound the chemical controls on barrier corrosion and degradation for the purposes of sensitivity analysis.

## II.4. REFERENCE GROUNDWATER COMPOSITIONS

Whilst it is acceptable to have six groundwaters for the purposes of bounding/sensitivity calculations, there is a need to reduce the number further for reference case calculations. The suitability of each of the six bound waters was reviewed as follows.

- Waters **Nos 11 and 12** would occur only at or near localities where there are, or have been, surface water bodies with high evaporation rates. That is, these groundwaters would be most likely to occur in certain extremely arid environments. Whilst in principle such environments might be considered for borehole disposal in some cases, they are not as widely distributed in regions of the world. Consequently Nos 11 and 12 are not considered further.
- Waters like the halite saturated brine, No. 9, are more widely distributed than waters Nos 11 and 12. However, chloride brines like water No. 9 tend to occur at relatively great depths (reflecting partly their high densities) and are most typically distributed in regions where presently there are evaporite deposits.
- In contrast to water No. 9, water **No. 6** is diagenetically altered marine water. Such waters are very widely distributed, not only in present coastal regions, but also inland. These latter occurrences reflect the past penetration of seawater into the sub-surface during periods of relatively high sea level, or the preservation of connate marine water.
- Water No. 10 is fresh water that has reacted with minerals in mafic crystalline rock and consequently acquired its alkaline pH. The water is broadly similar to water No. 5, but is more oxidising and alkaline. Water No. 5 is one that has reacted with granitic rock, thereby gaining a moderately alkaline composition. Waters like both Nos 10 and 5 are quite widely distributed in areas of crystalline rock. However, on a global scale, in continental areas rocks of broadly granitic composition are more common than are rocks of gabbroic composition.
- Water **No. 1** is an example of acid rainwater. Clearly, fresh meteoric water will occur globally; this one's acid composition makes it an extreme example of meteoric water.

Given the requirement to select three waters, so as to reduce the number of calculations to a manageable level, and to ensure that each of the selected waters has a wide distribution, Nos 1, 5 and 6 are chosen.

TABLE 37. GEOCHEMICAL DETERMINANDS FOR SELECTED GROUNDWATERS

| Determinand | Units | No. 1. Acid meteoric water | | | No. 2. Ocean standard water | | |
|---|---|---|---|---|---|---|---|
| | | Value | Source of data | Notes | Value | Source of data | Notes |
| Temperature | °C | 6 | [48] | 1 | 16.1 | [58] | 4 |
| pH | pH | 4.1 | [47] | 2,3 | 8.2 | [59] | 5 |
| Eh | mV | 996 | [47] | 2,3 | 751 | | 6 |
| Dissolved $O_2$ | mg/kg | 12.0 | [47] | 2,3 | 7.97 | | 6 |
| Na | mg/kg | 0.11 | [47] | 2,3 | 10 770 | [60] | |
| K | mg/kg | 0.08 | [47] | 2,3 | 399 | [60] | |
| Mg | mg/kg | 0.05 | [47] | 2,3 | 1290 | [60] | |
| Ca | mg/kg | 0.16 | [47] | 2,3 | 412 | [60] | |
| Si | mg/kg | | | | 2.8 | [60] | |
| Al | mg/kg | | | | 0.001 | [60] | |
| Fe | mg/kg | | | | 0.000 055 | [60] | |
| Mn | mg/kg | | | | 0.000 014 | [60] | |
| Cl | mg/kg | 0.53 | [47] | 2,3 | 19 354 | [60] | |
| $SO_4$ | mg/kg | 2.88 | [47] | 2,3 | 2708 | [60] | |
| $H_2S$ | mg/kg | | [47] | | | | |
| N | mg/kg | 0.34 | [47] | 2,3 | 0.042 | [60] | 7 |
| TIC | mg/kg | 0.23 | [47] | 2,3 | 27.6 | [60] | |

TABLE 37. GEOCHEMICAL DETERMINANDS FOR SELECTED GROUNDWATERS (cont.)

| Determinand | Units | No. 3. Diagenetic water of seawater origin, Chalk, Trunch, UK | | | No. 4. Diagenetic water of meteoric origin, Chalk, Trunch, UK | | |
|---|---|---|---|---|---|---|---|
| | | Value | Source of data | Notes | Value | Source of data | Notes |
| Temperature | °C | 20.0 | [50] | 8 | 10 | Estimated | 14 |
| pH | pH | 8.2 | [59] | 9 | 7.09 | [50] | 15 |
| Eh | mV | -234 | [50] | 10,11,12,13 | -154 | [50] | 15,16,17,18 |
| Dissolved $O_2$ | mg/kg | | | | | | |
| Na | mg/kg | 11 100 | [50] | 10,11,12 | 41 | [50] | 15,16,17 |
| K | mg/kg | 283 | [50] | 10,11,12 | 2.9 | [50] | 15,16,17 |
| Mg | mg/kg | 1363 | [50] | 10,11,12 | 12.5 | [50] | 15,16,17 |
| Ca | mg/kg | 647 | [50] | 10,11,12 | 120 | [50] | 15,16,17 |
| Si | mg/kg | 4.0 | [50] | 10,11,12 | 2.79 | [50] | 15,16,17 |
| Al | mg/kg | 0.007 | [50] | 10,11,12 | 0.000 1 | [50] | 15,16,17 |
| Fe | mg/kg | 8.32 | [50] | 10,11,12 | 2.35 | [50] | 15,16,17 |
| Mn | mg/kg | | | | | | |
| Cl | mg/kg | 19 682 | [50] | 10,11,12 | 104.2 | [50] | 15,16,17 |
| $SO_4$ | mg/kg | 2850 | [50] | 10,11,12 | 66 | [50] | 15,16,17 |
| $H_2S$ | mg/kg | 3.63E-06 | [50] | 10,11,12 | 2.73E-06 | [50] | |
| N | mg/kg | | | | 0.20 | [50] | |
| TIC | mg/kg | 4.71 | [50] | 10,11,12 | 67.35 | [50] | 15,16,17 |

TABLE 37. GEOCHEMICAL DETERMINANDS FOR SELECTED GROUNDWATERS (cont.)

| Determinand | Units | No. 5. JNC Fresh Reducing High pH (FRHP) | | | No. 6. JNC Saline Reducing High pH (FRHP) | | |
|---|---|---|---|---|---|---|---|
| | | Value | Source of data | Notes | Value | Source of data | Notes |
| Temperature | °C | 25 | [62] | | 25 | [62] | |
| pH | pH | 8.46 | [62] | 18 | 7.95 | [62] | 18 |
| Eh | mV | -281 | [62] | 18 | -303 | [62] | 18 |
| Dissolved $O_2$ | mg/kg | | | | | [62] | |
| Na | mg/kg | 81.61 | [62] | 18 | 14 185 | [62] | 18 |
| K | mg/kg | 2.40 | [62] | 18 | 414.5 | [62] | 18 |
| Mg | mg/kg | 1.22 | [62] | 18 | 6.05 | [62] | 18 |
| Ca | mg/kg | 4.37 | [62] | 18 | 13.39 | [62] | 18 |
| Si | mg/kg | 9.52 | [62] | 18 | 8.29 | [62] | 18 |
| Al | mg/kg | 0.01 | [62] | 18 | 0.000 1 | [62] | 18 |
| Fe | mg/kg | 0.000 1 | [62] | 18 | 0.002 2 | [62] | 18 |
| Mn | mg/kg | | | | | | |
| Cl | mg/kg | 0.52 | [62] | 18 | 20 917 | [62] | 18 |
| $SO_4$ | mg/kg | 10.66 | [62] | 18,19 | 2891 | [62] | 18,19 |
| $H_2S$ | mg/kg | | [62] | | | [62] | |
| N | mg/kg | 0.32 | [62] | 18 | 72.13 | [62] | 18 |
| TIC | mg/kg | 42.52 | [62] | 18 | 415.58 | [62] | 18 |

TABLE 37. GEOCHEMICAL DETERMINANDS FOR SELECTED GROUNDWATERS (cont.)

| Determinand | Units | No. 7. Fresh, high-pH water, Toki Granite, Tono, Japan | | | No. 8. Halite-saturated brine based on Sellafield groundwater, UK | | |
|---|---|---|---|---|---|---|---|
| | | Value | Source of data | Notes | Value | Source of data | Notes |
| Temperature | °C | 25 | [56] | 20 | 25 | Temperature for thermodynamic data in GWB HMW database | 22 |
| pH | pH | 10.1 | [55] | 21 | 6.26 | [49] | 22,23,24,25 |
| Eh | mV | -400 | [55] | 21 | -100 | [49] | 22,23,24,25,26 |
| Dissolved $O_2$ | mg/kg | | | | | | |
| Na | mg/kg | 25.4 | [55] | 21 | 100 300 | [49] | 22,23,24,25 |
| K | mg/kg | 2.3 | [55] | 21 | 458.3 | [49] | 22,23,24,25 |
| Mg | mg/kg | 0.3 | [55] | 21 | 449.1 | [49] | 22,23,24,25 |
| Ca | mg/kg | 5.4 | [55] | 21 | 2237 | [49] | 22,23,24,25 |
| Si | mg/kg | 1.9 | [55] | 21 | | | |
| Al | mg/kg | 0.19 | [55] | 21 | | | |
| Fe | mg/kg | 8.90 | [55] | 21 | | | |
| Mn | mg/kg | 0.16 | [55] | 21 | | | |
| Cl | mg/kg | 4.4 | [55] | 21 | 159 100 | [49] | 22,23,24,25 |
| $SO_4$ | mg/kg | 4.6 | [55] | 21 | 1764 | [49] | 22,23,24,25 |
| $H_2S$ | mg/kg | | | | | | |
| N | mg/kg | 17.79 | [55] | 21 | | | |
| TIC | mg/kg | 18.4 | [55] | 21 | 13.77 | [49] | 22,23,24,25 |

TABLE 37. GEOCHEMICAL DETERMINANDS FOR SELECTED GROUNDWATERS (cont.)

| Determinand | Units | No. 9. Saline, Ca-Cl matrix porewater from Lac du Bonnet Granite Batholith, Whiteshell, Manitoba, Canada | | | No. 10. Fresh, high-pH water from gabbro at East Bull Lake, Ontario, Canada | | |
|---|---|---|---|---|---|---|---|
| | | Value | Source of data | Notes | Value | Source of data | Notes |
| Temperature | °C | 25 | Temperature for thermodynamic data in GWB HMW database | | 25 | [51] | 32 |
| pH | pH | 8.74 | [49] | 24,27,28,29 | 10.4 | [51] | 33 |
| Eh | mV | -297 | [49] | 30 | 220 | [51] | 33,34 |
| Dissolved $O_2$ | mg/kg | | | | | | |
| Na | mg/kg | 1376 | [49] | 24,27,28,29 | 65 | [51] | 33,34 |
| K | mg/kg | 19.2 | [49] | 24,27,28,29 | 0.2 | [51] | 33,34 |
| Mg | mg/kg | 0.26 | [49] | 24,27,28,29 | 0.6 | [51] | 33,34 |
| Ca | mg/kg | 26 620 | [49] | 24,27,28,29 | 0.4 | [51] | 33,34 |
| Si | mg/kg | 1.44 | [49] | 29,31 | 12.1 | [51] | 33,34 |
| Al | mg/kg | 0.00 | [49] | 29,31 | N.R. | [51] | 33,34 |
| Fe | mg/kg | 0.01 | [49] | 29,31 | 1.13 | [51] | 33,34 |
| Mn | mg/kg | | | | 0.04 | [51] | 33,34 |
| Cl | mg/kg | 48 350 | [49] | 24,27,28,29 | 10.9 | [51] | 33,34 |
| $SO_4$ | mg/kg | 1210 | [49] | 24,27,28,29 | 9.9 | [51] | 33,34 |
| $H_2S$ | mg/kg | | | | | | |
| N | mg/kg | 0.02 | [49] | 29,31 | | | |
| TIC | mg/kg | 0.11 | [49] | 24,27,28,29 | 30.9 | [51] | 33,34,35 |

TABLE 37. GEOCHEMICAL DETERMINANDS FOR SELECTED GROUNDWATERS (cont.)

| Determinand | Units | No. 11. Alkaline, Na-Cl brine from Lake Magadi, Kenya | | | No. 12. Alkaline, Na-Cl-SO4 brine, based on brine from Searles Lake, California, U.S.A | | |
|---|---|---|---|---|---|---|---|
| | | Value | Source of data | Notes | Value | Source of data | Notes |
| Temperature | °C | 25 | Temperature for thermodynamic data in GWB HMW database | | 25 | Temperature for thermodynamic data in GWB HMW database | |
| pH | pH | 10.3 | [61] | 36 | 10 | [54] | 38 |
| Eh | mV | 600 | [61] | 37 | 630 | [54], [52] | 39 |
| Dissolved $O_2$ | mg/kg | 3.5 | [61] | 37 | 3 | [54], [52] | 39 |
| Na | mg/kg | 68 685 | [61] | 36 | 90 230 | [52] | 40,41 |
| K | mg/kg | 964 | [61] | 36 | 18 130 | [52] | 40,41 |
| Mg | mg/kg | | | | 0.04 | [52] | 40,41 |
| Ca | mg/kg | | | | 0.2 | [52] | 40,41 |
| Si | mg/kg | 255 | [61] | 36 | | | |
| Al | mg/kg | | | | | | |
| Fe | mg/kg | | | | | | |
| Mn | mg/kg | | | | | | |
| Cl | mg/kg | 41 134 | [61] | 36 | 104 800 | [52] | 40,41 |
| $SO_4$ | mg/kg | 1591 | [61] | 36 | 39 700 | [52] | 40,41 |
| $H_2S$ | mg/kg | | | | | | |
| N | mg/kg | | | | | | |
| TIC | mg/kg | 12 047 | [61] | 36 | 3941 | [52] | 40,41 |

Notes: 1. Mean daily temperature averages -8.3 °C in January and 18.7 °C in July.

2. Data from Hubbard Brook Experimental Forest, New Hampshire, U.S.A. Values here calculated from reported values expressed in mmol/l, assuming the density of water to be 1 kg/l.

3. The water composition from Hubbard Brook, reported in [47] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. In this simulation charge was balanced by adjusting Cl-, the TIC was constrained by equilibrium with atmospheric $CO_2$ and the redox state was constrained by equilibrium with atmospheric oxygen.

4. Compiled from data between 1901 and 2000.

5. [59] quotes surface values measured for 1994 from the GLODAP dataset. These values range from 7.9 to 8.25 with a mean value of 8.08.

6. The seawater composition reported in [60] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. In this simulation the redox state was constrained by equilibrium with atmospheric oxygen.

7. Concentrations exclude dissolved $N_2$ gas; element occurs also as dissolved nitrogen ($N_2$) gas. Species other than $NO_3^-$ are often important in the upper ocean (e.g. $NO_2^-$, $NH_4^+$).

8. Value reported for a depth of 480.5 m.

9. pH of modern seawater specified since the origins of the salinity is considered to be seawater and since [50] note that the pH of the flowing waters sampled in nearby boreholes, which is up to 7.3, is likely to be lower than the pH of the deeper interstitial waters.

10. Reported concentration units in [50] are mg/l; here recalculated to units of mg/kg using a density of 1.026305, the same as the density of seawater at a similar chlorinity, reported by [57].

11. Analysis of porewater from a depth of 480.5 m in the Trunch borehole and represents the most saline water from the Chalk at this locality.

12. The porewater composition from a depth of 480.5 m in the Trunch borehole, reported in [50] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. In this simulation TIC, Si, Al, Fe and HS- were controlled by equilibrium with respect to calcite, chalcedony, kaolinite, siderite and pyrite respectively.

13. The Eh is quoted for the $SO4^{2-}/HS^-$ redox couple.

14. Depth of sample is not reported. However the sample is stated to be 'shallow' and in the nearby Trunch borehole the temperature at 100 m depth is about 10 degrees; this value is used here.

15. Analysis of 'shallow' flowing water from a borehole near to the Trunch borehole, is the lowest-pH water reported in [50].

16. Reported concentration units in [50] are mg/l; here values taken to be the same as for units of mg/kg consistent with a density of 1.00.

17. Analysis of 'shallow' flowing water from a borehole near to the Trunch borehole, reported in [50], was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. In this simulation Si, Al, Fe and HS- were controlled by equilibrium with respect to chalcedony, kaolinite, siderite and pyrite respectively.

18. The concentration is modelled using PHREEQE, but shown to be similar to natural Japanese groundwater of extreme composition.

19. Total S is reported in [62], given here as $SO_4^{2-}$.

20. Assumed normal geothermal gradient for Japan - reasonable based upon published data for the Tono area.

21. The analysis is of the highest pH water from the Tono area, from a depth of 561 m below ground level in the Toki Granite.

22. The water composition from DET 1 of Sellafield borehole BH3, reported in [49] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the Harvie-Moller-Weare thermodynamic database thermo_hmw.dat. The removal of water of neutral pH until halite saturation was simulated.

23. pH was constrained by specifying equilibrium with respect to calcite.

24. Charge was balanced by adjusting Cl-.

25. The composition in [49] is reported in mg/l; here the composition used as input to the GWB calculation was recalculated to mg/kg by specifying an assumed density of 1.192 kg/l (equivalent to the mass of 1 kg water plus mass of solids, and with $Cl^-$ adjusted to achieve charge balance).

26. The redox condition was calculated by carrying out a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. The water composition output by the simulation described in Note 12 was used as input, Fe was constrained by equilibrium with siderite and $HS^-$ was constrained by equilibrium with pyrite. Note that the result of this calculation is an approximation because the Debye-Huckel equation was used to calculation activities.

27. The composition of the most saline porewater collected in unfractured rock from boreholes at the Whiteshell URL, reported in [53] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the Harvie-Moller-Weare thermodynamic database thermo_hmw.dat. The pH was adjusted until calcite saturation was achieved.

28. Most saline porewater collected in unfractured rock from boreholes at the Whiteshell URL.

29. Values reported in units of mg/l; here recalculated to units of mg/kg using a density of 1.066, calculated using the relationship between density and TDS of density = 0.000795*TDS (in g/l) +0.997151, given in [53].

30. The redox condition was calculated by carrying out a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. The water composition output by the simulation described in Note 16 was used as input, Fe was constrained by equilibrium with annite and $HS^-$ was constrained by equilibrium with pyrite, Si was constrained by equilibrium with quartz and Al was constrained by equilibrium with kaolinite. Note that the result of this calculation is an approximation because the Debye-Huckel equation was used to calculation activities.

31. The composition of the most saline porewater collected in unfractured rock from boreholes at the Whiteshell URL, reported in [53] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the Harvie-Moller-Weare thermodynamic database thermo_hmw.dat.

32. [51] do not indicate a precise temperature, but state that temperatures are < 25 °C.

33. Most alkaline groundwater sampled from East Bull Lake, between 75-243 m depth in gabbro (*sensu lato*).

34. Reported concentration units in [51] are mg/l; here values taken to be the same as for units of mg/kg consistent with a density of 1.00.

35. Calculated from alkalinity reported in mg/l $HCO_3^-$, assuming that all alkalinity is due to carbonate alkalinity.

36. Reported concentration units in [61] are mg/l; here recalculated to units of mg/kg using a density of 1.21, assuming that the density is equal to the reported TDS (210,000 mg/l) + mass of 1 kg of water in 1 l of solution.

37. The redox condition was calculated by carrying out a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. The water composition output by the simulation described in Note 24 was used as input. The redox constraint was specified by equilibrium with the atmosphere. Note that the result of this calculation is an approximation because the Debye-Huckel equation was used to calculation activities.

38. The maximum pH referred to in [54] is 9.9. An upper limiting pH of 10 is therefore used here; no pH is quoted in [52].

39. The redox condition was calculated by carrying out a simulation using Geochemist's Workbench Version 6.0.3 and the thermodynamic database thermo.dat. The water composition output by the simulation described in Note 26 was used as input. The redox constraint was specified by equilibrium with the atmosphere. Note that the result of this calculation is an approximation because the Debye-Huckel equation was used to calculation activities.

40. The composition of water sample SE7 was given by [52] was used as input to a simulation using Geochemist's Workbench Version 6.0.3 and the Harvie-Moller-Weare thermodynamic database thermo_hmw.dat. Sample SE7 was chosen because it is the most $SO_4^{2-}$-rich among the samples considered in this paper.

41. The GWB model adjusted Na+ to balance the charge and constrained concentrations of $Ca^{2+}$ and $Mg^{2+}$ by specifying equilibrium with respect to calcite and dolomite respectively.

# APPENDIX III
# SCENARIO GENERATION APPROACH

The approach used is illustrated in Fig. 5 and is described below.

A panel, consisting of the attendees of the first consultants' meeting to develop this TECDOC (i.e. Gerard Bruno, Ian Crossland, Luis Jova Sed, Richard Little and Philip Metcalf), identified scenarios for consideration in the GSA. The components of the disposal system were divided into internal and external components (Fig. 22). The internal components are situated within the spatial and temporal boundaries of the system, whilst the external components are situated outside these boundaries[17]. External factors (EFEPs) were regarded as boundary conditions or forcing functions for the system model. They were considered as scenario generating features, events and processes (FEPs). The panel considered each of the four external factors identified in Fig. 22 and, using information relating to the assessment context (Section 2) and system description (Section 3), assigned the following 'states' for each of the external factors for the purpose of defining a 'Design Scenario'[18]:

- Repository factors – the borehole is assumed to be constructed, operated and closed as designed and planned (i.e. consistent with section 3.1);
- Geological processes and events – the geosphere is assumed to be as described in section 3.2 with no unexpected features, processes or events (e.g. earthquakes);
- Climate processes and events – constant climate conditions are assumed (a simplifying assumption), but with allowance for continuous gradual surface erosion; and
- Future human actions and behaviours – after 30 years of institutional control, it is assumed that water is abstracted from a borehole drilled 100 m down the hydraulic gradient from the disposal borehole and used for domestic purposes (drinking) and agricultural purposes (watering of cows and irrigation of root and green vegetables) (i.e. consistent with Sections 3.2 and 3.3). Construction of a dwelling above the disposal borehole at the end of the institutional control period is also considered, but it is assumed that there is no intrusion into the borehole's disposal zone (consistent with Sections 3.3).

---

[17] Repository factors are considered to be external since they relate to decisions concerning borehole design, operation and closure which are taken before the start of the post-closure period - the time period of interest for the GSA.

[18] The Design Scenario represents how the disposal system can be expected to evolve assuming the boreholes design functions as planned; it provides a benchmark against which alternative scenarios can be compared.

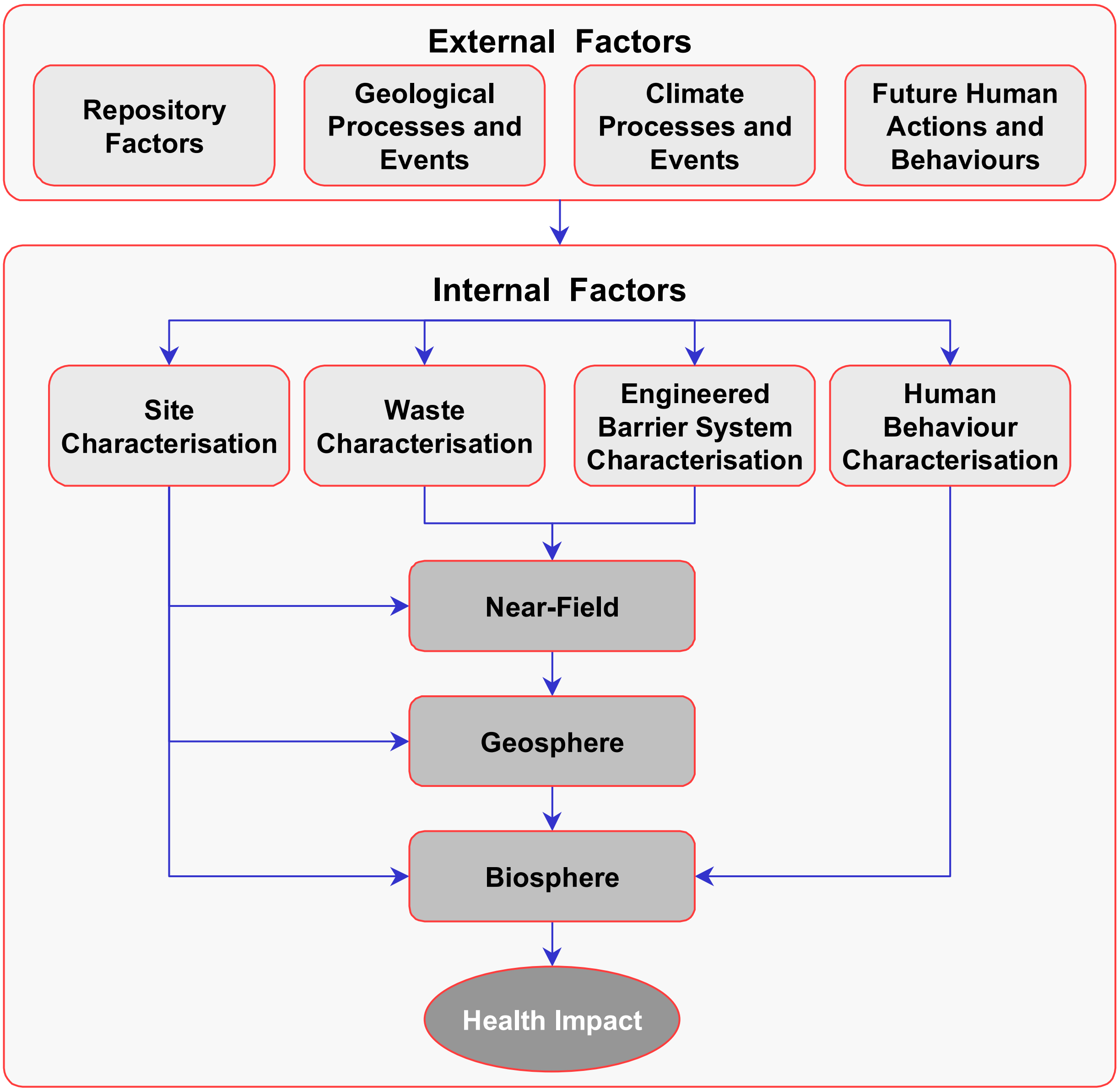


*FIG. 22. External and internal factors (reproduced courtesy of IAEA [12]).*

The panel then identified alternative scenarios by considering possible alternative conditions for the EFEPs (i.e. the scenario generating FEPs), consistent with the assessment context and system description (Table 11). Four alternative scenarios were identified:

- the Defect Scenario;
- the Unexpected Geological Characteristics;
- the Changing Environmental Conditions Scenario; and
- the Borehole Disturbance Scenario.

# APPENDIX IV
# SCREENED FEP LIST FOR THE DESIGN SCENARIO

This Appendix documents the screening of Features, Events, and Processes (FEPs) in the Design Scenario in the Generic Safety Assessment (GSA) for borehole disposal of Categories 3 to 5 Disused Sealed Radioactive Sources (DSRS). The FEPs are listed in the following table and are then discussed in more detail in the text that follows. The text of this Annex is structured according to the FEP Numbers, to provide traceability.

## *0 ASSESSMENT CONTEXT FACTORS*

***0.01 Assessment purpose – Yes,*** see Section 2.2 for the four main purposes of the assessment.

***0.02 Regulatory requirements and Exclusions***

1 *0.2.01 Protection of human health and the environment –* ***Yes,*** see Sections 2.2 and 2.4, especially Box 1 for protection objective and criteria. Impacts on non-human biota and non-radiological impacts are considered to be beyond the scope of the current study, so the focus is on radiological impacts upon human health.

2 *0.2.02 Phases of disposal –* ***Yes,*** see Sections 2.2 and 2.7. Assessment is of the post-closure phase, although it is recognized that operational and closure issues need to be considered when assessing post-closure safety.

3 *0.2.03 Technical requirements –* ***Yes,*** see Sections 2. 2 and 2.5. End points considered are waste activity levels expressed as total activity values and per waste package activity values. Output of assessment will help provide information on suitable inventories, engineering, institutional control period and hydrochemical characteristics.

***0.03 Assessment philosophy***

4 *0.3.01 Assessment approach –* ***Yes,*** see Section 2.6. The ISAM Safety Assessment Approach is being used, consistent with best international practice.

*0.3.02 Uncertainties, treatment of*

5 *0.3.02.01 Future uncertainties –* ***Yes,*** see Sections 2.6.3 and 3. This type of uncertainty is treated using a transparent and comprehensive scenario development and justification methodology.

6 *0.3.02.02 Model uncertainties –* ***Yes,*** see Sections 2.6.3 and 6. This type of uncertainty is treated using alternative conceptualizations and mathematical representations of the system.

7 *0.3.02.03 Parameter/data uncertainties –* ***Yes,*** see Sections 2.6.3 and 6. This type of uncertainty is treated using a deterministic sensitivity analysis.

8 *0.3.02.04 Subjective uncertainties –* ***Yes,*** see Section 2.6.3. This type of uncertainty is treated using a systematic and transparent assessment approach which allows subjective judgements to be document, justified and quantified (as far as possible).

9 *0.3.03 Sensitivity analysis, performance of –* ***Yes,*** see Section 6 for deterministic sensitivity analysis.

*0.3.04 Confidence, model*

10 *0.3.04.01 Verification, performance of –* ***Yes,*** see Section 5.5. The software tool used (AMBER) has been successfully used in over 20 countries by over 60 organizations and has associated verification documentation.

11 *0.3.04.02 Calibration, performance of –* ***No,*** calibration is a site specific procedure and therefore not possible for a generic safety assessment.

12 *0.3.04.03 Validation, performance of –* ***No,*** validation is not considered possible for a long term generic safety assessment.

13 *0.3.05 Modelling approach –* ***Yes,*** see Sections 2.6 and 6. The approach used aims to balance simplicity, conservatism and realism. Deterministic calculations are used. The emphasis is to understand the behaviour of the system better and to identify the importance of specific components of the system in providing a level of post-closure safety that meets the relevant regulatory compliance criteria.

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

| | | |
|---|---|---|
| | ***0*** | ***ASSESSMENT CONTEXT FACTORS*** |
| | ***0.04*** | ***Assessment bounding conditions*** |
| *14* | *0.4.01* | *Assessment timeframe* – ***Yes****,* see Sections 2.7 and 4.2. Calculations are undertaken out to a time when it can be demonstrated that the peak value of the primary safety indicator (dose) has been passed. Institutional control period assumed to last 30 years after closure. |
| *15* | *0.4.02* | *Assessment domain* – ***Yes****,* see Sections 3 and 4.2.1. Assumed to be limited to the immediate vicinity of the disposal borehole (i.e. within a radius of about 100 m) since a water abstraction borehole is assumed to be sunk 100 m from the disposal borehole and the water used for domestic and agricultural purposes by humans. |
| *16* | *0.4.03* | *Future human action assumptions* – ***Yes****,* see Sections 3.3 and 4.2.1. No consideration is given to the development of new societal structures and technologies. |
| *17* | *0.4.04* | *Future human behaviour (target group) assumptions* – ***Yes****,* see Sections 3.3 and 4.2.1. It is assumed that humans are exposed once institutional control of the site is lost either due to use contaminated groundwater abstracted from a borehole sunk 100 m from the disposal borehole, or due to inhalation of contaminated gas in dwelling constructed directly above the disposal borehole. |
| *18* | *0.4.05* | *Target audience (Stakeholder involvement)* – ***Yes****,* see Section 2.3. Two audiences are considered – 'developers' and 'regulators'. |
| *19* | *0.4.06* | *Assessment endpoints* – ***Yes****,* see Sections 2.5 and 6. Primary end points are waste activity levels, which can be expressed as total activity values and per waste package activity values. |
| *20* | *0.4.07* | *Dose response assumptions* – ***No****,* see Section 2.5. Risks of deleterious health effects are not considered as end points in the current study. |
| *21* | *0.4.08* | *Results, presentation of* – ***Yes****,* see Section 6. Results presented in tabular form. |
| *22* | *0.4.09* | *Disposal Facility Assumptions* – ***Yes****,* see Sections 3.1 and 4.2.1. It is assumed that the disposal borehole is constructed, operated and closed as planned. |
| | ***1*** | ***EXTERNAL FACTORS*** |
| | ***1.1*** | ***Disposal facility factors*** |
| *23* | *1.1.01* | *Investigations, site* – ***Yes****,* although the assessment is generic and therefore it is assumed that there is no site specific information available from site investigation (see Section 3.2), data (e.g. hydraulic gradients, conductivities, porosities) are presented in Section 3.2 that implicitly assume there has been some site investigation of the synthesised sites. It is assumed that any investigation boreholes have been appropriately backfilled and do not compromise the long term safety of the disposal system. |
| *24* | *1.1.02* | *Design, disposal facility* – ***Yes****,* see Section 3.1.2 and Table 4. It is assumed that the disposal borehole is designed with appropriate safety features and functions. |
| *25* | *1.1.03* | *Schedule and planning* – ***Yes****,* see Sections 3.1.2 and 4.2.1. It is assumed that the disposal borehole is constructed, operated and closed as planned. |
| *26* | *1.1.04* | *Construction, disposal facility* – ***Yes****,* see Sections 3.1.2 and 4.2.1. It is assumed that the disposal borehole is constructed as planned. |
| *27* | *1.1.05* | *Operation, disposal facility* – ***Yes****,* see Sections 3.1.2 and 4.2.1. It is assumed that the disposal borehole is operated as planned. |
| *28* | *1.1.06* | *Closure, disposal facility* – ***Yes****,* see Sections 3.1.2 and 4.2.1. It is assumed that the disposal borehole is closed as planned. |
| *29* | *1.1.07* | *Institutional controls* – ***Yes****,* see Sections 2.7 and 4.2.1. It is assumed that institutional controls are in place for a period of 30 years after closure. |
| *30* | *1.1.08* | *Quality assurance* – ***Yes****,* see Section 4.2.1. It is assumed that appropriate quality assurance is applied to the design, construction, operation and closure of the disposal borehole. |
| *31* | *1.1.09* | *Administrative control, disposal facility* – ***Yes****,* see Sections 2.7 and 4.2.1. It is assumed that institutional controls are in place during the construction, operation and closure of the disposal borehole and for a period of 30 years after closure. |
| *32* | *1.1.10* | *Accidents and unplanned events* – ***No****,* see Section 4.2.1. It is assumed that the disposal borehole is closed as planned and there are no accidents or unplanned events. |

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

| | ***1*** | ***EXTERNAL FACTORS*** | |
|---|---|---|---|
| *33* | | *1.1.11* | *Retrievability* – ***No,*** see Section 3.1.2. Each waste package is backfilled into the borehole immediately following its emplacement. |
| *34* | | *1.1.12* | *Motivation and knowledge issues* – ***Yes,*** see Section 4.2.1. It is assumed that no markers are fixed at the site to reveal the location of a radioactive waste disposal facility but land use controls are in place during the institutional control period. |
| *35* | | *1.1.13* | *Nuclear Criticality* – ***No,*** such effects are considered to be insignificant for the typical inventories to be disposed. |
| | ***1.2*** | ***Geological processes and effects*** | |
| *36* | | *1.2.01* | *Tectonic movement* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in a geologically stable area with no or extremely limited tectonic activity over the timescales of interest in the safety assessment. |
| *37* | | *1.2.02* | *Orogeny* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in geologically stable area and there is no orogenic activity over the timescales of interest in the safety assessment. |
| *38* | | *1.2.03* | *Seismicity* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in a geologically stable area with no or extremely limited seismic activity over the timescales of interest in the safety assessment. |
| *39* | | *1.2.04* | *Volcanic and magmatic activity* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in geologically stable area and there is no volcanic and magmatic activity over the timescales of interest in the safety assessment. |
| *40* | | *1.2.05* | *Metamorphism* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in geologically stable area and there is no metamorphic activity over the timescales of interest in the safety assessment. |
| *41* | | *1.2.06* | *Hydrothermal activity* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in geologically stable area and there is no hydrothermal activity over the timescales of interest in the safety assessment. |
| *42* | | *1.2.07* | *Erosion and sedimentation* – ***Yes,*** see Sections 3.2, 3.3, 4.1 and 4.2.1. It is assumed that there is gradual net erosion on a regional and local scale. |
| *43* | | *1.2.08* | *Diagenesis* – ***No,*** diagenesis is not considered to be a significant process affecting the disposal system over the depths and timescales of interest in the safety assessment. |
| *44* | | *1.2.09* | *Pedogenesis* – ***Yes,*** see Section 3.3 and 4.2.1. Need to consider soil contaminated by irrigation water. |
| *45* | | *1.2.10* | *Salt diapirism and dissolution* – ***No,*** assume disposal borehole is located in an area that has no natural resources requiring excavation by extensive surface excavation or underground mining (see Section 3.2). |
| *46* | | *1.2.11* | *Undetected geological features* – ***No,*** see Section 4.1. The geosphere is assumed to be as described in Section 3.2 with no unexpected features, processes or events. |
| *47* | | *1.2.12* | *Hydrological/hydrogeological response to geological changes* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in geologically stable area and there are no significant geological changes over the timescales of interest in the safety assessment. |
| *48* | | *1.2.13* | *Geomorphologic response to geological changes* – ***No,*** see Sections 3.2 and 4.2.1. It is assumed that the disposal borehole is located in geologically and geomorphologically stable area and there are no significant changes over the timescales of interest in the safety assessment. |
| | ***1.3*** | ***Climate processes and effects*** | |
| *49* | | *1.3.01* | *Climate change, global* – ***No,*** see Section 4.1. Constant climate conditions are assumed (a simplifying assumption). |
| *50* | | *1.3.02* | *Climate change, regional and local* – ***No,*** see Section 4.1. Constant climate conditions are assumed (a simplifying assumption). |
| *51* | | *1.3.03* | *Sea level change* – ***No,*** see Section 3.3. It is assumed that the site is located in a position that will not be susceptible to possible future sea level rises. |
| *52* | | *1.3.04* | *Periglacial effects* – ***No,*** see Section 3.3. No consideration of extreme conditions such as permafrost. |
| *53* | | *1.3.05* | *Glacial and ice sheet effects, local* – ***No,*** see Section 3.3. No consideration of extreme conditions such as glaciation. |

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

| | ***1*** | ***EXTERNAL FACTORS*** | |
|---|---|---|---|
| *54* | | *1.3.06* | *Warm climate effects (tropical and desert)* – ***Yes****,* see Section 3.3. It is assumed that the climate is consistent with the assumption of self-sufficient agriculture land use. Such land use is possible in tropical climates and, if there is a sufficient supply of freshwater, arid conditions. |
| *55* | | *1.3.07* | *Hydrological/hydrogeological response to climate changes* – ***No****,* since constant climate conditions are assumed (see Section 4.1). |
| *56* | | *1.3.08* | *Ecological response to climate changes* – ***No****,* since constant climate conditions are assumed (see Section 4.1). |
| *57* | | *1.3.09* | *Human behavioural response to climate changes* – ***No****,* since constant climate conditions are assumed (see Section 4.1). |
| *58* | | *1.3.10* | *Geomorphologic response to climate changes* – ***No****,* since constant climate conditions are assumed (see Section 4.1). |
| | ***1.4*** | ***Future human actions*** | |
| *59* | | *1.4.01* | *Human influences on climate* – ***No****,* since constant climate conditions are assumed (see Section 4.1). |
| *60* | | *1.4.02* | *Knowledge and motivational issues (Disposal facility)* – ***Yes****,* see Section 4.2.1. It is assumed that no markers are fixed at the site to reveal the location of a radioactive waste disposal facility but land use controls are in place during the institutional control period to prevent human intrusion. The impact of deliberate human intrusion is considered to be beyond the scope of the current assessment (Section 1.3). |
| *61* | | *1.4.03* | *Drilling activities (human intrusion)* – ***Yes****,* see Sections 3.2, 4.1 and 4.2.1. It is assumed that a water abstraction borehole is drilled 100 m from the disposal borehole and only once there is no institutional control over the site. |
| *62* | | *1.4.04* | *Mining and other underground activities (human intrusion)* – ***No****,* see Sections 3.2 and 3.3. It is assumed that the disposal borehole is located in an area that has no natural resources requiring excavation by extensive underground mining. Furthermore, human activities are assumed to be limited to agricultural activities. |
| *63* | | *1.4.05* | *Un-intrusive site investigation* – ***No****,* see Sections 3.2 and 3.3. It is assumed that the disposal borehole is located in an area that has no natural resources and human activities are assumed to be limited to agricultural activities. Therefore, it is considered that there is no un-intrusive site investigation. |
| *64* | | *1.4.06* | *Surface excavations* – ***No****,* see Sections 3.2 and 3.3. The disposal zone is assumed to be at least 30 m below the ground surface and it is considered that any surface excavations associated with agricultural land use will not extend down to such depths. |
| *65* | | *1.4.07* | *Pollution* – ***No****,* it is assumed that human activities do not significantly affect the disposal system. |
| *66* | | *1.4.08* | *Site Development* – ***Yes****,* see Sections 3.2, 4.1 and 4.2.1. It is assumed that a water abstraction borehole is drilled 100 m from the disposal borehole and only once there is no institutional control over the site. |
| *67* | | *1.4.09* | *Archaeology* – ***No****,* see Section 3.3. Human activities are assumed to be limited to agricultural activities. |
| *68* | | *1.4.10* | *Water management (wells, reservoirs, dams)* – ***Yes****,* see Sections 3.2, 4.1 and 4.2.1. It is assumed that a water abstraction borehole is drilled 100 m from the disposal borehole and only once there is no institutional control over the site. |
| *69* | | *1.4.11* | *Social and institutional developments* – ***Yes****,* see Sections 2.7, 3.3 and 4.2.1. It is assumed that land use controls are in place during the institutional control period to prevent human intrusion. But at the end of the period, controls are assumed to be no longer in place. |
| *70* | | *1.4.12* | *Technological developments* – ***No****,* see Sections 3.3 and 4.2.1. No consideration is given to the development of new technologies. |
| *71* | | *1.4.13* | *Remedial actions* – ***No****,* see Sections 2.7 and 4.2.1. It is assumed that the disposal system performs appropriately and so there is no need for remedial actions during the period of active institutional control. |
| *72* | | *1.4.14* | *Explosions and crashes* – ***No****,* it is assumed that there are no explosions or crashes. |

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

## *2 DISPOSAL SYSTEM DOMAIN FACTORS*

### *2.1 Waste, waste form & engineered features*

| | | |
|---|---|---|
| *73* | *2.1.1* | *Inventory, waste* – ***Yes,*** see Section 3.1.1 and Appendix V. Assume a unit inventory of 1 TBq per waste package of each of the emboldened radionuclides in Table 3 is disposed in the borehole. |
| *74* | *2.1.2* | *Waste form materials, characteristics and degradation processes* – ***Yes,*** see Sections 3.1.1, 3.1.2 and 4.2.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. |
| *75* | *2.1.3* | *Container materials, characteristics and degradation/failure processes* – ***Yes,*** see Sections 3.1.2 and 4.2.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. |
| *76* | *2.1.4* | *Buffer/backfill materials, characteristics and degradation processes* – ***Yes,*** see Sections 3.1.2 and 4.2.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. |
| *77* | *2.1.5* | *Other engineered barrier system characteristics and degradation processes* – ***Yes,*** see Sections 3.1.2 and 4.2.1 and Appendix V. See Tables 4, 5 and 12 and Figs 2, 3 and 4 for details. |

### *2.2 Geological environment*

| | | |
|---|---|---|
| *78* | *2.2.1* | *Stratigraphy* – ***Yes,*** see Sections 3.2, 4.1 and 4.2.1. Although there is no explicit consideration of the stratigraphy of the synthesised geospheres, it is noted that the geology is not homogeneous, although any variation can be adequately represented through the use of averaged hydrological and geochemical parameter values. For disposal in the unsaturated zone, a total depth of unsaturated zone of 90 m is assumed. For disposal in the saturated zone, a total depth of saturated zone of 50 m is assumed. Characteristics are not assumed to change with time (see Section 4.2.1). |
| *79* | *2.2.2* | *Host lithology* – ***Yes,*** see Sections 3.2, 3.4, 4.1 and 4.2.1. Key physical characteristics of synthesised geospheres are summarized in Table 7. Characteristics are not assumed to change with time (see Section 4.2.1). |
| *80* | *2.2.3* | *Disturbed zone, host lithology* – ***Yes,*** see Section 3.2, 4.1 and 4.2.1. Disturbed zone is assumed to be part of the near field. Voids and cracks in the host geology immediately adjacent to the borehole are assumed to be grouted and sealed during the drilling process. |
| *81* | *2.2.4* | *Discontinuities, large scale (in geosphere)* – ***No,*** it is assumed that there are no large-scale discontinuities. |
| *82* | *2.2.5* | *Contaminant migration path characteristics (in geosphere)* – ***Yes,*** see Sections 3.2 and 4.2.1. Consider both porous and fracture flow and transport in the unsaturated and saturated geosphere. Characteristics are not assumed to change with time (see Section 4.2.1). |
| *83* | *2.2.6* | *Mechanical processes and conditions (in geosphere)* – ***No,*** it is assumed that there are no significant mechanical processes and conditions affecting the geosphere and that the disposal borehole will not affect the mechanical properties of the geosphere. |
| *84* | *2.2.7* | *Hydraulic/hydrogeological processes and conditions (in geosphere)* – ***Yes,*** see Sections 3.2, 3.4 and 4.2.1. A range of conditions is considered (see Tables 7, 8 and 9). Conditions are not assumed to change with time (see Section 4.2.1). |
| *85* | *2.2.8* | *Chemical/geochemical processes and conditions (in geosphere)* – ***Yes,*** see Sections 3.2, 3.4 and 4.2.1. Conditions in the geosphere are assumed not to change with time. |
| *86* | *2.2.9* | *Biological/biochemical processes and conditions (in geosphere)* – ***Yes,*** see Sections 3.2, 3.4 and 4.2.1. Conditions in the geosphere are assumed not to change with time. |
| *87* | *2.2.10* | *Thermal processes and conditions (in geosphere)* – ***No,*** see Sections 2.5, 3.2, 3.4 and 4.2.1. It is assumed that there are no significant sources of thermal heat in the geosphere and that the inventory does not significantly affect the thermal properties of the geosphere. |
| *88* | *2.2.11* | *Gas sources and effects (in geosphere)* – ***No,*** see Section 3.2. It is assumed that there are no significant sources of geothermal heat or gas in the vicinity of the disposal borehole. |
| *89* | *2.2.12* | *Geological resources (in geosphere)* – ***Yes,*** see Sections 3.2, 4.1 and 4.2.1. Water assumed to be abstracted from the geosphere. |

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

| | | | |
|---|---|---|---|
| | 2 | ***DISPOSAL SYSTEM DOMAIN FACTORS*** | |
| | **2.3** | ***Surface environment*** | |
| *90* | | *2.3.1* | *Topography and morphology* – ***Yes***, see Section 3.3. It is assumed that the biosphere has subdued relief. |
| *91* | | *2.3.2* | *Biomes* – ***Yes***, see Sections 3.3 and 4.2.1. It is assumed that a range of crops and livestock is raised consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. Assume contamination due to irrigation of crops and watering of animals. |
| *92* | | *2.3.3* | *Soil and sediment* – ***Yes***, see Sections 3.3 and 4.2.1. It is assumed that soils have similar mineralogical properties to those of the underlying geosphere from which they are assumed to have been derived. It is also assumed that they are capable of supporting a range of crops. Assume contamination due to irrigation of crops. |
| *93* | | *2.3.4* | *Aquifers and water-bearing features, near surface* – ***Yes***, see Sections 3.3, 4.1 and 4.2.1. Water assumed to be abstracted from the geosphere. |
| *94* | | *2.3.5* | *Terrestrial surface water bodies* – ***No***, see Section 3.3. Interest limited to water in abstraction borehole. |
| *95* | | *2.3.6* | *Coastal features* – ***No***, see Section 3.3. Disposal borehole is assumed to be located in a position that will not be susceptible to coastal processes. |
| *96* | | *2.3.7* | *Marine features* – ***No***, see Section 3.3. Disposal borehole is assumed to be located in a position that will not be susceptible to coastal processes and possible future sea level rises and so marine features are not considered to be relevant. |
| *97* | | *2.3.8* | *Atmosphere* – ***Yes***, see Section 4.2.1. Needs to be considered for the suspension of contaminated soil and gas inhalation pathways. |
| *98* | | *2.3.9* | *Vegetation* – ***Yes***, see Sections 3.3 and 4.2.1. It is assumed that a range of crops is raised consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. |
| *99* | | *2.3.10* | *Animal populations* – ***Yes***, see Sections 3.3 and 4.2.1. It is assumed that a range of animals is raised consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. |
| *100* | | *2.3.11* | *Meteorology* – ***Yes***, see Section 3.3. It is assumed that the climate is consistent with the assumption of self-sufficient agriculture land use and is non-extreme. |
| *101* | | *2.3.12* | *Hydrological regime and water balance (near surface)* – ***Yes***, see Section 3.2. Infiltration into the geosphere influences leaching of radionuclides from contaminated soil and the flux of water in the geosphere. |
| *102* | | *2.3.13* | *Erosion and deposition* – ***Yes***, see Sections 3.2, 3.3, 4.1 and 4.2.1. It is assumed that there is gradual net erosion on a regional and local scale resulting in the loss of the closure zone over a 100,000 year period. |
| *103* | | *2.3.14* | *Ecological/biological/microbial systems* – ***Yes***, see Sections 3.3 and 4.2.1. It is assumed that a range of crops is grown, consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. It is assumed that the crops are grown on soil contaminated with water from the abstraction borehole. |
| *104* | | *2.3.15* | *Animal/Plant intrusion* – ***No***, see Section 4.2.1. Given the assumed low erosion rate and the depth of the disposal zone it is considered that there is no need to consider biotic intrusion. |
| | **2.4** | ***Human behaviour*** | |
| *105* | | *2.4.1* | *Human characteristics (physiology, metabolism)* – ***Yes***, see Section 5.4. Implicitly considered in dose factors for ingestion and inhalation of radionuclides. |
| *106* | | *2.4.2* | *Adults, children, infants and other variations* – ***Yes***, see Section 2.5. Consider annual individual effective dose to an average adult member of a hypothetical critical group. |
| *107* | | *2.4.3* | *Diet and fluid intake* – ***Yes***, see Sections 3.3 and 4.2.1. Ingestion of contaminated water, crops and animal produce. |
| *108* | | *2.4.4* | *Habits (non-diet-related behaviour)* – ***Yes***, see Sections 3.3 and 4.2.1. The assumed human habits give raise to exposure via ingestion of crops, soil and animal products, inhalation of gases and dust, and external irradiation from contaminated soil. |
| *109* | | *2.4.5* | *Community characteristics* – ***Yes***, see Sections 3.3 and 4.2.1. Assume a self-sufficient agriculture community. Two exposure groups considered: farmer and house dweller. |
| *110* | | *2.4.6* | *Food preparation and water processing* – ***Yes***, see Sections 3.3 and 4.2.1. Although it is assumed that the abstracted water used is not treated or stored before use, food is assumed to be processed before consumption. |

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

| | | |
|---|---|---|
| | ***2*** | ***DISPOSAL SYSTEM DOMAIN FACTORS*** |
| *111* | *2.4.7* | *Dwellings* – ***Yes****,* see Sections 3.3 and 4.2.1. At end of institutional control period, it is assumed that a dwelling can be constructed above the disposal borehole. |
| *112* | *2.4.8* | *Natural/semi-natural land and water use* – ***No****,* see Sections 3.3 and 4.2.1. Assume self-sufficient agriculture rather than natural/semi-natural land use. |
| *113* | *2.4.9* | *Rural and agricultural land and water use* – ***Yes****,* see Sections 3.3 and 4.2.1. Assume self-sufficient agriculture and abstracted groundwater used for domestic and agricultural purposes. |
| *114* | *2.4.10* | *Urban and industrial land and water use* – ***No****,* see Sections 3.3 and 4.2.1. Assume self-sufficient agriculture rather than urban and industrial land use. |
| *115* | *2.4.11* | *Leisure and other uses of environment* – ***No****,* see Sections 3.3 and 4.2.1. Assume self-sufficient agriculture rather than leisure or other use. |
| | ***3*** | ***CONTAMINANT FACTORS*** |
| | ***3.1*** | ***Contaminant characteristics*** |
| *116* | *3.1.1* | *Radioactive decay and in-growth* – ***Yes****,* see Section 3.1.1 and Appendix I. |
| *117* | *3.1.2* | *Radionuclide properties, other* – ***Yes****,* see Section 3.1.1. It is assumed that the radionuclides in the disused sources are in a physical state that means that they are soluble. |
| *118* | *3.1.3* | *Organics and potential for organic forms* – ***No****,* it is assumed that there is no significant organic component in the waste. |
| *119* | *3.1.4* | *Chemical/organic toxin stability* – ***No,*** see Sections 1.3 and 2.2.4. Non-radiological impacts, which might arise from the content of chemically or biologically toxic materials in the waste or engineered barrier materials, are considered to be beyond the scope of the GSA. |
| *120* | *3.1.5* | *Inorganic solids/solutes* – ***Yes****,* see Section 3.1.1 and FEP 3.1.2. |
| *121* | *3.1.6* | *Volatiles and potential for volatility* – ***Yes****,* see Section 3.1.1. Iodine is potentially volatile. |
| *122* | *3.1.7* | *Noble gases* – ***Yes****,* Rn-222 in-grown from Ra-226 (see Table 34). |
| | ***3.2*** | ***Contaminant release and migration factors*** |
| *123* | *3.2.1* | *Contaminant release pathways* – ***Yes****,* see Section 4.2.1. Consideration is given to releases via water and gas pathways. |
| *124* | *3.2.2* | *Chemical/geochemical-mediated processes, effects on contaminant release and migration* – ***Yes****,* see Sections 3.1, 3.2 and 4.2.1. Consideration is given to a range of near field and geosphere chemical conditions and sorption processes. |
| *125* | *3.2.3* | *Microbial/biological-mediated processes, effects on contaminant release and migration* – ***No****,* assume no need to represent microbial/biological-mediated processes explicitly. However, these processes are implicitly represented through considering a range of near field and geosphere chemical conditions (see Sections 3.1.3 and 3.2). |
| *126* | *3.2.4* | *Water-mediated migration of contaminants* – ***Yes****,* see Sections 3.2 and 4.2.1. Consideration given to advection, dispersion and diffusion. |
| *127* | *3.2.5* | *Solid-mediated migration of contaminants* – ***Yes****,* see Section 4.2.1. Erosion of soil contaminated by irrigation water considered. Soil assumed to be contaminated with radionuclides from borehole once closure zone is removed by erosion (after 100 000 years). |
| *128* | *3.2.6* | *Gas-mediated migration of contaminants* – ***Yes****,* see Section 4.2.1. Scenario considers release of radionuclides in the gas phase from the borehole. |
| *129* | *3.2.7* | *Atmospheric migration of contaminants* – ***Yes****,* see Section 4.2.1. Scenario considers release of contaminated gas into a dwelling and suspension and dispersion of soil contaminated by irrigation water considered. |
| *130* | *3.2.8* | *Animal, plant and microbe mediated migration of contaminants* – ***Yes****,* see Section 4.2.1. Irrigation of crops and watering of animals considered. |
| *131* | *3.2.9* | *Colloids mediated migration of contaminant* – ***No****.* Assume that in systems with a cement grout near field, colloids are not readily formed due to the chemical conditions. |

SCREENED FEP LIST FOR THE DESIGN SCENARIO (cont.)

| | ***3*** | ***CONTAMINANT FACTORS*** | |
|---|---|---|---|
| | ***3.3*** | ***Exposure factors*** | |
| *132* | | *3.3.1* | *Food chains, uptake of contaminants in* – ***Yes***, see Sections 3.3 and 4.2.1. Ingestion of contaminated crops and animal produce considered. |
| *133* | | *3.3.2* | *Drinking water, foodstuffs and drugs, contaminant concentrations in* – ***Yes***, see Sections 3.3 and 4.2.1. Scenario includes consideration of the consumption of contaminated drinking water, crops and animal produce and inhalation of contaminated gas. |
| *134* | | *3.3.3* | *Environmental media, contaminant concentrations in* – ***Yes***, see Section 4.2.1. Need to consider contaminant concentrations in soil, air, crops and animals. |
| *135* | | *3.3.4* | *Non-food products, contaminant concentrations in* – ***No***, see Sections 3.3 and 4.2.1. Humans are assumed not to be exposed via non-food products for the scenario. |
| *136* | | *3.3.5* | *Exposure modes* – ***Yes***, see Sections 3.3 and 4.2.1. Scenario includes consideration of the ingestion, inhalation gas and external irradiation. |
| *137* | | *3.3.6* | *Dosimetry* – ***Yes***, see Sections 2.4 and 2.5. Consider annual individual effective dose to an average adult member of a hypothetical critical group. |
| *138* | | *3.3.7* | *Radiological toxicity/effects* – ***Yes***, see Sections 2.4 and 2.5. Consider annual individual effective dose to an average adult member of a hypothetical critical group. |
| *139* | | *3.3.8* | *Chemical toxicity/effects* – ***No,*** see Sections 1.3 and 2.2.4. Non-radiological impacts, which might arise from the content of chemically or biologically toxic materials in the waste or engineered barrier materials, are considered to be beyond the scope of the GSA. |
| *140* | | *3.3.9* | *Radon and radon daughter exposure* – ***Yes***, see Section 4.2.1. Rn-222 in-grows from Ra-226. |

# APPENDIX V
# DETAILED NEAR FIELD FEP LIST

This Appendix lists and discusses the detailed near field Features, Events, and Processes (FEPs) in the Generic Safety Assessment (GSA) for borehole disposal of Categories 3 to 5 Disused Sealed Radioactive Sources (DSRS). The FEPs are listed in the following table and are then discussed in more detail in the text that follows. The text of this Annex is structured according to the FEP Numbers, to provide traceability.

| Category | FEP | FEP | |
|---|---|---|---|
| 2.1 | Waste, waste form & engineered features | | |
| | 2.1.1 | Waste inventory | |
| | | 2.1.1.1 | Radionuclide content |
| | | 2.1.1.2 | Chemical content |
| | 2.1.2 | Source characteristics and degradation processes | |
| | | 2.1.2.1 | Characteristics of sources |
| | | 2.1.2.2 | Degradation of metallic sources |
| | | 2.1.2.3 | Degradation of ceramic and glass sources |
| | | 2.1.2.4 | Degradation of powder sources |
| | | 2.1.2.5 | Degradation of gas and liquid sources |
| | 2.1.3 | Container characteristics and degradation/failure processes | |
| | | 2.1.3.1 | Characteristics of containers |
| | | 2.1.3.2 | General corrosion |
| | | 2.1.3.3 | Localized corrosion |
| | | 2.1.3.4 | Stress corrosion cracking |
| | | 2.1.3.5 | Corrosion fatigue |
| | | 2.1.3.6 | Hydrogen-related effects |
| | | 2.1.3.7 | Galvanic corrosion |
| | | 2.1.3.8 | Weld attack |
| | 2.1.4 | Backfill characteristics and degradation processes | |
| | | 2.1.4.1 | Characteristics of backfill |
| | | 2.1.4.2 | Chloride attack |
| | | 2.1.4.3 | Sulphate attack |
| | | 2.1.4.4 | Carbonation |
| | 2.1.5 | Other engineered features: characteristics and degradation processes | |
| | | 2.1.5.1 | HDPE casing |
| | | 2.1.5.2 | Centralisers |
| | | 2.1.5.3 | Anti-intrusion barrier |
| | | 2.1.5.4 | Native soil/crushed rock |
| | 2.1.6 | Mechanical processes and conditions | |
| | | 2.1.6.1 | Container collapse |
| | | 2.1.6.2 | Material volume changes |
| | | 2.1.6.3 | Fracturing of cement grout |

DETAILED NEAR FIELD FEP LIST (cont.)

| Category | FEP | FEP | |
|---|---|---|---|
| | 2.1.7 | Hydrological processes and conditions | |
| | | 2.1.7.1 | Infiltration and movement of water in the borehole |
| | | 2.1.7.2 | Degree of saturation |
| | | 2.1.7.3 | Resaturation of the borehole |
| | | 2.1.7.4 | Gas mediated water flow |
| | | 2.1.7.5 | Coupled hydraulic processes including temperature, chemical or electrical gradients |
| | 2.1.8 | Chemical processes and conditions | |
| | | 2.1.8.1 | pH conditions |
| | | 2.1.8.2 | Redox conditions |
| | | 2.1.8.3 | Chloride and sulphate conditions |
| | | 2.1.8.4 | Mineralization change |
| | | 2.1.8.5 | Effects of chelating agents |
| | | 2.1.8.6 | Colloid formation |
| | | 2.1.8.7 | Precipitation/dissolution reactions (solubility limitation) |
| | 2.1.9 | Biological processes and conditions | |
| | | 2.1.9.1 | Microbial growth and poisoning |
| | | 2.1.9.2 | Microbially/biologically mediated processes |
| | | 2.1.9.3 | Microbial/biological effects of evolution of redox and pH |
| | 2.1.10 | Thermal processes and conditions | |
| | | 2.1.10.1 | Radiogenic, chemical and biological heat production from thewastes |
| | | 2.1.10.2 | Chemical heat production from engineered features |
| | | 2.1.10.3 | Temperature evolution |
| | | 2.1.10.4 | Temperature dependence of processes |
| | 2.1.11 | Radiation effects | |
| | | 2.1.11.1 | Effects on containers |
| | | 2.1.11.2 | Effects on cement grout |
| | | 2.1.11.3 | Effects on other engineered features |
| | | 2.1.11.4 | Effects on pH |
| | | 2.1.11.5 | Effects on redox |
| | | 2.1.11.6 | Decay product gas generation |
| | 2.1.12 | Gas sources and effects | |
| | 2.1.13 | Extraneous materials | |

FEP 2.1. WASTE, WASTE FORM & ENGINEERED FEATURES

## FEP 2.1.1. Waste inventory

### *FEP 2.1.1.1. Radionuclide content*

Description – Mass of radioactive material disposed in the borehole.

Treatment in GSA – Unit inventory of 1 TBq per waste package is assumed for each of the 11 radionuclides that appear in bold font in Table 3. The change in radionuclide inventories due to radioactive decay and in-growth after disposal is taken into account.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.1.2. Chemical content*

Description – Mass of non-radioactive material disposed in the borehole.

Treatment in GSA – Chemical contaminants are not considered in the GSA since non-radiological impacts, which might arise from the content of chemically or biologically toxic materials in the disused sources are beyond the scope of the GSA (see Section 1.3 and 2.4).

Inclusion of FEP – Excluded in all scenarios.

## FEP 2.1.2. Source characteristics and degradation processes

### *FEP 2.1.2.1. Characteristics of sources*

Description – The physical and chemical characteristics of the disused sources at the time of disposal and evolution of these properties with time. This includes processes that are relevant specifically as sources degradation processes, rather than processes that contribute to the general evolution of the borehole.

Treatment in the GSA – Table 12 summarizes the characteristics of the sources considered in the GSA. A range of different physical and chemical forms is considered including metallic, ceramic, glass, powder, gas and liquid.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.2.2. Degradation of metallic sources*

Description – Some of the sources considered in the GSA can occur in metallic form (e.g. Co-60, see Table 12). The metal will corrode with time resulting in the release of radionuclides into water and the generation of hydrogen gas.

Treatment in the GSA – Degradation of the metallic sources is assumed to occur once the capsule containing the source and the failed source container is breached, allowing the entry of water and its contact with the source. Degradation occurs through various corrosion processes (see FEP 2.1.3) resulting in the release of radionuclides into water. It is considered that the amount of hydrogen gas generated is small in comparison to that generated by the corrosion of the capsule and disposal container.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.2.3. Degradation of ceramic and glass source*

Description – Some of the sources considered in the GSA can occur in ceramic or glass form (e.g. Sr-90, see Table 12). The ceramic/glass will dissolve with time resulting in the release of radionuclides into water.

Treatment in the GSA – Dissolution of the ceramic/glass sources is assumed to occur once the capsule containing the source and the failed source container is breached, allowing the entry of water and its contact with the source. The rate of dissolution will be affected by the geochemical conditions in the borehole.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.2.4. Degradation of powder sources*

Description – Some of the sources considered in the GSA can occur as powders (e.g. Cs-137 and Ra-226, see Table 12). The powder will dissolve with time resulting in the release of radionuclides into water. For soluble powders (e.g. Ra-226), the dissolution is assumed to be instantaneous on contact with water.

Treatment in the GSA – Dissolution of the powder sources is assumed to occur once the capsule containing the source and the failed source container is breached, allowing the entry of water and its contact with the source. The GSA takes account of the solubility of the powder under the various geochemical conditions assessed.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.2.5. Degradation of gas and liquid sources*

Description – Some of the sources considered in the GSA can occur as gas (e.g. H-3 and Kr-85, see Table 12) and liquid (e.g. H-3, see Table 12).

Treatment in the GSA – No degradation of the gas and liquid is assumed to occur other than radioactive decay (see FEP 3.1.1). Once the capsule containing the source and the failed source container is breached, it is assumed that the gas and liquid are released immediately.

Inclusion of FEP – Excluded in all scenarios (other than radioactive decay - see FEP 3.1.1).

## FEP 2.1.3. Container characteristics and degradation/failure processes

### *FEP 2.1.3.1. Characteristics of containers*

Description – The characteristics of the various containers in which the disused sources are enclosed.

Treatment in the GSA – Three ‘containers’ are identified in Section 3.1.2 for use in the borehole disposal concept.

- The **source container** within which the source material is sealed. It is conservatively assumed that the source container will have failed prior to disposal and so no credit is taken for it.
- The Type 304 stainless steel **capsule** containing the source container. Until breached, it isolates the source container from water, animals and humans and prevents escape of gas from the source container. Once breached, it limits the fraction of radionuclides available for release from the capsule until the entire capsule has been corroded.
- The Type 316 L stainless steel **disposal container**, which contains the capsule and containment barrier. Until breached, it isolates source container, capsule and containment barrier from water, animals and humans. Once it and the capsule are both breached, the disposal container can limit the fraction of radionuclides available for release into the borehole until the entire container has been corroded.

For the Design Scenario, it is assumed that none of the closure welds on the capsule and disposal container are defective. For Defect Scenario D1, it is assumed that the closure weld in one 316 L dipsosal container is defective. For Defect Scenario D2, it is assumed that the closure weld in one 304 capsule is defective. For Defect Scenario D4, it is assumed that the closure weld in one 316 L disposal container and one 304 capsule and the faulty capsule is in the faulty container.

Inclusion of FEP – Capsule and disposal container included in all scenarios. Source container excluded from all scenarios.

### *FEP 2.1.3.2. General corrosion*

Description – Stainless steels are subject to general corrosion at a rate that varies with time, temperature, redox conditions, pH, and salinity. Stainless steels are protected by the formation of a stable Cr(III) oxide or hydroxide film (variously represented by $Cr_2O_3$, $Cr(OH)_3$, or CrOOH).

On freshly polished surfaces, the corrosion rate will continue to decrease with time for several years after exposure to the corrosive environment as the passive film develops. The film is typically amorphous, although for some passive materials re-crystallization of the oxide can occur over time, resulting in an increase in corrosion rate.

The general corrosion rate of stainless steel is typically not a strong function of the redox potential, here interpreted in terms of the corresponding dissolved $O_2$ concentration. Increasing $[O_2]$ leads to an increase in $E_{CORR}$, but provided the potential is within the passive range the corrosion rate is determined more by the properties of the oxide film than by the rate of the cathodic reaction (the reduction of $O_2$). An increase in $E_{CORR}$, however, will result in an increase in the potential drop across the passive film and the ‘leakage current’ (which corresponds to the rate of general corrosion) will increase accordingly. In contrast, the corrosion rate of active materials may be proportional to the $[O_2]$ if the rate of corrosion is cathodically limited.

The protectiveness of the passive film depends on the solution pH. The minimum solubility of Cr(III) oxides lies between pH 7 and pH 8.5, depending upon the stable form. The solubility increases at both lower and higher pH, although the rate of increase in solubility is much greater in acidic solutions. Furthermore, the stability of the oxides of other alloying elements at higher pH maintains a stable passive film in the alkaline range.

Chloride ions tend to de-stabilise the passive film on stainless steels. Although the effect of $Cl^-$ is most significant for the initiation and propagation of localized corrosion, $Cl^-$ ions also tend to decrease the stability of the passive oxide film and lead to an increase in general corrosion rate.

Treatment in the GSA – General corrosion of the stainless steel capsule and disposal container is one of the main corrosion processes included in the GSA. The corrosion rate is taken to be a function of redox potential, pH, and $Cl^-$ concentration (see FEP 2.1.8).

Isothermal conditions are assumed, so the temperature dependence of the general corrosion rate is not considered (see FEP 2.1.10.4).

It is assumed that the general corrosion rate attains a steady state soon after emplacement of the waste and does not change with time other than due to the evolution of porewater pH with time.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.3.3. Localized corrosion*

Description – Localized corrosion of stainless steels can take the form of discrete pitting of exposed surfaces or of crevice corrosion in geometrically occluded regions or under surface deposits. Localized attack is favoured by higher temperatures, lower pH, increased $Cl^-$ concentrations, and more-positive $E_{CORR}$ (or $E_H$) values. A number of oxyanions, including $SO_4^{2-}$, inhibit the aggressive effect of $Cl^-$.

The initiation of localized corrosion occurs if the corrosion potential $E_{CORR}$ exceeds the breakdown potential of the passive film. Crevice corrosion tends to initiate more easily than pitting as the occluded region serves to both concentrate aggressive ions (such as $Cl^-$) and also create a differential $O_2$ concentration cell, leading to the spatial separation of anodic and cathodic reactions and the resulting localized attack. Once initiated, a pit or crevice will continue to propagate until some process leads to the loss of the critical pit or crevice chemistry and the cessation of corrosion. The rate of propagation of localized corrosion can be several orders of magnitude higher than the rate of general corrosion.

Type 316L stainless steel is more resistant to localized corrosion than Type 304 because of the addition of Mo. Molybdenum provides stability at low pH because of the formation of $MoO_2$ or $MoO_3$ phases which are stable in acidic solutions. Type 304 stainless steel can also become sensitised during welding because of the formation of chromium carbides at grain boundaries, leading to an increased susceptibility to intergranular SCC.

Once initiated, a crevice (as assumed here) will propagate through the wall thickness until perforation of the shell occurs at a particular location within the crevice. Following initial perforation, the area of through-wall corrosion will extend over the entire creviced region (provided the through-wall penetration does not result in the loss of the critical crevice chemistry) and may extend beyond the area of the original occluded region if precipitated corrosion product acts as its own crevice former. Adjacent creviced regions may coalesce to produce larger defects in the container, although the rate of crevice propagation will slow with time as the cathode:anode surface area ratio diminishes as more of the container wall is corroded.

Treatment in the GSA – Localized corrosion is included in the GSA corrosion assessment as a failure mechanism for the stainless steel waste capsule and disposal container.

Neither grade of stainless steel is deemed to be susceptibility to pitting or crevice corrosion during Stage 1 or 2 of cement grout degradation because of the high pH of the cement grout porewater contacting the capsule and disposal container. This conclusion is based on a comparison of reported $E_{CORR}$ and breakdown potentials measured at high pH. During Stages 3 and 4, both materials may be susceptible to localized corrosion in aerated groundwaters (in which $E_{CORR}$ exceeds the repassivation potential for crevice corrosion) but not in anaerobic (reducing) waters. The concentration of $Cl^-$ is sufficient to induce localized corrosion even in the fresh groundwaters considered in the GSA.

The conditions of potential, $Cl^-$ concentration, and pH for the initiation of localized corrosion have been converted to an equivalent pH value. In this way, the time at which localized corrosion is possible can be estimated from the time-dependence of the cement grout porewater pH.

To maintain conservatism, the potential at which localized corrosion initiates is taken to be 200 mV more negative than the re-passivation potential for crevice corrosion. The conservatism in this treatment arises from three factors (i) the choice of crevice corrosion rather than pitting (pitting occurs at more positive potential), (ii) the selection of the re-passivation potential as the criterion for initiation, and (iii) the use of a value 200 mV more negative than that reported to account for the stochastic nature of re-passivation potentials.

Based on this approach, the equivalent pH values for the initiation of localized corrosion for Types 304 and 316L stainless steel are taken to be pH 11 and pH 10 (or the background pH of the groundwater for alkaline waters). The higher pH value for Type 304 stainless steel reflects the greater susceptibility of this material to localized corrosion and the possibility of sensitisation of the capsule closure weld.

Crevice propagation is not explicitly treated in the GSA corrosion analysis as the rate of corrosion is relatively fast compared with the predicted container lifetimes. Based on reported crevice propagation rates, through-wall perforation will occur within a few years of initiation. Growth of the perforation (and of adjacent perforations) will occur at a similar rate, possibly leading to through-wall perforation on most of the container surface within a period of, say, 100 years. This period is short compared with the estimated lifetimes of $>10^4$ years. Therefore, no credit is taken for the remaining mass-transfer resistance offered by the capsule and disposal container for the period between the initiation of localized corrosion and such extensive localized attack that the vessel no longer restricts mass transport into or out of the failed container.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.3.4. Stress corrosion cracking*

Description – Stress corrosion cracking (SCC) of stainless steels is known to occur in chloride solutions. Cracking results from the presence of an applied tensile stress or from residual stress in welds that have not undergone a stress-relief treatment.

Cracks typically initiate from pits and propagate relatively rapidly in a direction normal to the principal tensile stress.

From an environmental viewpoint, the conditions that support cracking are similar to those that produce pitting of the exposed surface.

Treatment in the GSA – SCC is not included as a failure mechanism in the GSA corrosion analysis. The initiation (and relatively rapid propagation) of crevice corrosion is considered to occur under less aggressive conditions than cracking (see FEP 2.1.3.3). Given that crevice propagation is rapid, failure of the container will occur via this mechanism before failure by SCC.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.3.5. Corrosion fatigue*

Description – Corrosion fatigue is a result of the action of a corrosive environment and a cyclic load resulting in cracking. The corrosion component enhances the crack growth rate that would otherwise be observed in the absence of the environment (i.e. pure fatigue).

Treatment in the GSA – Corrosion fatigue is not included as a failure mechanism in the GSA corrosion analysis because of the absence of cyclic loading of the capsule or disposal container.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.3.6. Hydrogen-related effects*

Description – Many metals are susceptible to failure due to the absorption of atomic hydrogen. Failure often takes the form of cracks or blisters due to the accumulation of atomic or molecular hydrogen at defects in the material. Ferritic steels are particularly susceptible to hydrogen effects because of the high diffusivity of hydrogen. The susceptibility to hydrogen damage generally increases with increasing strength of the material because the higher potential stress gradients that can be created cause greater segregation of absorbed hydrogen.

Austenitic stainless steels (such as Types 304 and 316L) are generally less susceptible to hydrogen effects than ferritic materials (e.g. carbon or mild steels) because the diffusivity of hydrogen in the austenite phase is several orders of magnitude lower than in the ferrite phase.

Treatment in the GSA – Hydrogen-related degradation mechanisms are not included in the corrosion analysis for the GSA because of the generally lower susceptibility of austenitic stainless steels to hydrogen effects.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.3.7. Galvanic corrosion*

Description – Galvanic corrosion occurs when two metals are coupled together in a conductive medium. One of the metals acts as the anode and corrodes faster than if it were not coupled, and the other metal becomes the cathode and corrodes more slowly. The severity of galvanic corrosion depends on the separation of the two metals (in terms of mV) in the so-called galvanic series, the relative surface areas of the materials, and the conductivity of the electrolyte.

Treatment in the GSA – Galvanic corrosion is not included in the corrosion analysis for the GSA because of the absence of dissimilar metal contacts for either the capsule or the disposal container.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.3.8. Weld attack*

Description – Welds are often locations for preferential corrosion. The enhanced susceptibility of welds results from (i) micro-scale galvanic cells that can be created due to the use of a dissimilar weld material, (ii) microstructural differences between the weld metal, heat-affected zone, and base metal, or (iii) segregation of certain alloying elements to grain boundaries (sensitisation).

Stainless steels can be susceptible to preferential weld attack if steps are not taken to avoid the effects listed above. Type 304 stainless steel is susceptible to intergranular attack or enhanced SCC due to sensitisation of grain boundaries.

Treatment in the GSA – The possibility of enhanced susceptibility of sensitised welds for the Type 304 capsule is implicitly included in the GSA corrosion analysis through the use of a higher pH threshold for the initiation of localized corrosion.

Inclusion of FEP – Implicit in enhanced susceptibility of Type 304 capsules to the initiation of localized corrosion assumed for all scenarios.

## FEP 2.1.4. Backfill characteristics and degradation processes

### *FEP 2.1.4.1. Characteristics of backfill*

Description – Chemical and physical characteristics of the backfill used in the borehole disposal concept.

Treatment in the GSA – Cement 'backfill' is used as a chemical and physical barrier in five locations in the borehole disposal concept (see Section 3.1.2):

- The containment barrier – the space between the capsule and the disposal container is backfilled with cement grout;
- The disposal zone backfill - cement grout is used to separate disposal containers in vertical dimension from one another, and in the horizontal dimension from the borehole casing;
- The disposal zone plug at base of borehole;
- The disturbed zone backfill - cement grout is used to fill the gap between the casing and the host rock and any voids/cracks in the host rock immediately adjacent to the borehole; and
- The closure zone backfill – it is assumed that the first 5 m from the ground surface is native soil/crushed rock and the remainder down to the disposal zone is cement grout.

For all scenarios other than Defect Scenario D3, it is assumed that cement grout emplaced under appropriate QA/QC is present in all five locations. For Defect Scenario D3, it is assumed that the cement grout in the disposal and disturbed zone has not been emplaced under appropriate QA/QC and so degrades more rapidly.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.4.2. Chloride attack*

Description – The effect of chloride ions in groundwater coming into the borehole on the cement grout backfill used in the borehole (e.g. [71]). Chloride will to some extent become bound to solid phases as a consequence of reactions within the cement grout. Some chloride will form solid compounds such as Friedel salts ($Ca_3Al_2O_6.CaCl_2.10H_2O$) whilst some chloride will sorb to the surfaces of calcium silicate hydrates (CSH). However, the extent to which this binding occurs will depend upon the concentrations and characteristics of other constituents within the pore fluid. Notably carbonate and sulphate will generally act to diminish the binding of chloride. The chemical composition of the cement grout is also a significant control. In reality this process would have less effect on the strength and pH-buffering capacity of the cement grout barrier than would attack by sulphate and/or carbonate. Furthermore, it would reduce the availability of chloride ions for corrosion.

Treatment in the GSA – Chloride attack of the cement grout is not taken into account explicitly. Instead illustrative calculations are undertaken in which the capacity for chemical buffering capacity and ability to physically retard fluid flow is diminished in comparison with the reference case. These calculations are designed to illustrate the possible significance of attack not only by chloride, but also by sulphate and carbonate. Additionally, from the perspective of corrosion, it is conservative to assume that the concentrations of chloride in the porewater contacting the steel barriers would not be diminished by reactions in the cement grout.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.4.3. Sulphate attack*

Description – The effect of sulphate ions in groundwater coming into the borehole on the cement grout backfill used in the borehole. These ions diffusing into cements react with certain phases forming larger volume products. Initially, this volume increase will reduce the interconnected porosity and hence the permeability. However, once the volume increase has proceeded to the extent that it cannot be accommodated by the porosity, there will be an overall internal expansion that eventually causes stress, cracking and exfoliation of the reacted zone [67]. The range of reactions involved is complex and depends on the conditions, particularly the concentration of sulphate. Ettringite and gypsum are among the products. The attack depletes the reservoir of alkalinity (calcium hydroxide) in cement. An overall effect of this is to reduce the capacity of cementitious backfill to buffer pH to high values. To predict the behaviour of the cement grout and the temporal evolution of the porewater chemistry would require the development of complex coupled models taking into account a complete physical and chemical description of the cement grout-porefluid system. The detailed evolution of this system will be case-specific.

Treatment in the GSA – It is assumed that sulphate resistant cement grout is used (see Section 3.1.2). Nevertheless, sulphate attack will occur. However, it is not treated explicitly in the GSA. To do so would be unjustified in the absence of more site specific and engineered barrier-specific information (e.g. porewater composition, groundwater flow rate and cement grout composition) and without developing detailed coupled models. Instead illustrative calculations are undertaken in which the capacity for chemical buffering and ability to physically retard fluid flow is diminished in comparison with the reference case. These calculations are designed to illustrate the possible significance of attack not only by sulphate, but also by chloride and carbonate.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.4.4. Carbonation*

Description – The effect of carbonate ions in groundwater coming into the borehole on the cement grout backfill used in the borehole. However, to predict the overall influence of carbonate attack on the behaviour of the cement grout and the temporal evolution of the porewater chemistry would require the development of complex coupled models. Furthermore, these models would need to take into account a complete physical and chemical description of the cement grout-porefluid system. The detailed evolution of this system will be case-specific. The carbonate will tend to reduce the ability of cement to impose a high pH on borehole water [67], by reacting with the main source of alkalinity, calcium hydroxide and by limiting access of the migrating porewater to reactive cementitious phases. On its own this effect on pH would be detrimental with respect to the longevity of the steel barriers. However, carbonation will also tend to seal the porosity which may decrease the porosity of the cement grout, at least at relatively early times. Thus, the flux of water past the steel barriers could be diminished, which would tend to enhance the longevity of these barriers.

Treatment in the GSA – Carbonation is not treated explicitly. To do so would be unjustified in the absence of site specific and engineered barrier-specific information (e.g. exact porewater composition, groundwater flow rate and cement grout composition) and without developing detailed coupled models. Instead illustrative calculations are undertaken in which the capacity for the chemical buffering capacity and ability to physically retard fluid flow is diminished in comparison with the reference case. These calculations are designed to illustrate the possible significance of attack not only by carbonate, but also by chloride and sulphate.

Inclusion of FEP – Included in all scenarios.

## FEP 2.1.5. Other engineered features: characteristics and degradation processes

### *FEP 2.1.5.1. HDPE casing*

Description – High-density polyethylene (HDPE) casing emplaced at time of drilling to help ensure the borehole is dry during emplacement of the disposal containers. Top sections are withdrawn at closure of borehole down to 1 m of the disposal zone.

Treatment in the GSA – HDPE is subject to various corrosion processes leading to a loss of mechanical integrity. The leaching of plasticizers results in embrittlement of the plastic and eventual cracking and loss of structure. Some forms of HDPE are also susceptible to stress corrosion cracking. Conservatively assumed HDPE casing fails immediately on closure of the borehole and so is not represented in the post-closure GSA calculations. It is assumed that any binding between radionuclides and organic products of the breakdown of the HDPE would have an insignificant effect on radionuclide migration.

Inclusion of FEP – Implicitly included in all scenarios since it is a component of the reference design. However it is not explicitly modelled in post-closure GSA calculations. There is little information with which to judge whether or not organics released from the degradation of HDPE could complex with radionuclides to the extent that the mobility of radionuclides is affected significantly. It is therefore assumed that the chemical effects of HDPE breakdown would be insignificant.

### *FEP 2.1.5.2. Centralisers*

Description – The casing is fitted with centralisers to ensure that the casing is in the middle of the borehole. These centralisers are made of thin mild steel plates inserted vertically to ensure that they do not hamper the flow of the backfill slurry.

Treatment in the GSA – The centralisers will be subject to similar corrosion processes as the capsules and disposal containers (see FEP 2.1.3). Since they are made of mild rather than stainless steel, corrosion will occur much faster. The centralisers perform no role as a barrier to radionuclide migration and so are not represented in the post-closure GSA calculations.

Inclusion of FEP – Implicitly included in all scenarios since they are a component of the reference design. However they are not explicitly modelled in post-closure GSA calculations.

### *FEP 2.1.5.3. Anti-intrusion barrier*

Description – An anti-intrusion barrier (for example a metallic ‘drill deflector’) is placed above the disposal zone in order to deter/prevent human intrusion.

Treatment in the GSA – The role of the barrier is to deter/prevent human intrusion. It is not considered to be a barrier to radionuclide migration by groundwater and gas pathways and so is not explicitly represented in the post-closure GSA calculations.

Inclusion of FEP – Implicitly included in all scenarios since it is a component of the reference design. However it is not explicitly modelled in post-closure GSA calculations.

### *FEP 2.1.5.4. Native soil/crushed rock*

Description – Native soil/crushed rock used to fill the top 5 m of the closure zone.

Treatment in the GSA – The role of the barrier is to deter/prevent human intrusion. It is not considered to be a barrier to radionuclide migration by groundwater and gas pathways and so is not explicitly represented in the post-closure GSA calculations

Inclusion of FEP – Implicitly included in all scenarios since it is a component of the reference design. However it is not explicitly modelled in post-closure GSA calculations.

## FEP 2.1.6. Mechanical processes and conditions

### *FEP 2.1.6.1. Container collapse*

Description – The processes that lead to the collapse of the containers in the post-closure period.

Treatment in the GSA – As noted in FEP 2.1.3.1, there are three containers considered in the GSA (the source container, the capsule and the disposal container). The source container and the capsule have significant voidage, whereas the disposal container is backfilled with the cement grout that forms the containment barrier. Whilst the source container is assumed to have failed prior to closure, the capulse that contains it and its associated source is assumed to be intact, as is the disposal container.

With the ingress of groundwater into the borehole, the disposal container will be subject to gradual corrosion which will eventually lead to the breach of the container (see FEP 2.1.3). Corrosion of the disposal container will not result in its collapse since it is backfilled with the cement grout containment barrier.

Following ingress of water into the disposal container, the capsule will be subject to corrosion (see FEP 2.1.3). Corrosion will lead to breaches in the capsule. In addition, the cement grout containment barrier in the disposal container will be subject to expansive reaction with ions in the incoming groundwater, particularly sulphate (see FEP 2.1.4.3). Ultimately the combination of these processes might lead to the collapse of the capsule due to its significant voidage. However, the impact of this possible collapse is not considered to be significant in terms of increasing the release rate of radionuclides given that the capsule will have to be significantly corroded prior to collapse and so longer performing the role of a significant barrier.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.6.2. Material volume changes*

Description – The effects of volume changes in materials used in borehole. The volume changes associated the main materials used in the borehole are as follows:

- Cements can show volume increased due to their degradation (see FEP 2.1.4); and
- Corrosion of metal containers usually leads to corrosion products that have larger volumes than the original metals (see FEP 2.1.3).

Treatment in the GSA – It is considered that volume changes will not be significant in the borehole although they might promote some localized fracturing of the cement grout (see FEP 2.1.6.3).

Inclusion of FEP – Included implicitly in all scenarios through consideration of increase permeability of cement grout with time.

### *FEP 2.1.6.3. Fracturing of cement grout*

Description – Cement of the containment barrier and the backfill may fracture due to applied stresses (e.g. from material volume changes – see FEP 2.1.6.2) and/or degradation.

Treatment in the GSA – It is considered that fracturing of the cement grout in the borehole will occur due to volume changes and cement grout degradation. This is implicitly considered through consideration of increase permeability of cement grout with time.

Inclusion of FEP – Included implicitly in all scenarios.

## FEP 2.1.7. Hydrological processes and conditions

### *FEP 2.1.7.1. Infiltration and movement of water in the borehole*

Description – Water flow into and through the borehole is governed by the hydraulic gradient, hydraulic conductivity, porosity, and the degree of saturation in the borehole and, in the case of the borehole in the unsaturated zone, the percolation rate in the unsaturated zone.

Treatment in the GSA – It is assumed that the infiltration rate into the borehole is time variant due to changes in the hydraulic conductivity and porosity of the cement grout in the borehole as a consequence of cement grout degradation.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.7.2. Degree of saturation*

Description – The degree of saturation can affect the flow of water through the borehole (see FEP 2.1.7.1) and also the corrosion processes. Atmospheric corrosion typically exhibits a threshold relative humidity of 60-70% below which there is insufficient surface moisture to support electrochemical reactions [74]. In aerated systems, the corrosion rate of non-passive materials is often determined by the rate of supply of $O_2$. As a consequence, the corrosion rate can be higher in unsaturated systems as the rate of supply of $O_2$ through the vapour phase is orders of magnitude higher than through aqueous solution.

For passive materials such as Types 304 and 316L stainless steel, the corrosion behaviour is determined by the properties of the passive film. Corrosion is therefore anodically, rather than cathodically, limited and corrosion rates are similar in the vapour phase and in aqueous solutions, for equivalent chloride concentration and redox conditions.

Thin moisture films, as formed on surfaces in humid atmospheres, can exhibit higher solute concentrations because of evaporative concentration mechanisms.

Treatment in the GSA – The degree of saturation of the borehole is explicitly taken into account in the calculation of water flows in the GSA.

The corrosion rate and susceptibility to localized corrosion is assumed to be the same for saturated and unsaturated sites. It is implicitly assumed that the relative humidity in the borehole will always exceed the threshold of 60-70% RH for corrosion processes.

It is assumed that evaporative concentration of electrolytes in thin moisture films does not occur because of the absence of thermal gradients assumed for the GSA (see FEP 2.1.10).

Inclusion of FEP – Included in all scenarios.

### *1.1.1.1. FEP 2.1.7.3. Resaturation of the borehole*

Description – At closure, the borehole will be unsaturated (be it in the unsaturated or saturated zone). With time, the borehole in the saturated zone will resaturate. The rate of resaturation will be dependent on the hydraulic conditions in the borehole and the surrounding geosphere, and the generation rate of gases and the associated gas pressure.

Treatment in the GSA – It is assumed that the borehole in the unsaturated zone remains unsaturated and the degree of saturation is consistent with the surrounding unsaturated zone.

For the borehole in the saturated zone, it is assumed that it is immediately resaturated on closure since the HDPE casing is conservatively assumed to fail on closure (see FEP 2.1.5.1) allowing the ingress of groundwater. Even for the low flow rate system, the assumed hydraulic parameters given in Table 7 give a resaturation time of less than 20 years.

It is assumed that the generation of gas from the corrosion of the disposal containers and capsules does not result in the build up of pressure in the borehole (see FEP 2.1.7.4) and so has no impact on the resaturation process.

Inclusion of FEP – Included in all scenarios for the borehole in the saturated zone.

### *FEP 2.1.7.4. Gas mediated water flow*

Description – Gas generation within the borehole may affect water flow within the borehole if significant gas pressures are generated.

Treatment in the GSA – It is assumed that the corrosion of the containers in the saturated zone results in the generation of gases, primarily hydrogen, at a maximum rate of 1E-5 $m^3/y$. This rate of gas generation is assumed to be less than the rate of gas loss and so there is no build up of gas pressure in the borehole. Therefore there is no impact of gas on water flows.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.7.5. Coupled hydraulic processes including temperature, chemical or electrical gradients*

Description – Fluid flow driven by temperature, chemical or electrical gradients, rather than due to hydraulic pressure gradients.

Treatment in the GSA – It is assumed that significant chemical and electrical gradients do not exist in the borehole. It is also assumed that significant temperature gradients do not exist in the borehole (see FEP 2.1.10)

Inclusion of FEP – Excluded in all scenarios.

## FEP 2.1.8. Chemical processes and conditions

### *FEP 2.1.8.1. pH conditions*

Description – The main factors affecting the pH in the borehole are the pH of the infiltrating water and the cement grout in the containment barrier and disposal/disturbed zone backfill.

The chemical degradation of the cement grout will cause the pH of the cement grout porewater to evolve over time as alkaline mineral phases dissolve and are flushed out of the cement grout. A model for the evolution of the cement grout porewater pH developed by Berner [34], [35] is used to determine the number of pore volumes corresponding to different stages in the porewater evolution. The time-dependence of the number of pore volumes is a function of the assumed hydraulic conductivity of the site.

Corrosion processes are typically sensitive to changes in pH. The rate of corrosion is often a minimum at a pH in the range pH 7-9, corresponding to the minimum solubility of protective oxide films. Amphoteric materials exhibit increased corrosion rates with increasing pH, although the rate of corrosion for stainless steels is lower in alkaline solution than in the neutral pH range.

Similarly, the susceptibility of stainless steel to localized corrosion is higher at lower pH, again because of the poorer properties of the oxide film in acidic solutions.

The pH of the environment in contact with the waste capsule and the disposal container will be conditioned for some time after emplacement by the cementitious backfill materials. The time dependence of the pH depends on the local hydraulic conductivity. Eventually, the porewater pH will equilibrate with that of the local groundwater. Therefore, the stainless steel waste capsule and disposal container will be exposed to a range of pH values over their service life.

Treatment in the GSA – A range of infiltrating waters with differing pH values are assumed in the GSA (see Table 8).

Evolution of the borehole pH is included in the GSA. A four-stage cement grout degradation model is assumed, with Stage 1 corresponding to pH control by NaOH/KOH (pH 13.5), Stage 2 is dominated by equilibrium with Portlandite ($Ca(OH)_2$) (pH 12.5), Stage 3 represents slow leaching of CSH phases, and Stage 4 corresponds to equilibrium with the background groundwater.

The rate of general corrosion and susceptibility to localized corrosion are assumed to be functions of pH.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.8.2. Redox conditions*

Description – Oxidation/reduction conditions in the borehole and their change with time due to processes such as the corrosion of the capsule and disposal container resulting in the consumption of oxygen.

The corrosion behaviour of materials depends on the redox potential of the environment through its effect on the controlling parameter, the corrosion potential. In general, more-positive redox potentials result in more-positive corrosion potentials. For passive materials, such as stainless steels, an increase in redox potential can lead to an increase in the rate of general corrosion, although not to the same extent as it would for an active material. Increasing corrosion potential (and redox potential) may induce localized corrosion of passive materials.

Treatment in the GSA – A range of redox potentials is considered in the GSA (see Table 8). Although the borehole in the saturated zone will initially be aerobic on closure, it is assumed that it rapidly becomes anaerobic due to the ingress of reducing groundwater and the loss of oxygen through processes such as corrosion. Thereafter, it is assumed that redox potentials remain constant, i.e. positive (oxidising) for the unsaturated system and negative (reducing) for the saturated system. Although corrosion will have the continued effect of reducing potentials further, the extent to which this occurs will be minimized by incoming water and, in the case of the unsaturated borehole, air. Accurate predictions of the actual redox state attained would require detailed case-specific information and the development of sophisticated coupled models. However, it is conservative to assume that conditions are more oxidising than would be the case were the effects of corrosion on redox to be taken into account. Consequently, it is justified to ignore these effects.

The effect of redox potential on both general and localized corrosion is explicitly included in the corrosion estimates for the waste capsule and disposal container.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.8.3. Chloride and sulphate conditions*

Description – Many of the groundwaters considered in the GSA contain high levels of $Cl^-$ and $SO_4^{2-}$ ions. Chloride ions are known to lead to localized corrosion and SCC of stainless steels and may, under some circumstances lead to an increase in the rate of general corrosion.

Sulphate ions can inhibit the aggressiveness of $Cl^-$ ions, although in the groundwater solutions considered for the GSA the relative concentration of sulphate is too low to have a significant effect.

Sulphate may also act as an electron acceptor for sulphate-reducing bacteria (see FEP 2.1.9).

Sulphate and chloride ions also promote the degradation of cement grout (see FEP 2.1.4).

Treatment in the GSA – The effects of $Cl^-$ ions on the general and localized corrosion of stainless steels are fully accounted for in the lifetime predictions for the waste capsule and disposal container.

No inhibitive effect of $SO_4^{2-}$ ions is assumed because of the high $[Cl^-]:[SO_4^{2-}]$ ratio of the groundwaters considered in the GSA.

The effect on the porewater $SO_4^{2-}$ concentration of interaction with the cement grout cannot be considered explicitly, but the possible significance can be judged by means of alternative calculations representing alterntive physical and chemical evolutions of the cement grout (see FEP 2.1.4.3).

Chloride and sulphate concentrations are assumed to remain constant with time.

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.8.4. Mineralization change*

Description – Long term chemical changes occurring in the cement grout in the containment barrier and disposal/disturbed zone backfill that could affect borehole performance.

Cement ages to produce minerals such as portlandite and tobermorite. Prolonged contact between cement grout and groundwater leaches out portlandite (calcium hydroxide) and a proportionately greater loss of calcium than silicon from the CSH gel that gives the materials their strength [63]. Reactions with species such as carbonate, sulphate and magnesium in groundwater could continue into the long term, with species such as calcium carbonate, ettringite and magnesium sulphate being produced. Most of these processes would restrict to some degree the ability of the cement grout to impose a high pH into the long term, and could also lead to loss of physical integrity. They could also affect the permeability of the cement grout; in the shorter-term loss of porosity diminishes permeability; in the longer-term a loss of physical integrity could enhance porosity. The overall temporal variations in physical and chemical properties and the extent to which the performance of the barrier is enhanced or diminished, depends upon a complex coupling between these processes. To predict these effects would require detailed case-specific information and the development of sophisticated coupled models.

Treatment in the GSA – Mineralization is considered in the cement grout degration model adopted for the GSA (see Appendix VIII).

Inclusion of FEP – Included in all scenarios.

### *FEP 2.1.8.5. Effects of chelating agents*

Description – The effect of chelating agents on the performance of the borehole.

Chelating agents are organic compounds, usually carboxylic acids, which have a number of locations in each molecule that can complex with a single metal atom. The resulting complexes are usually highly stable, a factor that can increase significantly the solubilities of certain radionuclides, e.g. Pu with the acidic degradation products of cellulose [68].

Treatment in the GSA – It is assumed that the effect of any chelating agents present in the groundwater and the borehole does not have a significant impact on the performance of the borehole. The only significant source of organic matter within the borehole is HDPE casing. There is little information with which to judge whether or not organics released from the degradation of HDPE could complex with radionuclides to the extent that the mobility of radionuclides is affected significantly. It is therefore assumed that the chemical effects of HDPE breakdown would be insignificant. It is also assumed that the borehole is sited so that anthropogenic chelating agents produced at or near the surface (e.g. chelating agents such as those that might arise from landfill sites or industrial activities) could not penetrate to the depths of the wastes.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.8.6. Effects of colloids*

Description – The existence of colloidal particles in borehole water and the effect of these particles on the performance of the borehole.

Colloids are dispersions of finely divided particles in a dispersing medium. Particle diameters are typically less than 1 μm. A variety of colloidal substances exist in groundwater, including humic substances, micro-organisms, mineral precipitates and weathering products [66]. Colloids could also be generated from materials in a borehole.

Colloids could potentially represent a route for increasing the rate of movement of radionuclides away from the borehole, because their high specific surface areas might encourage sorption. However, aggregation with other, similar particles, or filteration in the borehole or geosphere may prevent colloids from being mobile over significant distances.

Colloids can be generated in cements [66]. Their movement into a cement grout could potentially lead to pore blockage.

Treatment in the GSA – It is assumed that the effect of any colloids present in the groundwater and the borehole does not have a significant impact on the performance of the borehole. It is assumed that transport of radionuclides would not be enhanced significantly by colloids originating in the cement grout because the integrity of the steel barriers would be maintained until the cement grout had already been substantially degraded. The possibility for significant colloidal transport to occur could be minimized by siting the borehole within a sufficiently low-permeability lithology.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.8.7. Precipitation/dissolution reactions (solubility limitation)*

Description – The implications that conditions in the borehole (particularly of pH, Eh and concentrations of complexing ions for radioelements) have for radioelement solubility and the nature of precipitated phases.

Solubility can be defined as the measured aqueous concentration of an element in equilibrium with a solid phase under a given set of conditions. This concentration is determined by the equilibrium constant for the dissolution of the solubility-limiting solid phase and the equilibrium constants for the formation of other soluble species, usually complexes. The solubility-limiting solid phase is the most thermodynamically stable solid that can form under the prevailing conditions [66].

It is important not to create the impression that solubility-limiting reactions defined in this way always impose maximum concentration limits on solutes. In fact, in some cases, metastable solution-solid reactions may give rise to higher aqueous concentrations than would be caused by true solubility limitation as defined in the previous paragraph.

An increasing pH tends to decrease the solubilities of radioelements. This is because many of the most stable solid phases are hydroxides, and increasing the concentration of hydroxyl ions in solution will drive the solubility equilibrium towards the solid phase, reducing the solution concentration of the radioelement. This effect occurs with a cementitious backfill.

The anaerobic conditions drive the most stable oxidation state to a lower level (for elements such as actinides where a choice exists). In general, the lower the oxidation state the lower the limiting solubility.

Some solubilities of radioelements are increased by the presence of complexing ions. One example is the effect of carbonate ions on uranium solubility.

Treatment in the GSA – In the GSA the release functions of the various radionuclides depends upon whether or not they are considered to be solubility limited (see Appendix X).

Inclusion of FEP – Included in all scenarios.

## FEP 2.1.9. Biological processes and conditions

### *FEP 2.1.9.1. Microbial growth and poisoning*

Description – A range of microbes will inevitably be introduced into the borehole during its construction and in the operational phase. Growth requires the presence of water and suitable nutrients (e.g. organic material such as cellulose). Although cellulose will not be found in the borehole, simple organic molecules containing oxygen, nitrogen or sulphur, that might be present in the borehole, can also act as nutrients for microbes. Plastics and most other polymers are relatively inert towards microbes and in general do not support their growth.

Only some of the microbes present at borehole closure will find the subsequent conditions suitable for their growth. Besides requiring certain types of nutrient, individual microbial populations will only operate under particular conditions of temperature, pH and redox potential and salinity.

Alkaliphillic microbes can grow as biofilms on the surface of cement grout, though with a penetration of less than 1 mm. This might block the passage of water through such a cementitious backfill, and decrease the rate at which groundwater moves.

Microbial growth can lead to the formation of acidic and oxidising species that can participate in corrosion of the steels (see FEP 2.1.9.2).

Poisoning of microbial processes can occur in a number of ways, including changing the pH to a value where the microbial population ceases to function.

Treatment in the GSA – Given the absence of cellulose in the borehole and the initial high pH conditions, it is considered that microbial growth will not be significant.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.9.2. Microbially/biologically mediated processes*

Description – Microscopic organisms, including bacteria, protozoans, yeast, viruses and algae, may affect the performance of different engineered barriers, including the containers and backfill. Key processes could include the following.

- Microbiologically influenced corrosion (MIC). Microbial activity can induce corrosion of metallic structures either through the production of aggressive metabolic by-products or by creating occluded regions for localized corrosion. Stainless steels are known to be susceptible to MIC [70]. The key to MIC is microbial activity. If microbes are not active then they cannot produce aggressive metabolic by-products (such as sulphide ions or organic acids) or the extracellular polymeric substance (i.e. slime) that creates localized environments.
- Degradation of sulphate ions. Hydrogen formed during corrosion can react with sulphate ions in groundwater to yield hydrogen sulphide [72].
- Biofilm growth. Biofilms could potentially grow on the surfaces of cement grout and containers. In the case of a cementitious backfill, this could lead to blocking of pores, restricting groundwater movement [67].

Treatment in the GSA – These processes are not included in the corrosion analysis in the GSA. Microbial activity near the capsule and disposal container surfaces will not occur during Stages 1 and 2 because of the high pH. The environment will only become less inhospitable for microbes during Stage 3 or 4, by which time many of the containers are already estimated to have failed.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.9.3. Microbial/biological effects of evolution of redox and pH*

Description – Microbial and biological processes can affect both redox potential and pH. A microbial population that changes these features could result in conditions where that population fails to thrive. At this point, a further population may become active. For example, sulphur-oxidising bacteria cause the formation of sulphuric acid by the oxidation of sulphur-containing species. However, this type of bacteria requires oxygen in order to thrive.

Treatment in the GSA – The impact of any microbial and biological processes on redox and pH are considered to be minimal. pH evolution is considered to be driven by the degradation of cement grout (see FEP 2.1.8.1) and no evolution of redox conditions is assumed (see FEP 2.1.8.2).

Inclusion of FEP – Excluded in all scenarios.

## FEP 2.1.10 Thermal processes and conditions

### *FEP 2.1.10.1. Radiogenic, chemical and biological heat production from the wastes*

Description – The heating effect produced by radioactive decay, chemical reactions (such as corrosion) and microbiological processes in the waste.

For the first few decades after borehole closure, relatively short lived radionuclides such as Co-60 and Cs-137 will be the main sources of any radiogenic heat production. Thereafter, limited radiogenic heating could continue but at a lower level due to the decay of any long lived isotopes present.

Treatment in the GSA – For the purposes of the GSA, it is assumed that any heat production has limited impact on the performance of the borehole. Calculations presented in [9] suggest a maximum increase in temperature of less than 2°C for inventories considered for disposal to the borehole disposal concept.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.10.2. Chemical heat production from engineered features*

Description – Hydration, which is part of the chemical process of cement grout curing, has a heat of reaction that could potentially lead to temperature increases in the borehole. However, the period of heat generation is of the order of a few months.

Treatment in the GSA – Cement hydration will have ended, and the associated heat dissipated, short after borehole closure. It is considered that the heat production during curing will not have a significant impact on the long term safety of the borehole.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.10.3. Temperature evolution*

Description – A range of processes could potentially generate heat in a closed borehole (see FEPs 2.1.10.1 and 2.1.10.2). These processes could contribute to temperature profiles across the borehole and into the host rock. Although the effect on temperature may only be temporary, it could have a permanent effect on borehole safety if it causes cracking in any backfill, cement structures and the immediately surrounding host rock. Water flow rates might increase and gas could migrate more easily.

Treatment in the GSA – It is considered that the temperature rise in the borehole will be limited (see FEPs 2.1.10.1 and 2.1.10.2). Therefore, isothermal conditions are assumed for the GSA.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.10.4. Temperature dependence of processes*

Description – Temperature increases in a closed borehole could lead to changes in the rates of a number of chemical and physical processes in the borehole, including:

- Corrosion of metals;
- Mineralization reactions, particularly of the cement present;
- Solubility limits for radioactive contaminants;
- The extent of sorption of radionuclides on borehole components;
- The rate of gas generation;
- Fluid pressure, density and viscosity; and
- The rate of resaturation of the borehole.

Treatment in the GSA – The processes listed above might have their rates changed on a short-term basis as the temperature in the borehole rises and then falls to near ambient in the initial period following borehole closure. However, it is considered that the temperature rise in the borehole will be limited (see FEPs 2.1.10.1 and 2.1.10.2) and so the impact on these processes is assumed to be insignificant. Therefore, isothermal processes are assumed for the GSA.

Inclusion of FEP – Excluded in all scenarios.

## FEP 2.1.11 Radiation effects

### *FEP 2.1.11.1. Effects on containers*

Description – Radiolysis of water by γ-radiation can accelerate corrosion processes on metals through the production of oxidising radiolysis products (the effects of α- and β-radiation and neutron irradiation are not considered here for intact containers containing used sources).

[73] have reviewed the evidence for the effects of γ-radiation on the corrosion of various metallic materials. For stainless steels, no acceleration of general corrosion was reported at an absorbed dose rate of $10^4$ Gy/hr (1 Mrad/hr). Radiation has also been found to inhibit pitting, probably due to the annealing of defects in the oxide film. There is some evidence for enhanced initiation of crevice corrosion at a dose rate of 2.8 Gy/hr, although higher dose rates appear necessary to sustain crevice propagation.

Treatment in the GSA – Radiation effects are not included in the corrosion analysis in the GSA. Many of the used sources will not produce an external radiation field and, even for those that do, the dose rate is likely to be significantly below the threshold for radiation-enhanced corrosion.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.11.2. Effects on cement grout*

Description – The action of radiation on cement grout components of the borehole. The action of radiation on cement grout is to produce hydrogen gas from the radiolysis of free water in the cement grout pores. The extent of gas formation by this route decreases rapidly following borehole closure as the radionuclides decay.

Treatment in the GSA – The rapid decrease in radioactivity in the post-closure period indicates that the amount of gas likely to be generated by this route is small and has no significant effect on borehole performance since any gas generated will be able to migrate up through the cement grout.

Inclusion of FEP – Excluded in all scenarios

### *FEP 2.1.11.3. Effects on other engineered features*

Description – The action of radiation on other components of the borehole, e.g the embrittlement of the HDPE casing.

Treatment in the GSA – It is considered that the shielding offered by the containers and cement grout will mean that the radioactive sources will have no significant effect on the other engineered features in the borehole. Even if embrittlement of the HDPE casing were to occur, this has implicitly been considered by conservatively assuming that the casing fails on closure of the borehole (see FEP 2.1.5.1).

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.11.4. Effects on pH*

Description – The change in pH in the borehole caused by radiolysis.

Radioactive decay leads to the formation of oxidising or acidic species such as hydrogen peroxide (formed by the radiolysis of water) and nitric acid (resulting from the nitrogen). Overall, the pH would decrease to acid values in the absence of cement grout in the borehole. Such species would then be potentially available to corrode the steel containers present.

The effect would fall off rapidly following borehole closure, in line with the extent of radioactive decay.

Treatment in the GSA – This process might bring forward the loss of integrity in the steel containers and initiate corrosion of metallic wastes. However, because radiolysis will decline rapidly following borehole closure and a sizeable proportion of the radiative energy emitted will be absorbed by the containers and cement grout in the borehole, this process is not considered to be significant in controlling borehole pH.

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.11.5. Effects on redox*

Description – The change in redox potential in the borehole caused by radiolysis.

Radiolysis of organic matter generates free radicals that are highly reactive towards oxygen in the borehole. This process could help convert the borehole from being initially aerobic to being anaerobic.

Treatment in the GSA – Limited occurrence of organic matter in the borehole is assumed so there is limited scope for the generation of free radicals and the resulting anaerobic conditions via radiolysis. Anaerobic conditions assumed for saturated zone borehole from closure onwards (see FEP 2.1.8.2).

Inclusion of FEP – Excluded in all scenarios.

### *FEP 2.1.11.6. Decay product gas generation*

Description – The production of gaseous isotopes from radioactive decay processes.

There are two main sources of gas in a borehole by this route:

- The production of helium as α–particles; and
- The generation of isotopes of radon in the decay of disposed and in-grown radium.

Treatment in the GSA – It is considered that helium will constitute only a small proportion of the total gas formed in the borehole and could be carried away from it in dissolved form [65]. However, the emission of radon gas from the borehole is considered.

Inclusion of FEP – Included for all scenarios.

## FEP 2.1.12. Gas sources and effects

Description – Factors within and around the sources, containers and engineered features resulting in the generation of gases and their subsequent effects on the borehole system.

Gas production may result from corrosion of metals in the sources, container and engineered materials. It may also be produced by radiation effects, including helium and radon as a products of radioactive decay and gases produced by radiolysis of water in cement grout (see FEP 2.1.11). Anions present in incoming groundwater (notably sulphate and nitrate) could become involved in gas production. Potential gases include hydrogen, oxygen, carbon dioxide, methane, nitrogen and hydrogen sulphide.

These gases could give rise to a range of hazards. Gas could be transported out of the borehole dissolved in groundwater or in the gas phase. This latter process could cause changes in the local chemical and hydraulic conditions; for instance elevated gas pressures could act as a driving force to expel contaminated water out of the borehole, or they may result in unsaturated conditions so that two-phase flow becomes important. Elevated gas pressures could also prevent the ingress of groundwater into the borehole. Gas production could also affect the mechanisms for radionuclide transport, i.e. gas-induced and gas-mediated transport. Some gases might be flammable or might form an explosive mixture; for instance hydrogen and methane could mix with oxygen and explode to damage the borehole. Some gases would be potentially toxic, notably hydrogen sulphide. However this species is highly reactive, and is likely to be converted to a solid sulphide within the borehole [65].

Treatment in the GSA – The main gas in the borehole is hydrogen formed as a result of corrosion of the containers. However, calculations suggest that less than 1E-5 $m^3/y$ is produced. Other gases could be produced in even smaller amounts by corrosion, radiolysis and microbial attack. Therefore, these gases are not considered in the GSA.

The main radioactive gases produced will be H-3 and Kr-85 (disposed) and Rn-222 (in-grown from Ra-226). These gases are considered in the GSA.

Inclusion of FEP – Included in all scenarios.

### FEP 2.1.13. Extraneous materials

Description – The effect of extraneous materials introduced into a borehole with waste packages and during borehole construction, operation and closure.

Treatment in the GSA – It is considered that appropriate QA/QC will be in place to ensure that no extraneous materials are introduced into the borehole other than microbes. Waste packages will inevitably contain microbes but it is considered that these will not have a significant impact on the performance of the borehole (see FEP 2.1.9).

Inclusion of FEP – Excluded in all scenarios.

# APPENDIX VI
# SCREENED FEP LIST FOR THE DEFECT SCENARIO

This Appendix documents the screening of Features, Events, and Processes (FEPs) in the Defect Scenario in the Generic Safety Assessment (GSA) for borehole disposal of Categories 3 to 5 Disused Sealed Radioactive Sources (DSRS). Modifications to the list derived in Appendix IV for the Design Scenario are underlined.

## *0 ASSESSMENT CONTEXT FACTORS*

***0.01 Assessment purpose – Yes,*** see Section 2.2 for the four main purposes of the assessment.

***0.02 Regulatory requirements and exclusions***

*1* *0.2.01* *Protection of human health and the environment* – ***Yes,*** see Sections 2.2 and 2.4, especially Box 1 for protection objective and criteria. Impacts on non-human biota and non-radiological impacts are considered to be beyond the scope of the current study, so the focus is on radiological impacts upon human health.

*2* *0.2.02* *Phases of disposal* – ***Yes,*** see Sections 2.2 and 2.7. Assessment is of the post-closure phase, although it is recognized that operational and closure issues need to be considered when assessing post-closure safety.

*3* *0.2.03* *Technical Requirements* – ***Yes,*** see Sections 2.1 and 2.5. End points considered are waste activity levels expressed as total activity values and per waste package activity values. Output of assessment will help provide information on suitable inventories, engineering, institutional control period and hydrochemical characteristics.

***0.03 Assessment philosophy***

*4* *0.3.01* *Assessment approach* – ***Yes,*** see Section 2.6. The ISAM Safety Assessment Approach is being used, consistent with best international practice.

*0.3.02* *Uncertainties, treatment of*

*5* *0.3.02.01* *Future uncertainties* – ***Yes,*** see Sections 2.6.3 and 3. This type of uncertainty is treated using a transparent and comprehensive scenario development and justification methodology.

*6* *0.3.02.02* *Model uncertainties* – ***Yes,*** see Sections 2.6.3 and 6. This type of uncertainty is treated using alternative conceptualizations and mathematical representations of the system.

*7* *0.3.02.03* *Parameter/data uncertainties* – ***Yes,*** see Sections 2.6.3 and 6. This type of uncertainty is treated using a deterministic sensitivity analysis.

*8* *0.3.02.04* *Subjective uncertainties* – ***Yes,*** see Section 2.6.3. This type of uncertainty is treated using a systematic and transparent assessment approach which allows subjective judgements to be document, justified and quantified (as far as possible).

*9* *0.3.03* *Sensitivity analysis, performance of* – ***Yes,*** see Section 6 for deterministic sensitivity analysis.

*0.3.04* *Confidence, model*

*10* *0.3.04.01* *Verification, performance of* – ***Yes,*** see Section 5.5. The software tool used (AMBER) has been successfully used in over 20 countries by over 60 organizations and has associated verification documentation.

*11* *0.3.04.02* *Calibration, performance of* – ***No,*** calibration is a site specific procedure and therefore not possible for a generic safety assessment.

*12* *0.3.04.03* *Validation, performance of* – ***No,*** validation is not considered possible for a long term generic safety assessment.

*13* *0.3.05* *Modelling approach* – ***Yes,*** see Sections 2.6 and 6. The approach used aims to balance simplicity, conservatism and realism. Deterministic calculations are used. The emphasis is to understand the behaviour of the system better and to identify the importance of specific components of the system in providing a level of post-closure safety that meets the relevant regulatory compliance criteria.

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | | | |
|---|---|---|---|
| | ***0*** | ***ASSESSMENT CONTEXT FACTORS*** | |
| | ***0.04*** | ***Assessment bounding conditions*** | |
| *14* | | *0.4.01* | *Assessment timeframe* – ***Yes****,* see Sections 2.7 and 4.2. Calculations are undertaken out to a time when it can be demonstrated that the peak value of the primary safety indicator (dose) has been passed. Institutional control period assumed to last 30 years after closure. |
| *15* | | *0.4.02* | *Assessment domain* – ***Yes****,* see Sections 3 and 4.3.1. Assumed to be limited to the immediate vicinity of the disposal borehole (i.e. within a radius of about 100 m) since a water abstraction borehole is assumed to be sunk 100 m from the disposal borehole and the water used for domestic and agricultural purposes by humans. |
| *16* | | *0.4.03* | *Future human action assumptions* – ***Yes****,* see Sections 3.3 and 4.3.1. No consideration is given to the development of new societal structures and technologies. |
| *17* | | *0.4.04* | *Future human behaviour (target group) assumptions* – ***Yes****,* see Sections 3.3 and 4.3.1. It is assumed that humans are exposed once institutional control of the site is lost either due to use contaminated groundwater abstracted from a borehole sunk 100 m from the disposal borehole, or due to inhalation of contaminated gas in dwelling constructed directly above the disposal borehole. |
| *18* | | *0.4.05* | *Target audience (Stakeholder involvement)* – ***Yes****,* see Section 2.3. Two audiences are considered – 'developers' and 'regulators'. |
| *19* | | *0.4.06* | *Assessment endpoints* – ***Yes****,* see Sections 2.5 and 6. Primary end points are waste activity levels, which can be expressed as total activity values and per waste package activity values. |
| *20* | | *0.4.07* | *Dose response assumptions* – ***No****,* see Section 2.5. Risks of deleterious health effects are not considered as end points in the current study. |
| *21* | | *0.4.08* | *Results, presentation of* – ***Yes****,* see Section 6. Results presented in tabular form. |
| *22* | | *0.4.09* | *Disposal Facility Assumptions* – ***Yes****,* see Section 4.3.1. It is assumed that not all components of the near field perform as envisaged in the Design Scenario due to either defective manufacturing of waste packages (e.g. welding defects), or defective implementation in the borehole (e.g. improper cement grout emplacement). This results in earlier release of radionuclides from the near field. |
| | ***1*** | ***EXTERNAL FACTORS*** | |
| | ***1.1*** | ***Disposal facility factors*** | |
| *23* | | *1.1.01* | *Investigations, site* – ***Yes****,* although the assessment is generic and therefore it is assumed that there is no site specific information available from site investigation (see Section 3.2), data (e.g. hydraulic gradients, conductivities, porosities) are presented in Section 3.2 that implicitly assume there has been some site investigation of the synthesised sites. It is assumed that any investigation boreholes have been appropriately backfilled and do not compromise the long term safety of the disposal system. |
| *24* | | *1.1.02* | *Design, disposal facility* – ***Yes****,* see Section 3.1.2 and Table 4. It is assumed that the disposal borehole is designed with appropriate safety features and functions. |
| *25* | | *1.1.03* | *Schedule and planning* – ***Yes****,* see Section 4.3.1. It is assumed that the disposal borehole is not operated as planned (see FEP 1.1.05). |
| *26* | | *1.1.04* | *Construction, disposal facility* – ***Yes****,* see Section 4.3.1. It is assumed that the disposal borehole is not constructed as planned resulting in earlier release of radionuclides from the near field. For Defect Scenario Variant D3, it is assumed that implacement and quality of cement grout is worse than the Design Scenario resulting in more rapid chemical and physical degradation of the disturbed zone cement grout. |
| *27* | | *1.1.05* | *Operation, disposal facility* – ***Yes****,* see Section 4.3.1. It is assumed that the disposal borehole is not operated as planned resulting in earlier release of radionuclides from the near field. For Defect Scenario Variant D3, it is assumed that implacement and quality of cement grout is worse than the Design Scenario resulting in more rapid chemical and physical degradation of the disposal zone cement grout. |
| *28* | | *1.1.06* | *Closure, disposal facility* – ***Yes****,* see Section 4.3.1. It is assumed that the disposal borehole is closed as planned. |

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | ***1*** | ***EXTERNAL FACTORS*** |
|---|---|---|
| *29* | *1.1.07* | *Institutional controls* – ***Yes****,* see Sections 2.7 and 4.3.1. It is assumed that institutional controls are in place for a period of 30 years after closure. |
| *30* | *1.1.08* | *Quality assurance* – ***Yes****,* see Section 4.3.1. It is assumed that appropriate quality assurance is applied to the operation and closure of the disposal borehole. It is assumed that defects arise in waste capsule and container welds and cement grout emplacement despite best efforts to eliminate them. |
| *31* | *1.1.09* | *Administrative control, disposal facility* – ***Yes****,* see Sections 2.7 and 4.3.1. It is assumed that administrative controls are in place during the construction, operation and closure of the disposal borehole and for a period of 30 years after closure. However, it is assumed that some defects may arise, despite best efforts to eliminate them. |
| *32* | *1.1.10* | *Accidents and unplanned events* – ***Yes****,* see Section 4.3.1. It is assumed that there are no accidents. However, it is assumed that defects arise in waste capsule and container welds and cement grout emplacement, despite best efforts to eliminate them. |
| *33* | *1.1.11* | *Retrievability* – ***No****,* see Section 3.1.2. Each waste package is backfilled into the borehole immediately following its emplacement. |
| *34* | *1.1.12* | *Motivation and knowledge issues* – ***Yes****,* see Section 4.3.1. It is assumed that no markers are fixed at the site to reveal the location of a radioactive waste disposal facility but land use controls are in place during the institutional control period. |
| *35* | *1.1.13* | *Nuclear Criticality* – ***No****,* such effects are considered to be insignificant for the typical inventories to be disposed. |

| | ***1.2*** | ***Geological processes and effects*** |
|---|---|---|
| *36* | *1.2.01* | *Tectonic movement* – ***No****,* see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in a geologically stable area with no or extremely limited tectonic activity over the timescales of interest in the safety assessment. |
| *37* | *1.2.02* | *Orogeny* – ***No****,* see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in geologically stable area and there is no orogenic activity over the timescales of interest in the safety assessment. |
| *38* | *1.2.03* | *Seismicity* – ***No****,* see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in a geologically stable area with no or extremely limited seismic activity over the timescales of interest in the safety assessment. |
| *39* | *1.2.04* | *Volcanic and magmatic activity* – ***No****,* see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in geologically stable area and there is no volcanic and magmatic activity over the timescales of interest in the safety assessment. |
| *40* | *1.2.05* | *Metamorphism* – ***No****,* see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in geologically stable area and there is no metamorphic activity over the timescales of interest in the safety assessment. |
| *41* | *1.2.06* | *Hydrothermal activity* – ***No****,* see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in geologically stable area and there is no hydrothermal activity over the timescales of interest in the safety assessment. |
| *42* | *1.2.07* | *Erosion and sedimentation* – ***Yes****,* see Sections 3.2, 3.3, 4.1 and 4.3.1. It is assumed that there is gradual net erosion on a regional and local scale. |
| *43* | *1.2.08* | *Diagenesis* – ***No****,* diagenesis is not considered to be a significant process affecting the disposal system over the depths and timescales of interest in the safety assessment. |
| *44* | *1.2.09* | *Pedogenesis* – ***Yes****,* see Section 3.3 and 4.3.1. Need to consider soil contaminated by irrigation water. |
| *45* | *1.2.10* | *Salt diapirism and dissolution* – ***No****,* assume disposal borehole is located in an area that has no natural resources requiring excavation by extensive surface excavation or underground mining (see Section 3.2). |
| *46* | *1.2.11* | *Undetected geological features* – ***No****,* see Section 4.1. The geosphere is assumed to be as described in Section 3.2 with no unexpected features, processes or events. |

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | | | |
|---|---|---|---|
| | ***1*** | ***EXTERNAL FACTORS*** | |
| *47* | | *1.2.12* | *Hydrological/hydrogeological response to geological changes* – ***No,*** see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in geologically stable area and there are no significant geological changes over the timescales of interest in the safety assessment. |
| *48* | | *1.2.13* | *Geomorphologic response to geological changes* – ***No,*** see Sections 3.2 and 4.3.1. It is assumed that the disposal borehole is located in geologically and geomorphologically stable area and there are no significant changes over the timescales of interest in the safety assessment. |
| | ***1.3*** | ***Climate processes and effects*** | |
| *49* | | *1.3.01* | *Climate change, global* – ***No,*** see Section 4.1. Constant climate conditions are assumed (a simplifying assumption). |
| *50* | | *1.3.02* | *Climate change, regional and local* – ***No,*** see Section 4.1. Constant climate conditions are assumed (a simplifying assumption). |
| *51* | | *1.3.03* | *Sea level change* – ***No,*** see Section 3.3. It is assumed that the site is located in a position that will not be susceptible to possible future sea level rises. |
| *52* | | *1.3.04* | *Periglacial effects* – ***No,*** see Section 3.3. No consideration of extreme conditions such as permafrost. |
| *53* | | *1.3.05* | *Glacial and ice sheet effects, local* – ***No,*** see Section 3.3. No consideration of extreme conditions such as glaciation. |
| *54* | | *1.3.06* | *Warm climate effects (tropical and desert)* – ***Yes,*** see Section 3.3. It is assumed that the climate is consistent with the assumption of self-sufficient agriculture land use. Such land use is possible in tropical climates and, if there is a sufficient supply of freshwater, arid conditions. |
| *55* | | *1.3.07* | *Hydrological/hydrogeological response to climate changes* – ***No,*** since constant climate conditions are assumed (see Section 4.1). |
| *56* | | *1.3.08* | *Ecological response to climate changes* – ***No,*** since constant climate conditions are assumed (see Section 4.1). |
| *57* | | *1.3.09* | *Human behavioural response to climate changes* – ***No,*** since constant climate conditions are assumed (see Section 4.1). |
| *58* | | *1.3.10* | *Geomorphologic response to climate changes* – ***No,*** since constant climate conditions are assumed (see Section 4.1). |
| | ***1.4*** | ***Future human actions*** | |
| *59* | | *1.4.01* | *Human influences on climate* – ***No,*** since constant climate conditions are assumed (see Section 4.1). |
| *60* | | *1.4.02* | *Knowledge and motivational issues (Disposal facility)* – ***Yes,*** see Section 4.3.1. It is assumed that no markers are fixed at the site to reveal the location of a radioactive waste disposal facility but land use controls are in place during the institutional control period to prevent human intrusion. The impact of deliberate human intrusion is considered to be beyond the scope of the current assessment (Section 1.3). |
| *61* | | *1.4.03* | *Drilling activities (human intrusion)* – ***Yes,*** see Sections 3.2, 4.1 and 4.3.1. It is assumed that a water abstraction borehole is drilled 100 m from the disposal borehole and only once there is no institutional control over the site. |
| *62* | | *1.4.04* | *Mining and other underground activities (human intrusion)* – ***No,*** see Sections 3.2 and 3.3. It is assumed that the disposal borehole is located in an area that has no natural resources requiring excavation by extensive underground mining. Furthermore, human activities are assumed to be limited to agricultural activities. |
| *63* | | *1.4.05* | *Un-intrusive site investigation* – ***No,*** see Sections 3.2 and 3.3. It is assumed that the disposal borehole is located in an area that has no natural resources and human activities are assumed to be limited to agricultural activities. Therefore, it is considered that there is no un-intrusive site investigation. |
| *64* | | *1.4.06* | *Surface excavations* – ***No,*** see Sections 3.2 and 3.3. The disposal zone is assumed to be at least 30 m below the ground surface and it is considered that any surface excavations associated with agricultural land use will not extend down to such depths. |

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | *1* | ***EXTERNAL FACTORS*** | |
|---|---|---|---|
| *65* | | *1.4.07* | *Pollution* – ***No,*** it is assumed that human activities do not significantly affect the disposal system. |
| *66* | | *1.4.08* | *Site Development* – ***Yes,*** see Sections 3.2, 4.1 and 4.3.1. It is assumed that a water abstraction borehole is drilled 100 m from the disposal borehole and only once there is no institutional control over the site. |
| *67* | | *1.4.09* | *Archaeology* – ***No,*** see Section 3.3. Human activities are assumed to be limited to agricultural activities. |
| *68* | | *1.4.10* | *Water management (wells, reservoirs, dams)* – ***Yes,*** see Sections 3.2, 4.1 and 4.3.1. It is assumed that a water abstraction borehole is drilled 100 m from the disposal borehole and only once there is no institutional control over the site. |
| *69* | | *1.4.11* | *Social and institutional developments* – ***Yes,*** see Sections 2.7, 3.3 and 4.3.1. It is assumed that land use controls are in place during the institutional control period to prevent human intrusion. But at the end of the period, controls are assumed to be no longer in place. |
| *70* | | *1.4.12* | *Technological developments* – ***No,*** see Sections 3.3 and 4.3.1. No consideration is given to the development of new technologies. |
| *71* | | *1.4.13* | *Remedial actions* – ***No,*** see Sections 2.7 and 4.3.1. It is assumed that, although there are defects in the welds/cement grout emplacement, the defects do not cause detectable releases of radionuclides during active institutional control. Therefore there are no remedial actions taken during the period of active institutional control. |
| *72* | | *1.4.14* | *Explosions and crashes* – ***No,*** it is assumed that there are no explosions or crashes. |

| | *2* | ***DISPOSAL SYSTEM DOMAIN FACTORS*** | |
|---|---|---|---|
| | ***2.1*** | ***Waste, waste form & engineered features*** | |
| *73* | | *2.1.1* | *Inventory, waste* – ***Yes,*** see Section 3.1.1 and Appendix V. Assume a unit inventory of 1 TBq per waste package of each of the emboldened radionuclides in Table 3 is disposed in the borehole. |
| *74* | | *2.1.2* | *Waste form materials, characteristics and degradation processes* – ***Yes,*** see Sections 3.1.1, 3.1.2 and 4.3.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. |
| *75* | | *2.1.3* | *Container materials, characteristics and degradation/failure processes* – ***Yes,*** see Sections 3.1.2 and 4.3.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. For the Defect Scenario Variant D1, it is assumed that there is a defect in the closure weld of one disposal container that results in the more rapid degradation of the container. For Variant D2, the closure weld on one waste capsule is assumed to have failed. For Variant D4, the closure weld on one capsule and one container has failed. |
| *76* | | *2.1.4* | *Buffer/backfill materials, characteristics and degradation processes* – ***Yes,*** see Sections 3.1.2 and 4.3.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. For the Defect Scenario Variant D3, it is assumed that implacement and quality of cement grout is worse than the Design Scenario resulting in more rapid chemical and physical degradation of the disposal and disturbed zone cement grout. |
| *77* | | *2.1.5* | *Other engineered barrier system characteristics and degradation processes* – ***Yes,*** see Sections 3.1.2 and 4.3.1 and Appendix V. See Tables 4, 5 and 11 and Figs 2, 3 and 4 for details. |
| | ***2.2*** | ***Geological environment*** | |
| *78* | | *2.2.1* | *Stratigraphy* – ***Yes,*** see Sections 3.2, 4.1 and 4.3.1. Although there is no explicit consideration of the stratigraphy of the synthesised geospheres, it is noted that the geology is not homogeneous, although any variation can be adequately represented through the use of averaged hydrological and geochemical parameter values. For disposal in the unsaturated zone, a total depth of unsaturated zone of 90 m is assumed. For disposal in the saturated zone, a total depth of saturated zone of 50 m is assumed. Characteristics are not assumed to change with time (see Section 4.3.1). |

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | | |
|---|---|---|
| | **2** | ***DISPOSAL SYSTEM DOMAIN FACTORS*** |
| *79* | *2.2.2* | *Host lithology* – ***Yes,*** see Sections 3.2, 3.4, 4.1 and 4.3.1. Key physical characteristics of synthesised geospheres are summarized in Table 7. Characteristics are not assumed to change with time (see Section 4.3.1). |
| *80* | *2.2.3* | *Disturbed zone, host lithology* – ***Yes,*** see Sections 3.2, 4.1 and 4.3.1. Disturbed zone is assumed to be part of the near field. Voids and cracks in the host geology immediately adjacent to the borehole are assumed to be grouted and sealed during the drilling process. |
| *81* | *2.2.4* | *Discontinuities, large scale (in geosphere)* – ***No,*** it is assumed that there are no large-scale discontinuities. |
| *82* | *2.2.5* | *Contaminant migration path characteristics (in geosphere)* – ***Yes,*** see Sections 3.2 and 4.3.1. Consider both porous and fracture flow and transport in the unsaturated and saturated geosphere. Characteristics are not assumed to change with time (see Section 4.3.1). |
| *83* | *2.2.6* | *Mechanical processes and conditions (in geosphere)* – ***No,*** it is assumed that there are no significant mechanical processes and conditions affecting the geosphere and that the disposal borehole will not affect the mechanical properties of the geosphere. |
| *84* | *2.2.7* | *Hydraulic/hydrogeological processes and conditions (in geosphere)* – ***Yes,*** see Sections 3.2, 3.4 and 4.3.1. A range of conditions is considered (see Tables 7, 8 and 9). Conditions are not assumed to change with time (see Section 4.3.1). |
| *85* | *2.2.8* | *Chemical/geochemical processes and conditions (in geosphere)* – ***Yes,*** see Sections 3.2, 3.4 and 4.3.1. Conditions in the geosphere are assumed not to change with time. |
| *86* | *2.2.9* | *Biological/biochemical processes and conditions (in geosphere)* – ***Yes,*** see Sections 3.2, 3.4 and 4.3.1. Conditions in the geosphere are assumed not to change with time. |
| *87* | *2.2.10* | *Thermal processes and conditions (in geosphere)* – ***No,*** see Sections 2.5, 3.2, 3.4 and 4.3.1. It is assumed that there are no significant sources of thermal heat in the geosphere and that the inventory does not significantly affect the thermal properties of the geosphere. |
| *88* | *2.2.11* | *Gas sources and effects (in geosphere)* – ***No,*** see Section 3.2. It is assumed that there are no significant sources of geothermal heat or gas in the vicinity of the disposal borehole. |
| *89* | *2.2.12* | *Geological resources (in geosphere)* – ***Yes,*** see Sections 3.2, 4.1 and 4.3.1. Water assumed to be abstracted from the geosphere. |
| | ***2.3*** | ***Surface environment*** |
| *90* | *2.3.1* | *Topography and morphology* – ***Yes,*** see Section 3.3. It is assumed that the biosphere has subdued relief. |
| *91* | *2.3.2* | *Biomes* – ***Yes,*** see Sections 3.3 and 4.3.1. It is assumed that a range of crops and livestock is raised consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. Assume contamination due to irrigation of crops and watering of animals. |
| *92* | *2.3.3* | *Soil and sediment* – ***Yes,*** see Sections 3.3 and 4.3.1. It is assumed that soils have similar mineralogical properties to those of the underlying geosphere from which they are assumed to have been derived. It is also assumed that they are capable of supporting a range of crops. Assume contamination due to irrigation of crops. |
| *93* | *2.3.4* | *Aquifers and water-bearing features, near surface* – ***Yes,*** see Sections 3.3, 4.1 and 4.3.1. Water assumed to be abstracted from the geosphere. |
| *94* | *2.3.5* | *Terrestrial surface water bodies* – ***No,*** see Section 3.3. Interest limited to water in abstraction borehole. |
| *95* | *2.3.6* | *Coastal features* – ***No,*** see Section 3.3. Disposal borehole is assumed to be located in a position that will not be susceptible to coastal processes. |
| *96* | *2.3.7* | *Marine features* – ***No,*** see Section 3.3. Disposal borehole is assumed to be located in a position that will not be susceptible to coastal processes and possible future sea level rises and so marine features are not considered to be relevant. |
| *97* | *2.3.8* | *Atmosphere* – ***Yes,*** see Section 4.3.1. Needs to be considered for the suspension of contaminated soil and gas inhalation pathways. |
| *98* | *2.3.9* | *Vegetation* – ***Yes,*** see Sections 3.3 and 4.3.1. It is assumed that a range of crops is raised consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. |

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | | |
|---|---|---|
| | **2** | ***DISPOSAL SYSTEM DOMAIN FACTORS*** |
| *99* | *2.3.10* | *Animal populations* – ***Yes****,* see Sections 3.3 and 4.3.1. It is assumed that a range of animals is raised consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. |
| *100* | *2.3.11* | *Meteorology* – ***Yes****,* see Section 3.3. It is assumed that the climate is consistent with the assumption of self-sufficient agriculture land use and is non-extreme. |
| *101* | *2.3.12* | *Hydrological regime and water balance (near surface)* – ***Yes****,* see Section 3.2. Infiltration into the geosphere influences leaching of radionuclides from contaminated soil and the flux of water in the geosphere. |
| *102* | *2.3.13* | *Erosion and deposition* – ***Yes****,* see Sections 3.2, 3.3, 4.1 and 4.3.1. It is assumed that there is gradual net erosion on a regional and local scale resulting in the loss of the closure zone over a 100,000 year period. |
| *103* | *2.3.14* | *Ecological/biological/microbial systems* – ***Yes****,* see Sections 3.3 and 4.3.1. It is assumed that a range of crops is grown, consistent with the assumption of self-sufficient agriculture in non-extreme climate conditions. It is assumed that the crops are grown on soil contaminated with water from the abstraction borehole. |
| *104* | *2.3.15* | *Animal/Plant intrusion* – ***No****,* see Section 4.3.1. Given the assumed low erosion rate and the depth of the disposal zone it is considered that there is no need to consider biotic intrusion. |
| | **2.4** | ***Human behaviour*** |
| *105* | *2.4.1* | *Human characteristics (physiology, metabolism)* – ***Yes****,* see Section 5.4. Implicitly considered in dose factors for ingestion and inhalation of radionuclides. |
| *106* | *2.4.2* | *Adults, children, infants and other variations* – ***Yes****,* see Section 2.5. Consider annual individual effective dose to an average adult member of a hypothetical critical group. |
| *107* | *2.4.3* | *Diet and fluid intake* – ***Yes****,* see Sections 3.3 and 4.3.1. Ingestion of contaminated water, crops and animal produce. |
| *108* | *2.4.4* | *Habits (non-diet-related behaviour)* – ***Yes****,* see Sections 3.3 and 4.3.1. The assumed human habits give raise to exposure via ingestion of crops, soil and animal products, inhalation of gases and dust, and external irradiation from contaminated soil. |
| *109* | *2.4.5* | *Community characteristics* – ***Yes****,* see Sections 3.3 and 4.3.1. Assume a self-sufficient agriculture community. Two exposure groups considered: farmer and house dweller. |
| *110* | *2.4.6* | *Food preparation and water processing* – ***Yes****,* see Sections 3.3 and 4.3.1. Although it is assumed that the abstracted water used is not treated or stored before use, food is assumed to be processed before consumption. |
| *111* | *2.4.7* | *Dwellings* – ***Yes****,* see Sections 3.3 and 4.3.1. At end of institutional control period, it is assumed that a dwelling can be constructed above the disposal borehole. |
| *112* | *2.4.8* | *Natural/semi-natural land and water use* – ***No****,* see Sections 3.3 and 4.3.1. Assume self-sufficient agriculture rather than natural/semi-natural land use. |
| *113* | *2.4.9* | *Rural and agricultural land and water use* – ***Yes****,* see Sections 3.3 and 4.3.1. Assume self-sufficient agriculture and abstracted groundwater used for domestic and agricultural purposes. |
| *114* | *2.4.10* | *Urban and industrial land and water use* – ***No****,* see Sections 3.3 and 4.3.1. Assume self-sufficient agriculture rather than urban and industrial land use. |
| *115* | *2.4.11* | *Leisure and other uses of environment* – ***No****,* see Sections 3.3 and 4.3.1. Assume self-sufficient agriculture rather than leisure or other use. |
| | **3** | ***CONTAMINANT FACTORS*** |
| | **3.1** | ***Contaminant characteristics*** |
| *116* | *3.1.1* | *Radioactive decay and in-growth* – ***Yes****,* see Section 3.1.1 and Appendix I. |
| *117* | *3.1.2* | *Radionuclide properties, other* – ***Yes****,* see Section 3.1.1. It is assumed that the radionuclides in the disused sources are in a physical state that means that they are soluble. |

SCREENED FEP LIST FOR THE DEFECT SCENARIO (cont.)

| | | |
|---|---|---|
| ***3*** | ***CONTAMINANT FACTORS*** | |
| *118* | *3.1.3* | *Organics and potential for organic forms* – ***No***, it is assumed that there is no significant organic component in the waste. |
| *119* | *3.1.4* | *Chemical/organic toxin stability* – ***No,*** see Sections 1.3 and 2.2.4. Non-radiological impacts, which might arise from the content of chemically or biologically toxic materials in the waste or engineered barrier materials, are considered to be beyond the scope of the GSA. |
| *120* | *3.1.5* | *Inorganic solids/solutes* – ***Yes***, see Section 3.1.1 and FEP 3.1.2. |
| *121* | *3.1.6* | *Volatiles and potential for volatility* – ***Yes***, see Section 3.1.1. Iodine is potentially volatile. |
| *122* | *3.1.7* | *Noble gases* – ***Yes***, Rn-222 in-grown from Ra-226 (see Table 34). |
| ***3.2*** | ***Contaminant release and migration factors*** | |
| *123* | *3.2.1* | *Contaminant release pathways* – ***Yes***, see Section 4.3.1. Consideration is given to releases via water and gas pathways. |
| *124* | *3.2.2* | *Chemical/geochemical-mediated processes, effects on contaminant release and migration* – ***Yes***, see Sections 3.1, 3.2 and 4.3.1. Consideration is given to a range of near field and geosphere chemical conditions and sorption processes. |
| *125* | *3.2.3* | *Microbial/biological-mediated processes, effects on contaminant release and migration* – ***No***, assume no need to represent microbial/biological-mediated processes explicitly. However, these processes are implicitly represented through considering a range of near field and geosphere chemical conditions (see Sections 3.1.3 and 3.2). |
| *126* | *3.2.4* | *Water-mediated migration of contaminants* – ***Yes***, see Sections 3.2 and 4.3.1. Consideration given to advection, dispersion and diffusion. |
| *127* | *3.2.5* | *Solid-mediated migration of contaminants* – ***Yes***, see Section 4.3.1. Erosion of soil contaminated by irrigation water considered. Soil assumed to be contaminated with radionuclides from borehole once closure zone is removed by erosion (after 100 000 years). |
| *128* | *3.2.6* | *Gas-mediated migration of contaminants* – ***Yes***, see Section 4.3.1. Scenario considers release of radionuclides in the gas phase from the borehole. |
| *129* | *3.2.7* | *Atmospheric migration of contaminants* – ***Yes***, see Section 4.3.1. Scenario considers release of contaminated gas into a dwelling and suspension and dispersion of soil contaminated by irrigation water considered. |
| *130* | *3.2.8* | *Animal, plant and microbe mediated migration of contaminants* – ***Yes***, see Section 4.3.1. Irrigation of crops and watering of animals considered. |
| *131* | *3.2.9* | *Colloids mediated migration of contaminant* – ***No***. Assume that in systems with a cement grout near field, colloids are not readily formed due to the chemical conditions. |
| ***3.3*** | ***Exposure factors*** | |
| *132* | *3.3.1* | *Food chains, uptake of contaminants in* – ***Yes***, see Sections 3.3 and 4.3.1. Ingestion of contaminated crops and animal produce considered. |
| *133* | *3.3.2* | *Drinking water, foodstuffs and drugs, contaminant concentrations in* – ***Yes***, see Sections 3.3 and 4.3.1. Scenario includes consideration of the consumption of contaminated drinking water, crops and animal produce and inhalation of contaminated gas. |
| *134* | *3.3.3* | *Environmental media, contaminant concentrations in* – ***Yes***, see Section 4.3.1. Need to consider contaminant concentrations in soil, air, crops and animals. |
| *135* | *3.3.4* | *Non-food products, contaminant concentrations in* – ***No***, see Sections 3.3 and 4.3.1. Humans are assumed not to be exposed via non-food products for the scenario. |
| *136* | *3.3.5* | *Exposure modes* – ***Yes***, see Sections 3.3 and 4.3.1. Scenario includes consideration of the ingestion, inhalation gas and external irradiation. |
| *137* | *3.3.6* | *Dosimetry* – ***Yes***, see Sections 2.4 and 2.5. Consider annual individual effective dose to an average adult member of a hypothetical critical group. |
| *138* | *3.3.7* | *Radiological toxicity/effects* – ***Yes***, see Sections 2.4 and 2.5. Consider annual individual effective dose to an average adult member of a hypothetical critical group. |
| *139* | *3.3.8* | *Chemical toxicity/effects* – ***No,*** see Sections 1.3 and 2.2.4. Non-radiological impacts, which might arise from the content of chemically or biologically toxic materials in the waste or engineered barrier materials, are considered to be beyond the scope of the GSA. |
| *140* | *3.3.9* | *Radon and radon daughter exposure* – ***Yes***, see Section 4.3.1. Rn-222 in-grows from Ra-226. |

# APPENDIX VII
# APPROACH FOR CONCEPTUAL MODEL DEVELOPMENT

Once the scenarios have been developed, their consequences are analysed. To allow this, it is necessary to develop a conceptual model of the disposal system, its environmental setting and the associated release, transport and exposure mechanisms and media. A conceptual model can be defined as 'a set of qualitative assumptions used to describe a system' [80]. A conceptual model comprises a description of:

- The model's features, events and processes (feps);
- The relationships between these feps; and
- The model's scope of application in spatial and temporal terms.

Enough detail is needed to allow appropriate mathematical models to be developed to describe the behaviour of the system and its components.

For the purpose of the current assessment the Interaction Matrix Approach is used to develop conceptual models in a traceable manner. This approach is based on ideas developed in BIOMOVS II and subsequently developed and enhanced in a number of studies such as Refs [12], [32], [82], [83]. The use of the Interaction Matrix allows the graphical representation of system interactions through the use of formalized procedures and has the advantage of allowing disposal system components to be included explicitly in the Interaction Matrix.

The approach starts with a top down approach to dividing the system into constituent parts. The main components are identified and listed in the leading diagonal elements (LDEs) of the matrix. The interactions between the LDEs are then noted in the off-diagonal elements (ODEs). When using the Interaction Matrix approach, the convention is to allocate ODEs in the direction of contaminant migration. In this way, contaminant migration pathways and the associated exposure pathways and exposure groups can be traced and translated into the conceptual model. Each transfer of contaminant from LDE to another LDE via an ODE can be represented by a mathematical formalism and incorporated into the mathematical model.

As noted above, the first step in developing the Interaction Matrix is to identify the main components of the disposal system that can be distinguished on the basis of their chemical and/or physical characteristics. At the top level, the disposal system can be divided into the near field, geosphere and biosphere. Based on the description of the disposal system (Section 3) and the scenarios to be assessed (Section 4), the near field, geosphere and biosphere components listed below can be identified.

## VII.1. NEAR FIELD COMPONENTS

Five near field components can be identified.

- **Source**: The source material, the source container (in which the radioactive source material is held), and the stainless steel capsule (in which the source container is assumed to be emplaced). It is conservatively assumed that the source container will have failed prior to disposal, however the stainless steel capsule is assumed to start to corrode once the disposal container has been breached. Once the disposal container has been breached, various corrosion mechanisms (including localized and general corrosion) are assumed to occur and cause the capsule to be breached (see Table 11).
- **Containment Barrier**: The barrier between the capsule and the disposal container, which is assumed to be cement grout. Physical and chemical degradation of the cement grout of barrier is assumed to start once the disposal container has started to degrade (see Table 11).
- **Disposal Zone**: The stainless steel disposal container, the disposal zone backfill (cement grout) and the associated borehole casing are considered to comprise the disposal zone. Whilst the HDPE casing is conservatively assumed to fail on closure, it is assumed that the stainless steel disposal container remains intact until breached by corrosion (see Table 11).

- **Closure Zone**: The cement grout backfill, the anti-intrusion barrier and the uppermost 5 m of native soil or crushed rock are considered to comprise the closure zone (Fig. 4).
- **Disturbed Zone and Plug**: The plug at the bottom of the borehole and the backfill in the disturbed zone between the casing and the native rock are assumed to be cement grout (Fig. 4).

## VII.2. GEOSPHERE COMPONENTS

At a high level (appropriate for the GSA), the geosphere can be divided into two zones.

- **Unsaturated Zone**: comprising the region between the ground surface and the water table, but excluding the rooting zone for major food crops (soil).
- **Saturated Zone**: comprising the region below the water table.

## VII.3. BIOSPHERE COMPONENTS

Given that the exposure pathways being considered in the Design Scenario are the domestic and agricultural use of contaminated water by humans and the inhalation of contaminated gas (Section 4.2.1), the biosphere can be sub-divided into six components.

- **Humans**: who are assumed to be farmers or house dwellers.
- **Soil**: the region in which significant biological activity occurs from the ground surface to the base of the rooting zone for major food crops.
- **Atmosphere**: the air breathed by humans and fauna, including dust in it. Includes air into which the contaminated gas is assumed to discharge from the borehole (i.e. the air in the dwelling constructed on top of the borehole).
- **Crops**: the root and green vegetables that are irrigated using contaminated water and are harvested by humans.
- **Animals**: the cattle that are raised by humans and are given contaminated drinking water.
- **Elsewhere**: Radionuclides can be lost by a number of mechanisms from the immediate vicinity of the release (e.g. ventilation of the dwelling, groundwater flow past the abstraction borehole). They are no longer of interest in the evaluation of individual doses since they are lost to locations where radionuclide concentrations are lower and the associated doses lower. For the purpose of this safety assessment and the conceptual model, these locations are described as being ‘elsewhere’.

## VII.4. INTERACTIONS BETWEEN COMPONENTS

Based upon expert judgement (gained from previous assessments of the borehole disposal concept such as Refs [12], [32], [84]) and information from the description of the disposal system and the scenarios to be assessed, key interactions between the various disposal system components have been identified that result in the release and migration of radionuclides through the system and the subsequent exposure of humans for both the Design and Defect Scenarios. These are shown on Fig. 7 for the case where the disposal zone is saturated and in Fig. 8 for the case in which it is unsaturated. The two cases are broadly similar, the main difference being the nature of water flow through the near field (saturated vs. unsaturated) and the exclusion of gas migration in the saturated case. The components and their interactions for the Defect Scenario are the same as those for the Design Scenario since the faster degradation rates, earlier failure times, and faster radionuclide migration times of the Defect Scenario can be accounted for by modifying the associated parameters in the mathematical model (e.g. container degradation rates) rather than fundamentally altering the Interaction Matrices.

# APPENDIX VIII
# CEMENT DEGRADATION MODEL

## VIII.1. IMPORTANT IMPACTS OF CEMENT EVOLUTION

Cement evolution may affect the overall functioning of the barrier system in the borehole in the following major ways.

- The period for which steel barrier integrity is maintained will depend upon evolving chemical reactions between porewater and cement phases. These reactions will influence the ability of the cement to buffer porewater pH and to control the accessibility of steel surfaces to certain aqueous constituents, principally chloride. High pH and low chloride will favour steel longevity (see Appendix I).
- The ability of the cement to sorb radionuclides that escape from the disposal container will depend upon the extent to which the mineral constituents of the cement have evolved physically and chemically. The evolution of solid grains will influence the surface areas that are available for sorption and the accessibility of the grains to migrating fluid. The pH evolution of the porewater will also influence sorption.
- Evolving chemical reactions within the cement may control the concentration of ligands that are available to complex with certain radionuclides, thereby increasing their mobility. For example, carbonate in the groundwater will tend to react with cementitious phases, thereby rendering the carbonate unable to complex with americium.
- Fluctuations in the permeability of the cement may influence the flux of water that is available to corrode steel barriers and to transport radionuclides.

## VIII.2. PROCESSES CONTROLLING CEMENT DEGRADATION

The chemical and physical evolution of the cement used in the borehole environment is a function of many factors (e.g. Refs [85], [86]), principally:

- The chemical composition of the natural groundwater;
- The chemical composition of the cement;
- The initial physical properties of the cement (which depend partially upon the methods used to prepare and emplace the cement);
- The flux of the groundwater; and
- The natural thermal gradient.

Complex couplings between these factors will determine their impacts on the capacity of the cement to buffer pH, which is a key parameter that affects the longevity of the steel barriers. In particular, chemical cement degradation processes will be coupled to the groundwater flux since mineral precipitation and dissolution will cause the cement's porosity and permeability to vary whilst the flux of groundwater will in turn influence the chemical reactions that occur. Similarly, these coupled processes will be affected by, and also affect, the physical integrity of the cement.

The approach taken in the GSA is to evaluate the performance of the barrier system for reasonable bounding assumptions relating to the chemical and physical evolution of the cement, rather than to undertake detailed coupled modelling of the cement and its evolution. To enable these bounding assumptions to be well-founded, it is appropriate to review how the key processes might influence the barrier function of the cement.

The following factors are particularly important.

- If the natural groundwater has a high pH initially, the stability of the cement will tend to be favoured; lower pH will tend to promote cement degradation.

- Reactions between the cement and chloride in the groundwater could produce $CaCl_2$, calcium aluminates and Friedel's salt, thereby reducing the concentration of chloride in the water that is available for participating in the corrosion of stainless steel.
- Reactions between cement and carbonate dissolved in the groundwater would result in the formation of solid calcium carbonate within the cement. This process would lead to a reduction in porosity and permeability, causing a decrease in the flux of groundwater passing through the cement. Potentially a consequence of this process could be an increase in the time for which high-pH conditions are maintained adjacent to the disposal containers. On the other hand, calcium carbonate precipitation along fluid flow paths, for example interconnected fractures, could have the effect of armouring the cement phases and restricting their access to the fluid. This process might effectively decrease the time for which the fluid contacting the steel barriers would have pH buffered at a high value.
- Sulphate in the groundwater would also react with the cement to form solid phases such as ettringite, monosulphatealuminate and gypsum. Precipitation of these minerals results in a significant solid volume increase. Initially, as in the case of calcium carbonate precipitation, the consequence would be a decrease in porosity and permeability, tending to prolong the period of high-pH buffering. However, the volume increase would eventually produce fracturing which would allow groundwater to flow relatively quickly to contact the steel barrier components. Thus, the buffering of pH to high values may be inhibited.
- If corrosion of the steel components of the barrier system occurs before the cement has degraded, the greater volume of the corrosion products compared with the original steel may cause cracking. The cracks may result in the permeability of the cement increasing significantly, leading in turn to greater fluxes of groundwater to the remaining steel. Overall, this process could potentially lead to more rapid breaching of the steel components than would otherwise occur.

The second process is considered to be of much less importance for the present work than the other processes. The extent to which binding of chloride occurs will depend upon the concentrations and characteristics of other constituents within the pore fluid. Notably carbonate and sulphate will generally act to diminish the binding of chloride. The chemical composition of the cement is also a significant control. In reality, chloride binding would have less effect on the strength and pH-buffering capacity of the cement barrier than would attack by sulphate and/or carbonate.

## VIII.3. AVAILABLE CEMENT DEGRADATION MODELS

Of particular interest in the present project is the temporal pH evolution of the porewater in the cement. The importance of this evolution is due to the strong influence of pH on the rates of corrosion of the steel barriers. The other evolutionary processes are of relevance mainly because they influence this pH evolution. Whilst chloride binding may also influence the corrosion rate of the steel, by decreasing the concentration of chloride in the porewater that contacts the steel, this process is assumed to be of secondary importance in the present project.

The precipitation of carbonate and sulphate phases could influence radionuclide migration in other ways besides affecting pH buffering. For example, this precipitation could affect sorption of radionuclides on cementitious phases or the generation of cement colloids. However, these influences cannot be predicted confidently and are considered to be generally positive so that they can be conservatively neglected in the present project.

Several stages can be identified in the pH evolution of cement porewater.

- Initially, the pore fluid produced by the cement contains relatively high concentrations of soluble metal hydroxides, NaOH and KOH. These hydroxides maintain the pH of pore fluids at values greater than about pH 13. There are only small quantities of NaOH and KOH present in the cement, so the period for which these high pH conditions is maintained is relatively short.
- After the soluble hydroxides have been leached, pH is regulated by the dissolution of portlandite, $Ca(OH)_2$. This latter phase buffers the Ca concentration in the fluid at around $2x10^{-2}$ M and causes the pH to be maintained at about 12.5 (at 25°C).
- Subsequently, dissolution of calcium silicate hydrate (C-S-H) gel controls pH. This process is probably the most important pH control over timescales relevant to performance assessment. C-S-H gel dissolution initially maintains Ca concentrations in the pore fluid at high values, comparable with that caused by the earlier portlandite buffering. However, C-S-H dissolution occurs incongruently, causing the Ca/Si ratio of the solid to decrease with time due to preferential Ca removal. Consequently the Ca/Si ratio decreases from about 2.5 to 1.7/1.8 when pH starts to decrease. When a Ca/Si ratio of about 0.85 has been reached the remaining C-S-H dissolves congruently at a pH of ~10.5.

Most cement-groundwater interaction models focus on representing the C-S-H gel, reflecting the complexity of the structure and chemical behaviour of this phase. The C-S-H gel is a hydration product of the tricalcium silicate ($3CaO.SiO_2$) and dicalcium silicate ($2CaO.SiO_2$) in the cement clinker. However, the chemical composition of the C-S-H gel is not fixed but has a variable Ca/Si ratio, ranging from about one to more than two. The structure of the gel is nearly amorphous, but is thought to have some clay-like layering, consisting of sheets of calcium silicate with interlayer calcium ions and water [85].

The degree to which the C-S-H phase dissolves incongruently increases with the Ca/Si ratio of the solid. Gels with Ca/Si > 2 equilibrate with aqueous solutions having Ca/Si > 10 000, whereas those having Ca/Si ≤ 1 buffer aqueous solutions at Ca/Si < 1. Although the dissolution behaviour is non-stoichiometric, it is thought that it is driven by thermodynamic equilibrium. The evidence seems to be good that tobermorite and jennite-like units occur in the C-S-H, but the quantities of bound hydroxyls and tetrahedral Al at certain Ca/Si ratios cannot be explained by a gel consisting entirely of tobermorite and jennite-like structural units. However, a solid solution between tobermorite and jennite-like units and calcium hydroxide may account for most of the bulk gel composition. In addition, at the high mean Ca/Si ratios found in Ordinary Portland Cement (OPC) pastes, there may be significant interlayering with AFm ($(Ca_2(Al,Fe)(OH_6)].X.nH_2O$ where X is a univalent anion or 'half' a divalent anion, such as hydroxyl, sulphate or carbonate).

Three kinds of model have been proposed to explain this C-S-H gel behaviour from a thermodynamic perspective.

1. Solubilities in the system $CaO\text{-}SiO_2\text{-}H_2O$ are recalculated to unique solubility products raised to fractional powers as a function of the Ca/Si ratio (e.g. Ref. [87]). However, this approach is inconsistent with the law of mass action, which requires that chemical reactions have non-fractional stoichiometric coefficients. Integer coefficients are required to ensure that aqueous solutions are electrically neutral. In other respects this model is attractive because variable solubility products are used to fit experimental data in the system $CaO\text{-}SiO_2\text{-}H_2O$.
2. The Gibbs-Duhem equation is applied at constant pressure and temperature to each phase in the 3-component system $CaO\text{-}SiO_2\text{-}H_2O$:

$$X_C^i d\mu_C^i + X_S^i d\mu_S^i + X_H^i d\mu_H^i = 0 \tag{8}$$

where $\mu_i$ are chemical potentials in each component *i*.

An expression of the following type can be written to relate the solids Ca/Si ratio to the aqueous phase's chemical composition:

$$R_{C/S} = \frac{X_C^S}{X_S^S} = \frac{-d\mu_S}{d\mu_C}\frac{1 - m_S^{aq} R_{H/S}}{55.51} + \frac{m_C^{aq} R_{H/S}}{55.51} \tag{9}$$

where $R_{H/S}$ is the molar $H_2O/SiO_2$ ratio of the solid and $m$ denotes molal units.

This approach suffers from the major disadvantage that it does not take into account any structural information about C-S-H gels, such as non-ideal mixing behaviour or miscibility gaps.

3. Solid-solution models of various types. The first such model was developed by Ref. [88] who concluded that C-S-H gel with Ca/Si > 1 could be described as a solid solution between $Ca(OH)_2$ and a calcium silicate component with low Ca/Si ratio. From the perspective of structural and aqueous chemical data, there is good evidence that C-S-H gel can be represented by a solid-solution. During recent years there have been advances in the construction of solid solution models for C-S-H gels.

Projects connected with radioactive waste disposal have tended to explain C-S-H gel behaviour using models of either the first or second type. Owing to the requirement to consider long time periods, incongruent C-S-H gel dissolution has often been modelled deterministically, taking account of the experimentally observed relationships between Ca/Si ratios and variations in pH and calcium and silicon concentrations. A recent, more thermodynamically defensible approach is describing the incongruent dissolution of CSH gel as a non-ideal solid solution-aqueous solution (SSAS).

## VIII.4. REPRESENTATION OF CEMENT DEGRADATION IN THE GSA

Detailed models of cement evolution of the kinds outlined in Section VIII.3 are inappropriate for the GSA. These models would take considerable resources to develop using experimental data for particular cement and fluid compositions. From the results obtained, it would then be necessary to abstract general evolutionary trends in pH that are appropriate for safety assessment calculations. Thus, in this case there is no advantage to be gained from developing such detailed models in comparison to deducing general temporal variations in pH directly from experimental information.

The approach taken for the GSA is to use a combination of experimental results and modelling results reported in Refs [86] and [89], to develop a generic model for the pH evolution of cement suitable for the GSA and use this as an analogue for the evolution of the cement's chemical and physical characteristics. The particular model proposed by Ref. [86] is widely used model and of the first type outlined in Section VIII.3.

Reference [86] predicted that a volume of fresh groundwater within the range c. 4500 to c. 7500 times the total pore volume would be required to completely degrade cement. Here, degradation is defined to have been completed when all the CSH-gel has dissolved. Reference [86] reported the following stages in the pH evolution of porewater flushing sulphate-resistant cement:

- Stage 1 has porewater pH of around 13.5, owing to the presence of significant NaOH and KOH and persists during flushing by about 100 pore volumes.
- Stage 2 has porewater pH of about 12.5, owing to buffering by $Ca(OH)_2$ and persists during flushing by approximately an additional 900 pore volumes.
- Stage 3 has porewater pH diminishing steadily from 12.5 to about the ambient groundwater pH, owing to buffering with C-S-H phases having progressively decreasing Ca/Si ratios. This stage persists during flushing by approximately an additional 4000 to 9000 pore volumes (depending upon the water composition).

The groundwater carbonate content was found to be an important control on the lifetime of the cement; the marl porewater with relatively high carbonate content degrades sulphate-resistant cement more rapidly than pure water [86].

It also appears that the composition of the cement exerts a significant impact upon the time taken for complete cement degradation to occur. When sulphate-resistant cement was modelled about 7500 pore volumes of pure water were required to achieve complete cement degradation [86].

In the GSA, the three reference waters, 1, 5 and 6 are considerably different in composition from those considered in Refs [86], [89]. Of these waters, reference water 1 has the closest overall composition to the fresh waters considered in Refs [86], [89]. However, the pH of this reference water (4.2) is much lower than those considered in Refs [86], [89] (around 7). Consequently, it is considered that the value of 7450 pore volumes would effectively be an upper limit on the longevity of the cement. A more reasonable limit, taking into account the low pH of the reference water, can be calculated by means of simple scoping calculations.

Data presented in Ref. [90] show that cement paste in Degerham cement has 38095 moles of leachable $OH^-$ per $m^3$ of cement. This concentration in the solid phase can be compared with the concentrations of $OH^-$ in Stage 1 porewater (pH 13.5, concentration of $OH^-$ c. $3.16 \times 10^{-14}$ molal), Stage 2 porewater (pH 12.5, concentration of $OH^-$ c. $3.16 \times 10^{-13}$ molal) and groundwater (pH 4.2, concentration of $OH^-$ c. $6.30957E^{-5}$ molal). For example, 1/4819 of the quantity of $OH^-$ present in the solid phase would need to be leached by groundwater occupying porosity equivalent to 0.25 of the cement volume, in order for the pH to be buffered by portlandite.

Note that the actual reference water 1 contains other pH-buffering constituents, notably small quantities of carbonate. To evaluate the potential significance of these, simple scoping calculations were carried out using the code Geochemist's Workbench v. 6.0 and the thermodynamic database 'thermo.dat' [91]. In the model, cement was approximated by portlandite, which was flushed by reference water 1. The variation in pH as a function of the quantity of reference water 1 is shown in Fig. 23.

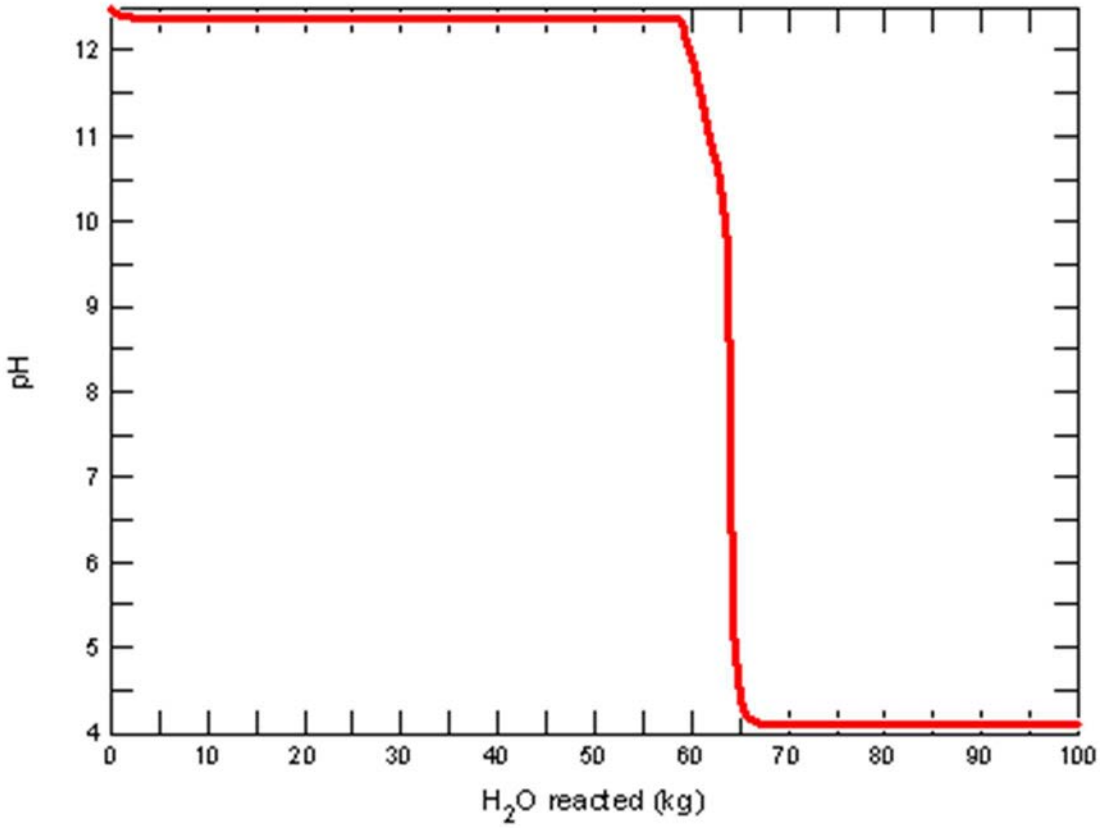


*FIG. 23. Variation in porewater pH as reference water 1 reacts with portlandite-equilibrated water in contact with 1 mole of portlandite. Reference water 1 inflows to the portlandite, equilibrates and then flows away, to be replaced by a new volume of reference water 1. Thus, about 65 kg of this water would need to flush 1 mole of portlandite to deplete its pH buffering capacity.*

Using the result shown in Fig. 23, again assuming that the cement has a porosity of 25%, and taking the portlandite to have a density of 2241.43 kg/m$^3$, 5900 pore volumes would be needed to deplete the pH buffering capacity of the cement.

Taking these results together implies that the acidic fresh water would indeed degrade the cement more readily than the fresh water considered by Ref. [86]. Furthermore, although the increased degradation rate cannot be estimated precisely, it would seem reasonable that there would be a reduction in longevity of the cementitious barrier of between 20% and 40%, compared to the freshwater case in Ref. [86].

Bearing in mind the uncertainties, a reference case for water 1 is defined in which the number of porewater flushes during Stages 2 and 3 are half those calculated for fresh water leaching of sulphate-resistant OPC in Ref. [86]. The initially most alkaline Stage 1 is specified to be of the same duration as in Ref. [86] because: (1) Reference [86] acknowledges that the model describes this initial stage inadequately, so that choosing a different duration would not be well-founded, and (2) in any case Stage 1 is very short compared to Stages 2 and 3 (only about 1%). In summary, for reference water 1, the various stages are:

- Stage 1 has porewater pH of around 13.5, owing to the presence of significant NaOH and KOH and persists during flushing by about 100 pore volumes.
- Stage 2 has porewater pH of about 12.5, owing to buffering by $Ca(OH)_2$ and persists during flushing by approximately an additional 400 pore volumes.

- Stage 3 has porewater pH diminishing steadily from 12.5 to the ambient groundwater pH, owing to buffering with C-S-H phases having progressively decreasing Ca/Si ratios. This stage persists during flushing by approximately an additional 3225 pore volumes.

The pH of the reference waters 5 (pH 8.46) and 6 (pH 7.95) are actually more alkaline than the waters considered by Refs [86], [89]. However, the reference waters contain different proportions of Cl, $CO_3$ and $SO_4$ to one another and to the marl water considered in Ref. [86]. The concentrations of these constituents in reference water 5 are less than in the marl water. In contrast, the concentrations in reference water 6 are higher than in the marl water. It is to be expected that these differences in chemical compositions would be reflected in different longevities of the cementitious barriers. However, for the reasons outlined in Section VIII.2, the precise differences cannot be estimated. It is unclear whether overall the differences in composition of the reference waters compared to the fresh water considered in Ref. [86] would lead to increases or decreases in the lifetimes of the barriers. Thus, the approach taken here for reference waters 5 and 6 is:

- Firstly to adopt the temporal variation in ph specified in Ref. [86] for fresh water in sulphate-resistant OPC as the reference case;
- Secondly to evaluate the possible significance of the cementitious barriers degrading more rapidly by calculating results for alternative cases in which:
  - The barrier degrades twice as quickly.
  - There is no cementitious barrier.

## VIII.5. CEMENT DEGRADATION TIMES FOR GSA REFERENCE CASES

Using the model described in Section VIII.4 and the groundwater flow characteristics described in Section 3.2, the cement degradation times given in Tables 38 and 39 have been calculated for the reference systems of interest. An Excel spreadsheet has been used to undertake these calculations.

TABLE 38. CEMENT DEGRADATION TIMES FOR THE REFERENCE CASES FOR THE DESIGN SCENARIO AND DEFECT SCENARIO D1, D2 AND D4

| | Geosphere | Duration (y) | | | |
|---|---|---|---|---|---|
| | | Stage 1 | Stage 2 | Stage 3 | Cumulative |
| Backfill cement | Unsaturated zone | 8.04E+02 | 3.22E+03 | 4.54E+04 | 4.94E+04 |
| | High flow (porous and fractured) | 5.14E+02 | 4.62E+03 | 3.71E+01 | 5.17E+03 |
| | Medium flow | 5.14E+02 | 4.62E+03 | 3.59E+03 | 8.73E+03 |
| | Low flow | 8.22E+03 | 7.39E+04 | 9.27E+05 | 1.01E+06 |
| Containment barrier cement[a] | Unsaturated zone | 1.41E+02 | 5.63E+02 | 7.95E+03 | 8.65E+03 |
| | High flow (porous and fractured) | 2.42E+02 | 2.18E+03 | 1.75E+01 | 2.44E+03 |
| | Medium flow | 2.42E+02 | 2.18E+03 | 1.70E+03 | 4.12E+03 |
| | Low flow | 3.88E+03 | 3.49E+04 | 4.38E+05 | 4.77E+05 |

**Note**: [a] Time from time of failure of the disposal container.

TABLE 39. CEMENT DEGRADATION TIMES FOR THE REFERENCE CASES FOR THE DEFECT SCENARIO D3

| | Geosphere | Duration (y) | | | |
|---|---|---|---|---|---|
| | | Stage 1 | Stage 2 | Stage 3 | Cumulative |
| Backfill cement | Unsaturated zone | 4.02E+02 | 1.61E+03 | 2.27E+04 | 2.47E+04 |
| | High flow (porous and fractured) | 2.57E+01 | 2.31E+02 | 1.85E+01 | 2.75E+02 |
| | Medium flow | 2.57E+01 | 2.31E+02 | 1.41E+03 | 1.66E+03 |
| | Low flow | 4.11E+03 | 3.70E+04 | 4.64E+05 | 5.05E+05 |
| Containment barrier cement[a] | Unsaturated zone | 7.52E+01 | 3.01E+02 | 4.24E+03 | 4.62E+03 |
| | High flow (porous and fractured) | 1.21E+01 | 1.09E+02 | 8.73E+00 | 1.30E+02 |
| | Medium flow | 1.21E+01 | 1.09E+02 | 6.63E+02 | 7.84E+02 |
| | Low flow | 1.94E+03 | 1.75E+04 | 2.19E+05 | 2.38E+05 |

**Note**: [a] Time from time of failure of the disposal container

# APPENDIX IX
# CORROSION OF STAINLESS STEEL WASTE CAPSULES AND DISPOSAL CONTAINERS

## IX.1. INTRODUCTION

The proposed design for the Borehole Disposal Concept (BDC) includes a robust engineered barrier system. Included in these barriers are a sealed AISI Type 304 stainless steel waste capsule and a sealed AISI Type 316L disposal container. These stainless steel barriers are surrounded by a cement grout barrier comprising a layer of sulphate-resistant cement grout between the waste capsule and the disposal container, referred to as the containment barrier, and another layer of the same material between the disposal container and a high-density polyethylene borehole casing, referred to as the disposal zone backfill. The cementitious material not only provides a mass transport barrier to the release of radionuclides but, more importantly from a corrosion viewpoint, chemically conditions the environment. The high pH of the cement grout porewater will substantially improve the corrosion resistance and performance of the stainless steel containers. As a consequence, if properly emplaced, this series of metallic and cementitious engineered barriers could potentially isolate the disposed sources from the external environment for very long periods of time.

The purpose of the corrosion model described below is to develop a sound mechanistic basis for long term estimates of the lifetimes of the disposal container and waste capsule. First, the corrosion behaviour of austenitic stainless steels (i.e. typically the AISI 300-series) is briefly reviewed along with a critical review of relevant corrosion data (Section IX.2). Next, potential target lifetimes for the borehole are defined, largely by reference to the containment of various potential radionuclides in the different sources that may be disposed (Section IX.3). The corrosion model is then described (Section IX.4). This description includes discussion of the structure of the model and a summary of the environmental conditions for the Design and Defect Scenarios considered. Any such model inevitably involves some simplification of the detailed mechanistic understanding into a form that is computationally tractable, and that abstraction process is also described. In addition, the mathematical implementation of the model and the quality assurance procedures used are described. Section IX.5 presents failure times for the reference systems considered in the GSA, together with ‘corrosion maps’, which, in a pictorial fashion, are used to relate various environmental conditions to the consequences for the performance of the borehole.

## IX.2. LITERATURE REVIEW AND SUMMARY OF DATA

### IX.2.1. Corrosion behaviour of stainless steels

### *IX.2.1.1. General Corrosion*

The corrosion behaviour of stainless steels has been extensively studied and is relatively well understood [112]. A wide range of stainless steel alloys has been developed to address specific corrosion issues and to provide suitable corrosion resistance in a range of environments. The most widely used group of stainless steels is probably the austenitic grades, generally referred to as the AISI 300-series alloys. These alloys typically contain ~18 wt.% Cr and 8-10 wt.% Ni. The two most common grades, Type 304 (UNS S30400) and Type 316 (UNS S31600), are distinguished by the addition of 2-3 wt.% Mo to the latter to improve the resistance to localized corrosion and SCC. Low-carbon grades (304L and 316L) are available to minimise the possibility of sensitisation of welds due to the precipitation of chromium carbides at grain boundaries.

Stainless steels are subject to general corrosion at a rate that varies with time, temperature, redox conditions, pH, and salinity [74], [85], [86], [87], [112], [116]). Stainless steels are protected by the formation of a stable Cr(III) oxide or hydroxide film (variously represented by $Cr_2O_3$, $Cr(OH)_3$, or CrOOH, [92]).

On freshly polished surfaces, the corrosion rate will continue to decrease with time for several years after exposure to the corrosive environment as the passive film develops. The film is typically amorphous, although for some passive materials re-crystallization of the oxide can occur over time, resulting in an increase in corrosion rate as in the case of Ti [106], [107].

The general corrosion rate of stainless steel is typically not a strong function of the redox potential, here interpreted in terms of the corresponding dissolved $O_2$ concentration. Increasing $[O_2]$ leads to an increase in $E_{CORR}$, but provided the potential is within the passive range the corrosion rate is determined more by the properties of the oxide film than by the rate of the cathodic reaction (the reduction of $O_2$). An increase in $E_{CORR}$, however, will result in an increase in the potential drop across the passive film and the 'leakage current' (which corresponds to the rate of general corrosion) will increase accordingly. In contrast, the corrosion rate of active materials, such as carbon or mild steel, can be proportional to the $[O_2]$ if the rate of corrosion is cathodically limited.

The protectiveness of the passive film depends on the solution pH [115]. The minimum solubility of Cr(III) oxides lies between pH 7 and pH 8.5, depending upon the stable form [115]. The solubility increases at both lower and higher pH, although the rate of increase in solubility is much greater in acidic solutions. Furthermore, the stability of the oxides of other alloying elements at higher pH maintains a stable passive film in the alkaline range.

Chloride ions tend to de-stabilise the passive film on stainless steels. Although the effect of $Cl^-$ is most significant for the initiation and propagation of localized corrosion, $Cl^-$ ions also tend to decrease the stability of the passive oxide film and lead to an increase in general corrosion rate [92].

The rate of general corrosion is dependent on the degree of passivity of the passive oxide film and can be measured as a simple weight-loss corrosion rate or as a passive current density in electrochemical experiments. Depending upon the range of T, pH, and $[Cl^-]$, the rate of general corrosion will typically be in the range 0.01-2 μm·/y (see below).

General corrosion can occur under saturated conditions (i.e. immersed in groundwater) or under unsaturated conditions. In the latter case, a threshold relative humidity (RH) for corrosion of ~60-70% is generally observed, below which corrosion is not possible because there is insufficient adsorbed water on the surface to sustain the electrochemical reactions that constitute the overall corrosion process [74].

### *IX.2.1.2. Localized Corrosion*

Stainless steel and other passive materials are known to be susceptible to localized corrosion in the form of pitting or crevice corrosion [74], [85], [86], [87], [116], [118], [123]. The mechanism of these two processes is similar, the major difference being the location at which the localized corrosion initiates; pitting occurs on the bold exposed surface and crevice corrosion initiates in geometrically occluded areas.

Localized corrosion is typically divided into initiation and propagation stages [123]. Initiation involves the development of a suitable environment (sometimes referred to as an incubation phase) and the localized breakdown of the passive film. Film breakdown can be meta-stable (i.e. the passive film attempts to and succeeds in self-healing) or stable (i.e. a sustained area of localized corrosion is generated). Propagation results in loss of wall thickness as the de-passivated material undergoes active corrosion in occluded regions (either created by the crevice former or, in the case of pitting, by a 'cap' of precipitated corrosion products) in which a low-pH, high-$[Cl^-]$ environment is maintained. Pit growth can be stifled, however, if this local environment is lost, as for example in the case of the exhaustion of the cathodic reactant (typically dissolved $O_2$), breakdown of the cap of corrosion products, iR drops down the occluded region, etc.

In general, the susceptibility to initiation and the severity of propagation increase with increasing electrochemical potential (E), temperature (T), and $[Cl^-]$ and decreasing pH. A number of oxyanions, including $SO_4^{2-}$, inhibit the aggressive effect of $Cl^-$ [112], [123].

Initiation is typically studied in simple exposure tests or electrochemically. In exposure tests, planar or creviced samples are exposed to an environment and the number of initiated pits or crevices observed. Electrochemically, the potential is scanned until film breakdown is observed (characterized by a rapid increase in the measured current) which defines a ‘breakdown’ or ‘pitting’ potential ($E_P$). The pitting potential moves to more ‘active’, i.e. more negative, values with increasing T and [$Cl^-$] [115]. Similar dependences can be developed for film breakdown potentials for crevice corrosion ($E_{CREV}$) by using samples with creviced or occluded regions. The crevice breakdown potential is typically 10’s to 100’s mV more negative than the equivalent potential for pitting as it is easier to develop the critical chemistry for film breakdown within the occluded region than it is for pitting of an exposed surface.

Under naturally corroding conditions, pitting or crevice corrosion will initiate if the value of the corrosion potential, $E_{CORR}$ (the natural electrochemical potential at which the stainless steel rests in the aqueous environment), exceeds the value of the film breakdown potential for either process. Mathematically, this condition is expressed as:

$$E_{CORR} \geq E_P, E_{CREV} \tag{10}$$

A re-passivation potential ($E_{RP}$ or $E_{RCREV}$ for pitting and crevice corrosion, respectively) can also be defined at which a propagating pit or crevice will re-passivate. The repassivation potential is often used as a conservative measure of the initiation of localized corrosion, the mathematical criterion for initiation then being:

$$E_{CORR} \geq E_{RP}, E_{RCREV} \tag{11}$$

The extent of propagation of localized corrosion can also be assessed by measuring the depth of attack as a function of time. For a range of materials including stainless steels [113], it is typically found that the rate of localized corrosion propagation decreases with time (t). The depth of local penetration D is given by:

$$D = kt^n \tag{12}$$

where k and n are material- and environment-specific constants.

Depending upon the values of k and n and the wall thickness, localized corrosion may effectively stop before penetrating the wall.

#### *IX.2.1.3. Stress Corrosion Cracking*

Stainless steels are also known to be susceptible to stress corrosion cracking (SCC). Cracking is most commonly associated with $Cl^-$ environments, although SCC also occurs in other solutions [102]. From a practical viewpoint, the ranges of T, pH, and [$Cl^-$] that support SCC have been defined for the SCC of Type 304 stainless steel, indicating that the severity of SCC increases with increasing T, [$O_2$], and [$Cl^-$] and decreasing pH [102].

As for localized corrosion, SCC can be divided into initiation and propagation stages. Initiation involves the formation of microscopic cracks from initially uncracked surfaces, and is often characterized by a threshold stress. Using a linear-elastic fracture mechanics approach, crack growth is characterized by a stress intensity factor ($K_I$), the magnitude of which depends on the applied or residual stress and the size and shape of the crack. In general, the crack growth rate increases with increasing $K_I$. Alternatively, crack growth can be modeled based on the known mechanism, be it a film-rupture/dissolution process, film-induced cleavage, or some other mechanism.

Pitting and SCC are closely related; cracks often initiate from pits on the surface. With increasing pH, the incidence of both pitting and SCC diminish, suggesting that stainless steel in contact with cement grout ought to be resistant to both forms of corrosion [102].

Welds are often prime locations for SCC. This enhanced susceptibility is the result of a number of factors, including: high residual stress, a sensitised microstructure because of preferential segregation of impurities and alloying elements (principally Cr and C) to grain boundaries, electrochemical differences between the base metal, heat-affected zone, and weld material, and local high hardness. This implies the need for well-defined welding procedures and QA processes for container fabrication.

#### *IX.2.1.4. Microbiologically Influenced Corrosion*

Microbial activity can induce corrosion of metallic structures either through the production of aggressive metabolic by-products or by creating occluded regions for localized corrosion. Stainless steels are known to be susceptible to microbiologically influenced corrosion (MIC) [70].

The key to MIC is microbial activity. If microbes are not active then they cannot produce aggressive metabolic by-products (such as sulphide ions or organic acids) or the extracellular polymeric substance (i.e. slime) that creates localized environments.

A number of environmental factors can limit microbial activity. In the present context, the elevated pH in the cement grout porewater will prevent microbial activity until the pH drops below a value of ~10.

For stainless steels, ennoblement of $E_{CORR}$ has to be observed, which may make the material more susceptible to localized corrosion. If locally acidic conditions can be formed under biofilms by acid-producing bacteria, de-passivation could occur at low enough pH. Preferential weld attack has also been observed on stainless steel in microbially active environments.

#### *IX.2.1.5. Preferential Corrosion of Welds*

Welds are often locations for preferential corrosion. The enhanced susceptibility of welds results from (i) Micro-scale galvanic cells that can be created due to the use of a dissimilar weld material; (ii) Microstructural differences between the weld metal, heat-affected zone, and base metal; or (iii) Segregation of certain alloying elements to grain boundaries (sensitisation).

Stainless steels can be susceptible to preferential weld attack if steps are not taken to avoid the effects listed above. Classically, Type 304 stainless steel is susceptible to intergranular attack or enhanced SCC due to sensitisation of grain boundaries [102].

### **IX.2.2. Corrosion data**

#### *IX.2.2.1. General corrosion*

The general corrosion rate of stainless steel has been measured under a wide range of conditions, including in highly alkaline ($pH \geq 10$) and near-neutral to moderately alkaline solutions and for exposure to various atmospheric conditions.

Under highly alkaline conditions (Table 40), a number of trends are observed. Rates are typically <1 μm/y and generally <0.1 μm/y. The corrosion rate tends to decrease with time of exposure and with increasing pH. The absence of $O_2$ also appears to result in a lower corrosion rate, although the limited data set makes firm conclusions difficult. The corrosion rate increases with increasing temperature, but there are too few data to draw any definitive conclusion about the effect of $Cl^-$ ions, although there is some indication for an increase in rate with increasing $[Cl^-]$. For the available data set, there is no apparent difference between the corrosion rates for Types 304 and 316 (or 316L) stainless steels.

Similar trends are observed for neutral to slightly alkaline solution (Table 41). Thus, the general corrosion rate tends to increase with increasing temperature and increasing salinity and the rate tends to be higher under aerated, as opposed to deaerated, conditions. Corrosion rates are significantly higher than in highly alkaline solution (with rates generally in the range 0.1-1 μm/y), but again there is no apparent difference between the two grades of material.

There are relatively few data under atmospheric exposure conditions (Table 42). The available data exhibit no obvious dependence on the nature of the atmosphere, with rates typically <0.1 μm·/y.

### *IX.2.2.2. Pitting*

Pitting is a result of the breakdown of the passive film by aggressive species, most commonly $Cl^-$ ions [123]. Table 43 summarizes a number of measurements of $E_P$ and $E_{RP}$ in $Cl^-$ solutions as a function of temperature for both Type 304 (Table 43(a)) and Type 316 (Table 43(b)) stainless steels.

When the studies are taken together, there is a wide scatter in values. This scatter is the result of different experimental techniques, different surface preparation methods, as well as the dependence of $E_P$ and $E_{RP}$ on environmental parameters such as temperature, pH, $[Cl^-]$, and the concentration of other aggressive and inhibitive anions.

A number of trends are apparent, however, from individual studies. For example, the pitting potential decreases linearly with $\log_{10}[Cl^-]$ with evidence for a threshold $[Cl^-]$ at low concentrations [95], [102], [104], [105], [118], [123]. Interestingly, the dependence of $E_P$ on $\log[Cl^-]$ is greater for the more-resistant Type 316 stainless steel, -206 to -220 mV/dec, than for Type 304 stainless steel, -127 to -152 mV/dec [105], [123]. However, the value of $E_P$ or $E_{RP}$ for Type 316 is typically 100 to 200 mV more positive than for Type 304 [105]. In addition, the re-passivation potential is typically 200 to 400 mV more negative than $E_P$ [95], making the former measure a more-conservative criterion for pitting.

The pitting potential decreases with increasing temperature [118], accounting for the increased susceptibility of these alloys at elevated temperature. Whereas the value of $E_P$ for Type 304 appears to decrease monotonically with increasing temperature, that for Type 316 exhibits a plateau at temperatures above ~70°C.

In keeping with the greater protectiveness of the passive film in alkaline solution, $E_P$ increases significantly with increasing pH at pH >10 [118]. Type 316 stainless steel exhibits an increase in $E_P$ above ~pH 10, whereas the increase for Type 304 occurs at >pH 11. At lower pH values, $E_P$ is only moderately dependent on the solution pH.

### *IX.2.2.3. Crevice Corrosion*

Crevice corrosion occurs under less-aggressive conditions than pitting because the occluded geometry helps establish differential chemical concentrations (notably of $O_2$ and $Cl^-$) inside and outside of the crevice [123]. Thus, crevice corrosion occurs at more-negative potentials and lower $[Cl^-]$ than pitting [123]. Similarly, crevice corrosion will occur at lower temperatures and at higher pH than is observed for pitting.

This greater susceptibility is reflected in more-negative crevice breakdown and re-passivation potentials than the corresponding values for pitting (cf. Tables 43 and 44). Comparison of values in Tables 44(a) and 44(b) shows that, as for pitting, Type 304 stainless steel is more susceptible to crevice corrosion than Type 316.

The effect of $SO_4^{2-}$ ions on the crevice corrosion of Types 304 and 316 stainless steel in $Cl^-$ solutions is to limit corrosion at higher $SO_4^{2-}$ concentrations. Reference [118] shows that sulphate ions are more effective as an inhibitor for crevice corrosion for Type 316 steel than for Type 304. For Type 316 an approximately equal concentration of $SO_4^{2-}$ to $Cl^-$ is able to inhibit crevice corrosion, whereas the concentration of $SO_4^{2-}$ has to be much greater than $Cl^-$ to have a similar effect for Type 304 [118].

Reference [102] describes the effect of Cl- concentration, pH, and temperature on the susceptibility of Type 304 stainless steel to pitting (and SCC). The susceptibility to pitting increases with decreasing pH, increasing $[Cl^-]$, and increasing temperature. It is interesting to note that, except for two indications of pitting at a $Cl^-$ concentration of $10^4$ $\mu g \cdot g^{-1}$ (which appears to be an experimental artifact), Type 304 stainless steel appears to be immune to pitting at pH 12 [102].

There are several publications of the localized corrosion penetration rates in the literature. [98] publication rates of pitting under a biofilm (which would have acted as a crevice former) of 0.86 mm/y for Type 304 and 0.36 mm/y for Type 316, illustrating the greater susceptibility of Type 304 to pit growth. [118] publications crevice propagation rates of between 0.001 and 0.017 mm/y for cold-rolled and annealed Type 316, respectively.

### *IX.2.2.4. Stress Corrosion Cracking*

Reference [102] describes the effect of $Cl^-$ concentration, pH, and temperature on the susceptibility of Type 304 stainless steel to SCC. The susceptibility to cracking increases with decreasing pH, increasing $[Cl^-]$, and increasing temperature. It is interesting to note that cracking is not observed at pH 12, except under boiling conditions.

Based on industrial experience, SCC of austenitic stainless steels is not observed at temperatures below 60°C in near-neutral pH solutions, regardless of the $Cl^-$ concentration [109].

As noted above, reference [102] illustrates the correlation between pitting an cracking. Pits initiate and grow under less-aggressive conditions than cracking. Pits act as crack nucleation sites because they serve as stress concentrators. Pitting, therefore, is a more conservative indicator of potential failure than cracking.

### *IX.2.2.5. Corrosion Potential*

The value of $E_{CORR}$ is strongly dependent on the dissolved $O_2$ concentration (Table 45 and [122]). The corrosion potential shifts to more-positive values by ~75 mV per order of magnitude increase in $O_2$ concentration [122]. Thus, under anaerobic conditions, $E_{CORR}$ will be 300 to 400 mV more negative than in aerated solutions. This is an important difference, as it renders the surface less susceptible to localized corrosion or SCC with decreasing $O_2$ concentration.

Except at low pH values (pH <3), $E_{CORR}$ is relatively insensitive to pH in $O_2$-containing solutions [122].

The corrosion potential tends to decrease with increasing $Cl^-$ concentration [95], reflecting the effect of $Cl^-$ on the passive film. The dependency of $E_{CORR}$ on $Cl^-$ is minor in deaerated solution [95].

## IX.3. TARGET LIFETIMES

It is useful to define 'target' lifetimes for the waste capsule and disposal container for comparison against the predicted lifetime of these engineered barriers. These target lifetimes are not requirements, but are instead simply indicators of the potential effect on the overall safety of the concept of the metallic barriers.

Table 46 defines a number of target lifetimes, largely based on the half-lives of various possible radionuclides in the disused sealed radioactive sources. Radionuclides with an expected maximum inventory of $\geq 10^5$ MBq are distinguished from radionuclides with lower expected inventories (based on the data in Appendix I). The target lifetimes are based on the assumption that the activity of a particular radionuclide has decayed to negligible levels after ten half-lives.

A target lifetime of 10 years would provide for both the safe handling and installation of the waste packages, as well as essentially providing absolute containment for short lived radionuclides such as Ir-192 and certain medical isotopes.

A lifetime of 300 years would provide containment for not only these species, but also comparatively longer-lived radionuclides such as H-3, Sr-90, Cs-137, and others.

Longer lifetimes only provide additional safety and absolute containment for a limited number of species. A lifetime of 20,000 years would provide containment of Am-241, Pu-238, Ni-63, Sm-151, and Ra-226. Very long lifetimes of $10^6$ years would also contain C-14. However, it is not feasible to contain the long lived daughters of radionuclides such as Pu-239 based on absolute containment by the waste packages alone.

## IX.4. CORROSION MODEL

### IX.4.1. Structure of model

#### *IX.4.1.1. System description*

The corrosion model is based on the system description in Figs 3 and 4 and Tables 43 and 44 of the main text. Briefly, the barriers considered here (in sequence from the source outwards) are:

- Source container;
- Type 304 stainless steel waste capsule (welded, minimum wall thickness 3 mm);
- Containment barrier cement grout (sulphate resistant cement grout , 41 mm thick);
- Type 316 stainless steel disposal container (welded, minimum wall thickness 6 mm);
- Disposal zone backfill (cement grout, 12.5 mm thick); and
- Hdpe borehole casing (10 mm thick).

The corrosion model specifically estimates the lifetimes of the Type 304 waste capsule and of the Type 316 disposal container, taking into account the conditioning of the local chemical environment by the cementitious containment barrier and disposal zone backfill. Corrosion of the waste capsule (and degradation of the containment barrier cement grout) is assumed to start immediately following the initial perforation of the disposal container.

Failure of the waste capsule or disposal container is defined as either:

1. A through-wall penetration by localized corrosion, SCC or a weld defect; or
2. Consumption of the corrosion allowance by general corrosion.

The corrosion allowance is defined as 80% of the wall thickness (i.e. 2.4 mm and 4.8 mm for the waste capsule and disposal container, respectively), with the remaining wall required for structural stability of the container. In other words, once 80% of the wall has been lost by general corrosion, the container is assumed to collapse from external loads and no longer provide a barrier function.

A lifetime is defined for the initial penetration, 10% perforation of the container, 50% perforation, and 100% perforation. These different fractional failure areas are provided because the waste capsule and disposal container will continue to act as a mass-transport barrier following the initial penetration. In the safety assessment code AMBER, these fractional failure areas can be used to modify the mass-transfer coefficient between the borehole compartments (see Appendix XI). Times for different fractional corroded areas are provided for localized corrosion (see below), but not for general corrosion where the entire surface is assumed to be uniformly corroded.

It is assumed that the HDPE borehole casing provides no barrier to the inflow of groundwater and does not impact the leaching behaviour of the cement grout barriers or the corrosion behaviour of the waste capsule or disposal container.

#### *IX.4.1.2. Decision Tree*

A decision-tree approach can be used to develop the corrosion model for the waste capsule and disposal container for the GSA. Fig. 24 shows the decision tree used for the current assessment. The decision tree is based on a number of underlying assumptions:

- The corrosion processes for Types 304 and 316 stainless steels are the same and differ only in the rate and/or criteria for initiation of localized corrosion and SCC.
- The disposal system is isothermal.
- Localized corrosion and SCC can only occur in the presence of oxygen (see below).

- Under aerobic conditions, a threshold ph can be defined below which localized corrosion and SCC are possible.
- Below this threshold ph value, a critical $Cl^-$ concentration exists for the initiation of localized corrosion and SCC.

### *IX.4.1.3. Scenario Definition*

For the GSA, this corrosion model has been applied to two different scenarios:

- The Design Scenario, which describes the expected behaviour of the system in which all barriers function as designed; and
- The Defect Scenarios, which account for failure in one or more of the engineered barriers.

Four Defect Scenario variants are considered:

- D1: initial failure of the closure weld on one disposal container in the borehole, all other barriers function as designed;
- D2: initial failure of the closure weld on one waste capsule in the borehole, all other barriers function as designed;
- D3: degraded/incomplete disposal zone cement grout affecting all disposal containers in the borehole, all other barriers function as designed; and
- D4: initial failure of the closure weld on both the waste capsule and disposal container in the same waste package, all other barriers function as designed.

## IX.4.2. Environmental Conditions

### *IX.4.2.1. Summary of groundwater and site conditions and porewater evolution*

As described in Section 3.2 and Appendix II, various groundwater compositions, groundwater transport mechanisms, degree of saturation, and cement grout porewater leaching conditions are considered in the GSA.

Table 47 summarizes the six groundwater compositions considered for the GSA for calculation purposes (see Appendix II). From a corrosion perspective, these waters can be described as either aerobic or anaerobic and either fresh ($[Cl^-] < 100$ mg kg$^{-1}$) or saline ($[Cl^-] > 10\,000$ mg kg$^{-1}$). The categorization of the different groundwaters is as follows:

- Groundwater #1: aerobic, fresh, high $[SO_4^{2-}]:[Cl^-]$, low pH;
- Groundwater #5: anaerobic, fresh, high $[SO_4^{2-}]:[Cl^-]$;
- Groundwater #6: anaerobic, saline, high $[SO_4^{2-}]$;
- Groundwater #10: aerobic, fresh, alkaline pH;
- Groundwater #11: aerobic, saline, high $[HCO_3^-]$, alkaline pH; and
- Groundwater #12: aerobic, saline, high $[SO_4^{2-}]$, alkaline pH.

The porewater in the containment barrier and disposal zone will undergo a change in pH as the cement grout is leached by contact with the groundwater. A four-stage cement grout porewater model is used, comprising the following processes:

- Stage 1: Porewater pH controlled by NaOH/KOH, pH 13.5;
- Stage 2: Porewater pH controlled by $Ca(OH)_2$, pH 12.5;
- Stage 3: Porewater pH evolves from control by $Ca(OH)_2$ to background groundwater pH; and
- Stage 4: Porewater pH determined by groundwater.

The number of pore volumes required to transition from one stage to the next are determined by the chemical conditions of the groundwater (see Appendix VIII).

The groundwater flow conditions (the relative importance of diffusion and advection) and the degree of saturation (saturated or unsaturated) determine the time required to exchange the appropriate number of pore volumes for each stage in the evolution of the porewater pH.

#### *IX.4.2.2. Abstraction of Environmental Conditions for the Corrosion Model*

The most important environmental factors for the corrosion behaviour of the waste capsule and disposal container are the porewater pH, the redox conditions, and the $Cl^-$ concentration.

A slightly modified pH evolution of the cement grout porewater is used in the corrosion model. During Stage 3, instead of assuming a continuous evolution in pH, a two-step evolution is assumed with a constant pH in each of Stage 3(a) and Stage 3(b). The transition from Stage 3(a) to Stage 3(b) occurs at a critical pH at and below which localized corrosion is possible in aerated environments. Replacement of the continuous decrease in pH during Stage 3 by a two-stage step function simplifies the estimation of the extent of general corrosion during this period. As discussed further below, the critical pH for localized corrosion for the two alloys is different.

### IX.4.3. Corrosion Model

#### *IX.4.3.1. overview of the corrosion model*

Tables 48 and 49 give a general overview of the processes considered (and not considered) in the GSA corrosion model. The rationale for including localized corrosion under only certain conditions is provided, as are the reasons for excluding other forms of corrosion from the analysis (Table 48). As will become apparent in the following discussion, the major form of corrosion for the Design Scenario is general corrosion, with some possibility of localized corrosion during the latter stages of Stage 3 and during Stage 4 for aerobic groundwaters only (Table 49). For anaerobic groundwaters, the only corrosion process will be general corrosion.

#### *IX.4.3.2. Treatment of general corrosion*

The rates of general corrosion of both Types 304 and 316 stainless steel were derived from the data in Tables 40, 41, and 42. There is some variability in the reported data, presumably as a consequence of differences in experimental techniques and procedures, and because of the difficulty in measuring the low corrosion rates observed for passive materials.

Expert judgment was used, therefore, to derive best-estimate corrosion rates as a function of pH, redox condition, and $Cl^-$ concentration. The following principles were used in deriving appropriate rates of general corrosion.

- The corrosion rate was assumed to be the same for both Type 304 and 316L stainless steel. Corrosion protection is provided by a Cr(III) oxide film and, since the Cr content is similar for the two alloys, the rate of general corrosion would be expected to be similar.
- The corrosion rate is a strong function of pH, with significantly lower rates in alkaline solution (Table 40) than in near-neutral pH solution (Table 41).
- The corrosion rate is a function of redox conditions, with an assumed factor of ten difference in rate in alkaline solution between anaerobic and aerobic environments.
- The corrosion rate is a weak function of Cl- concentration, with an assumed factor of two difference in rate in fresh and saline waters.
- The corrosion rate is the same for unsaturated and saturated conditions, on the assumption that the relative humidity in the borehole exceeds the threshold of 60-70% RH required to support electrochemical reactions.

The rates of general corrosion used in the corrosion model for the different stages in the evolution of the porewater pH are given in Table 50.

### *IX.4.3.3. Treatment of localized corrosion*

Both the initiation and propagation of localized corrosion are considered in the model.

The conditions under which initiation of localized corrosion could occur were determined by comparison of the value of $E_{CORR}$ and the critical potentials for localized corrosion (Equations 10 and 11). For the GSA corrosion model, the critical potential for the initiation of localized corrosion was conservatively taken as the crevice re-passivation potential $E_{RCREV}$. The use of $E_{RCREV}$ is conservative for the following reasons:

- Crevice corrosion initiates under less aggressive conditions than pitting because of the effect of the occluded environment in promoting the spatial separation of anodic and cathodic reactions; and
- The re-passivation potential is the potential at which an actively propagating crevice will re-passivate, rather than the potential at which the passive film first breaks down.

A further conservatism was introduced by using a value for $E_{RCREV}$ of 200 mV more negative than the best-estimate value derived from the data in Table 44 to account for the stochastic nature of these potentials [123].

In selecting the crevice re-passivation potential as the criterion for localized corrosion, there is an implicit assumption that a crevice, or some other form of occluded region, will be present on the surfaces of both the waste capsule and disposal container. This is a reasonable assumption as the presence of the porous cement grout backfill could create local differences in the environment at the container surface.

There are relatively few values for $E_{RCREV}$ under alkaline conditions in Table 44. Therefore, values for $E_{RCREV}$ were derived from both pitting and crevice breakdown potentials ($E_P$ and $E_{CREV}$, respectively) and the derived values compared with the few measured values of $E_{RCREV}$ in order to derive a best-estimate value for the GSA corrosion analysis, as follows:

- The film breakdown potentials for pitting in alkaline solution (pH 12) are +585 $mv_{sce}$ and +400 $mv_{sce}$ for Types 316 and 304 stainless steel, respectively [118];
- The crevice film breakdown potential ($E_{CREV}$) is between 60 to 70 mv [99] and 0 to 600 mv [126] more negative than the pit breakdown potential ($E_P$), with a best-estimate value of 200 mv;
- The re-passivation potential for pitting is 150 to 200 mv [121] to 170 to 500 mv [123] more negative than $E_P$, leading to a best-estimate difference of 200 mv between $E_{CREV}$ and $E_{RCREV}$ for crevice corrosion; and
- The derived value for the re-passivation potentials for crevice corrosion at pH 12 are, therefore, +185 $mv_{sce}$ and 0 $mv_{sce}$ for Types 316 and 304 stainless steel, respectively.

The derived value for $E_{RCREV}$ for Type 316 at pH 12 is consistent with the values of –50 to -150 $mV_{SCE}$ at near-neutral pH calculated from the expression given by [122] after correction by 300 mV for the effect of pH as suggested by reference [118].

For comparison, the value of $E_{CORR}$ of Type 316L stainless steel in aerated simulated cement grout porewater (pH 12.5 to 13.5) is $-110 \pm 20$ $mV_{SCE}$ [93]. Thus, the difference between the corrosion potential and crevice re-passivation potential for Type 316L stainless steel at pH 12 is of the order of 300 mV, and well in excess of the estimated 200 mV to account for variability about the mean value of $E_{RCREV}$. A slightly smaller difference can be expected for the less-resistant Type 304, but in both cases it is expected that localized corrosion will not initiate on the container during the alkaline phase in Stages 1 and 2.

The conclusion that neither the waste capsule nor the disposal container are susceptible to localized corrosion in the alkaline cementitious porewater environment is consistent with experimental work of Ref. [88] who found no pitting of Types 304L and 316L stainless steel in simulated cement grout porewaters.

Although localized corrosion is not predicted during Stages 1 and 2, the waste capsule and disposal container can become susceptible to localized attack during Stage 3 as the pH decreases or in the groundwater-dominated porewater during Stage 4.

Table 51 shows the derivation of the crevice re-passivation potential for the two materials in fresh and saline pore or ground waters for Stages 3 and 4. This derivation follows the same process used above for deriving $E_{RCREV}$ for alkaline solutions. First, a best-estimate for the $E_P$ value for each material was derived from the data in Table 43, for both fresh (defined as $[Cl^-] < 100$ mg kg$^{-1}$) and saline (defined as $[Cl^-] > 10\,000$ mg kg$^{-1}$) waters. As apparent from the data in Table 43, there is a lot of variability in the reported data, for reasons discussed above. However, best-estimate values for $E_P$ were derived from the available data based on expert judgement, and are given in the first row of Table 51. Second, following the arguments above, corresponding $E_{CREV}$ values were estimated by subtracting 200 mV from the best-estimate $E_P$ values. Next, a further 200 mV is subtracted to arrive at an estimated crevice re-passivation potential $E_{RCREV}$. Finally, yet another 200 mV is subtracted to give an estimated minimum $E_{RCREV}$ value that accounts for the stochastic nature of film breakdown and re-passivation processes. The validity of this approach can be assessed by comparing the derived best-estimate and minimum values of $E_{RCREV}$ to those predicted from the polynomial expression developed from experimental measurements by Ref. [122]. The experimentally based polynomial (strictly only valid for 6 to 24 mg m$^{-3}$ $Cl^-$ and 0.8 to 3.4 mg m$^{-3}$ $SO_4^{2-}$) predicts $E_{RCREV}$ values for Type 316L in the range of -150 mV in fresh water and -200 mV in saline solutions, which are in reasonable agreement with the derived minimum values in Table 51.

Localized corrosion will initiate if the corrosion potential $E_{CORR}$ exceeds the crevice re-passivation potential. Table 51 also contains best-estimate values for $E_{CORR}$ in aerated and deaerated solutions (equivalent to aerobic and anaerobic conditions) for both fresh and saline waters. These values were derived from the data in Table 45. The value of $E_{CORR}$ is relatively insensitive to the $[Cl^-]$ and the grade of material but is a strong function of the redox conditions, being some 400 to 500 mV more positive in aerated solution than in the absence of oxygen.

Comparison of the best-estimate $E_{CORR}$ to the estimated minimum $E_{RCREV}$ values suggests that localized corrosion will occur in aerated (aerobic) solution, but not under deaerated (anaerobic) conditions. This comparison would suggest, therefore, that crevice corrosion would initiate in the aerobic groundwaters considered here (namely, groundwaters 1, 10, 11, and 12, Table 47), but not in the anaerobic waters (groundwaters 5 and 6, Table 47). However, the data in Ref. [123] suggest that, despite the relatively positive redox potential (220 $mV_{SHE}$), the $Cl^-$ concentration in groundwater 10 (10.9 mg kg$^{-1}$) is too low to initiate localized corrosion. Therefore, in the GSA, localized corrosion is assumed to be only possible in groundwaters 1, 11, and 12.

The analysis above indicates that localized corrosion is not possible during Stages 1 and 2 because of the high porewater pH but that crevice corrosion will occur in three of the six groundwaters considered during Stage 4. For the three potentially aggressive groundwaters, the question is at what stage during the evolution of the porewater pH in Stage 3 localized corrosion will initiate? Since the corrosion analysis is based on the time-dependence of the porewater pH, it would be useful to define a threshold pH at and below which localized corrosion initiates. Based on the evidence from Ref. [118], it appears that such a threshold can be defined by the sharp increase in film breakdown potential with increasing pH. This sharp increase occurs at a pH of 9 to 10 for Type 316 and pH 11 to 12 for Type 304. Therefore, for the purposes of the GSA corrosion analysis, the threshold or critical pH ($pH_{CRIT}$) for the initiation of localized corrosion is defined as pH 10 for Type 316 stainless steel and pH 11 for Type 304. Thus, localized corrosion is assumed to initiate at some time during Stage 3 as the porewater pH in the containment barrier and disposal zone cement grout reaches these values.

Once initiated, localized corrosion is assumed to propagate to failure. Stifling of propagating crevices, as often observed experimentally [113], is assumed not to occur. Based on the highest propagation rate reported by [98] of 0.86 mm/y, the time to first penetration is taken to be 1 year following initiation. Thereafter, propagation will continue and the fraction of the surface area of the container that is corroded will increase with time, albeit at a diminishing rate as the cathode:anode surface area ratio decreases with time as more of the container is corroded. Based on expert judgment only, 100% perforation of the container is assumed to occur 100 y after initiation, with 10% and 50% perforation after 10 years and 30 years, respectively.

#### *IX.4.3.4. Corrosion processes not included in the model*

A number of corrosion processes are not explicitly included in the corrosion model (Table 48). Although non-stress-relieved locations around the closure weld could be susceptible to SCC, cracking is not explicitly included in the analysis because it is considered that localized corrosion will initiate (and result in failure) under milder environmental conditions than those required to initiate SCC.

Microbiologically influenced corrosion is not included in the model either, primarily because microbes will not be active for much of the lifetime of the containers due to the high porewater pH. Although microbes can always be found surviving in extreme conditions of elevated or sub-zero temperature, acidic or alkaline pH, high salinity, desiccation, irradiation, etc., each of these factors limits the biodiversity of the microbial population and in doing so limits the ability of microbes to establish aggressive environments to support MIC. In the present case, the elevated porewater pH during Stages 1, 2, and the early part of Stage 3 will severely limit microbial activity at the container surfaces. Therefore, since many of the predicted container lifetimes are within these early stages, MIC is not specifically included in the GSA corrosion model.

### IX.4.4. Mathematical implementation of model and quality assurance

The GSA corrosion model is primarily a conceptual model of the corrosion processes that are, and are not, important in determining the lifetimes of the waste capsule and disposal container. Mathematical implementation of the model is relatively simple. Based on the estimated periods for each stage in the evolution of the porewater pH and the general corrosion rates and localized corrosion behaviour during each stage, the extent and nature of the corrosion damage was manually calculated for each set of conditions considered and tabulated in a Microsoft Excel spreadsheet.

The quality assurance for the model was based on manual checks of selected predicted lifetimes to ensure consistency between various estimates.

## IX.5. FAILURE TIMES AND CORROSION MAPS FOR THE GSA

Using the model described in Section IX.4 and the groundwater flow characteristics described in Section 3.2, the failure times given in Table 52 have been calculated for the Design Scenario for the reference systems of interest. Calculated disposal container lifetimes range from $1.8 \times 10^4$ y for aerobic waters in the unsaturated zone to $4.8 \times 10^5$ y for anaerobic fresh waters in the saturated zone. The calculated lifetimes of the waste capsules (as measured from the time of emplacement) range from $2.4 \times 10^4$ y for aerobic waters in the unsaturated zone to $7.2 \times 10^5$ y for anaerobic fresh waters in the saturated zone. In the saturated cases considered, failure of both the disposal containers and waste capsules is by general corrosion. Failure is by localised corrosion for the unsaturated case. For all cases, failure occurs during Stages 3b or 4, depending upon the respective corrosion rates for the different geochemical conditions.

Calculated disposal container and waste capsule lifetimes for the four Defect Scenarios are given in Table 77 (Appendix XII). For Defect Scenario D1 (initial defect in a single disposal container), initial perforation of the disposal container leads to immediate degradation of the containment barrier cement grout and corrosion of the waste capsule. Therefore, for the defected disposal container, the lifetimes of the corresponding waste capsule (again, measured form the time of emplacement) ranges from $1.5 \times 10^4$ y to $2.4 \times 10^5$ y, depending upon geochemical conditions. All other 49 waste packages in the borehole behave as for the Design Scenario.

If the initial defect is in the waste capsule rather than the disposal container (Defect Scenario D2, Table 77), release from the failed waste capsule into the borehole occurs once the outer disposal container has failed (elapsed time of $1.8 \times 10^4$ y to $4.8 \times 10^5$ y), although complete corrosion of the defected waste capsule only occurs after an elapsed time of $2.4 \times 10^4$ y to $7.2 \times 10^5$ y.

Degraded disposal zone cement grout (Defect Scenario D3) has relatively little effect on the calculated lifetimes (Table 77), as there is still sufficient pH-buffering capacity in the degraded cement grout to ensure long containment periods. The most significant impact is for the unsaturated case, where the lifetimes are reduced by a factor of two.

Finally, defects in both the disposal container and waste capsule in a single waste package clearly allows for immediate release from that particularly package, although all other 49 packages in the borehole behave as in the Design Scenario. Corrosion of the defected waste capsule starts immediately, as groundwater is assumed to enter the containment barrier soon after emplacement, resulting in complete corrosion of the defected waste capsule after a period of $1.5 \times 10^4$ y to $2.4 \times 10^5$ y, depending upon geochemical conditions.

Using the corrosion results, corrosion maps can be developed to help guide the selection of suitable sites for the borehole disposal concept. The original aim of these maps was to identify site conditions that would be acceptable or unacceptable for the disposal of disused sealed radioactive sources in boreholes. It is not, however, easy to answer that question based on the corrosion analysis alone. First, the safety of a particular site is not solely a function of the containment period. Other site characteristics, such as the local hydrogeology and the nature of the biosphere, also a play a role in determining the dose consequences for a particular location.

Second, as demonstrated above, the corrosion behaviour of the disposal container and waste capsule are determined primarily by the conditioning of the near field environment by the containment barrier and disposal zone cement grout. To a first approximation, if the engineered barrier system behaves as designed, then the lifetimes of the stainless steel vessels are relatively independent of the nature of the surrounding groundwater, and waste capsule lifetimes in excess of $10^4$ y are likely.

Third, the conditions at a particular site are not static, but change with time as the disposal zone and containment barrier cement grout leaches. Thus, what may start out as a high-pH near field environment eventually becomes less alkaline as the pore chemistry is flushed by the groundwater.

The corrosion maps provided here summarise the calculated lifetimes for the waste capsule (measured from the time of emplacement) as a function of $E_H$, $Cl^-$ concentration, and <u>near field</u> pH. The latter is defined as the pH of the porewater to which the disposal container and waste capsule are exposed. For the Design Scenario, the near field pH will evolve over time in a manner similar to the model used here and, will for an extended period of time, protect the containers from excessive rates of corrosion by maintaining an alkaline near field environment.

Fig. 25 illustrates the effect of the near field pH and chloride concentration on the predicted lifetime of the waste capsule (as measured form the time of emplacement in the borehole). Under Design Scenario conditions, the near field pH will remain above pH 12 for an extended time and long waste capsule lifetimes are predicted under both aerobic (Fig. 25(a)) and anaerobic conditions (Fig. 25(b)). Under Defect Scenario conditions involving inadequate pH-buffering of the near field, the predicted lifetimes become shorter due either to accelerated general corrosion under anaerobic conditions, or possible localized corrosion under aerobic conditions, although the conditions that support localized corrosion were not found to exist for the references cases considered in the GSA.

These data can also be represented in terms of the effect of redox potential and chloride concentration (Fig. 26). Fig. 26(a) represents the expected behaviour under alkaline conditions and, in this sense, represents the expected behaviour for much of the duration of the Design Scenario. Long waste capsule lifetimes are predicted under all redox conditions because the high near field pH protects the disposal container and waste capsule from localized corrosion and limits the rate of general corrosion. At lower pH, however, potentially shorter waste capsule lifetimes are predicted, especially under aerobic conditions (Fig. 26(b)). These shorter lifetimes are the result of localized corrosion failure of the containers.

## IX.6. SUMMARY AND CONCLUSIONS

An analysis of the expected corrosion behaviour of the stainless steel disposal container and waste capsule for the borehole disposal concept for disused sealed radioactive sources has been carried out. The concept involves enclosing the disused sealed radioactive sources in a welded Type 304 stainless steel waste capsule, which is then placed in a welded Type 316L stainless steel disposal container. The gap between the waste capsule and disposal container and the region outside the disposal container are filled with cement grout to condition the near field pH and to provide a mass-transport barrier to the release of radionuclides.

The corrosion analysis developed for the GSA calculates the estimated lifetimes of the disposal container and waste capsule for a range of environmental conditions, including:

- Three different groundwaters of different salinity and redox potential; and
- Four different combinations of groundwater flow and degree of saturation.

The behaviour under the expected (Design Scenario) and upset (Defect Scenario) conditions has been considered.

The corrosion behaviour of the stainless steel containers is dominated by the alkaline near field pH and the redox conditions. If the near field pH remains in the alkaline range (pH >12), the vessels will undergo general corrosion at a rate that is estimated to range from 0.01 to 0.2 μm/y depending upon the salinity and redox potential of the surrounding environment. Estimated waste capsule lifetimes are in excess of $10^4$ y and as high as $7 \times 10^5$ y for fresh, anaerobic groundwaters.

At longer times after the cement grout porewater has been leached, or under defect conditions when the duration of pH control by the cement minerals is limited, localized corrosion is possible in aerobic environments. For the Design Scenario, localized corrosion is only possible for sites with high hydraulic conductivity (which result in the fastest cement grout leaching), although these conditions were not found to exist for the references cases considered in the GSA.

Defect Scenario variants have been considered, including:

- An initial defect in one disposal container closure weld;
- An initial defect in one waste capsule closure weld;
- Incomplete, or degraded disposal zone cement grout; and
- Initial defects in one waste capsule and the associated disposal container.

Of these different defects, a defect in the disposal container weld leads to shorter predicted waste capsule lifetimes than a defect in the waste capsule closure weld because the containment barrier cement grout is assumed to start to degrade immediately rather than only after failure of the disposal container. Any defect that compromises the ability of the cement grout to condition the near field pH can result in substantially shorter lifetimes in aerobic environments because of the possibility of rapid localized corrosion failure, although again these conditions were not found to exist for the references cases considered in the GSA.

Corrosion maps have been constructed summarizing the predicted lifetimes in terms of the effects of redox potential, groundwater chloride concentration, and near field pH. Provided the cement grout barriers are able to condition the near field pH for the predicted timescales, long waste capsule lifetimes (defined here as $>10^4$ y) are possible in a wide range of groundwater conditions. Anaerobic groundwaters provide greater assurance against early waste capsule failure in the event that a defect or other factor leads to faster degradation of the near field alkaline pH.

TABLE 40. LITERATURE GENERAL CORROSION RATES FOR STAINLESS STEEL IN HIGHLY ALKALINE SOLUTION

| Grade | pH | Temperature ($^{o}$C) | [Cl$^{-}$] (μg·g$^{-1}$) | Redox conditions | Other | Rate (μm·yr$^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|
| 304 | 12.8 | 30, 45 | | | 200 days | 0.000 3 | [96] |
| | 10.5 | | | | 60 days | 0.01 | |
| 304 | 13.3 | Ambient | 18 400 | Aerated | 28 days | 0.3 | [108] |
| 304 | 13 | 30 | | Deaerated | | 0.06 | [89] |
| | | 50 | | | | 0.18 | |
| | | 80 | | | | 0.82 | |
| 304 | 10 | 50 | | Deaerated | 230 days | 0.009 | [125] |
| | 12.5 | | | | | 0.005 5 | |
| | 13.5 | | | | | 0.006 3 | |
| 304 | 12.8 | 30 | | Deaerated | Calculated | | [96] |
| | | | | | 1 year | 0.055 | |
| | | | | | 10 years | 0.010 | |
| | | | | | 100 years | 0.002 | |
| | | | | | 1000 years | 0.000 3 | |
| | | | | | $10^4$ years | 0.000 06 | |
| 316 | 13.3 | Ambient | 18 400 | Aerated | 28 days | 0.6 | [108] |
| 316L | >13 | Ambient | 10 000 | Deaerated | 0.1 MPa $H_2$ | 0.03 | [120] |
| Stainless steel | 13 | Ambient | | Deaerated | 0.1 mol·dm$^{-3}$ KOH agar gel, 50 days | 0.4-1.6 | [119] |
| Stainless steel | 13.4 | Ambient | | Aerated | | 1-6 | [117] |
| Stainless steel | 12.9 | 25-80 | 10 000 | Deaerated | | <0.1 | [111] |

TABLE 41. LITERATURE GENERAL CORROSION RATES FOR STAINLESS STEEL IN NEUTRAL TO SLIGHTLY ALKALINE SOLUTION

| Grade | pH | Temperature ($^oC$) | [$Cl^-$] ($\mu g \cdot g^{-1}$) | Redox conditions | Other | Rate ($\mu m \cdot yr^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|
| 304 | Ambient | 90 | 7000-43 000 | Aerated | 10 hrs | 10-130 | [110] |
| 304L | Ambient | 25-100 | ‘Freshwater’ | Aerated | | 0.21 | [90] |
| 304L | Ambient | 27 | ‘Saltwater’ | Aerated | | 11.4 | [90] |
| | | 90 | | | | 5.82 | |
| 304 | Ambient | 25 | Interstitial clay water | Aerated | | 0.2-0.96 | [91] |
| | | 50 | | | | 0.22-0.23 | |
| | | 75 | | | | 0.3-0.35 | |
| 316 | Ambient | Ambient | 19 000 | Aerated | 8 years, Pacific Ocean seawater | 4 | [84] |
| 316L | Ambient | 30 | ‘Freshwater’ | Aerated | | 0.01 | [90] |
| | | 50-100 | | | | 0.25 | |
| 316L | Ambient | 27 | ‘Saltwater’ | Aerated | | 1.94 | [90] |
| 316 | Ambient | 25 | Interstitial clay water | Aerated | | 0.1-0.24 | [91] |
| | | 50 | | | | 0.1-0.34 | |
| | | 75 | | | | 0.1-0.17 | |
| Stainless steel | Ambient | 25-40 | Seawater<br>19 000 | Deaerated | 120 days | 0.8 | [126] |
| Stainless steel | Ambient | 25-40 | | 7.7 $\mu g \cdot g^{-1}$ $O_2$ | | 0.55 | [126] |
| | | | | 2.17 $\mu g \cdot g^{-1}$ $O_2$ | | 4.8 | |
| Stainless steel | 9.8 | 25 | 2000 | Deaerated | | 0.025-0.23 | [126] |
| | 9.4 | 80 | | | | 0.01-0.034 | |

TABLE 42. LITERATURE GENERAL CORROSION RATES FOR STAINLESS STEEL UNDER ATMOSPHERE CONDITIONS

| Grade | Temperature ($^oC$) | Redox conditions | Other | Rate ($\mu m \cdot yr^{-1}$) | Reference |
|---|---|---|---|---|---|
| 304 | Ambient | Aerated | Urban, 5-15 years | <0.03 | [101] |
| | | | Urban, 5-15 years | 0.022 | |
| | | | Marine, 5-15 years | 0.05-2 | |
| | | | Industrial/urban, 5-15 years | 0.01 | |
| 304 | Ambient | | Industrial/urban | 0.03-3 | [103] |
| 316 | Ambient | Aerated | Urban, 5-15 years | <0.03 | [101] |
| Stainless steel | Ambient | Aerated | Various atmospheres | 0.05 | [94] |

TABLE 43(a). LITERATURE DATA ON PITTING OF TYPE 304 STAINLESS STEELS

| Grade | Temperature ($^oC$) | [Cl$^-$] (mg·kg$^{-1}$) | Other | $E_P$ or $E_{RP}$ (mV$_{SCE}$) | Reference |
|---|---|---|---|---|---|
| 304 | 80 | 19 000 | Synthetic seawater | +50 ($E_P$) | [99] |
| 304 | 20 | 34 500 | With additions of $Na_2S_2O_3$ | ($E_P$) | [123](Fig. 7.15) |
| | | | 0 mol·dm$^{-3}$ | +30* | |
| | | | $4 \times 10^{-4}$mol·dm$^{-3}$ | -20 | |
| | | | $1 \times 10^{-3}$ mol·dm$^{-3}$ | +40 | |
| | | | $2 \times 10^{-3}$ mol·dm$^{-3}$ | -130 | |
| | | | $4 \times 10^{-3}$ mol·dm$^{-3}$ | -205 | |
| | | | 0.01 mol·dm$^{-3}$ | -195 | |
| | | | 0.1 mol·dm$^{-3}$ | -135 | |
| | | | 0.4 mol·dm$^{-3}$ | -95 | |
| | | | 1.0 mol·dm$^{-3}$ | -65 | |
| 304 | 80 | 34 500 | With additions of $Na_2S_2O_3$ | ($E_P$) | [123](Fig. 7.15) |
| | | | 0 mol·dm$^{-3}$ | -65* | |
| | | | $1 \times 10^{-4}$ mol·dm$^{-3}$ | -65 | |
| | | | $4 \times 10^{-4}$mol·dm$^{-3}$ | -255 | |
| | | | $1 \times 10^{-3}$ mol·dm$^{-3}$ | -265 | |
| | | | 0.01 mol·dm$^{-3}$ | -260 | |
| | | | 0.1 mol·dm$^{-3}$ | -190 | |
| 304 | 25 | 17 000 | With addition of 0.1 mol·dm$^{-3}$ $NaHCO_3$, pH 8 | +415 ($E_P$) | [123](Fig. 12.2) |
| | 40 | | | +320 | |
| | 60 | | | +155 | |
| | 90 | | | +65 | |
| 304 | 100 | 345 | Sensitized 304 | -55 ($E_P$) | [123](Fig. 12.5) |
| | 150 | | | -240 | |
| 304 | | Range 100-20 000 | | ($E_P$) | [123](Fig. 12.6) |
| | 20 | | | 750 – 152 log [Cl$^-$] | |
| | 40 | | | 628 – 140 log [Cl$^-$] | |
| | 60 | | | 554 – 144 log [Cl$^-$] | |
| | 80 | | | 500 – 145 log [Cl$^-$] | |
| 304 | Ambient | 34 500 | | +232 ($E_P$) | [123](Fig. 18.4) |
| 304 | | 3450 | With addition of 0.1 mol·dm$^{-3}$ $NaHCO_3$ | -70 ($E_P$) | [118](Table 4.3) |
| 304 | 30 | 660 | +50 µg·g$^{-1}$ $SO_4^{2-}$, 2 µg·g$^{-1}$ $Cu^{2+}$ | ($E_P$) | [118] (Table 4.10) |
| | | | Base metal | +390 | |
| | | | Weld HAZ | +190 | |
| | | | 60% cold work | +210 | |
| 304L | 30 | 142 000 | pH 9.3 | -51 ($E_P$) | [121] |
| | | | | -216 ($E_{RP}$) | |

TABLE 43(a). LITERATURE DATA ON PITTING OF TYPE 304 STAINLESS STEELS (cont.)

| Grade | Temperature (oC) | [Cl-] (mg·kg-1) | Other | EP or ERP (mVSCE) | Reference |
|---|---|---|---|---|---|
| 304 | | 18 400 | pH 3 | -5 ($E_P$) | [118] (Fig. 4.38) |
| | | | pH 4 | +10 | |
| | | | pH 5 | +15 | |
| | | | pH 6 | +25 | |
| | | | pH 7 | +40 | |
| | | | pH 8 | +50 | |
| | | | pH 9 | +60 | |
| | | | pH 10 | +70 | |
| | | | pH 11 | +80 | |
| | | | pH 12 | +400 | |
| 304 | 30 | 18 400 | | +60 ($E_P$) | [118] (Fig. 4.42) |
| 314 | 25 | 17 000 | pH 5 | +200 ($E_P$) | [118] (Table 4.15) |
| 304 | 25 | 34 500 | $H_2$ atmosphere 0.076 $\mu g \cdot g^{-1}$ $O_2$ | -50 ($E_P$) | [118] (Table 4.16) |
| | | | $N_2$ atmosphere 0.460 $\mu g \cdot g^{-1}$ $O_2$ | -20 | |
| | | | Ar atmosphere 0.057 $\mu g \cdot g^{-1}$ $O_2$ | +50 | |
| | | | $O_2$ atmosphere 30.1 $\mu g \cdot g^{-1}$ $O_2$ | +65 | |
| 304 | 20 | 345 | Mean values, $dE_P/d\log[Cl^-] = 127$ mV | +565 ($E_P$) | [105] |
| | | 3450 | 1000 grit | +460 | |
| | | 34 500 | | +315 | |
| 304 | 20 | 345 | Mean values, $dE_P/d\log[Cl^-] = 137$ mV | +495 ($E_P$) | [105] |
| | | 3450 | 220 grit | +385 | |
| | | 34 500 | | +220 | |
| 304 | 0 | 3450 | | +360 ($E_P$) | [114] |
| | 30 | | | +190 | |
| | 60 | | | +60 | |
| | 90 | | | -20 | |
| 304 | 25 | 34 500 | $H_2$ atmosphere 0.076 $\mu g \cdot g^{-1}$ $O_2$ | -50 ($E_P$) | [118](Table 4.16) |
| | | | $N_2$ atmosphere 0.460 $\mu g \cdot g^{-1}$ $O_2$ | -20 | |
| | | | Ar atmosphere 0.057 $\mu g \cdot g^{-1}$ $O_2$ | +50 | |
| | | | $O_2$ atmosphere 30.1 $\mu g \cdot g^{-1}$ $O_2$ | +65 | |
| 304 | 20 | 345 | Mean values, $dE_P/d\log[Cl^-] = 127$ mV | +565 ($E_P$) | [105] |
| | | 3450 | 1000 grit | +460 | |
| | | 34 500 | | +315 | |
| 304 | 20 | 345 | Mean values, $dE_P/d\log[Cl^-] = 137$ mV | +495 ($E_P$) | [105] |
| | | 3450 | 220 grit | +385 | |
| | | 34 500 | | +220 | |
| 304 | 0 | 3450 | | +360 ($E_P$) | [114] |
| | 30 | | | +190 | |
| | 60 | | | +60 | |
| | 90 | | | -20 | |

TABLE 43(b). LITERATURE DATA ON PITTING OF TYPE 316 STAINLESS STEELS

| Grade | Temperature (°C) | $[Cl^-]$ ($\mu g \cdot g^{-1}$) | Other | $E_P$ or $E_{RP}$ ($mV_{SCE}$) | Reference |
|---|---|---|---|---|---|
| 316L | 80 | 19 000 | Synthetic seawater | +150 ($E_P$) | [99] |
| 316L | 20 | 34 500 | With additions of $Na_2S_2O_3$ | ($E_P$) | [123](Fig. 7.15) |
| | | | 0 $mol \cdot dm^{-3}$ | +180* | |
| | | | $1 \times 10^{-4} mol \cdot dm^{-3}$ | +110 | |
| | | | $2 \times 10^{-3}$ $mol \cdot dm^{-3}$ | +125 | |
| | | | $4 \times 10^{-3}$ $mol \cdot dm^{-3}$ | +125 | |
| | | | 0.01 $mol \cdot dm^{-3}$ | +140 | |
| | | | 0.04 $mol \cdot dm^{-3}$ | -50 | |
| | | | 0.1 $mol \cdot dm^{-3}$ | -25 | |
| | | | 0.4 $mol \cdot dm^{-3}$ | +5 | |
| | | | 1.0 $mol \cdot dm^{-3}$ | +50 | |
| 316L | 80 | 34 500 | With additions of $Na_2S_2O_3$ | ($E_P$) | [123](Fig. 7.15) |
| | | | 0 $mol \cdot dm^{-3}$ | +55* | |
| | | | $1 \times 10^{-4} mol \cdot dm^{-3}$ | +55 | |
| | | | $2 \times 10^{-3}$ $mol \cdot dm^{-3}$ | +85 | |
| | | | $4 \times 10^{-3}$ $mol \cdot dm^{-3}$ | 0 | |
| | | | 0.01 $mol \cdot dm^{-3}$ | -135 | |
| | | | 0.04 $mol \cdot dm^{-3}$ | -115 | |
| | | | 0.1 $mol \cdot dm^{-3}$ | -100 | |
| 316L | | 19 000 | Seawater | ($E_P$/$E_{RP}$) | [123](Table 13.2) |
| | 18 | | $E_{CORR}$ = -155 $mV_{SCE}$ (8 mm crevice corrosion) | +505/+2 | |
| | 30 | | $E_{CORR}$ = -346 $mV_{SCE}$ (25-30 mm CC) | +274/-166 | |
| | 40 | | $E_{CORR}$ = -393 $mV_{SCE}$ (25-30 mm CC) | +156/-274 | |
| | 50 | | $E_{CORR}$ = -365 $mV_{SCE}$ (10 mm CC, 0.025 mm pit) | +155/-215 | |
| | 60 | | $E_{CORR}$ = -362 $mV_{SCE}$ (40 mm CC, 0.021 mm pit) | +28/-142 | |
| 316 | | 17 000 | With addition of 0.1 $mol \cdot dm^{-3}$ $NaHCO_3$ | +140 ($E_P$) | [118](Table 4.3) |
| 316 | | 31 000 | Oxygenated solution, 0.4-2 wt.% Mn | +210-245 ($E_P$) | [118] (Table 4.27) |
| 316L | 40 | 21 500 | | +275 ($E_P$) | [118](Fig. 4.36) |
| | 50 | | | +220 | |
| | 60 | | | +135 | |
| | 70 | | | +70 | |
| 316L | 30 | 142 000 | pH 9.3 | -48 ($E_P$)<br>-237 ($E_{RP}$) | [121] |

TABLE 43(b). LITERATURE DATA ON PITTING OF TYPE 316 STAINLESS STEELS (cont.)

| Grade | Temperature (oC) | [Cl-] (µg·g-1) | Other | EP or ERP (mVSCE) | Reference |
|---|---|---|---|---|---|
| 316 | | 18 400 | pH 3 | +285 ($E_P$) | [118] (Fig. 4.38) |
| | | | pH 4 | +285 | |
| | | | pH 5 | +285 | |
| | | | pH 6 | +285 | |
| | | | pH 7 | +285 | |
| | | | pH 8 | +290 | |
| | | | pH 9 | +305 | |
| | | | pH 10 | +350 | |
| | | | pH 11 | +460 | |
| | | | pH 12 | +585 | |
| 316L | 80 | 35 | NaCl solutions only | +115 ($E_P$) | [118](Fig. 4.41) |
| | | 345 | | -5 | |
| | | 3450 | | -105 | |
| 316L | 80 | 35 | $Cl^-/S_2O_3^{2-}$ mixtures, $[Cl^-]:[S_2O_3^{2-}] = 17$ | +45 ($E_P$) | [118](Fig. 4.41) |
| | | 345 | | -180 | |
| | | 3450 | | -215 | |
| | | 34 500 | | -275 | |
| 316 | 30 | 18 400 | Effect of temperature | +230 ($E_P$) | [118] (Fig. 4.42) |
| 316 | 20 | 345 | 120 grit finish, aerated solution | +317 ($E_P$) | [104] |
| | | 3450 | | +205 | |
| | | 10 300 | | +170 | |
| | | 34 450 | | +98 | |
| 316 | 20 | 3 450 | Mean values, $dE_P/d\log[Cl^-] = 206$ mV | +630 ($E_P$) | [105] |
| | | 34 450 | 1000 grit | +415 | |
| 316 | 20 | 345 | Mean values, $dE_P/d\log[Cl^-] = 220$ mV | +750 ($E_P$) | [105] |
| | | 3450 | 220 grit | +500 | |
| | | 34 500 | | +335 | |

TABLE 44(a). LITERATURE DATA ON CREVICE CORROSION OF TYPE 304 STAINLESS STEELS

| Grade | Temperature (°C) | [Cl$^-$] (µg·g$^{-1}$) | Other | $E_{CREV}$ or $E_{RCREV}$ (mV$_{SCE}$) | Reference |
|---|---|---|---|---|---|
| 304 | | 17 000 | | +131 ($E_{CREV}$) | [123](Fig. 18.4) |
| | | 34 500 | | +10 | |
| 304L | 10 | 19 000 | Seawater, pH 8.2 | -120 ($E_{RCREV}$) | [124] |
| | 20 | | | -140 | |
| | 30 | | | -150 | |
| | 40 | | | -155 | |
| | 50 | | | -175 | |
| | 60 | | | -175 | |
| | 70 | | | -200 | |
| | 80 | | | -210 | |
| 304 | 80 | 19 000 | Synthetic seawater | -10 ($E_{CREV}$) | [99] |

TABLE 44(b). LITERATURE DATA ON CREVICE CORROSION OF TYPE 316 STAINLESS STEELS

| Grade | Temperature (°C) | [Cl$^-$] (μg·g$^{-1}$) | Other | $E_{CREV}$ or $E_{RCREV}$ (mV$_{SCE}$) | Reference |
|---|---|---|---|---|---|
| 316L | 10 | 19 000 | Seawater, pH 8.2 | -80 ($E_{RCREV}$) | [124] |
| | 20 | | | -95 | |
| | 30 | | | -110 | |
| | 40 | | | -120 | |
| | 50 | | | -140 | |
| | 60 | | | -155 | |
| | 70 | | | -155 | |
| | 80 | | | -165 | |
| 316L | 23-50 | 6000-24 000 | 0-800 μg·g$^{-1}$ $S_2O_3^{2-}$,<br>800-3,400 μg·g$^{-1}$ $SO_4^{2-}$ | $E_{RCREV} = -301.5 - 3.7([Cl^-]-15) - 15.3([SO_4^{2-}]-2.1)$<br>$-188.7([S_2O_3^{2-}]-0.4) - 2(T-36.5)$<br>$-0.047(([Cl^-]-15)([SO_4^{2-}]-2.1)$<br>$+ 3.83([Cl^-]-15)([S_2O_3^{2-}]-0.4)$<br>$-0.75([Cl^-]-15)(T-36.5) + 0.35([Cl^-]-15)^2$<br>T in °C, concentrations in g/L | [122] |
| 316L | 80 | 19 000 | Synthetic seawater | +80 ($E_{CREV}$) | [99] |

TABLE 45. LITERATURE DATA ON CORROSION POTENTIAL OF STAINLESS STEELS

| Grade | pH | Temperature (°C) | [$Cl^-$] ($\mu g \cdot g^{-1}$) | Redox conditions | Other | $E_{CORR}$ ($mV_{SCE}$) | Reference |
|---|---|---|---|---|---|---|---|
| 304L | 8.2 | 24 | 19 000 | Aerated | Seawater | -90 | [124] |
| | | 30 | | | | -90 | |
| | | 50 | | | | -120 | |
| | | 60 | | | | -140 | |
| | | 70 | | | | -155 | |
| | | 80 | | | | -210 | |
| 304L | 9.3 | 30 | 142 000 | Deaerated | | -488 | [121] |
| 304 | 5 | 25 | 17 300 | Deaerated | | -464 | [118](Table 4.15) |
| 304 | | | 34 500 | Aerated | | -63 | [123](Fig. 18.4) |
| 304 | 4.5 | | 3 450 | Aerated | | -14 | [122] |
| | | | | | | | |
| 316L | 7 | | | 0.32 $\mu g \cdot g^{-1}$ $O_2$ | 0.5 m $Na_2SO_4$ | -117 | [122] |
| | 10 | | | | | -119 | |
| | 12 | | | | | -145 | |
| 316L | 8.2 | 24 | 19 000 | Aerated | Seawater | -80 | [124] |
| | | 30 | | | | -85 | |
| | | 50 | | | | -105 | |
| | | 60 | | | | -120 | |
| | | 70 | | | | -140 | |
| | | 80 | | | | -165 | |
| 316L | | 95 | 6-1000 | Deaerated | 10-1,000 $\mu g \cdot g^{-1}$ $NO_3^-$, 2 $\mu g \cdot g^{-1}$ $F^-$,<br>20-1,000 $\mu g \cdot g^{-1}$ $SO_4^{2-}$ | -739 to -454 | [121] |
| 316L | 9.3 | 30 | 142 000 | Deaerated | | -685 | [121] |
| 316L | 10 | 22 | 177 000 | Aerated | | +70 | [93] |
| | 12.6 | | | | | -80 | |
| | 13.6 | | | | | -125 | |
| 316L | 12.6 | 22 | | Aerated | | -100 | [93] |
| 316L | | 95 | 1000 | Aerated | | -125 | [95] |
| | | | 200 000 | | | -330 | |
| 316L | | | 19 000 | 0.45 $\mu g \cdot g^{-1}$ $O_2$ | | -86 | [122] |
| | | | | 2.6 $\mu g \cdot g^{-1}$ $O_2$ | | -44 | |
| | | | | 7.6 $\mu g \cdot g^{-1}$ $O_2$ | | -18 | |
| | | | | 34.7 $\mu g \cdot g^{-1}$ $O_2$ | | +47 | |
| 316L | 9.3 | 30 | 142 000 | Deaerated | | -685 | [121] |
| 316L | 10 | 22 | 177 000 | Aerated | | +70 | [93] |
| | 12.6 | | | | | -80 | |
| | 13.6 | | | | | -125 | |

TABLE 45. LITERATURE DATA ON CORROSION POTENTIAL OF STAINLESS STEELS (cont.)

| Grade | pH | Temperature (oC) | [Cl-] (µg·g-1) | Redox conditions | Other | ECORR (mVSCE) | Reference |
|---|---|---|---|---|---|---|---|
| 316L | 12.6 | 22 | | Aerated | | -100 | [93] |
| 316L | | 95 | 1000 | Aerated | | -125 | [95] |
| | | | 200 000 | | | -330 | |
| 316L | | | 19 000 | 0.45 µg·g$^{-1}$ $O_2$ | | -86 | [122] |
| | | | | 2.6 µg·g$^{-1}$ $O_2$ | | -44 | |
| | | | | 7.6 µg·g$^{-1}$ $O_2$ | | -18 | |
| | | | | 34.7 µg·g$^{-1}$ $O_2$ | | +47 | |

TABLE 46. TARGET LIFETIMES FOR THE WASTE CAPSULE AND DISPOSAL CONTAINER IN THE GENERIC SAFETY ASSESSMENT OF THE BOREHOLE DISPOSAL CONCEPT BASED ON RADIONUCLIDE ACTIVITY

| Target lifetime (years) | Description | Radionuclide | |
|---|---|---|---|
| | | Inventory >$10^5$ MBq | Other |
| 10 | Safe handling requirement<br>Containment of radionuclides with $t_{1/2} \leq 100$ days | Ir-192, Yb-169 | Hg-203 |
| 300 | Containment of radionuclides with $t_{1/2} \leq 30$ years | As above, plus<br>H-3, Co-60, Se-75, Kr-85, Sr-90, Cs-137, Pm-147 | As above, plus<br>Na-22, Mn-54, Fe-55, Co-57, Zn-65, Y-88, Cd-107, Ba-133, Eu-152, Gd-153, Au-195, Tl-204, Pb-210, Po-210, Cf-252, |
| $2 \times 10^4$ | Containment of radionuclides with $t_{1/2} \leq 2000$ years | As above, plus<br>Ra-226, Am-241 | As above, plus<br>Ni-63, Sm-151, Pu-238 |
| $10^6$ | Containment of radionuclides with $t_{1/2} \leq 10^5$ years | As above, plus<br>Pu-239 | As above |

TABLE 47. GROUNDWATERS CONSIDERED IN THE GSA CORROSION ANALYSIS

| Groundwater ID | $[Cl^-]$ ($\mu g \cdot g^{-1}$) | $[SO_4^{2-}]$ ($\mu g \cdot g^{-1}$) | Total inorganic carbon ($\mu g \cdot g^{-1}$) | $E_H$ ($mV_{SHE}$) | pH |
|---|---|---|---|---|---|
| 1 | 0.53 | 2.88 | 0.23 | 996 | 4.10 |
| 5 | 0.52 | 10.66 | 42.5 | -281 | 8.46 |
| 6 | 20 917 | 2891 | 416 | -303 | 7.95 |
| 10 | 10.9 | 9.9 | 30.9 | 220 | 10.40 |
| 11 | 41 134 | 1591 | 12 047 | 600 | 10.30 |
| 12 | 104 800 | 39 700 | 3941 | 630 | 10.00 |

TABLE 48: OVERVIEW OF VARIOUS PROCESSES IN THE GSA CORROSION MODEL.

| Process | Stages 1 and 2<br>($pH \geq 12.5$) | Stages 3 and 4<br>($pH < 12.5$) |
|---|---|---|
| General corrosion | Factor of two-fold higher rate in saline waters compared with fresh waters<br>Factor of 10-fold higher rate in aerobic compared with anaerobic conditions | Rate increases with decreasing pH, increasing $E_H$, and increasing [$Cl^-$] |
| Pitting | No pitting during these stages as $E_P$ and $E_{RP}$ exceed $E_{CORR}$ | Possible under aerobic, but not anaerobic, conditions.<br>$E_P$ decreases with increasing [$Cl^-$] |
| Crevice corrosion | No crevice corrosion during these stages as $E_{CREV}$ and $E_{RCREV}$ exceed $E_{CORR}$ | Possible under aerobic, but not anaerobic, conditions.<br>Crevice corrosion assumed to initiate at more-negative potential than pitting<br>$E_{RCREV}$ relatively insensitive to [$Cl^-$]<br>Susceptibility to localized corrosion (as determined by the condition $E_{CORR} \geq E_{RCREV}$) converted to a critical pH. $pH_{CRIT} = 11$ for Type 304 and 10 for Type 316, reflecting the greater susceptibility of the lower-grade alloy |
| Stress corrosion cracking | Not specifically included in model as failure assumed to occur by localized corrosion first | Not specifically included in model as failure assumed to occur by localized corrosion first |
| Microbiologically influenced corrosion | No microbial activity because of elevated pH | Not explicitly included as failure by general or localized corrosion generally occurs at pH values greater than those at which microbial activity would be expected. |
| Preferential attack on welds | No difference in weld behaviour at elevated pH | Greater sensitivity of Type 304 due to possible sensitisation of weld, reflected in the lower $pH_{CRIT}$ for localized corrosion |
| Effect of redox conditions | Factor of 10-fold higher rate in aerobic compared with anaerobic conditions | Localized corrosion possible under aerobic, but not anaerobic, conditions |
| Material-specific issues | Same rate of general corrosion for both materials.<br>$E_P$ and $E_{CREV}$ for Type 316 ~100 to 200 mV more positive than for Type 304 | Same rate of general corrosion for both materials.<br>Type 304 more sensitive to localized corrosion, reflected in higher critical pH |

TABLE 49. SUMMARY OF THE GSA CORROSION MODEL

| | Aerobic conditions | Anaerobic conditions |
|---|---|---|
| Stage 1 (pH 13.5) | General corrosion only | General corrosion only |
| Stage 2 (pH 12.5) | General corrosion only | General corrosion only |
| Stage 3(a) ($pH_{CRIT} < pH < 12.5$) | General corrosion only | General corrosion only |
| Stage 3(b) ($pH_{GW} < pH \leq pH_{CRIT}$) | General and localized corrosion | General corrosion only |
| Stage 4 ($pH_{GW}$) | General and localized corrosion | General corrosion only |

TABLE 50. RATES OF GENERAL CORROSION USED IN THE GSA CORROSION MODEL*

| Groundwater ID | Groundwater characteristics | Stage 1 (pH 13.5) | Stage 2 (pH 12.5) | Stage 3(a) ($\mathrm{pH_{CRIT}} < \mathrm{pH} < 12.5$) | Stage 3(b) ($\mathrm{pH_{GW}} < \mathrm{pH} \leq \mathrm{pH_{CRIT}}$) | Stage 4 ($\mathrm{pH_{GW}}$) |
|---|---|---|---|---|---|---|
| 1 | Aerobic, fresh, pH 4.1 | 0.1 | 0.1 | 0.1 | 0.5 | 1 |
| 5 | Anaerobic, fresh, pH 8.5 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| 6 | Anaerobic, saline, pH 8 | 0.02 | 0.02 | 0.02 | 0.05 | 1 |
| 10 | Aerobic, fresh, pH 10.4 | 0.1 | 0.1 | 0.1 | 0.15 | 0.2 |
| 11 | Aerobic, saline, pH 10.3 | 0.2 | 0.2 | 0.2 | 1 | 2 |
| 12 | Aerobic, saline, pH 10.0 | 0.2 | 0.2 | 0.2 | 1 | 2 |

* Rates in $\mu\mathrm{m}\cdot\mathrm{yr}^{-1}$

TABLE 51. DERIVATION OF THRESHOLD POTENTIALS FOR LOCALIZED CORROSION IN SLIGHTLY ALKALINE TO NEAR-NEUTRAL PH ENVIRONMENTS*

| | Type 304 | | Type 316/316L | |
|---|---|---|---|---|
| | Fresh water | Saline water | Fresh water | Saline water |
| $E_P$ ($\mathrm{mV_{SCE}}$) | +400 | +150 | +500 | +300 |
| Est. $E_{CREV}$ ($\mathrm{mV_{SCE}}$) | +200 | -50 | +300 | +100 |
| Est. $E_{RCREV}$ ($\mathrm{mV_{SCE}}$) | 0 | -250 | +100 | -100 |
| Est. minimum $E_{RCREV}$ ($\mathrm{mV_{SCE}}$) | -200 | -450 | -100 | -300 |
| $E_{CORR}$ ($\mathrm{mV_{SCE}}$) Aerated | -100 | -150 | -100 | -150 |
| $E_{CORR}$ ($\mathrm{mV_{SCE}}$) Deaerated | -600 | -550 to -600 | -600 | -550 to -600 |

* See text for detailed description of the derivation.

TABLE 52. FAILURE TIMES FOR THE REFERENCE CASES

| Geosphere | Disposal container failure times (y)[a] | | | | | Waste capsule failure times (y)[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial perf | 10% perf | 50% perf | 100% perf | Failure mode[b] | Initial perf | 10% perf | 50% perf | 100% perf | Failure mode[b] |
| Unsaturated zone, groundwater #1 | 1.76E+04 | 1.76E+04 | 1.76E+04 | 1.76E+04 | LC, Stage 3b | 2.40E+04 | 2.40E+04 | 2.40E+04 | 2.40E+04 | LC, Stage 3b |
| High flow (porous and fractured), groundwater #5 | 4.80E+05 | 4.80E+05 | 4.80E+05 | 4.80E+05 | GC, Stage 4 | 7.20E+05 | 7.20E+05 | 7.20E+05 | 7.20E+05 | GC, Stage 4 |
| Medium flow, groundwater #5 | 4.80E+05 | 4.80E+05 | 4.80E+05 | 4.80E+05 | GC, Stage 4 | 7.20E+05 | 7.20E+05 | 7.20E+05 | 7.20E+05 | GC, Stage 4 |
| Low flow, groundwater #6 | 2.40E+05 | 2.40E+05 | 2.40E+05 | 2.40E+05 | GC, Stage 3b | 3.60E+05 | 3.60E+05 | 3.60E+05 | 3.60E+05 | GC, Stage 3b |

**Notes:** [a] Time from time of waste emplacement.

[b] GC= General Corrosion; LC= Localised Corrosion; Stage refers to the stage of the cement grout degradation model (see Appendix VIII) in which the container/capsule fails.

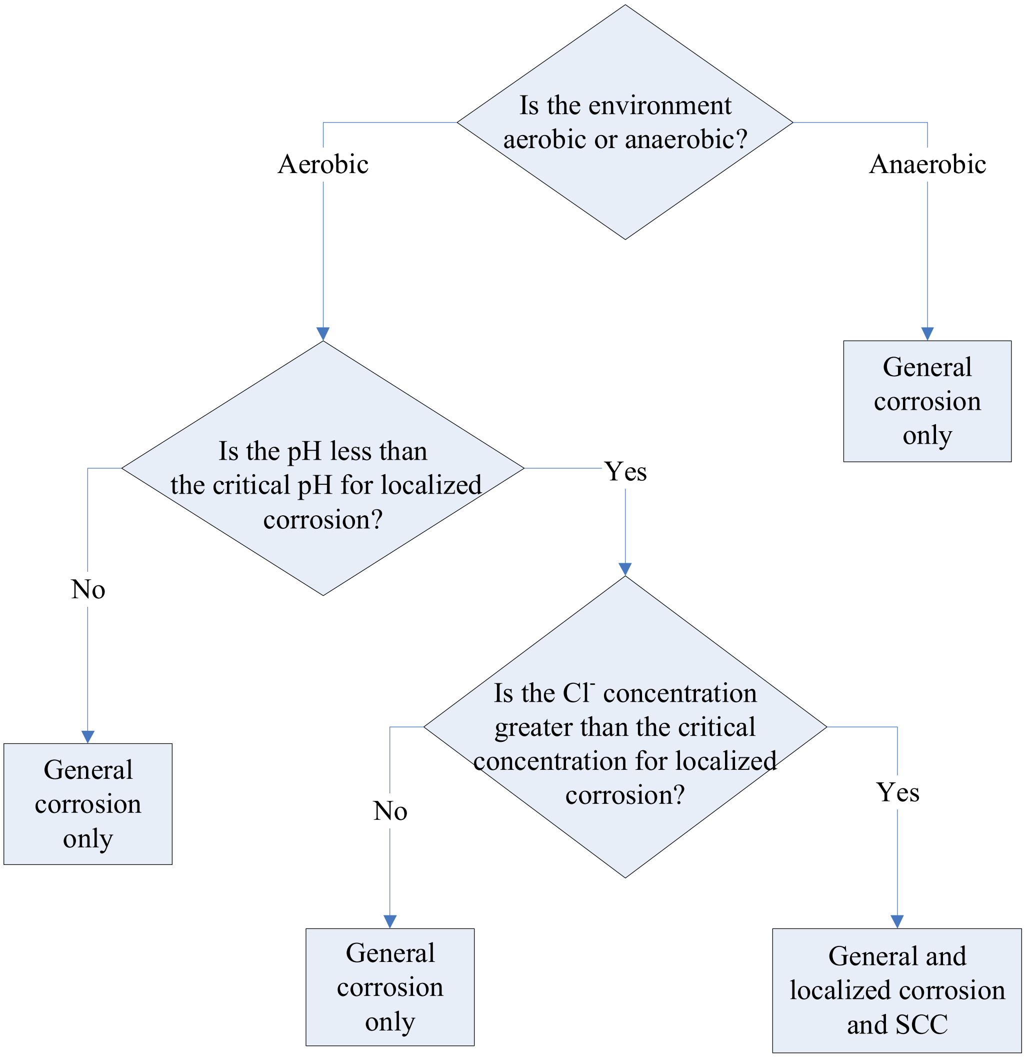
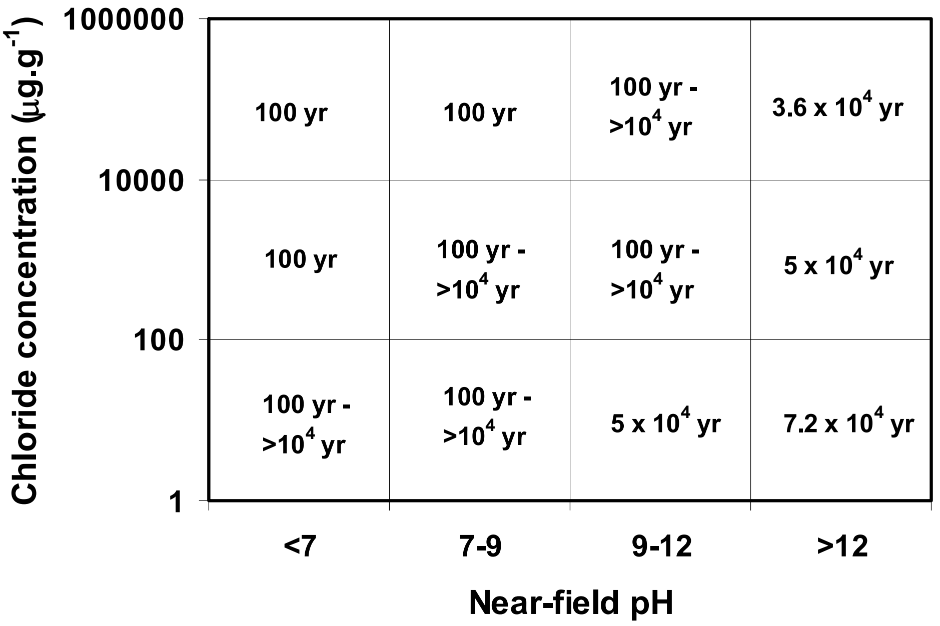
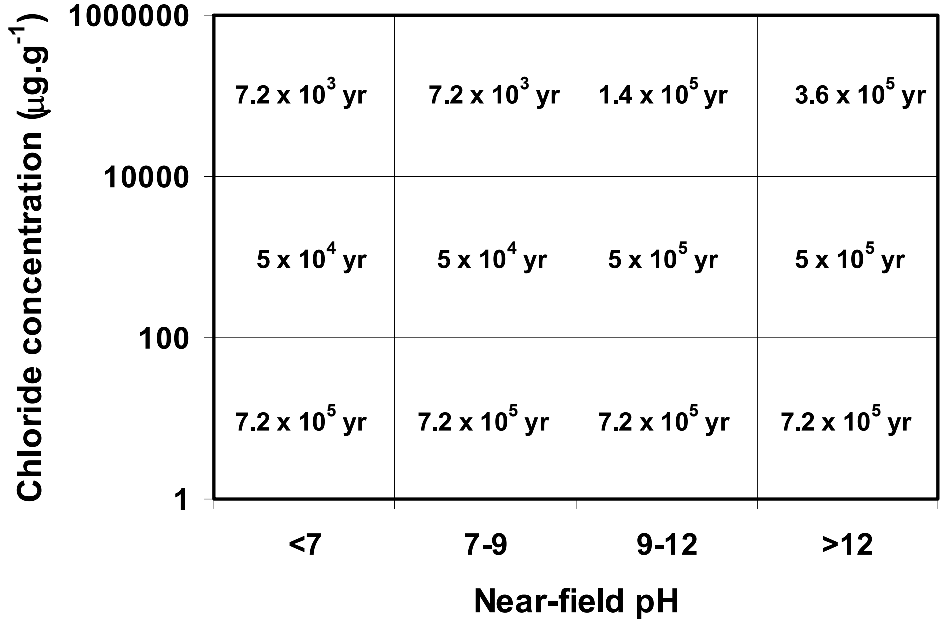


*FIG. 24. Decision tree for the corrosion model used for the borehole disposal concept generic safety assessment.*

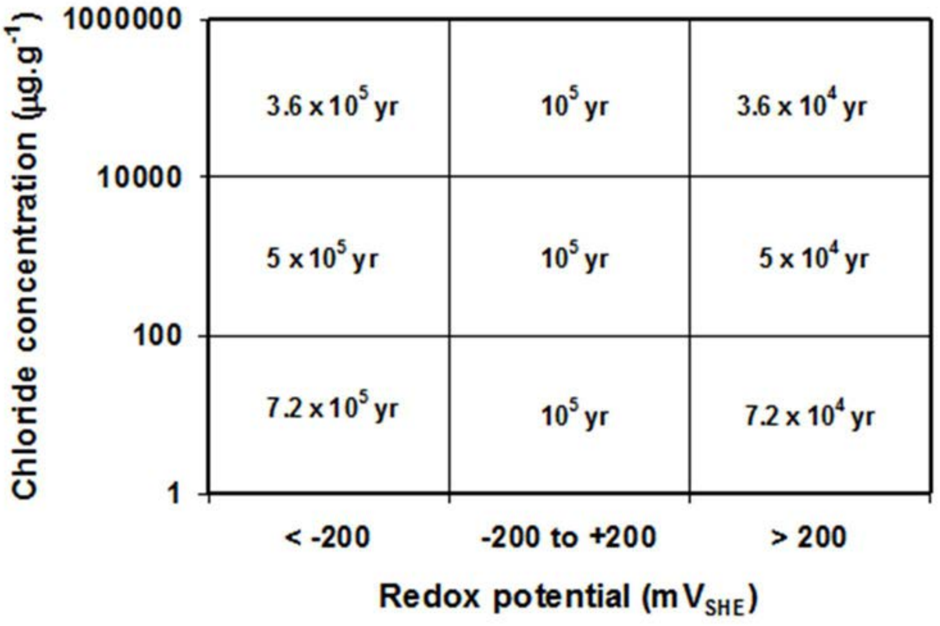


(a) Aerobic conditions.

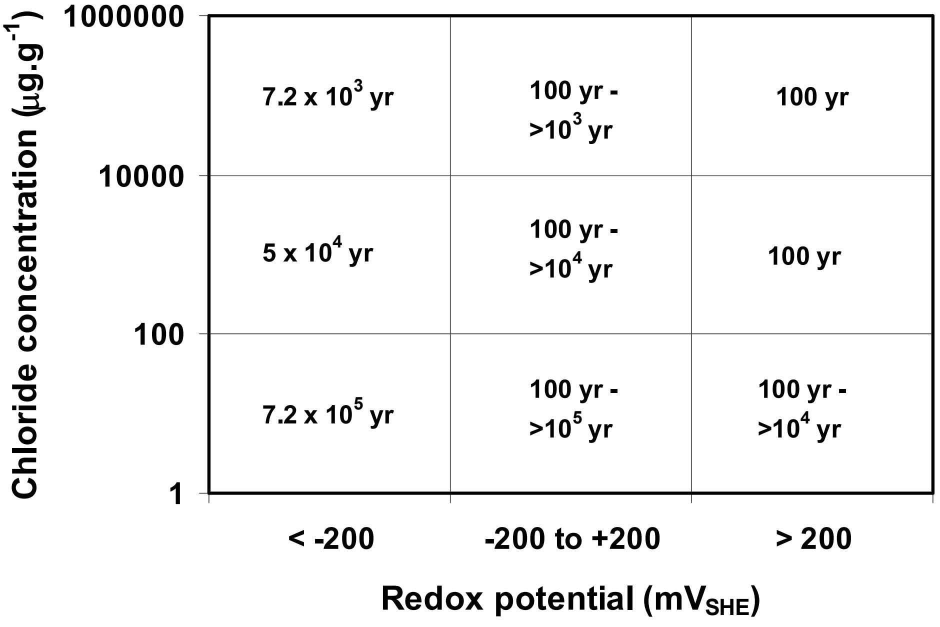


(b) Anaerobic conditions.

*FIG. 25. Corrosion maps illustrating the effect of the near field pH and chloride concentration on the predicted lifetimes of the waste capsule for the borehole disposal concept.*



(a) Alkaline pH (pH > 12).



(b) Ambient pH.

*FIG. 26. Corrosion maps illustrating the effect of the chloride concentration and redox potential on the predicted lifetimes of the waste capsule for the borehole disposal concept.*

# APPENDIX X
# CALCULATION OF SOLUBILITY CONDITIONS

This appendix provides background information in a series of tables concerning the potential for solubility limitation of the radionuclides assessed in GSA.

It is not possible to calculate precise limiting solubilities for the radionuclides of interest, nor to be entirely confident that a solubility control would or would not exist. There are many reasons for these limitations, but notably:

- Thermodynamic data are of uncertain quality or absent for mineral phases that could contain the radionuclides of interest.
- Kinetic factors will control whether or not a true solubility limit is reached.
- There is an uncertainty about the exact chemical form of the wastes.

To estimate whether or not a mineral phase is likely to control the aqueous concentrations of the radionuclides of interest in the waters considered, two approaches were used:

- Calculations were carried out using the computer code Geochemists Workbench version 6.0 [79] in conjunction with the thermodynamic database 'thermo.com.v8.r6+.dat'.
- A brief iterature search was carried out.

The results are summarized in Table 54. Supporting results are shown in Tables 55 to 58 for the three reference waters identified in Section 3.2 (i.e. water Nos 1, 5 and 6).

Table 55 provides information for a 'cement' porewater for each of the three reference waters, denoted C1, C5 and C6, corresponding to groundwaters Nos 1, 5 and 6 respectively. Each of the simplified model cement porewaters has been derived by taking a groundwater composition and content by fixing the pH at 12.5 and constraining the calcium and bicarbonate content content by specifying equilibrium with portlandite and calcite respectively. The resulting water is considered to represent the water that would result from the interaction of the groundwater with the cement grout in the borehole. In contrast Table 56 provides information for the unmodified background groundwater (suitable for use once the cement grout has degraded).

Note that in some cases, from a thermodynamic point of view, it would be expected that a radionuclide would be released from the waste form instantaneously (because it occurs within a solid that is very soluble), but would then precipitate in a less soluble mineral that is not present initially within the waste form. In such cases, it might be appropriate to simulate release from the waste by a solubility-limiting approach, using the secondary phase to calculate the concentration of the radionuclide of interest. Relevant information is provided in Table 57 (for cement waters) and Table 58 (for unmodified background groundwaters). However, it is necessary to bear in mind that reaction kinetics may be too slow to allow this secondary mineral phase to form. Therefore, it would be conservative to assume instantaneous release in these cases.

Note that there are several limitations with the results of these calculations.

- The thermodynamic data used for the solubility calculations are of uncertain quality.
- The solid phases used in the calculations to represent the solids present in the waste forms only approximate the phases actually containing the radionuclides considered. As a result, the calculated solubilities may actually depart significantly from the actual solubilities.
- The calculations are all thermodynamic equilibrium calculations. It is unclear whether or not equilibrium would actually occur. A particular issue is the fact that the waste forms themselves may be only metastable. That is, the calculations may indicate that the waste form would be dissolved, to be replaced by another, lower solubility phase which would thereafter control the aqueous concentration of the radionuclide that it contains. However, in reality, formation of such a lower solubility phase may not occur for kinetic reasons, meaning that a solubility control is never actually achieved.

Further relevant information is provided in Ref. [136]. These authors calculated the solubilities of plutonium, neptunium, uranium, americium, actinium, thorium, protactinium, lead, and radium using the EQ3/6 thermodynamic database developed for the Yucca Mountain project (Data0.ymp.R2). The solubilities of the various radionuclides are reported as a function of pH for a range of water compositions, based on the following water analysis.

TABLE 53. COMPOSITION OF J13 WATER

| Component | Concentration (mg/L)[a] | Uncertainty | Source |
|---|---|---|---|
| $Na^+$ | 45.8 | 2.29 | DTN: MO0006J13WTRCM.000 |
| $K^+$ | 5.04 | 0.61 | DTN: MO0006J13WTRCM.000 |
| $Ca^{2+}$ | 13.0 | 0.99 | DTN: MO0006J13WTRCM.000 |
| $Mg^{2+}$ | 2.01 | 2.01 | DTN: MO0006J13WTRCM.000 |
| Si ($SiO_2$(aq)) | 28.5 (60.97) | 1.85 | DTN: MO0006J13WTRCM.000 |
| $Cl^-$ | 7.14 | 0.61 | DTN: MO0006J13WTRCM.000 |
| $F^-$ | 2.18 | 0.29 | DTN: MO0006J13WTRCM.000 |
| $NO_3^-$ | 8.78 | 1.03 | DTN: MO0006J13WTRCM.000 |
| $SO_4^{2-}$ | 18.4 | 1.03 | DTN: MO0006J13WTRCM.000 |

NOTES: [a] DTN: MO0006J13WTRCM.000 contains recommended mean values of major constituents in J-13 well water.

The solubilities of solid phases containing the above radionuclides were calculated using the code EQ3NR and the above water composition. For each phase, a number of calculations were performed in which the pH was varied between 3.5 and 9. For each solubility-controlling phase, sensitivity calculations were also carried out in which the concentration of a particular constituent was increased to 10x, 100x and 1000x the initial value. Thus, the overall range of water compositions spanned those considered by the borehole disposal project.

Key conclusions from the work in Ref. [136] are that:

- Pu could be solubility-limited by $PuO_2$.
- Am could be solubility-limited by $AmOHCO_3$, $Am(OH)_3$ and $Am(OH)_3$(am). However, the publication considered that the first of these, $AmOHCO_3$ is most likely to be the solubility-limiting phase in practice in the above water and through a pH range from 5.9 to 8.4 and temperatures from 25 to 90°C.
- Ra is considered potentially to be solubility limited by $RaSO_4$. However, it is also noted that field studies have shown that radium concentrations in some natural waters are orders of magnitude below levels corresponding to $RaSO_4$ saturation. Instead, the TECDOC points out that natural concentrations are more likely to be controlled by the solubilities of radium in solid solution in more common sulfate solids such as $SrSO_4$ or $BaSO_4$.
- Pb is one of the least mobile of the common heavy metals. In low-pH, $SO_4$-rich waters or neutral to alkaline, carbonate-rich waters dissolved lead concentrations are considered very likely to be limited by either $PbSO_4$ or lead hydroxycarbonate formation.
- Cs is not expected to be solubility-limited.
- Sr is quite soluble and it is considered that under repository conditions, the most likely solubility-limiting phases would be Strontium strontianite ($SrCO_3$) or celestite ($SrSO_4$). It was assumed conservatively that Sr would not be solubility-limited in the repository.

TABLE 54. SUMMARY OF THE SOLUBILITY CONDITIONS FOR THE GSA

| Radionuclide | Physical/chemical form in disused source | Important natural minerals (not including phases within which the radionuclide might co-precipitate and not exhaustive) | Scope for solubility limitation in cement-buffered porewater (based on calculation results in Tables 55 and 57) | Scope for solubility limitation in groundwater (based on calculation results in Tables 56 and 58) |
|---|---|---|---|---|
| H-3 | Often tritium gas or tritiated water | If located in tritiated water may occur within any hydrated mineral phase | No | No |
| Co-60 | Metallic form in thin discs or small cylindrical pellets. Very low solubility. | Sulphides and arsenides, including linnaeite ($Co_3S_4$) cobaltite, (CoAsS), and smaltite ($CoAs_2$) | No | No |
| Ni-63 | Solid, electrical deposition on metal foil | Tends to occur as an alloy with native Fe (notably in meteorites) | Ni in waste form would be very soluble in all waters.<br>Ni could be solubility-limited by bunsenite (NiO) or possibly metastable $Ni(OH)_2$ in all waters. | Ni in waste form would be very soluble in all waters.<br>In waters 5 and 6, Ni could be solubility-limited by a sulphide phase such as polydymite or possibly vaseite. Alternatively, limitation could be by metastable bunsenite (NiO) or $Ni(OH)_2$ . |
| Kr-85 | Gas | None | No | No |
| Sr-90 | Oxide or titanate form.<br>Often silver plated for medical applications.<br>Ceramic or glass bead or rolled silver foil for other applications | The main minerals are strontianite ($SrCO_3$) and celestite ($SrSO_4$) | SrO in waste form likely to be very soluble in all waters.<br>Strontianite could be a potential solubility-limiting phase in all waters. | SrO in waste form likely to be very soluble in all waters. No information concerning solubility of titanite, but unlikely to be a true equilibrium solubility control<br>Strontianite could be a potential solubility-limiting phase in waters 5 and 6. |
| Cs-137 | Only used as a salt (often caesium chloride).<br>Sometimes ceramic form for weak sources (very low solubility) | Pollucite ($2Cs_2O.2Al_2O_3.9SiO_2.H_2O$), occurs in Rhodizite (a borate) and in some K-ores | No | No |

TABLE 54. SUMMARY OF THE SOLUBILITY CONDITIONS FOR THE GSA (cont.)

| Radionuclide | Physical/chemical form in disused source | Important natural minerals (not including phases within which the radionuclide might co-precipitate and not exhaustive) | Scope for solubility limitation in cement-buffered porewater (based on calculation results in Tables 55 and 57) | Scope for solubility limitation in groundwater (based on calculation results in Tables 56 and 58) |
|---|---|---|---|---|
| Pb-210 | Solid, mainly carbonate, and sulphate | Occurs in a wide range of sulphides, oxides and sulphates, the most common of which are galena (PbS), anglesite ($PbSO_4$), minim ($Pb_3O_4$) and cerussite ($PbCO_3$) | The Pb-carbonate and sulphate in the waste form is likely to be very soluble in all waters.<br>In water C1 there could potentially be a solubility control by minium ($Pb_3O_4$) or possibly by metastable $Pb_4SO_7$. In waters C5 and C6 there could potentially be a solubility control by $Pb_4SO_7$. However, in all waters $Pb_4SO_7$ is moderately soluble. | Dissolution of the waste form could be solubility-limited; in water 1, release could be controlled by solubility of $PbSO_4$; in waters 5 and 6 release could be controlled by solubility of $PbCO_3$. |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble | Ra occurs in ores of U (represented by $UO_2$) | The solubility of Ra in the waste form is likely to be very high in all waters; in all cases the solubilitiy of $RaCl_2.2H_2O$ is very high.<br>$RaSO_4$ could be a solubility-controlling phase in all waters. | The solubility of Ra in the waste form is likely to be very high in all waters; in all cases the solubilitiy of $RaCl_2.2H_2O$ is very high.<br>There is a possibility for solubility control by $RaSO_4$ in all the waters. |
| Pu-238 (+ Rn gas)<br>Pu-239 | Used in RTGs, and for neutron generators and calibration. Sources typically have Pu oxide in ceramic. | None – occurs only in extremely small abundances in some uranium ores | The waste form could potentially be poorly soluble; $PuO_2$ could be a solubility-controlling phase in all waters. | The waste form could potentially be poorly soluble; $PuO_2$ could be a solubility-controlling phase in all waters. |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used.<br>For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form.<br>Sometimes in sintered form. | None | In water C1 $AmO_2$ in the waste form could be a solubility-limiting phase. However, $AmO_2$ is very soluble in waters C5 and C6.<br>$Am(OH)_3$ could be a solubility-limiting phase in all waters. | Dissolution of the waste form is unlikely to be solubility-limited; in all waters the solubility of $AmO_2$ is very high.<br>$AmOHCO_3$ could be a solubility-controlling phase in waters 5 and 6. |

TABLE 55. ESTIMATED SOLUBILITIES FOR MINERAL PHASES THAT ARE CONSIDERED TO REPRESENT THE SOLIDS OCCURRING WITHIN THE WASTE FORMS WHEN THE WASTE FORMS ARE CONTACTED BY MODELLED CEMENT POREWATER

| Radionuclide | Physical/chemical form | Potential solubility-controlling phase in waste form | Cement water C1 | Cement water C5 | Cement water C6 |
|---|---|---|---|---|---|
| | | | Solubility (mg/kg) | Solubility (mg/kg) | Solubility (mg/kg) |
| H-3 | Often tritium gas or tritiated water | None | n.a. | n.a. | n.a. |
| Co-60 | Metallic form in thin discs or small cylindrical pellets. Very low solubility. | Co metal | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| Ni-63 | Solid, electrical deposition on metal foil | Ni metal | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| Kr-85 | Gas | None | n.a. | n.a. | n.a. |
| Sr-90 | Oxide or titanate form.<br>Often silver plated for medical applications.<br>Ceramic or glass bead or rolled silver foil for other applications | SrO | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| Cs-137 | Only used as a salt (often caesium chloride).<br>Sometimes ceramic form for weak sources (very low solubility) | $Cs_2NaAmCl_6$ (only chloride in the database) | Not calculated; at logK for the dissolution reaction is 11.7089 (i.e. the chloride is very soluble) | Not calculated; at logK for the dissolution reaction is 11.7089 (i.e. the chloride is very soluble) | Not calculated; at logK for the dissolution reaction is 11.7089 (i.e. the chloride is very soluble) |
| Pb-210 | Solid, mainly carbonate, and sulphate | Cerussite ($PbCO_3$) | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| | | Anglesite ($PbSO_4$) | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble | $RaCl_2.2H_2O$ | Not calculated; very high | Not calculated; very high | Not calculated; very high |

TABLE 55. ESTIMATED SOLUBILITIES FOR MINERAL PHASES THAT ARE CONSIDERED TO REPRESENT THE SOLIDS OCCURRING WITHIN THE WASTE FORMS WHEN THE WASTE FORMS ARE CONTACTED BY MODELLED CEMENT POREWATER (cont.)

| Radionuclide | Physical/chemical form | Potential solubility-controlling phase in waste form | Cement water C1 | Cement water C5 | Cement water C6 |
|---|---|---|---|---|---|
| | | | Solubility (mg/kg) | Solubility (mg/kg) | Solubility (mg/kg) |
| Pu-238 (+ Rn gas) | | $PuO_2$ | 2.51e-10 | 3.198e-12 | 2.98e-12 |
| Pu-239 | Used in RTGs, and for neutron generators and calibration. Sources typically have Pu oxide in ceramic. | $PuO_2$ | 2.51e-10 | 3.198e-12 | 2.98e-12 |
| Pu-238 (+ Rn gas) | | $PuO_2(OH)_2$ | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| Pu-239 | | $PuO_2(OH)_2$ | Not calculated; very high | Not calculated; very high | Not calculated; very high |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used.<br>For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form.<br>Sometimes in sintered form. | $AmO_2$ | 8.15e-07 | Not calculated; very high | Not calculated; very high |

TABLE 56. ESTIMATED SOLUBILITIES FOR MINERAL PHASES THAT ARE CONSIDERED TO REPRESENT THE SOLIDS OCCURRING WITHIN THE WASTE FORMS, WHEN THE WASTE FORMS ARE CONTACTED BY GROUNDWATER

| Radionuclide | Physical/chemical form | Potential solubility-controlling phase in waste form | Water No. 1 | Water No. 5 | Water No. 6 |
|---|---|---|---|---|---|
| | | | Solubility (mg/kg) | Solubility (mg/kg) | Solubility (mg/kg) |
| H-3 | Often tritium gas or tritiated water | None | n.a. | n.a. | n.a. |
| Co-60 | Metallic form in thin discs or small cylindrical pellets. Very low solubility. | Co metal | Not calculated; at 25ºC, logK for the oxidation reaction is 52.530 7 (i.e. the metal is very unstable) | Not calculated; at 25ºC, logK for the oxidation reaction is 52.530 7 (i.e. the metal is very unstable) | Not calculated; at 25ºC, logK for the oxidation reaction is 52.530 7 (i.e. the metal is very unstable) |
| Ni-63 | Solid, electrical deposition on metal foil | Ni metal | Not calculated; at 25ºC, the log K for the oxidation reaction is 50.991 4 (i.e. the metal is very unstable) | Not calculated; at 25ºC, the log K for the oxidation reaction is 50.991 4 (i.e. the metal is very unstable) | 2.64e+03 |
| Kr-85 | Gas | None | n.a. | n.a. | n.a. |
| Sr-90 | Oxide or titanate form.<br>Often silver plated for medical applications.<br>Ceramic or glass bead or rolled silver foil for other applications | SrO | Not calculated; at 25ºC, logK for the dissolution reaction is 41.891 6 (i.e. the oxide is very unstable) | Not calculated; at 25ºC, logK for the dissolution reaction is 41.891 6 (i.e. the oxide is very unstable) | Not calculated; at 25ºC, logK for the dissolution reaction is 41.891 6 (i.e. the oxide is very unstable) |
| Cs-137 | Only used as a salt (often caesium chloride).<br>Sometimes ceramic form for weak sources (very low solubility) | $Cs_2NaAmCl_6$ (only chloride in the database) | Not calculated; at logK for the dissolution reaction is 11.708 9 (i.e. the chloride is very soluble) | Not calculated; at logK for the dissolution reaction is 11.708 9 (i.e. the chloride is very soluble) | Not calculated; at logK for the dissolution reaction is 11.708 9 (i.e. the chloride is very soluble) |
| Pb-210 | Solid, mainly carbonate, and sulphate | Cerussite ($PbCO_3$) | Not calculated; very high[a] | 0.0248 3 | 0.0312 |
| | | Anglesite ($PbSO_4$) | 154.5 | Not calculated; very higha[a,b] | Not calculated; very high[a,d] |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble | $RaCl_2.2H_2O$ | Not calculated; very high[a] | Not calculated; very high[a] | Not calculated; very high[a] |

TABLE 56. ESTIMATED SOLUBILITIES FOR MINERAL PHASES THAT ARE CONSIDERED TO REPRESENT THE SOLIDS OCCURRING WITHIN THE WASTE FORMS, WHEN THE WASTE FORMS ARE CONTACTED BY GROUNDWATER (cont.)

| Radionuclide | Physical/chemical form | Potential solubility-controlling phase in waste form | Water No. 1 | Water No. 5 | Water No. 6 |
|---|---|---|---|---|---|
| | | | Solubility (mg/kg) | Solubility (mg/kg) | Solubility (mg/kg) |
| Pu-238 (+ Rn gas) | Used in RTGs, and for neutron generators and calibration. Sources typically have Pu oxide in ceramic. | $PuO_2$ | 0.000 253 6 | 3.254e-12 | 9.008e-11 |
| Pu-239 | | $PuO_2$ | 0.000 253 6 | 3.254e-12 | 9.008e-11 |
| Pu-238 (+ Rn gas) | | $PuO_2(OH)_2$ | 9.858 | Not calculated; very high[a,c] | Not calculated; very high[a,c,e] |
| Pu-239 | | $PuO_2(OH)_2$ | 9.858 | Not calculated; very high[a,c] | Not calculated; very high[a,c,e] |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used.<br>For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form.<br>Sometimes in sintered form. | $AmO_2$ | Not calculated; very high[a] | Not calculated; very high[a] | Not calculated; very high[a] |

**Notes:**

[a] Here ‘very high’ means that, when an attempt is made to calculate a solubility of the solubility-limiting phase, using Geochemist’s Workbench v. 6.0 and the thermodynamic database ‘thermo.com.v8.r6+.dat’, unrealistically high concentrations are calculated. These concentrations are sufficiently high (ionic strength >1 molal) that the geochemical model implemented in the code becomes inaccurate.

[b] Due to the chemical speciation of Pb being dominated by hydroxide species under the ambient pH conditions.

[c] Due to the chemical speciation of Pu being dominated by hydroxide species under the ambient pH conditions.

[d] Due to the chemical speciation of Pb being dominated by carbonate species under the ambient chemical conditions.

[e] Due to the chemical speciation of Pu being dominated by the $Pu^{3+}$ species under the ambient conditions.

TABLE 57. SOLUBILITIES OF POTENTIAL SOLID RADIONUCLIDE-BEARING PHASES THAT WOULD BE STABLE IN THE MODELLED CEMENT POREWATERS

| Radionuclide | Physical/chemical form | Potential alternative Solubility-Controlling Phase | Cement water C1 | Cement water C5 | Cement water C6 |
|---|---|---|---|---|---|
| | | | Solubility (mg/kg) | Solubility (mg/kg) | Solubility (mg/kg) |
| Ni | Solid, electrical deposition on metal foil | $Ni(OH)_2$ | 0.131 | 0.131 | 0.155 |
| | | Bunsenite (NiO) | 0.069 22 | 0.069 4 | 0.080 7 |
| Sr-90 | Oxide or titanate form. | Strontianite ($SrCO_3$) | 4.61 | 4.71 | 12.76 |
| | Often silver plated for medical applications. | Celestite ($SrSO_4$) | >1000 | >250 | 365.4 |
| | Ceramic or glass bead or rolled silver foil for other applications | | | | |
| Pb-210 | Solid, mainly carbonate, and sulphate | Minium ($Pb_3O_4$) | 3.65 | Not calculated; very high[a] | Not calculated; very high[a] |
| | | $Pb_4SO_7$ | 538 | 287. | 158. |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble | $RaSO_4$ | 1.27 | 0.358 | 0.012 69 |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used. For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form. Sometimes in sintered form | $AmOHCO_3$ | 3814 | 3815 | 3811 |
| | | $Am(OH)_3$ | 8.843e-06 | 8.85e-06 | 8.840e-06 |

**Notes**:

[a] Here ‘very high’ means that, when an attempt is made to calculate a solubility of the solubility-limiting phase, using Geochemist’s Workbench v. 6.0 and the thermodynamic database ‘thermo.com.v8.r6+.dat’, unrealistically high concentrations are calculated. These concentrations are sufficiently high (ionic strength >1 molal) that the geochemical model implemented in the code becomes inaccurate.

[b]. The thermodynamic database used here (‘thermo.com.v8.r6+.dat’) contains data for only three Be-bearing solids (Be metal, $Be_{13}U$ and bromellite (BeO)). Of these, only bromellite is likely to show low solubility. However, Ref. [34] notes that although the Nagra/PSI thermodynamic database does not contain thermodynamic data for beryllium, Ref. [140] report data that implies that beryllium may form polynuclear complexes below pH c. 6 (mainly the trimer $Be_3(OH)_3^{3+}$), and anionic hydroxides ($Be(OH)_3^-$, $Be(OH)_4^{2-}$) above pH ~ 10. Reference [34] interpreted these data to mean that within these pH ranges Be solubility would be > $10^{-3}$ mol/l (>10 mg/kg). However, Ref. [34] also concluded from the data in Ref. [34] that in the pH range from about 7 -10 where solubility limitation by α-$Be(OH)_2$(s) is possible, consistent with aqueous beryllium concentrations of <$10^{-6}$ mol/l (< 0.009 mg/kg).

TABLE 58. SOLUBILITIES OF SOLID PHASES THAT ARE NOT KNOWN TO OCCUR WITHIN THE WASTE FORMS, BUT WHICH WOULD BE STABLE IN THE PRESENCE OF AT LEAST ONE OF THE THREE GROUNDWATERS CONSIDERED

| Radionuclide | Physical/chemical form | Potential alternative solubility-controlling phase | Water No. 1 | Water No. 5 | Water No. 6 |
|---|---|---|---|---|---|
| | | | Solubility (mg/kg) | Solubility (mg/kg) | Solubility (mg/kg) |
| Ni-63 | Solid, electrical deposition on metal foil | $Ni(OH)_2$ | Not calculated; very high[a] | 5.24 | 182 |
| | | Bunsenite (NiO) | Not calculated; very high[a] | 2.77 | 94.5 |
| | | Polydymite ($Ni_3S_4$) | Not calculated; very high[a] | 1.26e-05 | 3.23e-16 |
| | | Vaesite ($NiS_2$) | Not calculated; very high[a] | 0.000160 | 2.72e-20 |
| Sr-90 | Oxide or titanate form. | Strontianite ($SrCO_3$) | Not calculated; very high[a] | 0.06295 | 0.141 |
| | Often silver plated for medical applications. | Celestite ($SrSO_4$) | Not calculated; very high[a] | Not calculated; very high[a] | Not calculated; very high[a] |
| | Ceramic or glass bead or rolled silver foil for other applications | | | | |
| Ra-226 (+ Rn gas) | Very reactive alkaline earth metal in form of salts (e.g. bromides, chlorides, sulphates or carbonates). All soluble | $RaSO_4$ | 0.30 | 0.1301 | 0.1643 |
| Am-241 | Chemical characteristics similar to rare earth metals. Americium oxides normally used. | $AmOHCO_3$ | Not calculated; very high[a] | 0.01250 | 0.1065 |
| | For neutron sources, fine americium oxide powder used mixed with beryllium powder. Often in pellet form. | | | | |
| | Sometimes in sintered form. | | | | |

**Notes**: [a] Here 'very high' means that, when an attempt is made to calculate a solubility of the solubility-limiting phase, using Geochemist's Workbench v. 6.0 and the thermodynamic database 'thermo.com.v8.r6+.dat', unrealistically high concentrations are calculated. These concentrations are sufficiently high (ionic strength >1 molal) that the geochemical model implemented in the code becomes inaccurate.

[b] The thermodynamic database used here ('thermo.com.v8.r6+.dat') contains data for only three Be-bearing solids (Be metal, $Be_{13}U$ and bromellite (BeO)). Of these, only bromellite is likely to show low solubility. However, Ref. [34] notes that although the Nagra/PSI thermodynamic database does not contain thermodynamic data for beryllium, [140] report data that implies that beryllium may form polynuclear complexes below pH c. 6 (mainly the trimer $Be3(OH)_3^{3+}$), and anionic hydroxides ($Be(OH)_3$ –, $Be(OH)_4^{2-}$) above pH ~ 10. Reference [34] interpreted these data to mean that within these pH ranges Be solubility would be > $10^{-3}$ mol/l (>10 mg/kg). However, Ref. [34] also concluded from the data in Ref. [140] that in the pH range from about 7 -10 where solubility limitation by α-$Be(OH)_2$(s) is possible, consistent with aqueous beryllium concentrations of <$10^{-6}$ mol/l (< 0.009 mg/kg).

# APPENDIX XI
# ASSESSMENT MODEL

## XI.1. DESIGN SCENARIO

It is important to note that the release and migration processes described in Section XI.1.1 are assumed to occur only once the capsule containing the source container has started to fail (see Section 4). Details concerning the mathematical model used to represent the failure of capsule and other near field engineered barriers are given in Appendix XI.3.

The processes identified in leading and off diagonal elements in the Interaction Matrices in Figs 7 and 8 are listed in Table 59. The associated equations are listed in Table 59 and discussed below.

### XI.1.1. Release processes

As discussed in Section 5.2.1, the radionuclides in the source container could be in a number of different physical and chemical forms and release of radionuclides could occur on breaching of the waste capsule due to the following mechanisms.

- Instantaneous release of gas for radionuclides that are in gaseous form (H-3 and Kr-85) or which have gas phase progeny (Rn-222 for Ra-226 and Pu-238). For calculation of doses to the House Dweller Exposure Group via the inhalation of radioactive gases, the concentration of radionuclides to which the house dweller is exposed via inhalation can be calculated as a linear function of the amount of radionuclides in the disposal borehole (see Equation 47 to Equation 52). Therefore, there is no need to represent explicitly the release of radionuclides in gaseous form between different parts of the disposal system, and so inter-compartmental transfer rates need not be specified.
- Instantaneous dissolution of radionuclides that are in a form that would result in immediate release to water once the capsule containing the source has failed (e.g. liquid, soluble solid, surface contamination) (H-3, Ni-63, Sr-90, Cs-137, Pb-210, Ra-226 and Am-241).

TABLE 59. RELEASE AND MIGRATION PROCESSES AND ASSOCIATED EQUATIONS FOR THE DESIGN SCENARIO

| System Component | Process | Equation/comment |
|---|---|---|
| Near Field | Dissolution | Once water contacts the source, it is assumed that radionuclides in the source can be dissolved and transferred from the capsule containing the source into the surrounding containment barrier/disposal zone due to advection, dispersion and/or diffusion. Instantaneous dissolution congruent release models are considered depending on the chemical and physical form of the source. |
| | Gas release | Equation 49 |
| | Sorption | Equation 17, Equation 19 to Equation 21, Equation 23 to Equation 26, Equation 28 and Equation 29 |
| | Decay | Equation 1 |
| | Degradation | See Appendix XI.3 |
| | Advection | Equation 17, Equation 21, Equation 25, Equation 26 |
| | Dispersion | Implicitly represented through the discretisation of the geosphere into a series of compartments and allowing compartment widths to increase perpendicular to groundwater flow |
| | Diffusion | Equation 23, Equation 24, Equation 28, Equation 29 |
| | Groundwater flow | Equation 22, Equation 27 |
| | Percolation | Set equal to the minimum of the infiltration rate of water through the unsaturated zone, and the hydraulic conductivity of the disposal zone and containment barrier |
| | Gas migration | Equation 49, Equation 52 |
| Geosphere | Sorption | Equation 19, Equation 25, Equation 26, Equation 28, Equation 29, Equation 31 |
| | Decay | Equation 1 |
| | Advection | Equation 25, Equation 26 |
| | Dispersion | Implicitly represented through the discretisation of the geosphere into a series of compartments and allowing compartment widths to increase perpendicular to groundwater flow |
| | Diffusion | Equation 28, Equation 29, Equation 30, Equation 31 |
| | Groundwater flow | Equation 27 |
| | Percolation | Rate specified in Section 3.2.1 |
| | Recharge | Not explicitly represented. Implicitly represented via percolation and groundwater transport. |
| | Abstraction | Equation 32 |
| Biosphere | Excretion by humans | Not explicitly represented. Implicitly represented by modelling the abstraction of water from the geosphere from consumption by humans and assuming it is directed to the 'elsewhere' compartment (Equation 32). |
| | Excretion by animals | Not explicitly represented. Implicitly represented by not modelling the loss of activity from the soil due to uptake by flora. |
| | Bioturbation | Not explicitly represented. Implicitly represented by assuming uniform concentration of radionuclides in the soil. |
| | Ploughing | Not explicitly represented. Implicitly represented by assuming uniform concentration of radionuclides in the soil. |
| | Gas Dispersion | Equation 48, Equation 53 |
| | Decay | Equation 1 |
| | Precipitation | Not explicitly represented. Implicitly represented via percolation in unsaturated zone and groundwater flow in saturated zone. |
| | Sorption | Equation 35, Equation 46 |
| | Suspension | Equation 35 |
| | Deposition onto soil | Not explicitly represented. Implicitly represented by not modelling the loss of activity from the soil due to suspension. |
| | Deposition onto flora | Equation 43 |
| | Translocation | Equation 43 |
| | Root uptake | Equation 43 |
| | Erosion | Equation 34 |
| | Percolation | Equation 25 |
| | Death and decay of crops | Not explicitly represented. Implicitly represented by not modelling the loss of activity from the soil due to uptake by crops. |
| | Cultivation | Considered by modelling the ingestion of crops by humans (Equation 42) |
| | Harvesting | Considered by modelling the ingestion of crops by humans (Equation 42) |
| | Rearing | Considered by modelling the ingestion of animals by humans (Equation 44) |
| | Food preparation losses | Equation 43 |

- Congruent release of radionuclides that are in a form that would result in slow release to water (e.g. solid with low solubility) (Co-60, Pu-238 and Pu-239).

It is recognized that the instantaneous dissolution and congruent release mechanisms could, under certain circumstances, be solubility limited (see Table 15 and Appendix X). However, no solubility limitation is considered for the reference case calculations (a conservative assumption).

For the congruent release model, it is assumed that once the engineered barriers containing the disused sealed radioactive source have failed, the source will begin to corrode/dissolve and radionuclides become available for release. The fraction of the inventory released in any time period is equal to the amount which becomes available divided by the inventory remaining in the source. For short time periods this simplifies to the rate of change of availability with time divided by the amount which remains unavailable.

It is assumed that the source is a sphere of material whose radius decreases with time as it dissolves / corrodes. Ignoring decay (since this will automatically be calculated by AMBER), the amount available at a time t, is therefore equal to:

$$I \times \left( \frac{\frac{4}{3}\pi r^3 - \frac{4}{3}\pi (r - C_r t)^3}{\frac{4}{3}\pi r^3} \right) \tag{13}$$

where:

*I* is the radionuclide inventory (Bq);

r is the initial radius of the source (m);

$C_r$ is the corrosion / dissolution rate (m/y).

Cancelling terms and expanding gives:

$$I \times \left( \frac{r^3}{r^3} - \left[ \frac{r^3}{r^3} - \frac{3r^2 C_r t}{r^3} + \frac{3r C_r^2 t^2}{r^3} - \frac{C_r^3 t^3}{r^3} \right] \right) \tag{14}$$

Therefore the amount available at time *t* equals:

$$I \times \left( \frac{3r^2 C_r t}{r^3} - \frac{3r C_r^2 t^2}{r^3} + \frac{C_r^3 t^3}{r^3} \right) \tag{15}$$

Differentiating with respect to time gives the rate of change of the amount available with time:

$$I \times \left( \frac{3r^2 C_r}{r^3} - \frac{6r C_r^2 t}{r^3} + \frac{3C_r^3 t^2}{r^3} \right) \tag{16}$$

### K.1.2 Liquid Migration Processes

### *XI.1.1.1. Advective and dispersive release – disposal in the unsaturated zone*

The advective and dispersive transfer rate of radionuclides released from the capsule containing the source due to percolation of water through the near field ($\lambda_{UnsatLeach}$, in /y) is given by:

$$\lambda_{UnsatLeach} = \frac{q_{PERC}\ f}{L_c\ \vartheta_{wc}\ R_c} \tag{17}$$

where:

$q_{PERC}$ is the annual percolation rate through the capsule compartment (i.e. the compartment representing the capsule that contains the source) (m/y) (equal to the minimum of the infiltration rate of water through the unsaturated zone, and the hydraulic conductivity of the disposal zone and containment barrier);

$f$ is the fraction of the waste that is available for release (unitless) (given by Equation 55, Equation 56 and Equation 57);

$L_c$ is the length of the capsule compartment in the direction of water flow (m);

$\vartheta_{wc}$ is the water-filled porosity of the capsule compartment (unitless); and

$R_c$ is the element dependent retardation of the capsule compartment (unitless).

$\vartheta_{wc}$ is calculated using the following general formula:

$$\vartheta_w = \varepsilon\ \theta \tag{18}$$

where $\varepsilon$ is the degree of saturation (unitless) in the compartment and $\theta$ is the total porosity of the compartment (unitless).

For the purposes of the GSA, it is assumed that all the water-filled porosity contributes to flow and so total porosity and effective porosity have the same values.

$R_c$ is calculated using the following general formula:

$$R = 1 + \frac{\rho\ Kd}{\vartheta_w} \tag{19}$$

where:

$\rho$ is the dry bulk density of the compartment (kg/m$^3$); and

$Kd$ is the sorption coefficient of the element in the compartment (m$^3$/kg).

$\rho$ is calculated using the following general formula:

$$\rho = \rho_g\ (1-\theta) \tag{20}$$

where $\rho_g$ is the grain density of the compartment (kg/m$^3$).

### *XI.1.1.2. Advective and dispersive release - disposal in the saturated zone*

The advective transfer rate from the release of radionuclides from the capsule containing the source due to the flow of groundwater through the near field ($\lambda_{SatLeach,}$, in ) is given by:

$$\lambda_{SatLeach} = \frac{q_c\ f}{\vartheta_{wc}\ L_c\ R_c} \tag{21}$$

where:

$q_c$ is the Darcy velocity of the groundwater through the capsule compartment (m/y);

$\vartheta_{wc}$ is the water-filled porosity of the capsule compartment (unitless);

$L_c$ is the length of capsule compartment in the direction of groundwater flow (m); and

$R_c$ (unitless) is the retardation factor in the capsule compartment for the radionuclide.

$q_c$ is calculated by:

$$q_c = -K_c \frac{\partial H}{\partial x} \tag{22}$$

Where $K_c$ (m/y) is the hydraulic conductivity of the capsule compartment and $\partial H/\partial x$ is the hydraulic gradient (unitless).

The dispersion of radionuclides in the direction of groundwater movement (longitudinal dispersion) is not represented explicitly as a mathematical model. This is because when a flow path is divided into a number of equally sized compartments in the direction of groundwater flow, the mathematical representation as a series of well-mixed compartments introduces dispersion. The effective Peclet number (a measure of dispersion) is twice the number of compartments in the flow path (see discussion in Appendix II of [XI.1] [138]). Where the compartments are not of the same size, the effective Peclet number is dominated by the largest compartment.

### *XI.1.1.3. Diffusive Release – Disposal in the Unsaturated and Saturated Zones*

The diffusive release from the capsule compartment ($\lambda_{DiffRelF,}$, in /y) is given by:

$$\lambda_{DiffRelF} \quad = \quad \frac{A_{diff}\ f\ D_{Effc}}{R_c\ V_c\ \Delta_c\ \vartheta_{wc}} \tag{23}$$

where:

$A_{diff}$ (m$^2$) is the cross-sectional area relevant to the diffusive release from the capsule;

$f$ is the fraction of the waste that is available for release, $D_{Effc}$ (m$^2$/y) is the effective diffusion coefficient for the capsule compartment;

$R_c$ (unitless) is the retardation factor in the capsule compartment for the radionuclide;

$V_c$ (m$^3$) is the volume of the capsule compartment;

$\Delta_c$ (m) is a representative diffusion length between the capsule compartment and the adjacent compartment, generally taken to be the distance between the mid-points of the compartments in the direction of the diffusive flux; and

$\vartheta_{wc}$ is the water-filled porosity of the capsule compartment.

In addition to this ‘forward’ diffusive transfer rate, there is a need to represent a corresponding ‘backward’ diffusive transfer rate in the reverse direction from the compartment adjacent to the capsule compartment ($\lambda_{DiffRelB,}$, in /y). This transfer rate is given by:

$$\lambda_{DiffRelB} \quad = \quad \frac{A_{diff}\ f\ D_{EffA}}{R_A\ V_A\ \Delta_c\ \vartheta_{wA}} \tag{24}$$

where:

$D_{EffA}$ (m$^2$/y) is the effective diffusion coefficient for the compartment adjacent to the capsule compartment;

$R_A$ (unitless) is the retardation factor for the radionuclide in the compartment adjacent to the capsule compartment;

$V_A$ ($m^3$) is the volume of the compartment adjacent to the capsule compartment;

$\Delta_c$(m) is a representative diffusion length between the adjacent compartment and the capsule compartment, generally taken to be the distance between the mid-points of the compartments in the direction of the diffusive flux; and

$\vartheta_{wA}$ is the water-filled porosity of the compartment adjacent to the capsule compartment.

### *XI.1.1.4. Advective and dispersive transport – disposal in the unsaturated zone*

The transfer rate of contaminated water percolating (due to advection and dispersion) through the unsaturated near field, unsaturated geosphere and soil ($\lambda_{PERC}$, in /y) is given by:

$$\lambda_{PERC} = \frac{q_{PERC}}{L\,\vartheta_w\,R} \qquad (25)$$

where:

$q_{PERC}$ is the annual percolation rate through the compartment (m/y);

$L$ is the length of the compartment in the direction of water flow (m);

$\vartheta_w$ is the water-filled porosity of the compartment (unitless); and

$R$ is the element dependent retardation of the compartment (unitless) (given by Equation 7).

For flow in a fracture it is assumed that there is no retardation, and so R is unity.

### *XI.1.1.5. Advective and dispersive transport in the saturated zone*

For transport through the saturated zone, the advective transfer rate ($\lambda_A$, in /y) is given by:

$$\lambda_A = \frac{q}{\vartheta_w\,L\ \ R} \qquad (26)$$

where:

$q$ is the Darcy velocity of the groundwater in the compartment (m/y);

$\vartheta_w$ is the water-filled porosity of the compartment (unitless):

$L$ is the length of the compartment in the direction of water flow; and

$R$ is the element dependent retardation of the compartment (unitless).

$q$ is given by:

$$q = -K\frac{\partial H}{\partial x} \qquad (27)$$

where $K$ (m/y) is the hydraulic conductivity of the compartment and $\partial H/\partial x$ is the hydraulic gradient (unitless).

As discussed above, the dispersion of radionuclides in the direction of groundwater movement (longitudinal dispersion) is implicitly represented through the discretisation of the saturated zone into a series of compartments. Contaminant dispersion at right angles to the direction of groundwater movement in the saturated medium (transverse dispersion) is not represented explicitly as a process because the compartment dimensions can be defined to represent the increase in plume dimensions due to lateral spreading.

### *XI.1.1.6. Diffusive transport – disposal in the unsaturated and saturated zones*

The ‘forward’ diffusive transfer rate ($\lambda_{DiffD}$, in /y) is given by:

$$\lambda_{DiffD} \quad = \quad \frac{A_U \; D_{EffU}}{R_U \; V_U \; \Delta_U \; \vartheta_{wU}} \tag{28}$$

where:

$A_U$ (m$^2$) is the cross-sectional area relevant to the diffusive transfer from the upstream compartment;

$D_{EffU}$ (m$^2$/y) is the effective diffusion coefficient for the upstream compartment;

$R_U$ (unitless) is the retardation factor in the upstream compartment for the radionuclide;

$V_U$ (m$^3$) is the volume of the upstream compartment;

$\Delta_U$ (m) is a representative diffusion length between the upstream and downstream compartments, generally taken to be the distance between the mid-points of the compartments in the direction of the diffusive flux; and

$\vartheta_{wU}$ is the water-filled porosity of the upstream compartment.

In addition to this ‘forward’ diffusive transfer rate, there is a need to represent a corresponding ‘backward’ diffusive transfer rate in the reverse direction ($\lambda_{DiffU}$,, in /y). This transfer rate is given by:

$$\lambda_{DiffU} \quad = \quad \frac{A_U \, D_{EffD}}{R_D \; V_D \; \Delta_U \vartheta_{wD}} \tag{29}$$

where:

$A_U$ (m$^2$) is the cross-sectional area relevant to the transport;

$D_{EffD}$ (m$^2$/y) is the effective diffusion coefficient for the downstream compartment;

$R_D$ (unitless) is the retardation factor for the radionuclide in the downstream compartment;

$V_D$ (m$^3$) is the volume of the downstream compartment;

$\Delta_U$ (m) is a representative diffusion length between the upstream and downstream compartments, generally taken to be the distance between the mid-points of the compartments in the direction of the diffusive flux; and

$\vartheta_{wD}$ is the water-filled porosity of the downstream compartment.

The diffusive transfer rate from a fractured compartment into a matrix compartment ($\lambda_{rm}$, in /y) is given by:

$$\lambda_{rm} = \frac{2 \, a \, D_{Effm}}{\vartheta_{wf} \, \delta} \tag{30}$$

wthere:

$a$ is the flow wetted surface area per unit volume of rock (m$^2$/m$^3$);

$\vartheta_{wf}$ is the water-filled fracture porosity (unitless);

$D_{Effm}$ is the effective diffusion coefficient of the matrix compartment (m$^2$/y); and

$\delta$ is the depth of the matrix compartment (m).

The reverse transfer rate from a matrix compartment back to the fracture ($\lambda_{mr}$, in /y) is given by:

$$\lambda_{mr} = \frac{2\, D_{Effm}}{R_m\, \delta^2 \vartheta_{wm}} \tag{31}$$

where:

$R_m$ is the retardation coefficient of the radionuclide in the matrix;

$\vartheta_{wm}$ is the water-filled matrix porosity (unitless).

### *XI.1.1.7. Water abstraction*

The transfer rate of radionuclides in groundwater abstracted from the geosphere to soil due to irrigation of crops ($\lambda_{irrig}$, in /y) is given by:

$$\lambda_{irrig} = \frac{Dil\, V_{irrig}}{\vartheta_{ww} V_w R_w} \tag{32}$$

where:

$Dil$ is the fraction of the water demand supplied by contaminated water;

$V_{irrig}$ is the volume of irrigation water that reaches the soil ($m^3/y$);

$\vartheta_{ww}$ is the water-filled porosity of the compartment from which the water is abstracted (unitless);

$V_w$ is the volume of the compartment from which the water is abstracted ($m^3$);

$R_w$ is the retardation coefficient (unitless) of the compartment from which the water is abstracted.

For this abstraction, it is necessary to consider only the volume of irrigation water reaching the soil since it represents the transfer of radionuclides from the geosphere to the soil (rather than to the crops). Some of the water abstracted from the geosphere for irrigation purposes will be intercepted by the crops and will not reach the soil since it is either taken up directly into the crop or evaporated from the crop surface. This water is accounted for in the other water abstraction considered below.

The transfer rate of radionuclides due to abstraction of water for watering of animals and domestic purposes ($\lambda_{other}$, in /y) is given by:

$$\lambda_{other} = \frac{Dil\, V_{other}}{\vartheta_{ww} V_w R_w} \tag{33}$$

where:

$Dil$ is the fraction of the water demand supplied by contaminated water;

$V_{other}$ is the volume of water abstracted for watering of animals and domestic purposes (includes the volume of irrigation water not reaching the soil due to interception by crops) ($m^3/y$);

$\vartheta_{ww}$ is the water filled porosity of the compartment from which the water is abstracted (unitless);

$V_w$ is the volume of the compartment from which the water is abstracted ($m^3$); and

$R_w$ is the retardation coefficient (unitless) of the compartment from which the water is abstracted.

### *XI.1.1.8. Erosion*

The transfer rate of radionuclides by erosion of a compartment ($\lambda_{EROS}$, in /y) is given by:

$$\lambda_{EROS} = \frac{d_{EROS}}{D} \tag{34}$$

where:

$d_{EROS}$ is the erosion rate for the compartment (m/y); and

$D$ is the depth of the compartment from which erosion takes place (m).

#### *XI.1.1.9. Suspension*

The suspension of dust above a soil compartment is modelled by using dust loading factors, where the concentration of a radionuclide in the air above the soil, $C_{Air}$ (Bq/m$^3$) is given by:

$$C_{Air} = \chi_{Dry} \frac{(R_{Soil} - 1)}{R_{Soil}} c_{Dust} \tag{35}$$

where:

$\chi_{Dry}$ is the radionuclide concentration in the dry surface soil (Bq/kg dry weight soil);

$R_{Soil}$ is the retardation coefficient for soil compartment (unitless);

$c_{Dust}$ is the dust level in the air above the soil compartment (kg/m$^3$).

$\chi_{Dry}$ is given by:

$$\chi_{Dry} = \frac{C_{Soil}}{\rho_{Soil}} \tag{36}$$

where:

$C_{Soil}$ is the radionuclide concentration in the soil (Bq/m$^3$);

$\rho_{Soil}$ is the dry bulk density of the soil (kg/m$^3$).

$C_{Soil}$ is given by:

$$C_{Soil} = \frac{Amount_{Soil}}{V_{Soil}} \tag{37}$$

where:

$Amount_{Soil}$ is the amount of the radionuclide in the soil (Bq);

$V_{Soil}$ is the volume of the compartment representing the soil (m$^3$).

### XI.1.2. Gas migration processes

For calculation of doses to the House Dweller Exposure Group via the inhalation of radioactive gases, the concentration of radionuclides to which the house dweller is exposed via inhalation can be calculated as a linear function of the amount of radionuclides in the disposal borehole. Therefore, there is no need to represent explicitly the migration of radionuclides in gaseous form between different parts of the disposal system, and so inter-compartmental transfer rates need not be specified.

### XI.1.3. Exposure mechanisms

For the Design Scenario, it is assumed that exposure can only occur once the capsule has started to fail and the institution control period has ended (Section 4.2). Details concerning the mathematical model used to represent the failure of capsule and other near field engineered barriers are given in Appendix XI.3 and it is assumed that the institutional control period ends 30 years after site closure (Section 4.2).

The exposure mechanisms identified in the off diagonal elements in the Interaction Matrices in Figs 7 and 8 are listed in Table 60. Equations are given below that are used to calculate the annual effective dose received by an average adult member of an exposure group from these exposure mechanisms.

TABLE 60. EXPOSURE MECHANISMS AND ASSOCIATED EQUATIONS FOR THE DESIGN SCENARIO

| Mechanism | Medium | Equation |
|---|---|---|
| Ingestion | Groundwater | Equation 38, Equation 39 |
| | Soil | Equation 40, Equation 41 |
| | Crops | Equation 42, Equation 43 |
| | Animals | Equation 44, Equation 45 |
| Inhalation | Dust | Equation 46 |
| | Gas | Equation 47 to Equation 53 |
| External irradiation | Soil | Equation 54 |

### XI.1.3.1. Ingestion of Groundwater

The annual individual effective dose to a human from the consumption of drinking water ($D_{Wat}$, in Sv/y) is given by:

$$D_{Wat} = C_W \ Ing_{Wat} \ DC_{Ing} \tag{38}$$

where:

$C_W$ is the radionuclide concentration in the abstracted water (Bq/m$^3$);

$Ing_{Wat}$ is the individual ingestion rate of water (m$^3$/y);and

$DC_{Ing}$ is the dose coefficient for ingestion (Sv/Bq).

$C_W$ is given by:

$$C_W = \frac{Dil \ Amount_w}{\vartheta_w V_w R_w} \tag{39}$$

where:

$Dil$ is the contribution of the water from the abstraction borehole to the total water ingested;

$Amount_w$ is the amount of the radionuclide in the compartment from which the water is abstracted (Bq);

$\vartheta_w$ is the water-filled porosity of the compartment (unitless);

$V_w$ is the volume of the compartment from which the water is abstracted (m$^3$); and

$R_w$ is the retardation coefficient of the compartment from which the water is abstracted (unitless).

### XI.1.3.2. Ingestion of Soil

Soil can be inadvertently ingested by humans. The annual individual dose to a human from the ingestion of soil ($D_{Sed}$, in Sv/y) is given by:

$$D_{Sed} = \chi_{Wet} \ Ing_{Sed} \ O_{Out} \ DC_{Ing} \tag{40}$$

where:

$\chi_{Wet}$ is the radionuclide concentration in the soil (Bq/kg wet weight);

$Ing_{Sed}$ is the individual inadvertent ingestion rate of soil (kg wet weight /h);

$O_{Out}$ is the individual occupancy on the soil (h/y); and

$DC_{Ing}$ is the dose coefficient for ingestion (Sv/Bq).

$\chi_{Wet}$ is given by:

$$\chi_{Wet} = \frac{C_{Soil}}{\rho_{Soil} + \vartheta_{wSoil}\rho_{Wat}} \tag{41}$$

where:

$C_{soil}$ is the radionuclide concentration in the soil (Bq/m$^3$);

$\rho_{Soil}$ is the dry bulk density of the soil (kg/m$^3$);

$\vartheta_{wSoil}$ is the water filled porosity of the soil (unitless); and

$\rho_{Wat}$ the density of water (kg/m$^3$).

### *XI.1.3.3. Ingestion of Crops*

The annual individual effective dose to a human from the consumption of a crop, ($D_{Crop}$, in Sv/y), is given by:

$$D_{Crop} = \chi_{Crop}\, Ing_{Crop}\, DC_{Ing} \tag{42}$$

where:

$\chi_{Crop}$ is the radionuclide concentration in the crop (Bq/kg fresh weight of crop);

$Ing_{Crop}$ is the individual ingestion rate of the crop (kg fresh weight /y); and

$DC_{Ing}$ is the dose coefficient for ingestion (Sv/Bq).

The $\chi_{crop}$ term is calculated using:

$$\chi_{Crop} = (CF_{Crop} + (1 - f_{Prep})s_{Crop})\chi_{Dry} + \mu_{Crop} d_{Irr} C_W \frac{(1 - f_{Prep})(1 - f_{Trans})\, e^{-T\,W_{crop}} + f_{Trans}}{Y_{Crop}} \tag{43}$$

Where:

$CF_{crop}$ is the concentration factor for the crop (Bq/kg fresh weight of crop/Bq/kg (dry weight of soil));

$f_{Prep}$ is the fraction of external contamination on the crop lost due to food processing (unitless);

$s_{Crop}$ is the soil contamination on the crop (kg dry weight soil kg$^{-1}$ fresh weight of crop);

$\chi_{Dry}$ is the radionuclide concentration in the dry surface soil (Bq/kg dry weight soil);

$\mu_{crop}$ is the interception fraction for irrigation water on the crop (unitless);

$d_{Irr}$ is the depth of irrigation water applied to the crop (m/y);

$C_W$ is the radionuclide concentration in the abstracted water (Bq/m$^3$);

$f_{Trans}$ is the fraction of activity transferred from external to internal plant surfaces (unitless);

$T$ is the interval between irrigation and harvest (y);

$W_{crop}$ is the removal rate of irrigation water from the crop by weathering processes (weathering rate) (/y); and

$Y_{Crop}$ is the yield of the crop (kg fresh weight of crop /m$^2$/y).

### XI.1.3.4. Ingestion of Animals

The annual individual effective dose to a human from the consumption of animal produce ($D_{Anm}$, in Sv/y) is given by:

$$D_{Anm} = \chi_{Anm} Ing_{Anm} DC_{Ing} \tag{44}$$

where:

| | |
|---|---|
| $\chi_{Anm}$ | is the radionuclide concentration in the animal product (Bq/kg fresh weight of product); |
| $Ing_{Anm}$ | is the individual consumption rate of the animal product (kg fresh weight of product /y); |
| $DC_{Ing}$ | is the dose coefficient for ingestion (Sv/Bq). |

The $\chi_{Anm}$ term is calculated using:

$$\chi_{Anm} = CF_{Anm} C_W \; Ing_{AW} \tag{45}$$

where:

| | |
|---|---|
| $CF_{Anm}$ | is the concentration factor for the animal product (d kg$^{-1}$ fresh weight of product); |
| $C_w$ | is the radionuclide concentration in the water used for watering animals (Bq/m$^3$); |
| $Ing_{AW}$ | is the consumption rate of water by the animal (m$^3$/d). |

### XI.1.3.5. Inhalation of Dust

The annual individual dose to a human from the inhalation of dust ($D_{Dust}$, in Sv/y) is given by:

$$D_{Dust} = C_{Air} \; O_{Out} \; Inh_{Sed} \; DC_{Inh} \tag{46}$$

where:

| | |
|---|---|
| $C_{Air}$ | is the radionuclide concentration in the air above the soil (Bq/m$^3$); |
| $Inh_{Sed}$ | is the breathing rate of the human on the contaminated soil (m$^3$/h); |
| $DC_{Inh}$ | is the dose coefficient for inhalation (Sv/Bq). |

### XI.1.3.6. Inhalation of Gases

The annual individual dose to a human due to inhalation of gases (other than Rn-222) ($D_{gas}$, in Sv/y) is given by:

$$D_{gas} = D_{inhg} BR_{gas} \, O_{gas} \, C_{gas} \tag{47}$$

where:

| | |
|---|---|
| $D_{inhg}$ | is the dose coefficient for inhalation of the gaseous form of the radionuclide (Sv/Bq); |
| $BR_{gas}$ | is the breathing rate of the human in the house (m$^3$/h); |
| $O_{gas}$ | is the individual occupancy in the house (h/y); |
| $C_{gas}$ | is the concentration of the gas in the house (Bq/m$^3$). |

$C_{gas}$ is given by:

$$C_{gas} = \Phi_g \, A_b \, / \, (\lambda_v \, V_h) \tag{48}$$

where:

$\Phi_g$ (Bq m$^{-2}$ /y) is the flux of the radionuclide into the house;

$A_b$ (m$^2$) and $V_h$ (m$^3$) are the cross-sectional area of the borehole and total volume of the house;

$\lambda_v$ is the rate of ventilation of the house (/y).

$\Phi_g$ is given by:

$$\Phi_g = \frac{I_g \; f_g}{\tau_g A_b} \tag{49}$$

where:

$I_g$ is the disposed inventory of the radionuclide, decay-corrected to the start time of the capsule's physical failure (Bq);

$\tau_g$ is the timescale over which gas production is assumed to take place following failure of the capsule (y);

$f_g$ is the total fraction of the inventory of the radionuclide which is assumed to be released as gas.

For Rn-222, the dose coefficient for inhalation of is given in Sv/h/Bq/m$^3$, and so:

$$D_{Rn} = D_{InhRn} \; O_{gas} \; C_{Rnair} \tag{50}$$

where:

$D_{Rn}$ is the individual dose from the inhalation of Rn-222 (Sv/y);

$D_{inhRn}$ is the dose coefficient for inhalation of Rn-222 (Sv/h/Bq/m$^3$);

$O_{gas}$ is the individual occupancy in the house (h/y);

$C_{Rnair}$ is the concentration of Rn-222 in the house (Bq/m$^3$).

$C_{Rnair}$ is given by:

$$C_{Rnair} = \Phi_{Rn} \, A_b \, / \, ((\lambda_v + \lambda_{Rn}) \; V_h) \tag{51}$$

where:

$\Phi_{Rn}$ (Bq m$^{-2}$ /y) is the flux of Rn-222 into the house;

$A_b$ (m$^2$) is the cross-sectional area of the borehole;

$V_h$ (m$^3$) is the total volume of the house;

$\lambda_v$ is the rate of ventilation of the house (/y);

$\lambda_{Rn}$ is the Rn-222 decay rate (/y).

$\Phi_{Rn}$ is given by:

$$\Phi_{Rn} = \chi_{RaBh} \; \lambda_{Rn} \; \varepsilon_{Rn} \; \rho_{Bh} \; D_{Bh} \; e^{\frac{-d_{Bh}}{D_{Bh}}} \tag{52}$$

where:

$\chi_{RaBh}$ is the concentration of Ra-226 in the disposal zone (Bq/kg);

$\varepsilon_{Rn}$ is the Rn emanating fraction (unitless);

$\rho_{Bh}$ is the dry bulk density of the borehole's disposal zone (kg/m$^3$);

$D_{Bh}$ is the diffusion length for Rn in the borehole (m);

$d_{Bh}$ is the thickness of the borehole's closure zone (m).

$\chi_{RaBh}$ is calculated using:

$$\chi_{RaBh} = Amount_{RaBh} / (\rho_{Bh} V_{Bh}) \tag{53}$$

where:

| | |
|---|---|
| $Amount_{RaBh}$ (Bq) | is the amount of Ra-226 in the borehole's disposal zone; |
| $\rho_{Bh}$ | is the dry bulk density of the borehole's disposal zone ($m^3$ /kg); |
| $V_{Bh}$ | is the volume of the borehole's disposal zone ($m^3$). |

### *XI.1.3.7. External Irradiation*

The annual individual dose to a human from external irradiation from soil ($D_{ExSoil}$, in Sv/y) is given by:

$$D_{ExSoil} = C_{Soil}\ O_{Out}\ DC_{Exts} \tag{54}$$

where:

| | |
|---|---|
| $C_{Soil}$ | is the concentration in the soil ($Bq/m^3$); |
| $O_{Out}$ | is the individual occupancy outdoors on the contaminated soil (h/y); |
| $DC_{Exts}$ | is the dose coefficient for external irradiation from soil ($Sv/h/Bq/m^3$). |

## XI.2. DEFECT SCENARIO

The mathematical model for this scenario is the same as that for the Design Scenario discussed in Appendix XI.1, although some different parameter values are used (Appendix XII).

## XI.3. REPRESENTING NEAR FIELD DEGRADATION

It is necessary to consider the degradation of the following near field components (see Table 11):

- The stainless steel capsule that contains the source container (the source container is assumed to have failed before disposal) and the stainless steel disposal container that contains the capsule; and
- The containment barrier, the disposal zone backfill and plug, the closure zone backfill, and the disturbed zone backfill.

Degradation can affect both the physical and chemical performance of the near field components.

### **XI.3.1. Physical performance**

### *XI.1.3.1. Capsule and disposal container*

Failure times for each component are specified in Appendix XII based upon the corrosion modelling reported in Appendix XI. The physical performance of each of these components could fail in a linear manner over a period of time. It could start at a user-defined time ($t_{PhysDegStart}$, in y) (when the water/gas tightness of the component is first breached) and end at a user-defined time ($t_{PhysDegEnd}$, in y) (when the component has totally failed and is fully degraded). Between these two times, linear failure could be assumed. However, corrosion model results discussed in Appendix I indicate that the physical performance of each components can be consider to occur essentially instantaneously. Nevertheless, flexibility in the model is maintained by adopting the linear failure model but setting $t_{PhysDegEnd}$ to be marginally greater than $t_{PhysDegStart}$.

Prior to the start of the failure of the stainless steel capsule none of the waste is available for release. However, once the capsule starts to fail (at time $t_{CapPhysDegStart}$, in y), the fraction of the waste available for release is assumed to start to increase in a linear manner until all of the waste is assumed to be available once the capsule is fully degraded ((at time $t_{CapPhysDegEnd}$, in y). Thus, the value of the fraction of waste available for release ($f$, unitless) is a function of time:

$$f(t) = 0 \qquad t < t_{CapPhysDegStart} \tag{55}$$

$$f(t) = 1 \qquad t \geq t_{CapPhysDegEnd} \tag{56}$$

$$f(t) = \frac{t - t_{CapPhysDegStart}}{t_{CapPhysDegEnd} - t_{CapPhysDegStart}} \qquad otherwise \tag{57}$$

### *XI.1.3.2. Containment barrier and backfill material*

The hydraulic conductivity and total porosity of the cement grout containment barrier and backfill material are assumed to increase due to physical degradation (e.g. cracking) and chemical degradation (e.g. calcium leaching and sulphate attack) for all scenarios (see Appendix VIII). These changes can be represented by the definition of ‘undegraded’ and ‘degraded’ values for both parameters. A function, $f_{PhysDeg}$, can be used to describe the transition of the values from the undegraded state prior to the start of degradation (at time $t_{MatPhysDegStart}$, in y) to the end of degradation (at time $t_{MatPhysDegEnd}$ , in y):

$$f_{Phys\,Deg}(t) = 0 \qquad t < t_{MatPhysDegStart} \tag{58}$$

$$f_{Phys\,Deg}(t) = 1 \qquad t \geq t_{MatPhysDegEnd} \tag{59}$$

$$f_{PhysDeg}(t) = \frac{t - t_{MatPhysDegStart}}{t_{MatPhysDegEnd} - t_{MatPhysDegStart}} \qquad otherwise \tag{60}$$

The value of hydraulic conductivity at a given time (*K(t)*, in m/y) can be determined using the function as follows:

$$K(t) = (1 - f_{Phys\,Deg}(t))\; K_{UnDeg} + f_{Phys\,Deg}(t)\; K_{Deg} \tag{61}$$

where $K_{UnDeg}$ and $K_{Deg}$ are the undegraded and degraded hydraulic conductivities, respectively (both in m/y).

The same approach can be used to calculate the total porosity ($\theta$, unitless):

$$\theta(t) = (1 - f_{Phys\,Deg}(t))\; \theta_{UnDeg} + f_{Phys\,Deg}(t)\; \theta_{Deg} \tag{62}$$

where $\theta_{UnDeg}$ and $\theta_{Deg}$ are the undegraded and degraded total porosities, respectively (both unitless).

## XI.3.2. Chemical performance

Degradation of the chemical performance of cement grout containment barrier and backfill material is assumed to occur in all scenarios. The processes that lead to chemical degradation, such as calcium leaching and sulphate attack, are implicitly rather than explicitly modelled. Failure times for each component are specified in Appendix XII based upon cement grout degradation model presented in Apppendix VIII. It is assumed that the chemical performance of each of these components does not degrade instantaneously; degradation is assumed to occur in a linear manner over a period of time. It is assumed to start at a user-defined time ($t_{ChemDegStart}$, in y) and end at a user-defined time ($t_{ChemDegEnd}$, in y). Between these two times, linear degradation is assumed.

It is assumed that chemical evolution of the cement grout near field affects the near field sorption coefficients. An approach similar to that used for modelling the change in hydraulic conductivity and porosity is used to represent changes in sorption coefficients. A function, $f_{ChemDeg}$, can be used to describe the transition of the values from the undegraded state prior to the start of degradation (at time $t_{MatChemDegStart}$, in y) to the end of degradation (at time $t_{MatChemDegEnd}$, in y):

$$f_{Chem\,Deg}(t) = 0 \qquad t < t_{MatChemDegStart} \tag{63}$$

$$f_{Chem\,Deg}(t) = 1 \qquad t \geq t_{MatChemDegEnd} \tag{64}$$

$$f_{ChemDeg}(t) = \frac{t - t_{MatChemDegStart}}{t_{MatChemDegEnd} - t_{MatChemDegStart}} \qquad otherwise \tag{65}$$

The value of a radionuclide's near field sorption coefficient at a given time ($K_d(t)$, in $m^3$/kg) can be determined using the function as follows:

$$K_d(t) = (1 - f_{ChemDeg}(t))\; K_{dUnDeg} + f_{ChemDeg}(t)\; K_{dDeg} \tag{66}$$

where $K_{dUnDeg}$ and $K_{dDeg}$ are the undegraded and degraded sorption coefficients, respectively (both in $m^3$/kg).

# APPENDIX XII
# ASSESSMENT DATA

Table 61 lists the parameters used in the mathematical models described in Appendix XI and identifies the table in which the associated data can be found.

TABLE 61. PARAMETERS FOR THE MATHEMATICAL MODEL AND LOCATION OF ASSOCIATED VALUES

| Symbol | Definition | Units | Value |
|---|---|---|---|
| $\Delta_c$ | a representative diffusion length between the upstream and downstream compartments | m | Tables 75, 79 and 80 |
| $\Delta_U$ | a representative diffusion length between the capsule compartment and the adjacent compartment | m | Table 75 |
| $\delta$ | depth of the matrix compartment | m | Tables 79 and 80 |
| $\partial H/\partial x$ | hydraulic gradient | - | Tables 73 and 68 |
| $\varepsilon$ | degree of saturation | - | Tables 73, 78, 82 |
| $\varepsilon_{Rn}$ | Rn emanating fraction | - | Table 74 |
| $\theta$ | total porosity | - | Tables 73, 78, 82 |
| $\theta_{Deg}$ | total porosity of degraded cement grout | - | Table 73 |
| $\theta_H$ | total porosity of the base of the house | - | Table 82 |
| $\theta_{Undeg}$ | total porosity of undegraded cement grout | - | Table 73 |
| $\vartheta_w$ | water-filled porosity | - | Calculated using Equation 15 |
| $\vartheta_{wA}$ | water-filled porosity of the compartment adjacent to the capsule compartment | - | Calculated using Equation 15 |
| $\vartheta_{wB}$ | water-filled porosity of the downstream compartment | - | Calculated using Equation 15 |
| $\vartheta_{wc}$ | water-filled porosity of capsule compartment | - | Calculated using Equation 15 |
| $\vartheta_{wDC}$ | water-filled porosity of the contaminated drill core | - | Calculated using Equation 15 |
| $\vartheta_{wf}$ | water-filled fracture porosity | - | Calculated using Equation 15 |
| $\vartheta_{wm}$ | water-filled matrix porosity | - | Calculated using Equation 15 |
| $\vartheta_{wSoil}$ | water-filled porosity of the soil | - | Calculated using Equation 15 |
| $\vartheta_{wU}$ | water-filled porosity of the upstream compartment | - | Calculated using Equation 15 |
| $\vartheta_{ww}$ | water-filled porosity of the compartment from which the water is abstracted | - | Calculated using Equation 15 |
| $\lambda_A$ | advective transfer rate in the saturated zone | /y | Calculated using Equation 26 |
| $\lambda_{DiffD}$ | forward (downstream) diffusive transfer rate | /y | Calculated using Equation 28 |
| $\lambda_{DiffRelB}$ | backward diffusive transfer rate from the compartment adjacent to the capsule | /y | Calculated using Equation 24 |
| $\lambda_{DiffRelF}$ | forward diffusive release rate from capsule compartment | /y | Calculated using Equation 23 |
| $\lambda_{DiffU}$ | backward (upstream) diffusive transfer rate | /y | Calculated using Equation 29 |
| $\lambda_{EROS}$ | transfer rate due to erosion | /y | Calculated using Equation 34 |
| $\lambda_{irrig}$ | transfer rate in groundwater abstracted from the geosphere to soil due to irrigation of crops | /y | Calculated using Equation 32 |
| $\lambda_{mr}$ | diffusive transfer rate from matrix to fracture | /y | Calculated using Equation 31 |
| $\lambda_N$ | decay constant for radionuclide *N* | /y | Table 64 |
| $\lambda_{other}$ | transfer rate due to abstraction of water for watering of animals and domestic purposes | /y | Calculated using Equation 32 |
| $\lambda_{Perc}$ | advective and dispersive transfer rate through the unsaturated zone | /y | Calculated using Equation 25 |
| $\lambda_{rm}$ | diffusive transfer rate from fracture to matrix | /y | Calculated using Equation 30 |
| $\lambda_{Rn}$ | Rn-222 decay rate | /y | Table 64 |
| $\lambda_{SatLeach}$ | advective and dispersive transfer rate from capsule containing the source due to groundwater flow | /y | Calculated using Equation 21 |
| $\lambda_{UnsatLeach}$ | advective and dispersive transfer rate from capsule containing the source due to water percolation | /y | Calculated using Equation 17 |
| $\lambda_v$ | ventilation rate of the house | /y | Table 82 |
| $\mu_{crop}$ | interception fraction for irrigation water on the crop | - | Table 84 |
| $\rho$ | dry bulk density | $kg/m^3$ | Calculated using Equation 20 |
| $\rho_{Bh}$ | dry bulk density of the borehole's disposal zone | $kg/m^3$ | Calculated using Equation 20 |
| $\rho_g$ | grain density | $kg/m^3$ | Tables 73, 78,82, 65 and 67 |
| $\rho_{Soil}$ | dry bulk density of the soil | $kg/m^3$ | Calculated using Equation 20 |
| $\rho_{Wat}$ | density of water | $kg/m^3$ | 1000 $kg/m^3$ |
| $\tau_{gas}$ | timescale over which gas production is assumed to take place | y | Table 74 |
| $\Phi_{gas}$ | the flux of gas into the house | $Bq/m^2/y$ | Calculated using Equation 49 |
| $\Phi_{Rn}$ | the flux of Rn-222 into the house | $Bq/m^2/y$ | Calculated using Equation 52 |

TABLE 61. PARAMETERS FOR THE MATHEMATICAL MODEL AND LOCATION OF ASSOCIATED VALUES (cont.)

| *Symbol* | Definition | Units | Value |
|---|---|---|---|
| $X_{Anm}$ | radionuclide concentration in the animal product | Bq/kg fresh weight of product | Calculated using Equation 45 |
| $\chi_{Crop}$ | radionuclide concentration in the crop | Bq/kg fresh weight | Calculated using Equation 43 |
| $\chi_{Dry}$ | radionuclide concentration in the surface soil | Bq/kg dry weight | Calculated using Equation 36 |
| $\chi_{RaBh}$ | concentration of Ra-226 in the borehole's disposal zone | Bq/kg dry weight | Calculated using Equation 53 |
| $\chi_{Wet}$ | radionuclide concentration in the surface soil | Bq/kg wet weight | Calculated using Equation 41 |
| $A$ | flow wetted surface area per unit volume of rock | $m^2/m^3$ | Tables 62 and 63 |
| $A_b$ | cross-sectional area of the disposal borehole | $m^2$ | Table 74 |
| $A_{diff}$ | cross-sectional area relevant to the diffusive release from the capsule | $m^2$ | Table 75 |
| $Amount$ | amount of a radionuclide in a compartment | Bq or moles | Calculated using Equation 1 |
| $Amount_{RaBh}$ | amount of Ra-226 in the borehole's disposal zone | Bq | Calculated using Equation 1 |
| $Amount_{Soil}$ | amount of a radionuclide in the soil | Bq | Calculated using Equation 1 |
| $Amount_w$ | amount of a radionuclide in the compartment from which the water is abstracted | Bq | Calculated using Equation 1 |
| $A_U$ | cross-sectional area relevant to the diffusive transfer from the upstream compartment | $m^2$ | Tables 72 and 73 |
| $BR_{gas}$ | breathing rate of the human in the house | $m^3/h$ | Table 83 |
| $C_{Air}$ | concentration of a radionuclide in the air above the soil | $Bq/m^3$ | Calculated using Equation 35 |
| $c_{Dust}$ | dust level in the air above the soil compartment | $kg/m^3$ | Table 82 |
| $CF_{Anm}$ | concentration factor for the animal product | d/kg fresh weight of product | Table 72 |
| $CF_{crop}$ | concentration factor for the crop | Bq/kg fresh weight of crop/Bq/kg (dry weight of soil) | Table 68 |
| $C_{gas}$ | concentration of gas in the house | $Bq/m^3$ | Calculated using Equation 48 |
| $C_r$ | corrosion/dissolution rate of source | m/y | Table 73 |
| $C_{Rnair}$ | concentration of Rn-222 in the house | $Bq/m^3$ | Calculated using Equation 51 |
| $C_{Soil}$ | radionuclide concentration in the soil | $Bq/m^3$ | Calculated using Equation 37 |
| $C_W$ | radionuclide concentration in the abstracted water | $Bq/m^3$ | Calculated using Equation 39 |
| $D$ | depth of the compartment from which erosion takes place | m | Table 82 |
| $D_{Anm}$ | annual individual effective dose to a human from the consumption of animal produce | Sv/y | Calculated using Equation 44 |
| $D_{Bh}$ | diffusion length for Rn in the borehole | m | Table 74 |
| $d_{Bh}$ | thickness of the borehole's closure zone | m | Table 74 |
| $DC_{Exts}$ | dose coefficient for external irradiation from soil | $Sv/h/Bq/m^3$ | Table 65 |
| $DC_{Ing}$ | dose coefficient for ingestion | Sv/Bq | Table 65 |
| $DC_{Inh}$ | dose coefficient for inhalation | Sv/Bq | Table 65 |
| $D_{Crop}$ | annual individual effective dose to a human from the consumption of a crop | Sv/y | Calculated using Equation 42 |
| $D_{Dust}$ | annual individual dose to a human from the inhalation of dust | Sv/y | Calculated using Equation 46 |
| $D_{EffA}$ | effective diffusion coefficient for the compartment adjacent to the capsule compartment | $m^2/y$ | Table 76 |
| $D_{Effc}$ | effective diffusion coefficient for the capsule compartment | $m^2/y$ | Table 76 |
| $D_{EffD}$ | effective diffusion coefficient for the downstream compartment | $m^2/y$ | Table 76 |
| $D_{Effm}$ | effective diffusion coefficient for the matrix compartment | $m^2/y$ | Table 76 |
| $D_{EffU}$ | effective diffusion coefficient for the upstream compartment | $m^2/y$ | Table 76 |
| $d_{EROS}$ | erosion rate for the compartment | $m^2/y$ | Table 82 |
| $D_{ExSoil}$ | annual individual dose to a human from external irradiation from soil | $m^2/y$ | Calculated using Equation 54 |
| $D_{gas}$ | annual individual effective dose from inhalation of gases (other than Rn-222) | $m^2/y$ | Calculated using Equation 47 |
| $Dil$ | contribution of water from abstraction borehole to the total water demand | - | Table 81 |
| $D_{inhg}$ | dose coefficient for inhalation of the gaseous form of the radionuclide | Sv/Bq | Table 65 |
| $D_{inhRn}$ | dose coefficient for inhalation of Rn-222 | $Sv/h/Bq/m^3$ | Table 65 |

TABLE 61. PARAMETERS FOR THE MATHEMATICAL MODEL AND LOCATION OF ASSOCIATED VALUES (cont.)

| *Symbol* | Definition | Units | Value |
|---|---|---|---|
| $d_{Irr}$ | depth of irrigation water applied to the crop | m/y | Table 84 |
| $D_{Rn}$ | annual individual effective dose from inhalation of Rn-222 | Sv/y | Calculated using Equation 50 |
| $d_{Rn}$ | effective diffusion of Rn | $m^2/y$ | Table 82 |
| $D_{Sed}$ | annual individual dose to a human from the ingestion of soil | Sv/y | Calculated using Equation 40 |
| $D_{Wat}$ | annual individual effective dose from the consumption of drinking water | Sv/y | Calculated using Equation 38 |
| $f$ | fraction of the waste that is available for release | - | Calculated using Equation 55 to Equation 57 |
| $f_{ChemDeg}$ | extent of chemical degradation | - | Calculated using Equation 63 to Equation 65 |
| $f_g$ | total fraction of the inventory of a gas producing radionuclide which is assumed to be released as gas | - | Table 74 |
| $f_{PhysDeg}$ | extent of physical degradation | - | Calculated using Equation to Equation 60 |
| $f_{Prep}$ | fraction of external contamination on the crop lost due to food processing | - | Table 71 |
| $f_{Trans}$ | fraction of activity transferred from external to internal plant surfaces | - | Table 70 |
| $I_g$ | disposed inventory of the radionuclide, decay-corrected to the start time of the capsule's physical failure | Bq | Calculated from $I\,e^{-\lambda t}$ where $I$ is the initial inventory disposed (1E+12 Bq, Section 3.1.1), $\lambda$ (/y) is the decay constant (Table 64), and $t$ (y) is the start time of the capsule's physical failure (Tables 76 and 77) |
| $Ing_{Anm}$ | individual ingestion rate of animal product | kg fresh weight of product /y | Table 83 |
| $Ing_{AW}$ | consumption rate of water by the animal | $m^3/d$ | Table 83 |
| $Ing_{Crop}$ | individual ingestion rate of the crop | kg fresh weight /y | Table 83 |
| $Ing_{Sed}$ | individual inadvertent ingestion rate of soil | kg wet weight $h^{-1}$ | Table 83 |
| $Ing_{Wat}$ | individual ingestion rate of freshwater | $m^3/y$ | Table 83 |
| $Inh_{Sed}$ | breathing rate of the human on the contaminated soil | $m^3/h$ | Table 83 |
| $K$ | hydraulic conductivity of a medium | m/y | Tables 73 and 78<br>For cement grout in near field calculated using Equation 61 |
| $K_c$ | hydraulic conductivity of the capsule compartment | m/y | Table 73 |
| $Kd$ | sorption coefficient of the element in the compartment | $m^3/kg$ | Table 67<br>For cement grout in near field calculated using Equation 66 |
| $Kd_{Deg}$ | sorption coefficient of degraded cement grout | $m^3/kg$ | Table 67 |
| $K_{Deg}$ | Hydraulic conductivity of degraded cement grout backfill | m/y | Table 73 |
| $Kd_{UnDeg}$ | sorption coefficient of undegraded cement | $m^3/kg$ | Table 67 |
| $K_{UnDeg}$ | Hydraulic conductivity of undegraded cement grout backfill | m/y | Table 73 |
| $L$ | length of compartment in the direction of water flow | m | Tables 75, 79 and 80 |
| $L_c$ | length of capsule compartment in the direction of water flow | m | Table 75 |
| $O_{gas}$ | individual occupancy in the house | h/y | Table 83 |
| $O_{Out}$ | The individual occupancy on the soil | h/y | Table 83 |
| $Q$ | Darcy velocity of groundwater through a compartment | m/y | Calculated using Equation 27 |
| $q_c$ | Darcy velocity of groundwater through the capsule compartment | m/y | Calculated using Equation 22 |
| $q_{PERC}$ | annual percolation rate through the capsule compartment | m/y | Table 73 |
| $r$ | initial radius of the source | m | Table 73 |
| $R$ | element dependent retardation of the compartment | - | Calculated using Equation 16 |
| $R_A$ | element dependent retardation of the compartment adjacent to the capsule compartment | - | Calculated using Equation 16 |
| $R_c$ | element dependent retardation of the capsule compartment | - | Calculated using Equation 16 |
| $R_D$ | element dependent retardation of the downstream compartment | - | Calculated using Equation 16 |
| $R_m$ | element dependent retardation of the matrix compartment | - | Calculated using Equation 16 |
| $R_{Soil}$ | element dependent retardation of the soil compartment | - | Calculated using Equation 16 |
| $R_U$ | element dependent retardation of the upstream compartment | - | Calculated using Equation 16 |
| $R_w$ | element dependent retardation of the compartment from which the domestic and agricultural water is abstracted | - | Calculated using Equation 16 |
| $s_{Crop}$ | soil contamination on the crop | kg dry weight soil $kg^{-1}$ fresh weight of crop | Table 84 |
| $T$ | is the interval between irrigation and harvest | y | Table 84 |

TABLE 61. PARAMETERS FOR THE MATHEMATICAL MODEL AND LOCATION OF ASSOCIATED VALUES (cont.)

| *Symbol* | Definition | Units | Value |
|---|---|---|---|
| $t_{CapPhysDegStart}$ | time at which failure of the capsule's physical performance starts | y | Tables 76 and 77 |
| $t_{CapPhysDegEnd}$ | time at which failure of the capsule's physical performance ends | y | Tables 76 and 77 |
| $t_{ChemDegStart}$ | time at which failure of a barrier's chemical performance starts | y | Tables 76 and 77 |
| $t_{ChemDegEnd}$ | time at which failure of a barrier's chemical performance starts | y | Tables 76 and 77 |
| $t_{Delay}$ | average radon travel time from the soil into the house | y | Table 82 |
| $t_{MatChemDegStart}$ | time at which failure of the cement grout containment barrier's and cement grout backfill's chemical performance starts | y | Tables 76 and 77 |
| $t_{MatChemDegEnd}$ | time at which failure of the cement grout containment barrier's and cement grout backfill's chemical performance ends | y | Tables 76 and 77 |
| $t_{MatPhysDegStart}$ | time at which failure of the containment barrier and backfill material's physical performance starts | y | Tables 76 and 77 |
| $t_{MatPhysDegEnd}$ | time at which failure of the containment barrier and backfill material's physical performance ends | y | Tables 76 and 77 |
| $t_{PhysDegStart}$ | time at which failure of a barrier's physical performance starts | y | Tables 76 and 77 |
| $t_{PhysDegEnd}$ | time at which failure of a barrier's physical performance ends | y | Tables 76 and 77 |
| $V$ | volume of the compartment | $m^3$ | Derived from dimensions, Tables 75, 79, 80 and 82 |
| $V_A$ | volume of the compartment adjacent to the capsule compartment | $m^3$ | Derived from dimensions, Table 75 |
| $V_{Bh}$ | volume of the borehole's disposal zone | $m^3$ | Derived from dimensions, Section 3.1.2 |
| $V_c$ | volume of the capsule compartment | $m^3$ | Derived from dimensions, Table 5 |
| $V_D$ | volume of the downstream compartment | $m^3$ | Derived from dimensions, Tables 75, 79 and 80 |
| $V_{DC}$ | volume of the contaminated drill core | $m^3$ | Table 84 |
| $V_h$ | total volume of the house | $m^3$ | Derived from dimensions, Table 82 |
| $V_{irrig}$ | is the volume of irrigation water that reaches the soil | $m^3/y$ | Table 82 |
| $V_{other}$ | volume of water abstracted for watering of animals and domestic purposes (includes the volume of irrigation water not reaching the soil due to interception by crops) | $m^3/y$ | Table 82 |
| $V_{Soil}$ | volume of the compartment representing the soil | $m^3$ | Derived from dimensions, Table 82 |
| $V_w$ | volume of compartment from which water is abstracted | $m^3$ | Derived from dimensions, Tables 79 and 80 |
| $V_U$ | volume of the upstream compartment | $m^3$ | Derived from dimensions, Tables 75, 79 and 80 |
| $W_{crop}$ | removal rate of irrigation water from the crop by weathering processes (weathering rate) | /y | Table 69; |
| $Y_{Crop}$ | yield of the crop | kg (fresh weight of crop) $m^{-2/y}$ | Table 84 |

## XII.1. INVENTORY AND RADIONUCLIDE DATA

TABLE 62. RADIONUCLIDES DISPOSED AND ASSOCIATED DAUGHTERS CONSIDERED

| Disposed radionuclide[a] | Short lived daughter(s)[b] | Daughter(s) |
|---|---|---|
| H-3 | | |
| Co-60 | | |
| Ni-63 | | |
| Kr-85 | | |
| Sr-90 | * | |
| Cs-137 | * | |
| Pb-210 | * | |
| Ra-226 | * | →Pb-210*→ Po-210 |
| Pu-238 | | →U-234→ Th-230→ Ra-226*→ Pb-210*→ Po-210 |
| Pu-239 | | →U-235*→Pa-231→Ac-227* |
| Am-241 | | →Np-237→ Pa-233→ U-233→ Th-229* |

**Notes:** [a] For each disposed radionuclide, an inventory of 1 TBq per waste package is assumed (see Section 3.1.1). It is also assumed that there are 50 waste packages per borehole (see Section 3.1.2), giving a total inventory of 50 TBq for each radionuclide.

[b] * indicates a daughter with a half-life of less than 25 days (see Table 63).

TABLE 63. SHORT LIVED DAUGHTERS WITH HALF-LIVES OF LESS THAN 25 DAYS ASSUMED TO BE IN SECULAR EQUILIBRIUM WITH THEIR PARENTS

| Parent | Short lived daughters |
|---|---|
| Sr-90 | → Y-90 |
| Cs-137 | → (branching ratio 0.94) Ba-137m |
| Pb-210 | → Bi-210 |
| Ra-226 | → Rn-222→ Po-218 → (branching ratio 0.9998) Pb-214 → Bi-214 → (branching ratio 0.9998) Po-214 |
| | → (branching ratio 0.0002) At-218 → Bi-214 → (branching ratio 0.9998) Po-214 |
| Ac-227 | → (branching ratio 0.0138) Fr-223 →(branching ratio 0.9862) Th-227 →Ra-223→Rn-219→Po-215→Pb-211→ Bi-211 |
| | → (branching ratio 0.9972) →Tl-207 → (branching ratio 0.0028) Po-211 |
| Th-229 | → Ra-225 → Ac-225 → Fr-221 → At-217 → Bi-213 → (branching ratio 0.9784) Po-213 → Pb-209 |
| | → (branching ratio 0.0216) Tl-209 → Pb-209 |
| U-235 | → Th-231 |

TABLE 64. RADIONUCLIDE HALF-LIVES AND DECAY RATES

| Radionuclide | Half-life (y)[a] | Decay rate (/y)[b] |
|---|---|---|
| H-3 | 1.24E+01 | 5.59E-02 |
| Co-60 | 5.27E+00 | 1.32E-01 |
| Ni-63 | 9.60E+01 | 7.22E-03 |
| Kr-85 | 1.07E+01 | 6.48E-02 |
| Sr-90 | 2.91E+01 | 2.38E-02 |
| Cs-137 | 3.00E+01 | 2.31E-02 |
| Pb-210 | 2.23E+01 | 3.11E-02 |
| Po-210 | 3.79E-01 | 1.83E+00 |
| Rn-222 | 1.05E-02 | 6.60E+01 |
| Ra-226 | 1.60E+03 | 4.33E-04 |
| Ac-227 | 2.18E+01 | 3.18E-02 |
| Th-229 | 7.34E+03 | 9.44E-05 |
| Th-230 | 7.70E+04 | 9.00E-06 |
| Pa-231 | 3.28E+04 | 2.11E-05 |
| Pa-233 | 7.39E-02 | 9.38E+00 |
| U-233 | 1.59E+05 | 4.36E-06 |
| U-234 | 2.45E+05 | 2.83E-06 |
| U-235 | 7.04E+08 | 9.85E-10 |
| Np-237 | 2.14E+06 | 3.24E-07 |
| Pu-238 | 8.77E+01 | 7.90E-03 |
| Pu-239 | 2.41E+04 | 2.88E-05 |
| Am-241 | 4.32E+02 | 1.60E-03 |

**Notes:** [a] Data from Ref. [143].

[b] Decay constant = $\frac{\ln 2}{half\ life}$

TABLE 65. RADIONUCLIDE DOSE COEFFICIENTS FOR INGESTION, INHALATION AND EXTERNAL IRRADIATION

| Radionuclide | Dose coefficients for adults[a] | | | |
|---|---|---|---|---|
| | Ingestion (Sv/Bq)[b] | Inhalation (Sv/Bq)[b] | External irradiation from soil (Sv/h/Bq/m$^3$)[e] | Water immersion (Sv/h/Bq/m$^3$)[f] |
| H-3 | 1.8E-11 | 4.5E-11 | 0 | 0 |
| | | 1.8E-11 (HTO gas) | | |
| Co-60 | 3.4E-09 | 1.0E-08 | 3.0E-13 | 9.3E-13 |
| Ni-63 | 1.5E-10 | 1.3E-09 | 0 | 0 |
| Kr-85 | 0 | 9.2E-13[c] | 0 | 0 |
| Sr-90 | 3.1E-08 | 3.8E-08 | 7.9E-16 | 4.0E-15 |
| Cs-137 | 1.3E-08 | 4.6E-09 | 6.2E-14 | 2.0E-13 |
| Pb-210 | 6.9E-07 | 1.2E-06 | 1.5E-16 | 1.5E-15 |
| Po-210 | 1.2E-06 | 3.3E-06 | 9.5E-19 | 3.0E-18 |
| Ra-226 | 2.8E-07 | 3.5E-06 | 2.1E-13 | 6.5E-13 |
| | | 9.0E-09[d] | | |
| Ac-227 | 1.2E-06 | 5.7E-04 | 8.6E-18 | 1.4E-13 |
| Th-229 | 6.1E-07 | 8.6E-05 | 2.9E-14 | 1.1E-13 |
| Th-230 | 2.1E-07 | 1.4E-05 | 2.1E-17 | 1.2E-16 |
| Pa-231 | 7.1E-07 | 1.4E-04 | 3.4E-15 | 1.2E-14 |
| Pa-233 | 8.7E-10 | 3.9E-09 | 1.8E-14 | 6.7E-14 |
| U-233 | 5.1E-08 | 3.5E-06 | 2.4E-17 | 1.1E-16 |
| U-234 | 4.9E-08 | 3.5E-06 | 6.6E-18 | 5.0E-17 |
| U-235 | 4.7E-08 | 3.1E-06 | 1.3E-14 | 5.5E-14 |
| Np-237 | 1.1E-07 | 2.3E-05 | 1.4E-15 | 7.2E-15 |
| Pu-238 | 2.3E-07 | 4.6E-05 | 2.3E-18 | 2.9E-17 |
| Pu-239 | 2.5E-07 | 5.0E-05 | 5.1E-18 | 2.8E-17 |
| Am-241 | 2.0E-07 | 4.2E-05 | 7.2E-16 | 5.5E-15 |

**Notes:** [a] Values include effects of short lived (half-life less than 25 days) daughters not explicitly listed, assuming secular equilibrium at time of intake or exposure. A list of short lived daughters is given in Table 63.

[b] Data taken from Ref. [141].

[c] Value for gas rather than particulate, units are in Sv/h/Bq/m$^3$.

[d] Value for Rn-222 gas taken from Ref. [143]. Units are in Sv/h/Bq/m$^3$.

[e] Data taken from Ref. [142][127] assuming contamination to an infinite depth.

[f] Data taken from Ref. [127].

## XII.2. ELEMENT-DEPENDENT DATA

TABLE 66. EFFECTIVE DIFFUSION COEFFICIENTS ($M^2$/Y)

| Element | Capsule[c] | Cement[d] | | High Flow Rate Fractured System[e] | High and Medium Flow Rate Porous System[d] | Low Flow Rate System[d] |
|---|---|---|---|---|---|---|
| | | Undegraded | Degraded | | | |
| H | 1E-1 | 8E-5 | 4E-3 | 2E-6[d] | 2E-2 | 3E-3 |
| Be[a] | 4E-2 | 8E-5 | 4E-3 | 1E-5 | 2E-2 | 3E-3 |
| Co | 4E-2 | 8E-5 | 4E-3 | 9E-7[f] | 2E-2 | 3E-3 |
| Ni | 4E-2 | 8E-5 | 4E-3 | 9E-7 | 2E-2 | 3E-3 |
| Sr | 4E-2 | 8E-5 | 4E-3 | 1E-5 | 2E-2 | 3E-3 |
| Cs | 8E-2 | 8E-5 | 4E-3 | 3E-5 | 2E-2 | 3E-3 |
| Pb | 8E-2 | 8E-5 | 4E-3 | 1E-6[g] | 2E-2 | 3E-3 |
| Po | 8E-2 | 8E-5 | 4E-3 | 1E-6[h] | 2E-2 | 3E-3 |
| Ra | 8E-2 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |
| Ac[b] | 1E-1 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |
| Th | 1E-1 | 8E-5 | 4E-3 | 2E-7 | 2E-2 | 3E-3 |
| Pa | 1E-1 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |
| U | 1E-1 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |
| Np | 1E-1 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |
| Pu | 1E-1 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |
| Am | 1E-1 | 8E-5 | 4E-3 | 1E-6 | 2E-2 | 3E-3 |

**Notes:** [a] Sr used as an analogue.

[b] Am used as an analogue.

[c] Data for free water diffusion from Ref. [32]. Used for capsule compartment since capsule is assumed not to be backfilled (see Section 3.1.2).

[d] Data from Ref. [129].

[e] Data from Ref. [128].

[f] Ni used as an analogue.

[g] Sn used as an analogue.

[h] Pb used as an analogue.

## TABLE 67. SORPTION COEFFICIENTS ($M^3$ $KG^{-1}$)

| Element | Capsule[b] | Cement[c] | | Unsaturated Zone[f] | High and medium flow saturated zone[j] | Low flow saturated zone[j] | High values for soil[k] |
|---|---|---|---|---|---|---|---|
| | | Undegraded | Degraded | | | | |
| H[a] | 0 | 0 | 0 | 0 | 0 | 0 | 0.0001 |
| Be | 0 | 0.1[d] | 0.01[d] | 0.5[g] | 0.5[g] | 0.05[g] | 1.3 |
| Co | 0 | 0.1 | 0.01 | 0.1[h] | 0.1[h] | 1[h] | 0.54 |
| Ni | 0 | 0.1 | 0.01 | 0.1[h] | 0.1[h] | 1[h] | 0.67 |
| Sr | 0 | 0.1 | 0.01 | 0.005[g] | 0.005[g] | 0.001[g] | 0.11 |
| Cs | 0 | 0.001 | 0.005 | 0.05 | 0.05 | 0.01 | 1.8 |
| Pb | 0 | 0.5 | 0.1 | 0.1 | 0.1 | 1 | 0.54 |
| Po | 0 | 0.5 | 0.1 | 0.1[i] | 0.1[i] | 1[i] | 2.7 |
| Ra | 0 | 0.05 | 0.05 | 0.5 | 0.5 | 0.05 | 9.0 |
| Ac | 0 | 5 | 1 | 5 | 5 | 5 | 2.4 |
| Th | 0 | 5 | 1 | 1 | 1 | 1 | 5.4 |
| Pa | 0 | 0.5 | 0.1 | 1 | 1 | 1 | 2.7 |
| U | 0 | 1/5[e] | 0.1/1[e] | 1 | 1 | 1 | 1.5 |
| Np | 0 | 2/5[e] | 0.2/1[e] | 1 | 1 | 1 | 0.055 |
| Pu | 0 | 5 | 1 | 1 | 1 | 1 | 4.9 |
| Am | 0 | 5 | 1 | 5 | 5 | 5 | 8.1 |

**Notes:** 1. Data from Ref. [130].

[a] Assumed not to be sorbed in the geosphere.

[b] Capsule is assumed not to be backfilled and so has no sorption properties (see Section 3.1.2).

[c] Data from Ref. [129].

[d] Sr used as an analogue.

[e] First value is for oxidising conditions, second is for reducing conditions.

[f] Assumed to be the same as high/medium flow saturatesd zone.

[g] In the absence of data in Ref. [131], it is assumed that Sr sorption values are an order of magnitude lower than Cs values, consistent with the information given in Refs [130].

[h] Pd used as an analogue.

[i] Pb used as an analogue.

[j] Data from Ref. [131]. For high and medium flow saturated zones use data for sandstone with fresh type groundwater in [131]. For low flow saturated zone use data for mudstone with saline type groundwater in Ref. [131].

[k] Data from Ref. [23].

## TABLE 68. SOIL TO PLANT CONCENTRATION FACTORS (BQ/KG FRESH WT/BQ/KG DRY SOIL) FOR CROPS

| Element | Root vegetables[a] | Green vegetables[a] |
|---|---|---|
| H | 5E+0 | 5E+0 |
| Be | 1E-3 | 2E-3 |
| Co | 3E-2 | 3E-2 |
| Ni | 3E-2 | 3E-2 |
| Sr | 9E-2 | 3E+0 |
| Cs | 3E-2 | 3E-2 |
| Pb | 1E-2 | 1E-2 |
| Po | 2E-4 | 2E-4 |
| Ra | 4E-2 | 4E-2 |
| Ac | 1E-3 | 1E-3 |
| Th | 5E-4 | 5E-4 |
| Pa | 4E-2 | 4E-2 |
| U | 1E-3 | 1E-3 |
| Np | 1E-3 | 1E-2 |
| Pu | 1E-3 | 1E-4 |
| Am | 1E-3 | 1E-3 |

**Notes:** [a] Data from Ref. [23].

TABLE 69. WEATHERING RATES (/Y)

| Element | Root vegetables[a] | Green vegetables[a] |
|---|---|---|
| H | 1.8E+1 | 1.8E+1 |
| Be | 1.8E+1 | 1.8E+1 |
| Co | 1.8E+1 | 1.8E+1 |
| Ni | 1.8E+1 | 1.8E+1 |
| Sr | 1.8E+1 | 1.8E+1 |
| Cs | 1.8E+1 | 1.8E+1 |
| Pb | 1.8E+1 | 1.8E+1 |
| Po | 1.8E+1 | 1.8E+1 |
| Ra | 1.8E+1 | 1.8E+1 |
| Ac | 1.8E+1 | 1.8E+1 |
| Th | 1.8E+1 | 1.8E+1 |
| Pa | 1.8E+1 | 1.8E+1 |
| U | 1.8E+1 | 1.8E+1 |
| Np | 1.8E+1 | 5.1E+1 |
| Pu | 1.8E+1 | 5.1E+1 |
| Am | 1.8E+1 | 5.1E+1 |

**Notes:** [a] Data taken from Ref. [142].

## TABLE 70. FRACTION OF ACTIVITY TRANSFERRED FROM EXTERNAL TO INTERNAL PLANT SURFACES (-)

| Element | Root vegetables[b] | Green vegetables[b] |
|---|---|---|
| H | 2.0E-2 | 2.3E-2 |
| Be | 9.9E-2 | 1.8E-1 |
| Co | 1.7E-1 | 1.8E-1 |
| Ni | 3.9E-2 | 3.7E-1 |
| Sr | 1.4E-1 | 2.0E-1 |
| Cs | 3.0E-1 | 1.9E-1 |
| Pb | 2.2E-1 | 2.2E-1 |
| Po[a] | 2.2E-1 | 2.2E-1 |
| Ra | 9.9E-2 | 1.8E-1 |
| Ac | 2.9E-1 | 4.5E-1 |
| Th | 2.9E-1 | 3.8E-2 |
| Pa | 2.9E-1 | 4.5E-1 |
| U | 4.3E-2 | 3.6E-1 |
| Np | 2.9E-1 | 4.5E-1 |
| Pu | 4.3E-2 | 3.6E-1 |
| Am | 2.9E-1 | 2.8E-1 |

**Notes:** [a] Pb used as an analogue.

[b] Data taken from for root vegetables and leafy vegetables [132].

TABLE 71. FOOD PREPARATION LOSSES (-)

| Element | Root vegetables[a] | Green vegetables[b] |
|---|---|---|
| H | 0.0E+0 | 9.0E-1 |
| Be | 0.0E+0 | 9.0E-1 |
| Co | 0.0E+0 | 9.0E-1 |
| Ni | 0.0E+0 | 9.0E-1 |
| Sr | 0.0E+0 | 9.0E-1 |
| Cs | 0.0E+0 | 9.0E-1 |
| Pb | 0.0E+0 | 9.0E-1 |
| Po | 0.0E+0 | 9.0E-1 |
| Ra | 0.0E+0 | 9.0E-1 |
| Ac | 0.0E+0 | 9.0E-1 |
| Th | 0.0E+0 | 9.0E-1 |
| Pa | 0.0E+0 | 9.0E-1 |
| U | 0.0E+0 | 9.0E-1 |
| Np | 0.0E+0 | 9.0E-1 |
| Pu | 0.0E+0 | 9.0E-1 |
| Am | 0.0E+0 | 9.0E-1 |

**Notes:** [a] Data from Ref. [133].

[b] Data from Ref. [142].

TABLE 72. TRANSFER COEFFICIENTS TO ANIMAL PRODUCE

| Element | Beef (d/kg fresh weight)[a] | Cow's milk (d/l)[a] | Fish ($m^3$/kg fresh weight)[a] |
|---|---|---|---|
| H | 2.9E-2 | 1.5E-2 | 1E-3 |
| Be | 6.6E-4 | 2.6E-6 | 1E-1 |
| Co | 1.0E-2 | 3.0E-4 | 3E-1 |
| Ni | 5.0E-3 | 1.6E-2 | 1E-1 |
| Sr | 8.0E-3 | 2.8E-3 | 6E-2 |
| Cs | 5.0E-2 | 7.9E-3 | 2E+0 |
| Pb | 4.0E-4 | 3.0E-4 | 3E-1 |
| Po | 5.0E-3 | 3.4E-4 | 5E-2 |
| Ra | 9.0E-4 | 1.3E-3 | 5E-2 |
| Ac | 1.6E-4 | 4.0E-7 | 3E-2 |
| Th | 2.7E-3 | 5.0E-6 | 1E-1 |
| Pa | 5.0E-5 | 5.0E-6 | 1E-2 |
| U | 3.0E-4 | 4.0E-4 | 1E-2 |
| Np | 1.0E-3 | 5.0E-6 | 3E-2 |
| Pu | 1.0E-5 | 1.1E-6 | 3E-2 |
| Am | 4.0E-5 | 1.5E-6 | 3E-2 |

**Note:** [a] Data from Ref. [23]. Data for fish only used for variant calculation that assumes contaminated groundwater is used to supply a fish farm.

## XII.3. NEAR FIELD ELEMENT-INDEPENDENT DATA

TABLE 73. NEAR FIELD LIQUID RELEASE AND FLOW DATA

| Parameter | Units | Near field | | |
|---|---|---|---|---|
| | | Capsule | Cement | |
| | | | Undegraded | Degraded |
| Hydraulic conductivity | m/y | 1E+6[e] | 3.2E-1[h] | 3.2E+2[j] |
| Total porosity | - | 1.0E+0[f] | 1.0E-1[i] | 2.5E-1[i] |
| Grain density | $kg/m^3$ | 1.0E+3[g] | 2.4E+3[i] | 2.4E+3[i] |
| Hydraulic gradient in saturated zone[a] | - | | 0.01 | |
| Percolation rate in unsaturated zone[b] | m/y | | 5E-2 | |
| Degree of saturation in unsaturated zone[b] | - | | 3.3E-1 | |
| Initial radius of source[c] | m | | 5E-3 | |
| Corrosion/dissolution rate of source[d] | m/y | | 1E-8 | |

**Notes:** [a] See Table 8.

[b] See Section 3.2.1.

[c] Data from Ref. [135].

[d] Reference [131] gives a value of 1E-3 $g/m^2/d$ (approx. 1E-7 m/y) for glass at a temperature of 60°C and notes that the dissolution rate is about an order of magnitude lower at 20°C. It is conservatively assumed that the dissolution rate for ceramic will be the same as for glass.

[e] Nominal value adopted to ensure flow in the near field is not limited by the hydraulic conductivity of the capsule.

[f] Capsule assumed to be void space.

[g] Assumed to be the same as water.

[h] Based on data from Ref. [134] which gives range of 3.2E-3 to 3.2E-1 m/y for structural cement.

[i] Value consistent with the internal diameter of the capsule (see Table 5).

[j] Typical value for sand and gravel.

TABLE 74. NEAR FIELD GAS PARAMETERS

| Parameter | Units | Value |
|---|---|---|
| Timescale for gas production after failure of capsule[a] | y | 1E+2 |
| Cross-sectional area of borehole[b] | $m^2$ | 5.3E-2 |
| Fraction of radionuclide released as gas[c] | - | 1E+0 |
| Emanating fraction for Rn-222[a] | - | 2E-1 |
| Depth of closure zone[d] | m | 3E+1 |
| Diffusion length for Rn-222 in the borehole[a] | m | 1E+0 |

**Notes:**

[a] Data taken from Ref. [12].

[b] Assumes borehole diameter of 0.26 m (see Section 3.1.2).

[c] Conservative value.

[d] See Section 3.1.2.

TABLE 75. NEAR FIELD TRANSPORT DATA

| Compartment type | Disposal zone | Number of compartments | Length in direction of flow (m) | Area Perpendicular to flow ($m^2$) | Diffusion length (m)[q] | Area for diffusion ($m^2$)[s] |
|---|---|---|---|---|---|---|
| Capsule (containing source container) | Unsaturated | 10[c] | 5.50E-1[e] | 3.46E-4[n] | 2.58E-2 | 3.63E-2 |
| | Saturated | 1[d] | 1.05E-2[f] | 1.16E-1 (15) | 2.58E-2 | 3.63E-1 |
| Containment barrier | Unsaturated | 10[c] | 9.30E-1[g] | 8.33E-3[n] | 2.70E-2 | 3.36E-1 |
| | Saturated | 1[d] | 4.10E-2[h] | 9.58E-1[o] | 2.70E-2 | 3.36E+0 |
| Disposal zone (horizontally adjacent to capsule) | Unsaturated | 10[c] | 5.00E+0[i] | 5.01E-3 (16) | 3.14E-2 | 2.51E+0 |
| | Saturated | 1[d] | 1.25E-2[j] | 7.00E+0[o] | 3.14E-2 | 2.51E+1 |
| Disposal zone (vertically adjacent to capsule) | Unsaturated | 10[c] | 3.68E+0[k] | 1.04E-2[n] | -[r] | -[r] |
| | Saturated[a] | - | - | - | - | - |
| Disturbed zone (Backfill) | Unsaturated | 10[c] | 5.00E+0[l] | 3.30E-2[p] | 2.49E-1 | 4.08E+0 |
| | Saturated | 1[d] | 5.00E-2[m] | 1.30E+1[o] | 2.49E-1 | 4.08E+1 |
| Disposal zone (Plug) | Unsaturated | 1[c] | 5.00E-1[l] | 5.31E-2[n] | -[r] | -[r] |
| | Saturated[b] | - | - | - | - | - |

**Notes:**

[a] The material within the disposal zone vertically adjacent to the capsule is not explicitly modelled for saturated conditions as it is assumed not to participate in the transport of radionuclides.

[b] For saturated conditions, flow moves horizontally through the cement backfill of the disturbed zone between the casing and the borehole wall. The length of the disturbed zone in the direction of water flow is therefore the same as the distance between the borehole casing and borehole wall, i.e. 50 mm (Section 3.1.2). The plug is not modelled since it is assumed not to participate in the transport of radionuclides.

[c] The total vertical depth of the disposal zone is about 50 m (Section 3.1.2). For the unsaturated conditions, flow is vertically down the borehole and it is important to discretise the flow path of 50 m. It is considered appropriate to divide the 50 m length into 10 source compartments, 10 containment barrier compartments and 10 disposal zone compartments representing the disposal zone between the disposal containers, in order to provide adequate discretisation. The vertical flow will pass through the plug at the base of the borehole into the geosphere. It is assumed that the plug is 0.5 m thick and so can be represented by one compartment. In addition, flow will occur down the disposal zone between the disposal containers and the casing and down along the cement backfill between the casing and the borehole wall. These have a total length of 50 m and can be discretised into 10 compartments.

[d] For saturated conditions, flow is horizontal and so the flow path length through the disposals is equal to the diameter of the borehole (0.26 m) (Section 3.1.2) and so one compartment is sufficient to represent the flow path through each near field component.

[e] The length of the capsule is 110 mm (Table 5). For unsaturated conditions, flow percolates vertically down through all 50 capsules giving a total length of 5.5 m. This is divided between 10 compartments, giving a length in the direction of water flow of 0.55 m for each capsule compartment.

[f] The radius of the capsule is 10.5 mm (Table 5). For saturated conditions, flow moves horizontally through the capsules giving a length in the direction of groundwater flow of 0.0105 m for the capsule compartment.

[g] For unsaturated conditions, flow percolates vertically down through the borehole. The length of each cement grout containment barrier in the direction of water flow is 186 mm (Table 5). Over all 50 containers this gives a total length of 9.3 m. This is divided between 10 compartments, gives a length in the direction of water flow of 0.93 m for each cement grout containment barrier compartment.

[h] For saturated conditions, flow moves horizontally through the containment barrier. The length of the cement grout containment barrier in the direction of water flow is therefore the same as its thickness, i.e. 41 mm (Table 5).

[i] Flow will occur down the disposal zone between the disposal containers and the borehole casing. This has a total length of 50 m, i.e. 5 m per compartment.

[j] For saturated conditions, flow moves horizontally through the disposal zone. The length of the disposal zone in the direction of water flow is therefore the same as the distance between the disposal container and the borehole casing, i.e. 12.5 mm (Section 3.1.2).

[k] For unsaturated conditions, water flow is vertically down the borehole. It is noted in Section 3.1.2 that between 700 and 800 mm of backfill can be used between vertically adjacent disposal containers. Assuming a value of 750 mm, the total length of the backfill in the disposal zone between the disposal containers is 36.75 m. This is divided between 10 compartments, gives a length in the direction of water flow of 3.68 m for each disposal zone compartment.

[l] For unsaturated conditions, the vertical flow will pass through the plug at the base of the borehole into the geosphere. It is assumed that the plug is 0.5 m thick. In addition, flow will occur down along the backfill between the casing and the borehole wall. This has a total length of 50 m, i.e. 5 m per compartment.

[m] For saturated conditions flow moves horizontally through the backfill of the disturbed zone between the casing and the borehole wall. The length of the disturbed zone in the direction of water flow is therefore the same as the distance between the borehole casing and the borehole wall, i.e. 50 mm (Section 3.1.2). The plug is not modelled since it is assumed not to participate in the transport of radionuclide.

[n] For unsaturated conditions, water flow is vertically down the borehole. Therefore, the area of each compartment perpendicular to water flow is calculated using π ro2 where ro is the outer radius of the compartment (see Table 5 for data).

[o] For saturated conditions, flow moves horizontally through the borehole. Therefore, the area of each compartment perpendicular to water flow is calculated using a formula based on the depth of compartment multiplied by the diameter of compartment.

[p] For unsaturated conditions, water flow is vertically down the borehole. Therefore, the area of each compartment perpendicular to water flow is calculated using π (ro2 – ri2) where ro is the outer radius of the compartment and ri is the inner radius of the compartment (see Table 5 for data).

[q] Taken to be the distance between the mid points of the adjacent compartments.

[r] No diffusive transport is modelled from the disposal zone vertically adjacent to the capsule as, if diffusion dominates, horizontal diffusion from the disposal container is assumed to be of greater importance.

[s] Equal to the circumference of the compartment multiplied by its depth.

TABLE 76. TIMES FOR THE FAILURE OF THE PERFORMANCE OF THE NEAR FIELD COMPONENTS FOR THE DESIGN SCENARIO

| Component | Failure times (y, from time of disposal) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Unsaturated disposal zone<br>Groundwater #1 | | Saturated, high flow rate disposal zone<br>Groundwater #5 | | Saturated, medium flow rate disposal zone<br>groundwater #5 | | Saturated, low flow rate disposal zone<br>Groundwater #6 | |
| | Start of failure[c] | Totally failed[d] | Start of failure[c] | Totally failed[d] | Start of failure[c] | Totally failed[d] | Start of failure[c] | Totally failed[d] |
| Backfill Cement[a] | 4.02E+4 | 4.94E+4 | 5.14E+3 | 5.17E+3 | 5.14E+3 | 8.73E+3 | 8.22E+4 | 1.01E+6 |
| Stainless steel disposal container[b] | 1.76E+4 | 1.76E+4 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 2.40E+5 | 2.40E+5 |
| Containment Barrier[a] | 1.83E+4 | 4.94 E+4 | 4.82E+5 | 4.82E+5 | 4.82E+5 | 4.84E+5 | 2.79E+5 | 1.01E+6 |
| Stainless steel capsule[b] | 2.40E+4 | 2.40E+4 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 3.60E+5 | 3.60E+5 |

**Notes:**

[a] Data derived from Table 38.

[b] Data taken from Table 52.

[c] Represents start of degradation for cement grout (i.e. end of Stage 2/start of Stage 3).

[d] Represents end of degradation for cement grout (i.e. end of Stage 3/start of Stage 4).

TABLE 77. TIMES FOR THE FAILURE OF THE PERFORMANCE OF THE NEAR FIELD COMPONENTS FOR THE DEFECT SCENARIO VARIANTS

**Defect Scenario D1**

| Component | Failure Times (y, from time of disposal) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Unsaturated disposal zone | | Saturated, high flow rate disposal zone | | Saturated, medium flow rate disposal zone | | Saturated, low flow Rate disposal zone | |
| | Groundwater #1 | | Groundwater #5 | | Groundwater #5 | | Groundwater #6 | |
| | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] |
| Backfill cement grout[a] | 4.02E+3 | 4.94E+4 | 5.14E+3 | 5.17E+3 | 5.14E+3 | 8.73E+3 | 8.22E+4 | 1.01E+6 |
| Failed stainless steel disposal container[b] | 0 | 1.76E+4 | 0 | 4.80E+5 | 0 | 4.80E+5 | 0 | 2.40E+5 |
| Intact stainless steel disposal containers[c] | 1.76E+4 | 1.76E+4 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 2.40E+5 | 2.40E+5 |
| Containment barrier in failed disposal container[a] | 7.52E+3 | 4.94E+4 | 2.42E+4 | 2.44E+4 | 2.42E+4 | 4.12E+4 | 2.79E+5 | 1.01E+6 |
| Containment barrier in intact disposal containers[a] | 1.83E+4 | 4.94E+4 | 4.82E+5 | 4.82E+5 | 4.82E+5 | 4.84E+5 | 2.79E+5 | 1.01E+6 |
| Stainless steel capsule in failed disposal container[d] | 1.51E+4 | 1.51E+4 | 2.40E+5 | 2.40E+5 | 2.40E+5 | 2.40E+5 | 1.20E+5 | 1.20E+5 |
| Stainless steel capsule in intact disposal container[c] | 2.40E+4 | 2.40E+4 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 3.60E+5 | 3.60E+5 |

TABLE 77. TIMES FOR THE FAILURE OF THE PERFORMANCE OF THE NEAR FIELD COMPONENTS FOR THE DEFECT SCENARIO VARIANTS (cont.)

**Defect Scenario D2**

| Component | Failure times (y, from time of disposal) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Unsaturated disposal zone | | Saturated, high flow rate disposal Zone | | Saturated, medium flow rate disposal Zone | | Saturated, low flow rate disposal zone | |
| | Groundwater #1 | | Groundwater #5 | | Groundwater #5 | | Groundwater #6 | |
| | Start of Failure[e] | Totally Failed[f] | Start of Failure[e] | Totally Failed[f] | Start of Failure[e] | Totally Failed[f] | Start of Failure[e] | Totally Failed[f] |
| Backfill cement grout[a] | 4.02E+3 | 4.94E+4 | 5.14E+3 | 5.17E+3 | 5.14E+3 | 8.73E+3 | 8.22E+4 | 1.01E+6 |
| Stainless steel disposal containers [c] | 1.76E+4 | 1.76E+4 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 2.40E+5 | 2.40E+5 |
| Containment barrier in disposal containers[a] | 1.84E+4 | 4.94E+4 | 4.82E+5 | 4.82E+5 | 4.82E+5 | 4.84E+5 | 2.79E+5 | 1.01E+6 |
| Defective stainless steel capsule[g] | 0 | 2.40E+4 | 0 | 7.20E+5 | 0 | 7.20E+5 | 0 | 3.60E+5 |
| Intact stainless steel capsule[c] | 2.40E+4 | 2.40E+4 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 3.60E+5 | 3.60E+5 |

**Defect Scenario D3**

| Component | Failure times (y, from time of disposal) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Unsaturated disposal zone | | Saturated, high flow rate disposal Zone | | Saturated, medium flow rate disposal zone | | Saturated, low flow rate disposal zone | |
| | Groundwater #1 | | Groundwater #5 | | Groundwater #5 | | Groundwater #6 | |
| | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] |
| Backfill cement[h] | 2.01E+3 | 2.47E+4 | 2.57E+2 | 2.75E+2 | 2.57E+2 | 1.66E+3 | 4.11E+4 | 5.05E+5 |
| Stainless steel disposal container[c] | 8.87E+3 | 8.87E+3 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 2.40E+5 | 2.40E+5 |
| Containment Barrier[h] | 9.24E+3 | 2.47E+4 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 4.81E+5 | 2.59E+5 | 5.05E+5 |
| Stainless steel capsule[c] | 1.21E+4 | 1.21E+4 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 3.48E+5 | 3.48E+5 |

TABLE 77. TIMES FOR THE FAILURE OF THE PERFORMANCE OF THE NEAR FIELD COMPONENTS FOR THE DEFECT SCENARIO VARIANTS (cont.)

**Defect Scenario D4**

| Component | Failure times (y, from time of disposal) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Unsaturated disposal zone<br>Groundwater #1 | | Saturated, high flow rate disposal Zone<br>Groundwater #5 | | Saturated, medium flow rate disposal zone<br>Groundwater #5 | | Saturated, low flow rate disposal zone<br>Groundwater #6 | |
| | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] | Start of failure[e] | Totally failed[f] |
| Backfill cement grout[a] | 4.02E+3 | 4.94E+4 | 5.14E+3 | 5.17E+3 | 5.14E+3 | 8.73E+3 | 8.22E+4 | 1.01E+6 |
| Failed stainless steel disposal container[i] | 0 | 1.76E+4 | 0 | 4.80E+5 | 0 | 4.80E+5 | 0 | 2.40E+5 |
| Intact stainless steel disposal containers[c] | 1.76E+4 | 1.76E+4 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 4.80E+5 | 2.40E+5 | 2.40E+5 |
| Containment barrier in failed disposal container[a] | 7.52E+3 | 4.94E+4 | 2.42E+4 | 2.44E+4 | 2.42E+4 | 4.12E+4 | 2.79E+5 | 1.01E+6 |
| Containment barrier in intact disposal containers[a] | 1.83E+4 | 4.94E+4 | 4.82E+5 | 4.82E+5 | 4.82E+5 | 4.84E+5 | 2.79E+5 | 1.01E+6 |
| Failed stainless steel capsule in failed disposal container[i] | 0 | 1.51E+4 | 0 | 2.40E+5 | 0 | 2.40E+5 | 0 | 1.20E+5 |
| Stainless steel capsule in intact disposal container[c] | 2.40E+4 | 2.40E+4 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 7.20E+5 | 3.60E+5 | 3.60E+5 |

**Notes:**

[a] Data derived from Table 38.

[b] Assumes that one container has a defective weld. In light of the discussion in Appendix I, it is assumed that the defective container fails due to general corrosion rather than localized corrosion.

[c] Data taken from Table 52.

[d] Early failure of disposal container only affects failure time of capsule in that container.

[e] Represents start of degradation for cement grout (i.e. end of Stage 2/start of Stage 3).

[f] Represents end of degradation for cement grout (i.e. end of Stage 3/start of Stage 4).

[g] Assumes that one capsule has a defective weld. It is assumed that the defective weld allows access to 10% of the waste once the disposal container has failed. In light of the discussion in Appendix I, it is assumed that the defective capsule fails due to general corrosion rather than localized corrosion. It is assumed that, once the defective capsule fails, there is a ramp up to 100% of the waste being available. Note that although the defective capsule is assumed to have failed at t=0, no releases of radionuclides occur until the disposal container is breached.

[h] Data derived from Table 39.

[i] Assumes that one capsule has a defective weld and this is contained in a disposal container that also has a defective weld. It is assumed that the defective weld in the capsule allows access to 10% of the waste. In light of the discussion in Appendix I, it is assumed that the defective capsule and container fail due to general corrosion rather than localized corrosion. It is assumed that, once the defective capsule fails, there is a ramp up to 100% of the waste being available.

## XII.4. GEOSPHERE ELEMENT-INDEPENDENT DATA

TABLE 78. GEOSPHERE FLOW DATA

| Parameter | Units | Unsaturated geosphere |  |  | Saturated geosphere |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Porous system[c] | Fractured system[e] |  | Low flow | Medium flow | High flow |  |  |
|  |  |  |  |  |  |  | Porous system | Fractured system |  |
| Hydraulic conductivity[a] | m/y | - | Fracture | - | 1E-2 | 1E+1 | 1E+3 | Fracture | 1E+3 |
|  |  |  | Matrix | - |  |  |  | Matrix | - |
| Hydraulic gradient[a] | - | - | Fracture | - | 1E-2 | 1E-2 | 1E-2 | Fracture | 1E-2 |
|  |  |  | Matrix | - |  |  |  | Matrix | - |
| Percolation rate[a] | m/y | 5E-2 | Fracture | 5E-2 | - | - | - | Fracture | - |
|  |  |  | Matrix | - |  |  |  | Matrix | - |
| Total porosity | - | 1.5E-1[d] | Fracture | 1.5E-1[f] | 1E-2[h] | 1E-1[h] | 1E-1[h] | Fracture | 1E-1[f] |
|  |  |  | Matrix | 5E-3[f] |  |  |  | Matrix | 5E-3[f] |
| Degree of saturation | - | 3.3E-1[d] | Fracture | 3.3E-1[d] | 1E+0[i] | 1E+0[i] | 1E+0[i] | Fracture | 1E+0[i] |
|  |  |  | Matrix | 3.3E-1[g] |  |  |  | Matrix | 1E+0[i] |
| Grain density[b] | kg/m$^3$ | 2.65E+3 | Fracture | 2.65E+3 | 2.65E+3 | 2.65E+3 | 2.65E+3 | Fracture | 2.65E+3 |
|  |  |  | Matrix | 2.65E+3 |  |  |  | Matrix | 2.65E+3 |

**Notes:** [a] Flow in unsaturated zone represented using the percolations rate and so hydraulic conductivity and hydraulic gradient values do not need to be specified. Data for the saturated zone is taken from Table 7 and Section 3.2.1. It is assumed in the fractured high flow rate system that the matrix does not contribute to flow and so hydraulic conductivity and hydraulic gradient values do not need to be specified.

[b] Grain density of quartz assumed.

[c] Applicable to porous low, medium and high flow rate systems.

[d] Data from Section 3.2.1.

[e] Only applicable to fractured high flow rate system.

[f] For fractured system assume fracture porosity to be the same as for the porous system and matrix porosity to be 5E-3 (consistent with Ref. [128]).

[g] Assumed to be the same as for the fracture.

[h] Data from Table 8.

[i] By definition, the degree of saturation in the saturated zone is unity.

## TABLE 79. GEOSPHERE TRANSPORT DATA FOR DISPOSAL IN THE UNSATURATED ZONE

| Parameter | Units | Low Flow Rate System | | | Medium flow rate system | | | High flow rate system | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Unsaturated zone | | Saturated zone | Unsaturated zone | | Saturated zone | Porous system | | | Fractured system | | | |
| | | | | | | | | Unsaturated zone | | Saturated zone | Unsaturated zone | | Saturated zone | |
| Number of compartments | - | | 12$^{b}$ | 5$^{g}$ | | 12$^{b}$ | 5$^{j}$ | | 12$^{b}$ | 5$^{j}$ | Fracture | 12$^{b}$ | Fracture | 5$^{j}$ |
| | | | | | | | | | | | Matrix | 12$^{k}$ | Matrix | 5$^{k}$ |
| Length of each compartment in direction of water flow | m | | 5$^{c}$ | 20$^{h}$ | | 5$^{c}$ | 20$^{h}$ | | 5$^{c}$ | 20$^{h}$ | Fracture | 5$^{c}$ | Fracture | 20$^{h}$ |
| | | | | | | | | | | | Matrix | 5$^{k}$ | Matrix | 20$^{k}$ |
| Area of each compartment perpendicular to water flow | m$^{2}$ | Adjacent to borehole | 0.73$^{d}$ | 1$^{i}$ | Adjacent to borehole | 0.73$^{d}$ | 1$^{i}$ | Adjacent to borehole | 0.73$^{d}$ | 1$^{i}$ | Fracture adjacent to borehole | 0.73$^{d}$ | Fracture | 1$^{i}$ |
| | | | | | | | | | | | Matrix adjacent to b/h | -$^{l}$ | | |
| | | Below borehole | 0.79$^{e}$ | | Below borehole | 0.79$^{e}$ | | Below borehole | 0.79$^{e}$ | | Fracture below borehole | 0.79$^{e}$ | Matrix | -$^{l}$ |
| | | | | | | | | | | | Matrix below borehole | -$^{l}$ | | |
| Diffusion length between adjacent compartments | m | | 5$^{f}$ | 20$^{f}$ | | 5$^{f}$ | 20$^{f}$ | | 5$^{f}$ | 20$^{f}$ | Fracture | 5$^{f}$ | Fracture | 20$^{f}$ |
| | | | | | | | | | | | Matrix | 0.02$^{m}$ | Matrix | 0.02$^{m}$ |
| Area over which diffusion occurs$^{a}$ | m$^{2}$ | Adjacent to borehole | 0.73 | 1 | Adjacent to borehole | 0.73 | 1 | Adjacent to borehole | 0.73 | 1 | Fracture adjacent to borehole | 0.73 | Fracture | 1 |
| | | | | | | | | | | | Matrix adjacent to borehole (m$^{2}$ m$^{-3}$) | 0.15$^{n}$ | | |
| | | Below borehole | 0.79 | | Below borehole | 0.79 | | Below borehole | 0.79 | | Fracture below borehole | 0.79 | Matrix (m$^{2}$ m$^{-3}$) | 1$^{n}$ |
| | | | | | | | | | | | Matrix below borehole (m$^{2}$ m$^{-3}$) | 0.15$^{n}$ | | |

**Notes:** [a] Assumed to equal to the area of each compartment perpendicular to water flow.

[b] Ten compartments used to represent the unsaturated zone adjacent to the disposal (consistent with the number used for the discretisation of the disposal borehole (Table 75)) plus two additional compartments used to represent the 10 m of unsaturated zone between the base of the disposal borehole and the watertable (Section 3.2.1).

[c] The depth of disposal zone plus underlying unsaturated zone (60 m) divided by the number of compartments in the unsaturated zone.

[d] Assumes that the unsaturated zone is a circle with a radius of 1 m around the disposal borehole (radius 0.26 m). Area of unsaturated zone adjacent to the disposal borehole is therefore calculated using π (runsat2 – rbh2) where runsat is the outer radius of the unsaturated compartment and rbh is the outer radius of the disposal borehole compartment area.

[e] Assumes that the unsaturated zone is a circle with a radius of 1 m. Area of unsaturated zone adjacent to the disposal borehole is therefore calculated using $\pi\, r_{unsat}^2$ where $r_{unsat}$ is the radius of the unsaturated compartment.

[f] Assumed to be equal to the length of each compartment.

[g] For a diffusion dominated system (such as the low flow rate system), the error resulting from discretisation into compartments is equal to the inverse of the number of compartments squared [136]. Thus discretisation of the saturated geosphere into five compartments between the disposal borehole and the abstraction borehole results in an error of 4%.

[h] The distance to the abstraction borehole from the disposal borehole (100 m) divided by the number of compartments in the saturated zone.

[i] See Table 7.

[j] For an advection dominated system (such as the medium and high flow rate systems), the number of compartments ought to equal the Peclet number divided by two (see Ref. [138]). Peclet number is equal to the distance from the disposal borehole to the abstraction borehole (100 m – Table 7) divide by the longitudinal dispersion length (assumed to be 10% (see Ref. [12]) of the distance from the disposal borehole to the abstraction borehole).

[k] Assumes that each fracture compartment has an associated matrix compartment between which there is a diffusive flux.

[l] It is assumed that there is no flow water in the matrix.

[m] Value taken from Ref. [128] for rock matrix depth.

[n] Assumes that transverse diffusion occurs from/to fracture into/from rock matrix. Values represent the flow wetted surface area per unit volume of rock and are based on data given in Ref. [128] taking into the assumed degree of saturation (see Table 78).

TABLE 80. GEOSPHERE TRANSPORT DATA FOR DISPOSAL IN THE SATURATED ZONE

| Parameter | Units | Low flow rate system | Medium Flow rate system | High flow rate system | | |
|---|---|---|---|---|---|---|
| | | | | Porous system | Fractured system | |
| Number of compartments between the disposal borehole and the abstraction borehole | - | 5[e] | 5[f] | 5[f] | Fracture | 5[f] |
| | | | | | Matrix | 5[g] |
| Length of each compartment in direction of water flow[a] | m | 20 | 20 | 20 | Fracture | 20 |
| | | | | | Matrix | 20[g] |
| Area of each compartment perpendicular to water flow[b] | m$^2$ | 50 | 50 | 50 | Fracture | 50 |
| | | | | | Matrix | -[h] |
| Diffusion length between adjacent compartments[c] | m | 20 | 20 | 20 | Fracture | 20 |
| | | | | | Matrix | 0.02[i] |
| Area over which diffusion occurs[d] | m$^2$ | 50 | 50 | 50 | Fracture | 50 |
| | | | | | Matrix (m$^2$ m$^{-3}$) | 1[j] |

**Notes**: [a] The distance to the abstraction borehole from the disposal borehole (100 m) divided by the number of compartments in the saturated zone.

[b] See Table 8.

[c] Assumed to be equal to the length of each compartment.

[d] Assumed to equal to the area of each compartment perpendicular to water flow.

[e] For a diffusion dominated system (such as the low flow rate system), the error resulting from discretisation into compartments is equal to the inverse of the number of compartments squared [136]. Thus discretisation into five compartments results in an error of 4%.

[f] For an advection dominated system (such as the medium and high flow rate systems), the number of compartments ought to equal the Peclet number divided by two (see Ref. [138]). Peclet number is equal to the distance from the disposal borehole to the abstraction borehole (100 m – Table 7) divide by the longitudinal dispersion length (assumed to be 10% (see Ref. [12]) of the distance from the disposal borehole to the abstraction borehole).

[g] Assumes that each fracture compartment has an associated matrix compartment between which there is a diffusive flux.

[h] It is assumed that there is no flow water in the matrix.

[i] Value taken from Ref. [128] for rock matrix depth.

[j] Assumes that transverse diffusion occurs from/to fracture into/from rock matrix). Values represent the flow wetted surface area per unit volume of rock and are based on data given in Ref. [128] taking into the assumed degree of saturation (see Table 78).

TABLE 81. FRACTION OF WATER DEMAND SUPPLIED BY CONTAMINATED WATER FOR DIFFERENT GEOSPHERES AND CALCULATION CASES

| Geosphere | Drinking water only calculation case | | All other cases | |
|---|---|---|---|---|
| | Location of disposal zone | | Location of disposal zone | |
| | Unsaturated zone[a] | Saturated zone[a] | Unsaturated zone[b] | Saturated zone[b] |
| High flow rate system: porous system | 1.00E+0 | 1.00E+0 | 3.76E-2 | 1.00E+0 |
| High flow rate system: fractured system | 1.00E+0 | 1.00E+0 | 3.76E-2 | 1.00E+0 |
| Medium flow rate system | 3.42E-2 | 1.00E+0 | 3.76E-4 | 1.88E-2 |
| Low flow rate system | 3.42E-4 | 1.71E-3 | 3.76E-6 | 1.88E-5 |

**Notes:** [a] The minimum value of unity and the result of dividing the water flux, in which the contaminated plume is mixed (given in Table 7), by the assumed drinking water abstraction rate (2.92 $m^3/y$) (2 l/d per person).

[b] Data from Table 7.

## XII.5. BIOSPHERE ELEMENT-INDEPENDENT DATA

TABLE 82. BIOSPHERE COMPARTMENT PARAMETERS AND PROCESSES

| Parameter | Units | Exposure group: | Farmer | House dweller[i] | Site dweller |
|---|---|---|---|---|---|
| | | Compartment: | Surface soil | House | Surface soil |
| Depth | m | | 2.5E-1[a] | 2.4E+0[j] | 2.5E-1[a] |
| Length | m | | 3.51E+1[b] | 3.0E+0[j] | 3.51E+1[b] |
| Width | m | | 1E+1[b] | 4.0E+0[j] | 1E+1[b] |
| Total porosity | - | | 3E-1[a] | - | 3E-1[a] |
| Degree of saturation | - | | 3.3E-1[c] | - | 3.3E-1[c] |
| Grain density | $kg/m^3$ | | 2.65E+3[d] | - | 2.65E+3[d] |
| Percolation rate | m/y | | 5E-2[c] | - | 5E-2[c] |
| Inhalable dust concentration | $kg/m^3$ | | 2E-8[a] | - | 2E-8[a] |
| Erosion rate | m/y | | 3E-4[e] | - | 3E-4[e] |
| Volume of irrigation water that reaches the soil | $m^3/y$ | | 71[f] | - | -[l] |
| Volume of non-irrigation water plus irrigation water intercepted by crops | $m^3/y$ | | 195[g] | | -[l] |
| Ventilation rate | /y | | -[h] | 2.2E+3[k] | -[h] |
| Effective diffusion of Rn | $m^2/y$ | | -[h] | - | -[h] |
| Total porosity of the base of the house | - | | -[h] | - | -[h] |

**Notes:** [a] Data taken from Ref. [23].

[b] An area of 351 $m^2$ is required to grow root and green vegetables to meet the assumed demand of an exposure group of four people (Table 83), assuming the yields given in Table 84. Assuming a nominal width of 10 m, the length is therefore 35.1 m.

[c] See Section 3.2.1.

[d] Grain density of quartz.

[e] See Section 3.3.

[f] Value derived by multiplying the depth of irrigation water applied to root and green vegetables (Table L.84), the area of root and green vegetables required to meet the assumed demand of an exposure group of four people

(Table 83) (assuming the yields given in Table 84), and unity minus the interception fraction for irrigation water (Table 84).

[g] Value derived by summing the volume of water intercepted by crops and the volume of water required by cows and humans. The volume of water intercepted by crops is calculated by multiplying the depth of irrigation water applied to root and green vegetables (Table 84), the area of root and green vegetables required to meet the assumed demand of an exposure group of four people (Table 83) (assuming the yields given in Table 84), and the interception fraction for irrigation water (Table 84). The volume of water required by cows is calculated by multiplying the number of cows (i.e. four) required to meet the assumed meet and milk demands of an exposure group of four people (Table 83) by the annual water consumption rate of cows (derived from the daily rate given in Table 84). The volume of water required by humans is calculated by multiplying the number of humans in the exposure group (i.e. four) by the annual water consumption rate of humans (Table 83).

[h] Not relevant for soil compartment.

[i] Only exposed through inhalation of radioactive gases released to a house (see Section 4.2.1) and so, from a biosphere perspective, only need to consider volume and ventilation rate of house.

[j] Values taken from Ref. [32].

[k] Value taken from Ref. [82] for a modern, well insulated building.

[l] Does not use contaminated water.

TABLE 83. HUMAN BEHAVIOUR PARAMETERS

| Exposure Mechanism | | Units | Exposure group | | |
|---|---|---|---|---|---|
| | | | Farmer | House dweller | Site dweller[f] |
| Ingestion | Contaminated drinking water | $m^3/y$ | 0.73[a] | - | - |
| | Contaminated root vegetables | kg fw/y | 235[b] | - | 235[b] |
| | Contaminated green vegetables | kg fw/y | 62[b] | - | 62[b] |
| | Contaminated beef | kg fw/y | 95[b] | | - |
| | Contaminated cow's milk | kg fw/y | 300[b] | - | - |
| | Contaminated soil | kg fw/h | 1.5E-5[c] | - | - |
| | Contaminated fish | kg fw/y | 6.9[d] | - | - |
| Inhalation | Contaminated outdoor air | $m^3/h$ | 1[b] | - | - |
| | Contaminated indoor air | $m^3/h$ | - | 0.75[b] | - |
| Occupancy | Time spent on contaminated soil | h/y | 2192[b] | - | - |
| | Time spent in contaminated building | h/y | - | 6575[b] | - |
| | Time spent in contaminated water | h/y | 365[e] | - | - |

**Notes:** [a] See Section 3.3.

[b] Data taken from Ref. [23].

[c] Data taken from Ref. [137] assuming that the annual value quoted in Ref. [137] results from an exposure to contaminated soil of 8 hours per day.

[d] Data taken from Ref. [16]. Ingestion of fish only considered for the variant calculation that assumes contaminated groundwater is used to supply a fish farm.

[e] Assumes 1 h/d. Only considered for the variant calculation that assumes contaminated groundwater is used for bathing.

[f] Only exposed through growing crops on contaminated soil due to erosion of closure zone.

TABLE 84. NON-ELEMENT DEPENDENT PLANT PARAMETERS

| Parameter | Units | Root vegetables | Green vegetables |
|---|---|---|---|
| Soil contamination of crop | kg dw soil/kg fw crop[a] | 1.5E-4 | 1.0E-4 |
| Yield of crop | kg fw $m^{-2}/y$ [b] | 3.5E+0 | 3.0E+0 |
| Depth of irrigation water applied to crop | m/y [b,c] | 3.0E-1 | 3.0E-1 |
| Interception fraction for irrigation water | -[b,c] | 3.3E-1 | 3.3E-1 |
| Time interval between irrigation and harvesting | y[c,d] | 4.0E-2 | 2.E-2 |

**Notes**: [a] Data taken from Ref. [32].

[a] Data taken from Ref. [23].

[c] Irrigation of crop with contaminated water only considered for the liquid release calculation cases.

[d] Data taken from Ref. [16].

TABLE 85. NON-ELEMENT DEPENDENT ANIMAL PARAMETERS

| Parameter | Units | Cows |
|---|---|---|
| Consumption of water | $m^3/d$ | 6E-2[a] |

**Note:** [a] Data taken from Ref. [23].

# APPENDIX XIII
# ASSESSMENT RESULTS

TABLE 86. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR THE DESIGN SCENARIO

| Near Field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 9E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 87. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR THE DESIGN SCENARIO

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 4E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

## TABLE 88. TOTAL ACTIVITY LEVELS FOR GASEOUS RELEASE FOR THE DESIGN SCENARIO

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | n.a. | n.a. | * | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

## TABLE 89. PER PACKAGE ACTIVITY LEVELS FOR GASEOUS RELEASE FOR THE DESIGN SCENARIO

| Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | n.a. | n.a. | * | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

## TABLE 90. TOTAL ACTIVITY LEVELS FOR SOLID RELEASE FOR THE DESIGN SCENARIO

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | * | 2E+12 | 5E+11 | 4E+13 |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

## TABLE 91. PER PACKAGE ACTIVITY LEVELS FOR SOLID RELEASE FOR THE DESIGN SCENARIO

| Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | * | 4E+10 | 1E+10 | 9E+11 |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 92. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D1

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 6E+13 | 9E+13 | 2E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 7E+17 | 3E+16 | 6E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 1E+14 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 6E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 93. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D1

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 1E+12 | 2E+12 | 4E+14 |
| | | Fractured | * | * | * | * | * | * | * | * | 1E+16 | 7E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 6E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 94. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D2

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 8E+13 | 9E+13 | 3E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 9E+17 | 3E+16 | 6E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 1E+14 | 3E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 6E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 95. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D2

| Near field | Saturated geosphere | | Per Package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 6E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+16 | 7E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 5E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 6E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 96. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D3

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 1E+14 | 9E+13 | 3E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 6E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 1E+14 | 3E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 3E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 3E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 97. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D3

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 6E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 7E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 7E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 6E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 5E+10 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 2E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 98. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D4

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | 1E+14 | * | * | * | 2E+16 | * | * | 1E+16 | 6E+13 | 9E+13 | 2E+13 |
| | | Fractured | 1E+14 | * | * | * | 4E+16 | * | * | 6E+17 | 8E+17 | 3E+16 | 6E+15 |
| | Medium | Porous | 5E+15 | * | * | * | * | * | * | * | 2E+15 | 1E+14 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | 3E+15 | * | * | * | 2E+16 | 7E+17 | * | 2E+12 | 4E+12 | 9E+13 | 6E+12 |
| | | Fractured | 3E+15 | * | * | * | 3E+16 | * | * | 5E+13 | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | 1E+17 | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 99. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR DEFECT SCENARIO D4

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | 2E+12 | * | * | * | 3E+14 | * | * | 2E+14 | 1E+12 | 2E+12 | 4E+11 |
| | | Fractured | 2E+12 | * | * | * | 8E+14 | * | * | 1E+16 | 2E+16 | 7E+14 | 1E+14 |
| | Medium | Porous | 1E+14 | * | * | * | * | * | * | * | 4E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 6E+15 | * |
| Saturated | High | Porous | 6E+13 | * | * | * | 4E+14 | 1E+16 | * | 3E+10 | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | 6E+13 | * | * | * | 7E+14 | * | * | 1E+12 | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | 2E+15 | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 100. TOTAL ACTIVITY LEVELS FOR GASEOUS RELEASE FOR DEFECT SCENARIO D4[19]

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| 6E+12[20] | n.a. | n.a. | 1E+14 | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 101. PER PACKAGE ACTIVITY LEVELS FOR GASEOUS RELEASE FOR DEFECT SCENARIO D4[21]

| Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| 1E+11 [21] | n.a. | n.a. | 2E+12 | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

---

[19] Total activity levels for Defect Scenario D1, D2 and D3 are greater than 1E+18 Bq for all gases and so tables are not provided.

[20] Only applicable to unsaturated disposal zone. H-3 in saturated disposal zone is assumed to be dissolved in the groundwater.

[21] Per package activity levels for Defect Scenario D1, D2 and D3 are greater than 2E+16 Bq for all gases and so tables are not provided.

TABLE 102. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH NO CONGRUENT RELEASE

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 6E+14 | 1E+15 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+17 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+16 | 1E+15 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 6E+12 | 1E+14 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+14 | 8E+16 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 1E+16 | 7E+15 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 103. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH NO CONGRUENT RELEASE

| Near Field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 1E+13 | 2E+13 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+15 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+14 | 2E+13 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 1E+11 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 4E+12 | 2E+15 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+14 | 1E+14 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 104. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH FASTER CEMENT GROUT DEGRADATION (X10 FASTER THAN DESIGN)

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 8E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 105. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH FASTER CEMENT DEGRADATION (X10 FASTER THAN DESIGN)

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 5E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 106. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH INCREASED STAINLESS STEEL CORROSION RATES (X10 FASTER THAN DESIGN)

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | 6E+17 | 9E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 1E+12 | 7E+11 | 1E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 8E+13 | 2E+15 | 1E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+14 | 6E+14 | 4E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 107. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH INCREASED STAINLESS STEEL CORROSION RATES (X10 FASTER THAN DESIGN)

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | 1E16 | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+10 | 1E+10 | 2E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+12 | 4E+13 | 2E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+12 | 1E+13 | 8E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 108. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH CEMENT GROUT SORPTION DECREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 9E+13 | 9E+13 | 2E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 109. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH CEMENT GROUT SORPTION DECREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 6E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 110. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH CEMENT GROUT SORPTION INCREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 3E+14 | 2E+14 | 2E+15 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 6E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 9E+15 | 2E+14 | 2E+15 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 6E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 3E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 6E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 111. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH CEMENT GROUT SORPTION INCREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 5E+12 | 5E+12 | 3E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+14 | 4E+12 | 3E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 6E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 4E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 112. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH DISTANCE TO WELL SET TO 10 m

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+14 | 1E+14 | 7E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+17 | 3E+16 | 5E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 7E+13 | 8E+13 | 3E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 1E+16 | 6E+17 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 5E+12 | 8E+13 | 7E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 1E+13 | 6E+14 | 1E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 9E+12 | 1E+14 | 3E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 1E+17 | * |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 113. PER PACKAGE LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH DISTANCE TO WELL SET TO 10 m

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 6E+15 | 7E+14 | 9E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 1E+12 | 2E+12 | 7E+11 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 2E+14 | 1E+16 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 1E+11 | 2E+12 | 1E+10 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+11 | 1E+13 | 2E+10 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+11 | 2E+12 | 6E+11 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 2E+15 | * |

* denotes a total activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 114. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH DISTANCE TO WELL SET TO 1000 m

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 6E+13 | 7E+13 | 3E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 6E+14 | 6E+16 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 2E+13 | 2E+14 | 6E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 7E+16 | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 6E+15 | 1E+17 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 115. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH DISTANCE TO WELL SET TO 1000 m

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 1E+12 | 1E+12 | 6E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 7E+14 | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 1E+13 | 1E+15 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+11 | 4E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 1E+15 | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 1E+14 | 2E+15 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 116. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH GEOSPHERE SORPTION DECREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+14 | 1E+14 | 7E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+17 | 8E+16 | 6E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 9E+13 | 9E+13 | 5E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 1E+15 | 2E+16 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 1E+13 | 8E+13 | 2E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 1E+13 | 9E+13 | 1E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+12 | 5E+13 | 3E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | 8E+17 | 1E+16 | 4E+16 |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 117. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH GEOSPHERE SORPTION DECREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 4E+15 | 2E+15 | 1E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 2E+13 | 4E+14 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 2E+11 | 2E+12 | 5E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+11 | 2E+12 | 3E+11 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 5E+10 | 1E+12 | 6E+10 |
| | Low | Porous | * | * | * | * | * | * | * | * | 2E+16 | 2E+14 | 8E+14 |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 118. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH GEOSPHERE SORPTION INCREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | | Fractured | * | * | * | * | * | * | * | * | * | * | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 7E+15 | * |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+15 | 1E+15 | 1E+15 |
| | | Fractured | * | * | * | * | * | * | * | * | * | * | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 8E+16 | * |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 119. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH GEOSPHERE SORPTION INCREASED BY TWO ORDERS OF MAGNITUDE

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+12 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | * | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 1E+14 | * |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+13 | 2E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | * | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | 2E+15 | * |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 120. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH WATER USED FOR DRINKING ONLY

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 3E+11 | 6E+11 | 2E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 9E+14 | 1E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+14 | 2E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 2E+13 | 6E+14 | 2E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 1E+15 | 5E+16 | 1E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 1E+14 | 3E+13 | 2E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 121. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH WATER USED FOR DRINKING ONLY

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 8E+09 | 1E+10 | 3E+09 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 2E+13 | 2E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+12 | 4E+11 | 2E+11 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+11 | 1E+13 | 5E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+13 | 1E+15 | 3E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+12 | 6E+11 | 5E+11 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 6E+15 | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 122. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH WATER USED FOR FISH FARMING ONLY

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+13 | 8E+15 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+15 | 7E+17 | 2E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 9E+15 | 6E+16 | 5E+15 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 123. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH WATER USED FOR FISH FARMING ONLY

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 5E+11 | 2E+14 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+13 | 1E+16 | 4E+13 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+14 | 1E+15 | 1E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 124. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH WATER USED FOR BATHING ONLY

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | * | * | 3E+17 |
| | | Fractured | * | * | * | * | * | * | * | * | * | * | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | * | * |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 125. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR VARIANT CALCULATION WITH WATER USED FOR BATHING ONLY

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | * | * | 7E+15 |
| | | Fractured | * | * | * | * | * | * | * | * | * | * | * |
| | Medium | Porous | * | * | * | * | * | * | * | * | * | * | * |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 x$10^{16}$ Bq.

TABLE 126. TOTAL ACTIVITY LEVELS FOR EROSIVE RELEASE WITH EROSION RATE DECREASED BY AN ORDER OF MAGNITUDE

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | * | 1E+13 | 8E+12 | 3E+13 |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 127. PER PACKAGE ACTIVITY LEVELS FOR EROSIVE RELEASE WITH EROSION RATE DECREASED BY AN ORDER OF MAGNITUDE

| Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | * | 2E+11 | 2E+11 | 7E+11 |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 128. TOTAL ACTIVITY LEVELS FOR EROSIVE RELEASE WITH EROSION RATE INCREASED BY AN ORDER OF MAGNITUDE

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | 3E+10 | 9E+12 | 4E+10 | 6E+13 |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 129. PER PACKAGE ACTIVITY LEVELS FOR EROSIVE RELEASE WITH EROSION RATE INCREASED BY AN ORDER OF MAGNITUDE

| Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| * | * | * | * | * | * | * | 6E+08 | 2E+11 | 8E+08 | 1E+12 |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 130. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO CAPSULE

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 8E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+11 | 1E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 1E+13 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+14 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 131. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO CAPSULE

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 5E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 6E+09 | 2E+11 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+11 | 2E+14 | 4E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 1E+13 | 1E+13 | 9E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

## TABLE 132. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO CONTAINMENT BARRIER

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 9E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 133. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO CONTAINMENT BARRIER

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 134. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO DISPOSAL CONTAINER

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 9E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 1E+12 | 4E+13 | 6E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 8E+13 | 8E+15 | 3E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+14 | 7E+14 | 4E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than $1 \times 10^{18}$ Bq.

TABLE 135. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO DISPOSAL CONTAINER

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 3E+10 | 8E+11 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 2E+12 | 2E+14 | 6E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+12 | 1E+13 | 8E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 136. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO BACKFILL

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 8E+13 | 9E+13 | 5E+13 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 4E+12 | 9E+13 | 5E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | 3E+14 | 8E+15 | 2E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 2E+15 | 7E+14 | 5E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 137. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO BACKFILL

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | * | * | * | * | * | * | * | * | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | * | * | * | * | * | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 6E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | * | * | * | * | * | * | * | * | 9E+10 | 2E+12 | 1E+11 |
| | | Fractured | * | * | * | * | * | * | * | * | 5E+12 | 2E+14 | 5E+12 |
| | Medium | Porous | * | * | * | * | * | * | * | * | 3E+13 | 1E+13 | 1E+13 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

TABLE 138. TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO NEAR FIELD BARRIERS

| Near field | Saturated geosphere | | Total activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | 2E+12 | * | * | * | 1E+17 | * | * | 9E+16 | 8E+13 | 9E+13 | 5E+13 |
| | | Fractured | 2E+12 | * | * | * | 3E+17 | * | * | * | * | 3E+16 | 5E+15 |
| | Medium | Porous | 8E+13 | * | * | * | * | * | * | * | 3E+15 | 9E+13 | 2E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 3E+17 | * |
| Saturated | High | Porous | 2E+09 | * | 2E+14 | * | 7E+08 | 5E+12 | 3E+12 | 6E+08 | 2E+12 | 7E+10 | 2E+13 |
| | | Fractured | 2E+09 | * | 3E+14 | * | 1E+09 | 8E+13 | 3E+12 | 1E+10 | 1E+14 | 2E+14 | 1E+16 |
| | Medium | Porous | 2E+12 | * | * | * | 9E+16 | * | * | 2E+17 | 1E+14 | 6E+14 | 4E+14 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 139. PER PACKAGE ACTIVITY LEVELS FOR LIQUID RELEASE FOR CASE WITH NO NEAR FIELD BARRIERS

| Near field | Saturated geosphere | | Per package activity level (Bq) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | Flow rate | Flow type | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | High | Porous | 3E+10 | * | * | * | 3E+15 | * | * | 2E+15 | 2E+12 | 2E+12 | 1E+12 |
| | | Fractured | 4E+10 | * | * | * | 6E+15 | * | * | * | * | 6E+14 | 1E+14 |
| | Medium | Porous | 2E+12 | * | * | * | * | * | * | * | 5E+13 | 2E+12 | 5E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | 5E+15 | * |
| Saturated | High | Porous | 4E+07 | * | 3E+12 | * | 1E+07 | 1E+11 | 6E+10 | 1E+07 | 4E+10 | 1E+09 | 4E+11 |
| | | Fractured | 4E+07 | * | 5E+12 | * | 3E+07 | 2E+12 | 7E+10 | 2E+08 | 2E+12 | 3E+12 | 3E+14 |
| | Medium | Porous | 4E+10 | * | * | * | 2E+15 | * | * | 4E+15 | 3E+12 | 1E+13 | 8E+12 |
| | Low | Porous | * | * | * | * | * | * | * | * | * | * | * |

* denotes a per package activity level that is greater than $2 \times 10^{16}$ Bq.

TABLE 140. TOTAL ACTIVITY LEVELS FOR GASEOUS RELEASE FOR CASE WITH NO NEAR FIELD BARRIERS

| Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| 1E+11 [22] | n.a. | n.a. | 2E+12 | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 141. PER PACKAGE ACTIVITY LEVELS FOR GASEOUS RELEASE FOR CASE WITH NO NEAR FIELD BARRIERS

| Per Package Activity Level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| 2E+09[22] | n.a. | n.a. | 5E+10 | n.a. | n.a. | n.a. | * | * | n.a. | n.a. |

* denotes a per package activity level that is greater than 2 × $10^{16}$ Bq.

---

[22] Only applicable to unsaturated disposal zone. H-3 in saturated disposal zone is assumed to be dissolved in the groundwater.

TABLE 142. TOTAL ACTIVITY LEVELS FOR NO GEOSPHERE BARRIER

| Near field | Total activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | * | * | * | * | * | * | * | 3E+11 | 4E+11 | 2E+10 | 5E+12 |
| Saturated | * | * | * | * | * | * | * | * | 3E+13 | 7E+13 | 4E+10 |

* denotes a total activity level that is greater than 1 × $10^{18}$ Bq.

TABLE 143. PER PACKAGE ACTIVITY LEVELS FOR NO GEOSPHERE BARRIER

| Near field | Per package activity level (Bq) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Disposal zone | H-3 | Co-60 | Ni-63 | Kr-85 | Sr-90 | Cs-137 | Pb-210 | Ra-226 | Pu-238 | Pu-239 | Am-241 |
| Unsaturated | * | * | * | * | * | * | * | 6E+09 | 8E+09 | 5E+08 | 1E+11 |
| Saturated | * | * | * | * | * | * | * | * | 5E+11 | 1E+12 | 8E+08 |

* denotes a total activity level that is greater than 2 × $10^{16}$ Bq.

*FIG. 27. Pu-238 Doses for disposal in unaturated zone for variant cases.*

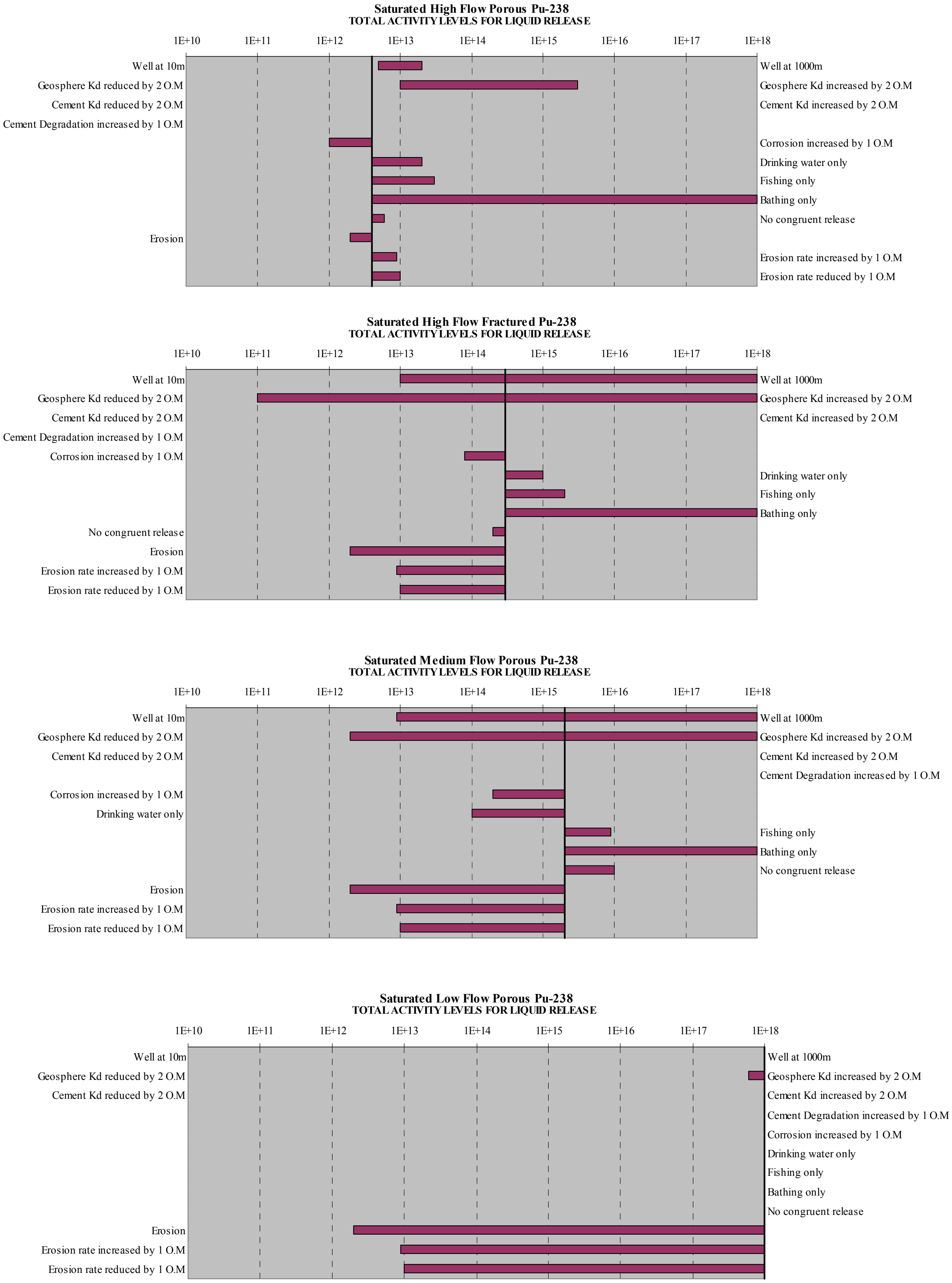


*FIG. 28. Pu-238 Doses for disposal in saturated zone for variant cases.*


Unsaturated High Flow Porous Pu-239
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

Unsaturated High Flow Fractured Pu-239
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

Unsaturated Medium Flow Porous Pu-239
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

Unsaturated Low Flow Porous Pu-239
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

*FIG. 29. Pu-239 Doses for disposal in unsaturated zone for variant cases.*

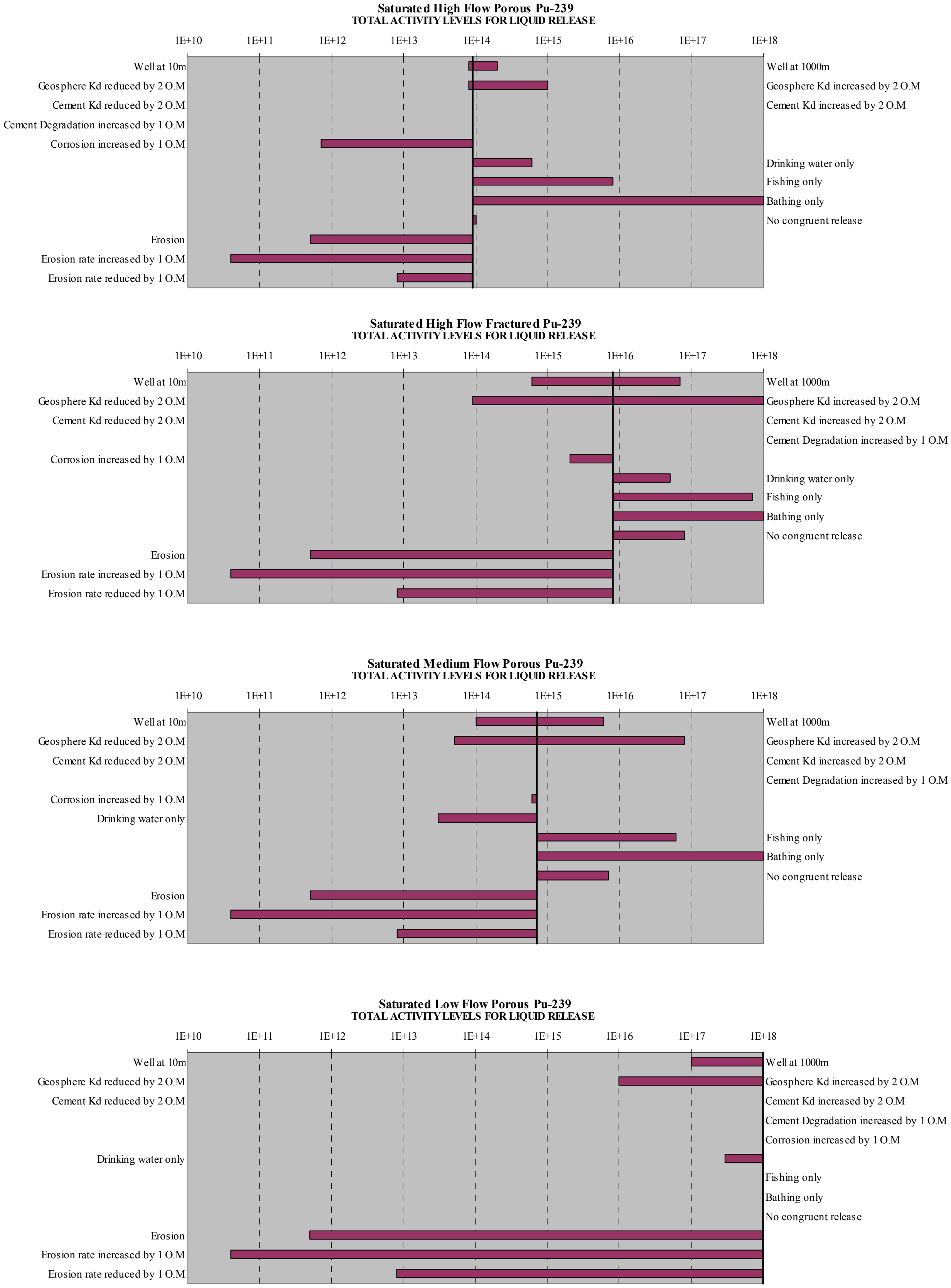
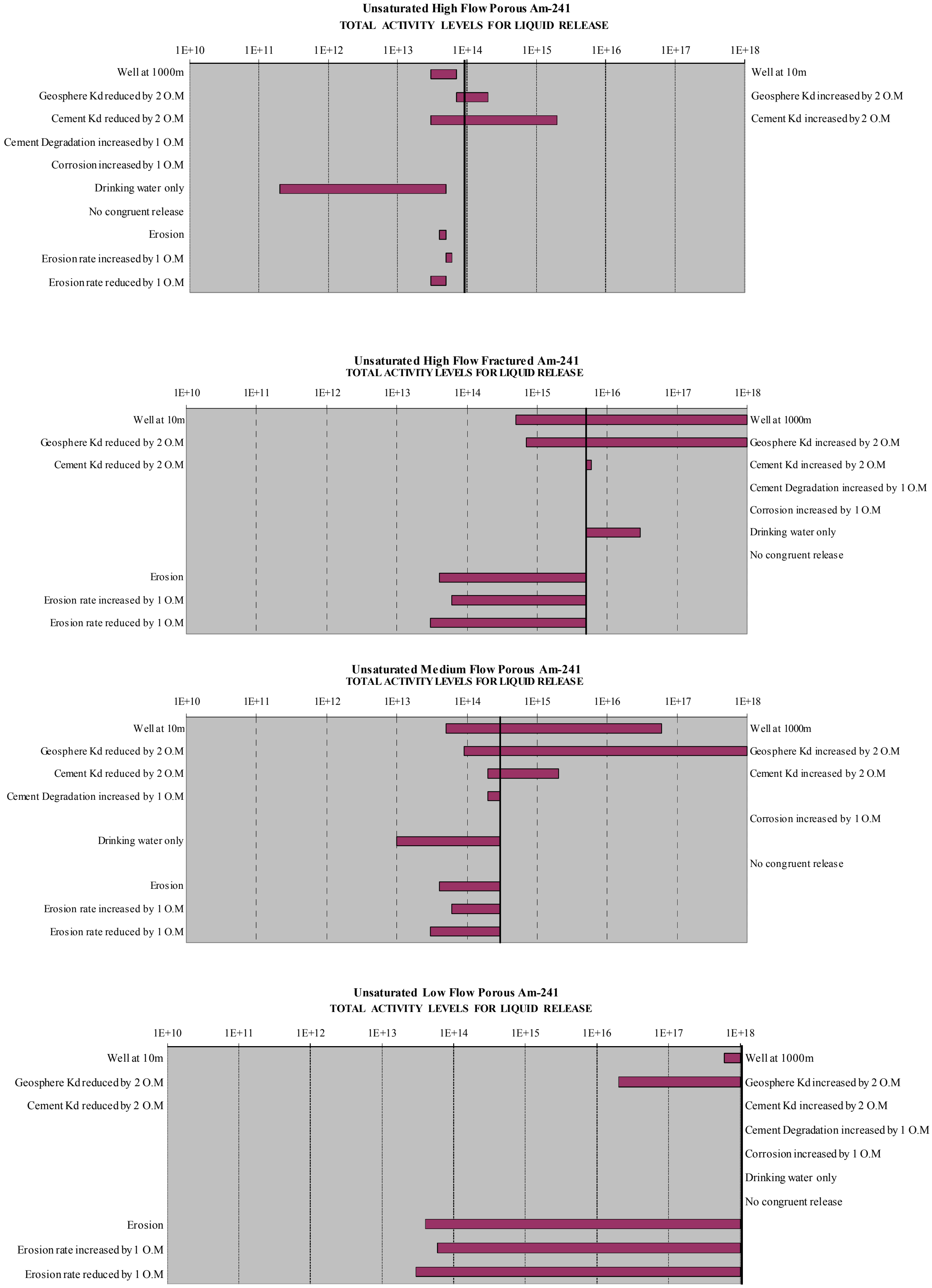


*FIG. 30. Pu-239 Doses for disposal in unsaturated zone for variant cases.*



Unsaturated High Flow Porous Am-241
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

Unsaturated High Flow Fractured Am-241
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

Unsaturated Medium Flow Porous Am-241
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

Unsaturated Low Flow Porous Am-241
TOTAL ACTIVITY LEVELS FOR LIQUID RELEASE

FIG. 31. *Am-241 Doses for disposal in unsaturated zone for variant cases.*

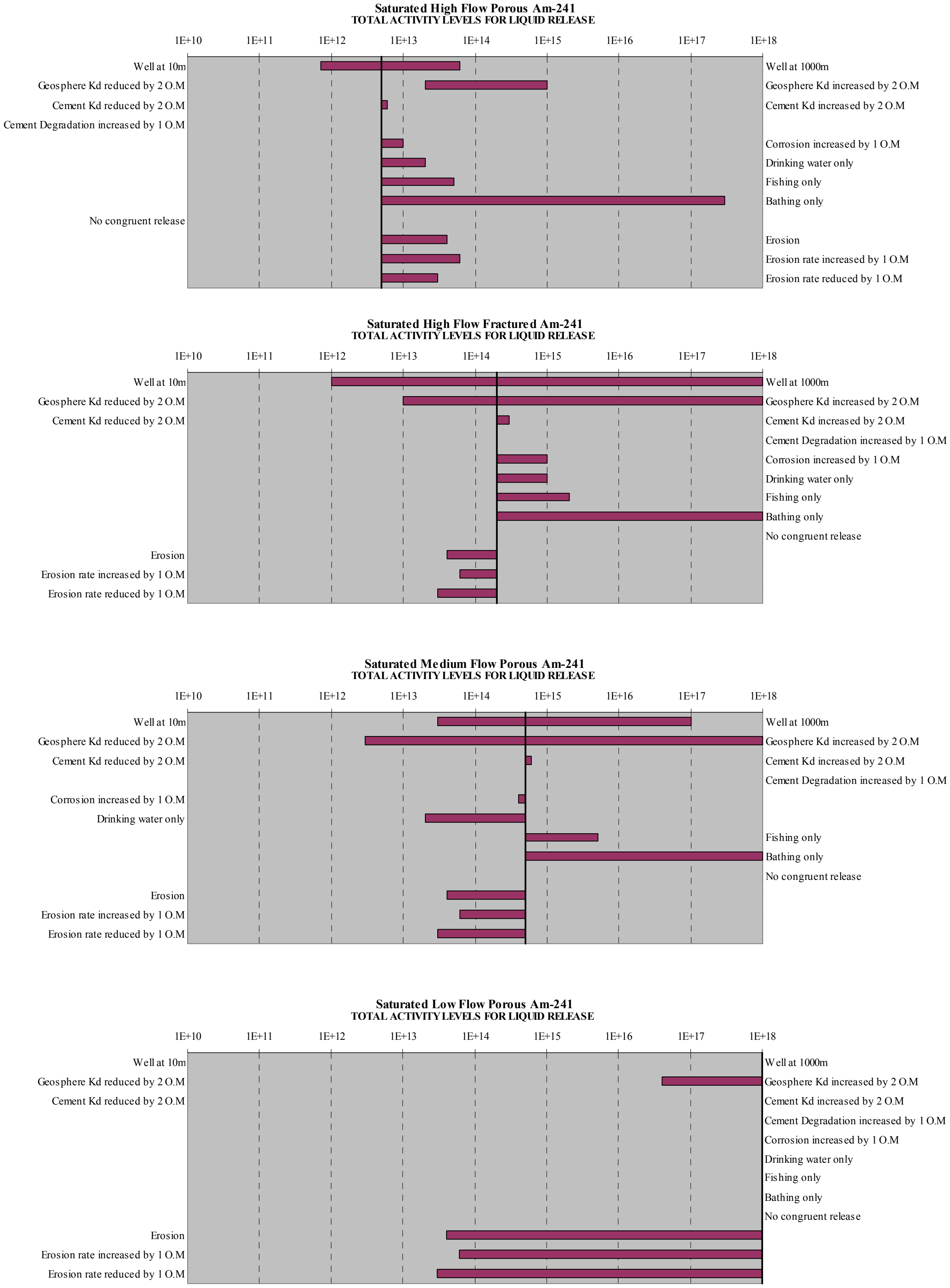


*FIG.32. Am-241 Doses for disposal in saturated zone for variant cases.*

# REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary, IAEA, Vienna (2007).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Categorization of Radioactive Sources, IAEA-TECDOC-1344, IAEA, Vienna (2003).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Management for the Prevention of Accidents from Disused Sealed Sources, IAEA-TECDOC-1205, IAEA, Vienna (2001).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Disposal Options for Disused Radioactive Sources, IAEA Technical Reports Series No. 436, IAEA, Vienna (2005).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Specific Safety Standards for Protecting People and the Environment: Disposal of Radioactive Waste, IAEA Specific Safety Requirements No. SSR-5, IAEA, Vienna (2011).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Disposal Facilities for Radioactive Waste, Specific Safety Guide No. SSG-14, IAEA, Vienna (2011).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal Facilities for Radioactive Waste, Specific Safety Guide No. SSG-29, IAEA, Vienna (2014).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Borehole Disposal Facilities for Radioactive Waste, IAEA Safety Series No. SSG-1, IAEA, Vienna (2009).

[9] SOUTH AFRICAN NUCLEAR ENERGY CORPORATION, Design for the Borehole Disposal Concept, Report GEA 1623, NECSA, Pretoria (2003).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Identification of Radioactive Sources and Devices, IAEA Nuclear Security Series No. 5, IAEA, Vienna (2007).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Socio-economic and Other Non-radiological Impacts of the Near Surface Disposal of Radioactive Waste, IAEA-TECDOC-1308, IAEA, Vienna (2002).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment Methodologies for Near Surface Disposal Facilities, IAEA, Vienna (2004).

[13] NATIONAL NUCLEAR REGULATOR, Licensing Guide: The Borehole Disposal Facility Safety Case, NNR Report, Revision 0, NNR, Centurion (2002).

[14] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiation Protection Recommendations as Applied to the Disposal of Long lived Solid Radioactive Waste, International Commission on Radiological Protection, ICRP Publication 81, Pergamon Press, Oxford (2000).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standdards Series No. GSR Part 3, IAEA, Vienna (2014).

[16] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, A Framework for Assessing the Impact of Ionising Radiation on Non-human Species, ICRP Publication 91, Pergamon Press, Oxford (2003).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, 'Reference Biospheres' for Solid Radioactive Waste Disposal, IAEA, Vienna (2003).

[18] PRÖHL, G., et al., Biosphere Models for Safety Assessment of Radioactive Waste Disposal, GSF-Bericht 06/04, National Research Centre for Environment and Health, Neuherberg (2004).

[19] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Pergamon Press, Oxford (1991).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Protection of the Environment from Ionising Radiation, C&S Papers Series (Print) No. 17, IAEA, Vienna (2003).

[21] FASSET, Framework for Assessment of Environmental Impact, Final Report produced under European Commission Contract FIGE-CT-2000-00102, available from http://www.fasset.org/ (2004).

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Report on Radioactive Waste Disposal, IAEA Technical Reports Series No. 349, IAEA, Vienna (1993).

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Derivation of Activity Limits for the Disposal of Radioactive Waste in Near Surface Disposal Facilities, IAEA-TECDOC-1380, IAEA, Vienna (2003).

[24] INTERNATIONAL ATOMIC ENERGY AGENCY, Net Enabled Waste Management Database (NEWMDB), http://www-newmdb.iaea.org/, IAEA, Vienna. Accessed January 2008.

[25] VAN BLERK, J.J., Analysis of a Post Closure Safety Assessment Methodology for Radioactive Waste Disposal Systems in South Africa, Ph.D. Thesis, Faculty of Natural Science, Department of Geohydrology, University of the Free State, Bloemfontein (2000).

[26] NUCLEAR INDUSTRY RADIOACTIVE WASTE EXECUTIVE, Generic Repository Studies: Generic Post-closure Performance Assessment, Nirex Report N/080, UK Nirex Limited, Harwell (2003).

[27] INTERNATIONAL ATOMIC ENERGY AGENCY, "Reference Biospheres" for Solid Radioactive Waste Disposal. Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, IAEA-BIOMASS-6, IAEA, Vienna (2003).

[28] LOONEY, B.B., GRANT, M.W., KING, C.M., Estimation of Geochemical Parameters for Assessing Subsurface Transport at the Savannah River Plant, Savannah River Laboratory Report DPST-85-904 (1987).

[29] NEUMAN, S.P., Universal Scaling of Hydraulic Conductivities and Dispersivities in Geological Media, Water Resources Research, Vol. 26, No. 8, pp. 1749-1758 (1990).

[30] KOERNER, R.M., HSUAN, Y.G., AND KOERNER, G.R., Geomembrane Lifetime Prediction: Unexposed and Exposed Conditions. Geosynthetic Institute, GRI White Paper No. 6, http://www.geosynthetic-institute.org/papers/paper6.pdf (2005).

[31] WIENHOLD, P., CHUDNOVSKY, A., Lifetime of High-Density Polyethylene Drain Pipe in an Aggressive Environment, Transportation Research Board Annual Meeting 2006 Paper #06-2377, http://pubsindex.trb.org/document/view/default.asp?lbid=777424 (2006).

[32] LITTLE, R.H., VAN BLERK, J.J., WALKE, R.C., BOWDEN, R.A., Generic Post-Closure Safety Assessment and Derivation of Activity Limits for the Borehole Disposal Concept, Quintessa Report QRS-1128A-6 v2.0, Quintessa Limited, Henley-on-Thames (2004).

[33] BRITISH STANDARD INSTITUTE, Code of Practice for Site Investigations, BS 5930:1999 (1999).

[34] BERNER, U., Evolution of porewater chemistry during degradation of cement in a radioactive waste repository environment, Waste Management, 12, 201-219 (1992).

[35] BERNER, U., Status of Cement Modelling: Future investigations in the view of cement/bentonite interactions, (Metcalfe, R., Walker, C., Eds) (Proc. Int. Workshop Tokyo, 2004), NUMO report TR-04-05, Tokyo (2004).

[36] ENVIROS AND QUINTESSA, AMBER 5.0 Reference Guide, Enviros Consulting Limited, Culham, and Quintessa, Henley-on-Thames (2006).

[37] BRITISH NUCLEAR FUELS LIMITED, Drigg Post-Closure Safety Case, British Nuclear Fuels plc, Sellafield (2002).

[38] ROBINSON, P.C., PENFOLD, J.S.S., LITTLE, R.H., WALKE, R.C., AMBER 5 Verification: Summary, Quintessa Report QSR-3001B-1, Quintessa Limited, Henley-on-Thames (2006).

[39] BYRNE, G.D., HINDMARSH A.C., A Polyalgorithm for the Numerical Solution of Ordinary Differential Equations, ACM Transactions on Mathematical Software, Vol. 1, No. 1, New York (1975) pp. 71-96.

[40] ROBINSON, P.C., DYLAN Time-stepping Algorithms: The Approach Used in the DYLAN Solver, Quintessa Report QSR-DYLAN-1, Quintessa Limited, Henley-on-Thames (2001).

[41] OECD NUCLEAR ENERGY AGENCY, Stakeholder Participation in Radiological Decision Making: Processes and Implications: Summary Report of the 3rd Villigen (Switzerland) Workshop, October 2003, Organization for Economic Co-operation and Development – Nuclear Energy Agency, Paris (2004).

[42] OECD NUCLEAR ENERGY AGENCY, Learning and Adapting to Societal Requirements for Radioactive Waste Management, Organization for Economic Co-operation and Development – Nuclear Energy Agency, Paris (2004).

[43] INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety Case and Safety Assessment for Disposal of Radioactive Waste, Specific Safety Guide No. SSG-23 , IAEA, Vienna (2012).

[44] MAUL, P.R., ROBINSON, P.C., Exploration of Important Issues for the Safety of SFR 1 using Performance Assessment Calculations, Swedish Nuclear Power Inspectorate Report 02:62, Stockholm (2002).

[45] PENFOLD J.S.S., LITTLE R.H., BOWDEN R.A., EGAN M.J., Preliminary Safety Assessment of Concepts for a Permanent Waste Repository at the Western Waste Management Facility Bruce Site, Quintessa Report QRS-1027B-1 v1.0, Henley-on-Thames (2003).

[46] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Management Systems – Requirements, ISO 9001:2000, ISO, Geneva (2000).

[47] APPELO, C.A.J., POSTMA, D., Geochemistry, groundwater and pollution, Balkema, Rotterdam, (1994) 24, Table 2.2.

[48] BAILEY, A.S., HORNBECK, J.W., CAMPBELL, J.L., EAGAR, C., Hydrometeorological database for Hubbard Brook Experimental Forest: 1955-2000, United States Department of Agriculture Forest Service, General Technical Report NE-305 (2002).

[49] BATH, A.H., et al., Geochemical Indicators of Deep Groundwater Movements at Sellafield, UK, Journal of Geochemical Exploration (2006) 90, 24-44.

[50] BATH, A.H., EDMUNDS, W.M., Identification of connate water in interstitial solution of Chalk sediment, Geochimica et Cosmochimica Acta (1981) 45, 1449-1461.

[51] BOTTOMLEY, D.J., GASCOYNE, M., KAMINENI, D.C., The geochemistry, age and origin of groundwater in a mafic pluton, East Bull Lake, Ontario, Canada, Geochimica et Cosmochimica Acta, (1990) 54, 933-1008.

[52] GALE, H.S., Salines in the Owens, Searles, and Panamint Basins, southeastern California, United States Geological Survey Bulletin, (1915) 580: 251-323.

[53] GASCOYNE, M., Hydrogeochemistry, groundwater ages and sources of salts in a granitic batholith on the Canadian Shield, southeastern Manitoba, Applied Geochemistry, (2004) 19, 519-560.

[54] HAY, R.L., GULDMAN, S.G., Diagenetic alteration of silicic ash in Searles Lake, California, Clays and Clay Minerals, (1987) 35, 449-457.

[55] IWATSUKI, T., ARTHUR, R.C., OTA, K., METCALFE, R., Solubility constraints on uranium concentrations in groundwaters of the Tono Uranium deposit, Japan, Radiochimica Acta, (2004) 92, 789-796.

[56] JAPAN NUCLEAR CYCLE DEVELOPMENT INSTITUTE, H12: Project to establish the scientific and technical basis for HLW disposal in Japan, Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC Technical Report JNC TN1410 2000-002, Tokai-mura, Japan (2000).

[57] MILLERO, F.J., The conductivity-density-salinity-chlorinity relationships for estuarine water. Limnology and Oceanography, (1984) 29, 1317-1321.

[58] NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, National Climate Data Center (NCDC), http://www.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html, (2006).

[59] ROYAL SOCIETY, Ocean acidification due to increasing atmospheric carbon dioxide, (2005).

[60] SUMMERHAYES, C.P., THORPE, S.A., Oceanography: An Illustrated Guide, (1996) Chapter 11, 165-181.

[61] SURDAM, R.C., SHEPPARD, R.A., Zeolites in saline, alkaline-lake deposits. In: SAND L.B., MUMPTON F.A., (Eds), Natural Zeolites, Occurrence, Properties, Use, New York, (1977) 145-174.

[62] YUI, M., SASAMOTO, H., ARTHUR, R.C., Geostatistical and geochemical classification of groundwaters considered in safety assessment of a deep geologic repository for high-level radioactive wastes in Japan. Geochemical Journal 38, (2004), 33-42.

[63] ATKINSON, A., HARRIS, A.W., HEARNE, J.A., Comparison of Materials for the Backfilling of Repositories, Nirex Report NSS/R306, UK (1997).

[64] BERNER, U.R., A Thermodynamic Description of the Evolution of Porewater Chemistry and Uranium Speciation during the Degradation of Cement, Technical Report, NTB 90-12, Nagra, Switzerland (1990).

[65] BIDDLE, P., DAVIES, A.A., McGAHAN, D.J., REES, J.H., RUSHBROOK, P.E., The Evolution of Minor Active and Toxic Gases in Repositories, Nirex Report NSS/R118, UK (1988).

[66] CHAMBERS, A.V., WILLIAMS, S.J., WISBEY, S.J., Nirex Near Field Research: Report on Current Status in 1994, Nirex Report S/95/011, UK (1995).

[67] FRANCIS, A.J., CATHER, R., CROSSLAND, I.G., Development of the Nirex Reference Vault Backfill: Report on Current Status in 1994, Nirex Report S/97/014, UK (1997).

[68] GREENFIELD, B.F., SPINDLER, M.W., WOODWARK, D.R., Summary of Effects of Organic Degradation Products on Near–field Radioelement Chemistry, Nirex Report NSS/R298, UK (1997).

[69] INTERNATIONAL ATOMIC ENERGY AGENCY, Development of specifications for radioactive waste packages, IAEA-TECDOC-1515, IAEA, Vienna (2006).

[70] LITTLE, B., WAGNER, P., MANSFELD, F., Microbiologically influenced corrosion of metals and alloys, Int. Mater, Rev. 36 (1991) 253-272.

[71] NIELSEN, E.P., HERFORTA, D., GEIKERB, M.R., Binding of chloride and alkalis in Portland cement systems, Cement and Concrete Research, 35, (2005) 117-123.

[72] NUCLEAR INDUSTRY RADIOACTIVE WASTE EXECUTIVE (NIREX), Post-closure Performance Assessment: Gas Generation and Migration, Nirex Report S/94/003, UK (1994).

[73] SHOESMITH, D.W., KING, F., The effects of gamma radiation on the corrosion of candidate materials for the fabrication of nuclear waste packages, Atomic Energy of Canada Limited Report, AECL-11999 (1999).

[74] SHREIR, L.L., Corrosion, 2nd edition, Newnes-Butterworths, London (1976).

[75] MINDESS, S., YOUNG, J.F., Concrete, Prentice-Hall, NJ (1981).

[76] GLASSER, F.P., MACPHEE, D.E., LACHOWSKI, E.E., Solubility modelling of cements: Implications for radioactive waste immobilisation, In: M.J. Apted and R.E. Westermann (Editors), Scientific Basis for Nuclear Waste Management XI. Materials Research Society, (1988) 331-341.

[77] GREENBERG, S.A., CHANG, T.N., Investigation of the colloidal hydrated calcium silicates: II Solubility relationships in the calcium oxide - silica - water system at 25°C, Journal of Physical Chemistry, (1965) 69: 182-188.

[78] KARLSSON, F., LINDGREN, M., SKAGIUS, K., WIBORGH, M., ENGKVIST, I., Evolution of geochemical conditions in SFL 3-5, SKB Report R-99-15 Swedish Nuclear Fuel and Waste Management Company, Stockholm (1999).

[79] BETHKE, C.M., The Geochemist's Workbench Release 6: GWB Essentials Guide: A User's Guide to Rxn, Act2, Tact, SpecE8, and Aqplot, Rockware, Golden, CO (2006) 76.

[80] BIOMOVS II, Development of a Reference Biospheres Methodology for Radioactive Waste Disposal, BIOMOVS II Technical Report No. 6, published on behalf of the BIOMOVS II Steering Committee by the Swedish Radiation Protection Institute, Sweden (1996).

[81] ANDERSSON, J., RIGGARE, P., SKAGIUS, K., Project SAFE - Update of the SFR-1 Safety Assessment Phase 1, SKB Report R-98-43, Swedish Nuclear Fuel and Waste Management Company, Stockholm (1998).

[82] BRITISH NUCLEAR FUELS LIMITED (BNFL), Drigg Post-Closure Safety Case, British Nuclear Fuels plc, Sellafield (2002).

[83] KOZAK, M.W., STENHOUSE, M.J., VAN BLERK, J.J., Borehole Disposal of Spent Sources, Volume II: Preliminary Safety Assessment of the Disposal Concept, NECSA Report GEA-1353 (NWS-RPT-00\013), South African Nuclear Energy Corporation, Pretoria (2000).

[84] ALEXANDER, A.L., SOUTHWELL, C.R., Forgeson, B.W., Corrosion of metals in tropical environments, part 5 – stainless steel, Corrosion 17, (1961) 345.

[85] AMERICAN SOCIETY FOR METALS INTERNATIONAL, Corrosion, Metals Handbook, Ninth edition, Volume 13, (ASM Handbook), Metals Park, OH (1987).

[86] AMERICAN SOCIETY FOR METALS INTERNATIONAL, Corrosion: Fundamentals, Testing, and Protection, American Society for Metals International, Volume 13A, (ASM Handbook), Metals Park, OH (2003).

[87] AMERICAN SOCIETY FOR METALS INTERNATIONAL, Corrosion: Materials, American Society for Metals International, Volume 13B, (ASM Handbook), Metals Park, OH (2005).

[88] BETTS, A.J., NEWMAN, R.C., The resistance of austenitic stainless steels to pitting corrosion in simulated BFS/OPC porewater containing thiosulphate ions, UK Nirex Report NSS/R164, National Decommissioning Authority, UK (1990).

[89] BLACKWOOD, D.J., et al., The localized corrosion of carbon steel and stainless steel in simulated repository environments, AEAT/ERRA 0318, (2002).

[90] BECHTEL SAIC COMPANY (BSC) Aqueous corrosion rates for waste package materials, Prepared for US DOE, ANL-DSD-MD-000001, (2004).

[91] CASTEELS, I., DRESSELAARS, G., TAS, H., Corrosion behaviour of container materials for geological disposal of high level waste. Commission of the European Communities Report, EUR 10398 EN, (1986) 3-40.

[92] CLAYTON, C.R., OLEFJORD, I., Passivity of austenitic stainless steels. In Corrosion Mechanisms in Theory and Practice (Dekker, M., Marcus, P., Oudar, J., Eds), New York, NY (1995), 175 199.

[93] CUI, I., SAGÜÉS, A., Corrosion performance of stainless steel clad rebar in simulated porewater and concrete, (Proc. Corrosion 2003, NACE International, Houston, U.S. 2003) .

[94] DECHEMA, Corrosion Handbook: Corrosive Agents and their Interaction with Materials, Volume 7 Atmosphere, (1990).

[95] DUNN, D.S., CRAGNOLINO, G.A., SRIDHAR, N., Localized corrosion initiation, propagation, and repassivation of corrosion resistant high-level nuclear waste container materials (Proc. CORROSION 96, NACE International, Denver, U.S. 1996).

[96] FUJISAWA R., KURASHIGE, T., INAGAKI, U., SENOO, M., Gas generation behavior of transuranic waste under disposal conditions (Proc. MRS Symposium Proceedings Volume 556, Boston, 1998), Vol. 556, (1999).

[97] FUKAYA, Y., AKASHI, M., Estimation of the cathodic hydrogen evolution rate on radioactive waste packaging materials (Proc. CORROSION 2003, NACE International, San Diego, U.S. 2003).

[98] GRIFFEN, R.B., CORNWELL, L.R., SEITZ, W., ESTES, E., Localized corrosion under biofouling (Proc. CORROSION 88, NACE International, Saint Louis, U.S. 1988).

[99] HARUKI, N., KIMURA, T., KURODA, M., MIYUKI, H., KUDO, T., Corrosion resistance of super stainless steel for condensers of power plants (Proc. Conf. on Stainless Steels, Chiba, 1991), Vol. 2 (1991).

[100] HOCH, A.R., NAISH, C.C., SHARLAND, S.M., SMITH, A.C., TAYLOR, K.J., Experiments And Modeling Studies Concerning Localized Corrosion Of Carbon Steel And Stainless Steel

Containers For Intermediate And Low Level Radioactive Waste (Proc. Symp. Materials Research Society, Boston, U.S. 1992) .

[101] JOHNSON, M.J., PAVLIK, P.J., Atmospheric corrosion of stainless steels (Ailor, W.H., Ed.), Atmospheric Corrosion, (1982) 461.

[102] JONES, R.H. (Ed.), Stress-Corrosion Cracking, ASM International, Materials Park, OH (1992).

[103] KEARNS, J.R., JOHNSON, M.J., FRANSON, I.A., The corrosion of stainless steels and nickel alloys in caustic solutions (Proc. CORROSION 84, NACE International, Houston, U.S. 1984).

[104] LAYCOCK, N.J., NEWMAN, R.C., Localized dissolution kinetics, salt films and pitting potentials, Corrosion Science 39, (1997) 1771 1790.

[105] LAYCOCK, N.J., NOH, J.S., WHITE, S.P., KROUSE, D.P., Computer simulation of pitting potential measurements, Corrosion Science 47, (2005) 3140–3177.

[106] MATTSSON, H., OLEFJORD, I., Analysis of oxide formed on Ti during exposure in bentonite clay-I. The oxide growth, Vol. 41, (1990) 383–390.

[107] MATTSSON, H., LI, C., OLEFJORD, I., Analysis of oxide formed on Ti during exposure in bentonite clay. II. The structure of the oxide. Vol. 41, (1990) 578–584.

[108] MCDONALD, D.B., SHERMAN, M.R., PFEIFER, D.W., VIRMANI, Y.P., Stainless steel reinforcing as corrosion protection, Reprint in Concrete International, No. 14034, (1995).

[109] MCINTYRE, D.R., Experience survey stress corrosion cracking of austenitic stainless steel in water, Materials Technology Institute, St. Louis, MO, (1987).

[110] MORSY, S.M., EL-RAGHY, S.M., ELSAED, A.A., EL-MEHAIRY A.E., Effect of cations on the corrosion of stainless alloys in saline water at elevated temperatures, Arab Republic of Egypt Atomic Energy Establishment Report 232 (1979).

[111] NAISH, C.C., BLACKWOOD, D.J., TAYLOR, K.J., THOMAS, M.I., The anaerobic corrosion of stainless steels in simulated repository backfill environments, Nirex Report NSS/R307 (1995).

[112] NEWMAN, R.C., Understanding the corrosion of stainless steel, Corrosion Vol. 57, (2001) 1030 1041.

[113] NEWMAN, R.C., FRANZ, E.M., Growth and repassivation of single corrosion pits in stainless steel, Corrosion Vol. 40, (1984) 325.

[114] PARK, J.O., MATSCH, S., BÖHNI, H., Effects of temperature and chloride concentration on pit initiation and early pit growth of stainless steel, Journal of The Electrochemical Society, Vol. 149, Issue 2, (2002) B34 B39.

[115] POURBAIX, M., Atlas of Electrochemical Equilibria in Aqueous Solutions, 2nd edn, Cebelcor, Brussels, Belgium, NACE International, Houston, TX, (1974).

[116] REVIE, R.W., Uhlig's Corrosion Handbook, 2nd edn, (WILEY, J., Ed.), New York (2000).

[117] RUBINSHTEJN, I.I., LASHCHEVSKAYA, D.E., RUBINSHTEJIN, E., MAMONTAVA, L.M., GULYAEV, V.A., Accelerated testing of the corrosion resistance of chromium nickel steels in model environments simulating the manufacturing conditions of the synthetic resin KFE, Mat. Primen, No. 3, (1977) 59.

[118] SEDRIKS, A.J., Corrosion of Stainless Steels, 2nd edn (Wiley, J., Ed.), New York, NY (1996).

[119] SHARLAND, S.M., (Proc. Nuclear Waste Packaging FOCUS' 91, La Grange Park, IL, 1991), place (year) 233–240.

[120] SMART, N.R., et al., The Anaerobic Corrosion of Carbon and Stainless Steels in Simulated Repository Environments: A Summary Review of Nirex Research, AEA Technology Report AEAT/ERRA-0313, (2004).

[121] SRIDHAR, N., CRAGNOLINO, G.A.,DUNN, D., Experimental investigations of localized corrosion of high-level container materials, Center for Nuclear Waste Regulatory Analyses, San Antonio, TX (1993) 93 004.

[122] SRIDHAR, N., BROSSIA, C.S., DUNN, D.S., ANDERKO, A., Predicting localized corrosion in seawater, Corrosion Vol. 60, (2004) 915 936.

[123] SZKLARSKA-SMIALOWSKA, Z., Pitting and Crevice Corrosion, NACE International, Houston, TX (2005).

[124] TANI, J., MAYUZUMI, M., Stress corrosion cracking of stainless steel canister for dry storage of spent fuel using concrete cask (Proc. Workshop on Long term Prediction of Corrosion Damage in Nuclear Waste Systems, Pennsylvania State University, PA 2007), place (year).

[125] WADA, R., NISHIMURA, T., FUJIWARA, K., TANABE, M., MIHARA, M., Experimental study of hydrogen gas generation rate from corrosion of Zircaloy and stainless steel under anaerobic alkaline condition (Proc. ICEM Conf. Radioactive Waste Management and Environmental Remediation, Nagoya, 1999), place (year).

[126] WHITE, J.H., YANIC, A.E., SCHICK, H., The corrosion of metals in the water of the Dead Sea, Corrosion Science 6, (1966) 447.

[127] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Online Database of Dose Coefficients from Federal Guidance Report No. 12, Date Accessed: 16 September 2004, http://www.ornl.gov/~wlj/fgr12tab.htm.

[128] ANDERSSON, J., SR 97 Data and Data Uncertainties. Compilation of Data and Data Uncertainties for Radionuclide Transport Calculations. SKB Technical Report TR-99-09, Swedish Nuclear Fuel and Waste Management Company, Stockholm (1999).

[129] SAVAGE, D., STENHOUSE, M.J., SFR Vault Database, SKI Report R02-53, Swedish Nuclear Power Inspectorate, Stockholm (2002).

[130] NATIONALE GENOSSENSCHAFT FÜR DIE LAGERUNG RADIOAKTIVER ABFÄLLE, Project Opalinus Clay: Models, Codes and Data for Safety Assessment. Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-level Waste and Long lived Intermediate-level Waste (Entsorgungsnachweis), Nagra Technical Report 02-06, Wettingen (2002).

[131] JAPAN NUCLEAR CYCLE DEVELOPMENT INSTITUTE: H12: Project to Establish the Scientific and Technical Basis of HLW Disposal in Japan, Supporting Report 3: Safety Assessment of the Geological Disposal System, JNC Report JNC TN1410 2000-004, Tokai-mura, Japan (2000).

[132] ASHTON, J., SUMERLING, T.J., Biosphere Database for Assessments of Radioactive Waste Disposals, UKDoE Report No. DoE/RW/88.083 (1988).

[133] SIMMONDS, J.R., CRICK, M.J., Transfer parameters for use in terrestrial foodchain models. National Radiological Protection Board, NRPB-M63, Chilton, UK (1982).

[134] NATIONALE GENOSSENSCHAFT FÜR DIE LAGERUNG RADIOAKTIVER ABFÄLLE, Report on Long term Safety of the L/ILW Repository at the Wellenberg Site, Nagra Report NTB 94-06, Wettingen (1994).

[135] ALLARD, B., HÖGLUND, L.O., SKAGIUS, K., Adsorption of Radionuclides in Concrete, SKB Progress Report SKB/SFR 91-02, Swedish Nuclear Fuel and Waste Management Company, Stockholm (1991).

[136] CARSLAW, H.S., JAEGER, J.C., Conduction of Heat in Solids, 2nd edn, Oxford University Press (1959).

[137] YU, C., et al., Data Collection Handbook to Support Modelling the Impacts of Radioactive Material in Soil, Argonne National Laboratory, Report ANL/EA15-8, Argonne, IL (1993).

[138] PENFOLD, J.S.S., LITTLE, R.H., ROBINSON, P.C., SAVAGE, D., Improved Safety Assessment Modelling of Immobilised LLW Packages for Disposal, Ontario Power Generation Technical Report 05386-REP-03469.3-10002-R00, Toronto (2002).

[139] CHEN, Y., et al., Dissolved concentration limits of radioactive elements, Sandia Report ANL-WIS-MD-000010 REV 02 (2003).

[140] BAES, C.F. Jr., MESMER, R.E., The Hydrolysis of Cations (Wiley, J., Reprint Edition), New York, NY (1976) 490pp.

[141] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Age-dependent doses to members of the public from intake of radionuclides: Part 5. Compilation of ingestion and inhalation dose coefficients. Annals of the ICRP 26(1), ICRP Publication 72, Pergamon Press. Oxford (1996).

[142] SMITH, G.M., FEARN, H.S., SMITH, K.R., DAVIS, J.P., KLOS, R., Assessment of the radiological impact of disposal of solid radioactive waste at Drigg, National Radiological Protection Board, NRPB-M148, Chilton (1988).

[143] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radionuclide Transformations Energy and Intensity of Emissions. International Commission on Radiological Protection, ICRP Publication 38, Oxford (1983).

[144] BROWNE, R.B., FIRESTONE, V.S., Table of the Radioactive Isotopes, New York, NY (1988).

[145] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFECTS OF ATOMIC RADIATION, Sources and Effects of Ionizing Radiation, United Nations, New York (2000).

# CONTRIBUTORS TO DRAFTING AND REVIEW

| | |
|---|---|
| Ahn, Sang-Myeon | Korea Institute of Nuclear Safety, Republic of Korea |
| Ahonen, L. | Geological Survey of Finland, Finland |
| Andrievskaya, L.A. | Federal Agency of the Atomic Energy, Russian Federation |
| Ávila Moreno, R. | Facilia AB, Sweden |
| Bérci, K. | ETV-ERŐTERV Power Engineering and Contracting Co., Hungary |
| Bennett, D.G. | International Atomic Energy Agency |
| Bruno, G. | Institut de Radioprotection et de Sûreté Nucléaire, France |
| Cochran, J.R. | Sandia National Laboratories, United States of America |
| Crossland, I. | Crossland Consulting Ltd., United Kingdom |
| Dadon, D. | Israel Atomic Energy Commission, Israel |
| Gera, F. | Private Consultant, Italy |
| Glover, E.T. | Ghana Atomic Energy Commission, Ghana |
| Goldammer, W. | Private Consultant, Germany |
| Guskov, A. | MosNPO ‘Radon’, Russian Federation |
| Hazan, J. | Israel Atomic Energy Commission, Israel |
| Ionescu, I.-A. | National Commission for Nuclear Activities Control, Romania |
| Ji, Sung-Hoon | Korea Atomic Energy Research Institute, Republic of Korea |
| Jova Sed, L.A. | International Atomic Energy Agency |
| King, F. | Integrity Corrosion Consulting Ltd., Canada |
| Kozak, M.W. | Intera, United States of America |
| Little, R. | Quintessa Limited, United Kingdom |
| Mbambo, Z. | National Nuclear Regulator, South Africa |
| Metcalfe, R. | Quintessa Limited, United Kingdom |
| Motiejunas, S. | Radioactive Waste Management Agency, Lithuania |
| Nair, R.N. | Bhabha Atomic Research Centre, India |
| Nel, L. | South African Nuclear Energy Corporation Limited, South Africa |
| Omondi Koteng, A. | Radiation Protection Board, Kenya |
| Rizzo, S. | Nucleco S.P.A., Italy |
| Schwartz, I. | Israel Atomic Energy Commission, Israel |

| | |
|---|---|
| Seitz, R. | Idaho Cleanup Project, United States of America |
| Steyn, I. | National Nuclear Regulator, South Africa |
| Sun, Qinghong | China Institute of Radiation Protection, China |
| Tkachenko, A. | MosNPO ‘Radon’, Russian Federation |
| Veselic, M. | Agency for Radwaste Management, Slovenia |

# ORDERING LOCALLY

In the following countries, IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

## CANADA

***Renouf Publishing Co. Ltd***

22-1010 Polytek Street, Ottawa, ON K1J 9J1, CANADA
Telephone: +1 613 745 2665 • Fax: +1 643 745 7660
Email: order@renoufbooks.com • Web site: www.renoufbooks.com

***Bernan / Rowman & Littlefield***

15200 NBN Way, Blue Ridge Summit, PA 17214, USA
Tel: +1 800 462 6420 • Fax: +1 800 338 4550
Email: orders@rowman.com Web site: www.rowman.com/bernan

## CZECH REPUBLIC

***Suweco CZ, s.r.o.***

Sestupná 153/11, 162 00 Prague 6, CZECH REPUBLIC
Telephone: +420 242 459 205 • Fax: +420 284 821 646
Email: nakup@suweco.cz • Web site: www.suweco.cz

## FRANCE

***Form-Edit***

5 rue Janssen, PO Box 25, 75921 Paris CEDEX, FRANCE
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: formedit@formedit.fr • Web site: www.form-edit.com

## GERMANY

***Goethe Buchhandlung Teubig GmbH***

Schweitzer Fachinformationen
Willstätterstrasse 15, 40549 Düsseldorf, GERMANY
Telephone: +49 (0) 211 49 874 015 • Fax: +49 (0) 211 49 874 28
Email: kundenbetreuung.goethe@schweitzer-online.de • Web site: www.goethebuch.de

## INDIA

***Allied Publishers***

1st Floor, Dubash House, 15, J.N. Heredi Marg, Ballard Estate, Mumbai 400001, INDIA
Telephone: +91 22 4212 6930/31/69 • Fax: +91 22 2261 7928
Email: alliedpl@vsnl.com • Web site: www.alliedpublishers.com

***Bookwell***

3/79 Nirankari, Delhi 110009, INDIA
Telephone: +91 11 2760 1283/4536
Email: bkwell@nde.vsnl.net.in • Web site: www.bookwellindia.com

## ITALY

***Libreria Scientifica "AEIOU"***

Via Vincenzo Maria Coronelli 6, 20146 Milan, ITALY
Telephone: +39 02 48 95 45 52 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Web site: www.libreriaaeiou.eu

## JAPAN

***Maruzen-Yushodo Co., Ltd***

10-10 Yotsuyasakamachi, Shinjuku-ku, Tokyo 160-0002, JAPAN
Telephone: +81 3 4335 9312 • Fax: +81 3 4335 9364
Email: bookimport@maruzen.co.jp • Web site: www.maruzen.co.jp

## RUSSIAN FEDERATION

***Scientific and Engineering Centre for Nuclear and Radiation Safety***

107140, Moscow, Malaya Krasnoselskaya st. 2/8, bld. 5, RUSSIAN FEDERATION
Telephone: +7 499 264 00 03 • Fax: +7 499 264 28 59
Email: secnrs@secnrs.ru • Web site: www.secnrs.ru

## UNITED STATES OF AMERICA

***Bernan / Rowman & Littlefield***

15200 NBN Way, Blue Ridge Summit, PA 17214, USA
Tel: +1 800 462 6420 • Fax: +1 800 338 4550
Email: orders@rowman.com • Web site: www.rowman.com/bernan

***Renouf Publishing Co. Ltd***

812 Proctor Avenue, Ogdensburg, NY 13669-2205, USA
Telephone: +1 888 551 7470 • Fax: +1 888 551 7471
Email: orders@renoufbooks.com • Web site: www.renoufbooks.com

## Orders for both priced and unpriced publications may be addressed directly to:

Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 2600 29302 or +43 1 26007 22529
Email: sales.publications@iaea.org • Web site: www.iaea.org/books

International Atomic Energy Agency
Vienna
ISBN 978–92–0–107117–0
ISSN 1011–4289