- HIDRA -

The International Project
On Inadvertant
Human Intrusion in the context of
Disposal of RadioActive Waste

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CONTENTS

1. INTRODUCTION ................................................................................................. 1

2. BACKGROUND .................................................................................................... 2
   2.1 SCENARIOS IN THE SAFETY CASE ................................................................. 2
   2.2 INADVERTENT INTRUSION .............................................................................. 3

3. PROJECT DESCRIPTION ..................................................................................... 5
   3.1 OBJECTIVES .................................................................................................... 5
   3.2 PROJECT SCOPE ............................................................................................. 5
   3.3 PROJECT ORGANISATION .............................................................................. 6
   3.4 PARTICIPANTS ................................................................................................. 7

4. IAEA AND ICRP RECOMMENDATIONS AND STANDARDS ......................... 8
   4.1 WASTE MANAGEMENT PRINCIPLES ............................................................. 9
   4.2 PROTECTION OF FUTURE GENERATIONS .................................................... 10
   4.3 FUTURE HUMAN ACTIONS IN THE CONTEXT OF A SAFETY CASE ............. 11
      4.3.1 Inadvertent Human Intrusion ..................................................................... 12
      4.3.2 Use of Stylised Scenarios ......................................................................... 13
      4.3.3 Inherent Protectiveness of Geological Disposal ......................................... 14
      4.3.4 Timing of Intrusion – Active and Passive Controls and Safety Features ..... 14
   4.4 INTRUSION CRITERIA (OPTIMISATION RATHER THAN A CONSTRAINT) .... 15
      4.4.1 ICRP and IAEA Criteria ............................................................................ 16

5. GENERAL APPROACH AND LINKS WITH THE SAFETY CASE ................... 18
   5.1 GENERAL APPROACH FOR IHI CONSIDERATION .................................. 18
      5.1.1 Societal Factors .......................................................................................... 19
      5.1.2 Safety Framework ....................................................................................... 20
      5.1.3 Human Intrusion Considerations ............................................................... 20

HIDRA

FINAL DRAFT JANUARY 2017
5.1.4 Analysis and Implementation of Measures ........................................ 20

5.2 HUMAN INTRUSION IN THE COMPONENTS OF THE SAFETY CASE 21

5.2.1 Safety Case Context ................................................................. 23
5.2.2 Safety Strategy ........................................................------------ 25
5.2.3 Disposal System Description .................................................... 26
5.2.4 Safety Assessment ................................................................. 28
5.2.5 System optimisation ............................................................... 29
5.2.6 Management of uncertainty related to human intrusion ............... 30
5.2.7 Limits, controls and conditions ............................................... 31
5.2.8 Integration of Safety Arguments .............................................. 32

6. HUMAN INTRUSION CONSIDERATIONS FOR DECISION MAKING IN THE SAFETY CASE ....................................................... 33

6.1 HUMAN INTRUSION CONSIDERATIONS FOR DECISION MAKING AT KEY STAGES IN THE EVOLVING SAFETY CASE .......... 33

6.1.1 Need for Action ................................................................. 34
6.1.2 Disposal Concept ................................................................. 34
6.1.3 Site Selection and Design ....................................................... 35
6.1.4 Construction ...................................................................... 35
6.1.5 Operation .......................................................................... 36
6.1.6 Closure ............................................................................... 36
6.1.7 Post-closure ........................................................................ 37

6.2 THE SAFETY CASE STORYLINE FOR HUMAN INTRUSION... 37

6.2.1 Phase 0: Operational Period ................................................... 38
6.2.2 Phase 1: Post-closure Active Control ........................................ 38
6.2.3 Phase 2: Post-closure Passive Control ....................................... 38
6.2.4 Phase 3: Distant Future, Knowledge of Facility Hazard is Lost... 39

HIDRA

FINAL DRAFT JANUARY 2017
6.3 DEVELOPING HUMAN INTRUSION SAFETY ARGUMENTS..40

7. SOCIETAL FACTORS ..............................................................................................................43

7.1 INTRODUCTION .................................................................................................................43

7.2 COMMUNICATION OF IHI SCENARIOS - HOW HUMAN INTRUSION SCENARIOS CAN BE USED TO EVALUATE AND COMMUNICATE THE INTRINSIC SAFETY OF RADIOACTIVE WASTE DISPOSAL FACILITIES ..............................................................................................................44

7.2.1 Effective communication during the life cycle of the disposal system 45

7.2.2 Possible cautious assumptions of IHI scenarios to be communicated 48

7.2.3 Use of probabilities/likelihoods in communication of IHI .......... 52

7.3 ROLE OF SOCIETAL FACTORS WHEN DEVELOPING IHI SCENARIOS 54

7.3.1 Technological development of society - global or local, present or future 54

7.3.2 Human diets, habits and settlement pattern, and political and economical changes influencing scenario selection .................................................................55

7.3.3 Deliberate vs inadvertent intrusion - what distinguishes inadvertent from deliberate intrusion? .................................................................57

7.4 PRESERVATION OF KNOWLEDGE ....................................................................................57

7.4.1 Knowledge preservation during the active control period.............. 59

7.4.2 Knowledge preservation beyond the active control period........... 59

7.4.3 Timeframe of the preservation of knowledge....................................62

8. STYLISED SCENARIOS .......................................................................................................64

8.1 INTRODUCTION .................................................................................................................64

8.2 RADIOACTIVE WASTE DISPOSAL SYSTEMS.................................................................67

8.3 STYLISED SCENARIOS BASED ON REPRESENTATIVE HUMAN INTRUSION EVENTS ..............................................................................................................69

8.3.1 Near Surface Disposal – Drilling ................................................................. 71

HIDRA

FINAL DRAFT JANUARY 2017
8.3.2 Near Surface Disposal – Excavation (Residence) ........................................ 72
8.3.3 Near Surface Disposal – Excavation (Road) ........................................... 73
8.3.4 Geological Disposal – Deep Drilling ....................................................... 74
8.3.5 Geological Disposal – Subsurface Mining ............................................. 76
8.3.6 Geological Disposal – Unconventional Mining (Soluble Rock) ............ 77

8.4 CUSTOMISATION OF A REPRESENTATIVE HUMAN INTRUSION SCENARIO .................................................................................................................. 78
8.4.1 Identify the Disposal System .................................................................... 78
8.4.2 Screen the Representative Human Intrusion Scenarios ......................... 79
8.4.3 Define the Human Intrusion Event Characteristics ............................... 80
8.4.4 Identification of Potential Impacts of the Human Intrusion Event .......... 81
8.4.5 Incorporating Measures .......................................................................... 83

8.5 DOCUMENTATION AND COMMUNICATION ....................................... 84
8.6 ADAPTATIONS OF THE HUMAN INTRUSION SCENARIOS ..................... 84

9. POTENTIAL MEASURES ........................................................................... 86
9.1 BACKGROUND AND RATIONALE ......................................................... 87
9.2 APPROACH FOR THE DERIVATION OF PROTECTIVE MEASURES 88
9.2.1 Step 1: Definition of the framework ..................................................... 89
9.2.2 Step 2: Compilation of general measures ............................................. 92
9.2.3 Step 3: Identification of potential/inherent measures .......................... 97
9.2.4 Step 4: Derivation of protective measures .......................................... 103

9.3 CATEGORIES OF MEASURES ................................................................. 108
9.3.1 Monitoring/ Surveillance ....................................................................... 108
9.3.2 Design of disposal facilities and engineering barriers ....................... 110
9.3.3 Knowledge management ...................................................................... 111

HIDRA

FINAL DRAFT JANUARY 2017
9.3.4 Siting................................................................................................. 113
9.3.5 Waste types and characteristics............................................. 115
9.4 SUMMARY ....................................................................................... 116
10. CONCLUSIONS ............................................................................ 119
11. REFERENCES .................................................................................. 124
ANNEX A. DATABASE ON POSSIBLE PROTECTIVE MEASURES 129
1. INTRODUCTION

The International Atomic Energy Agency (IAEA) has set out a framework of internationally agreed standards for nuclear safety, radiation protection, transport and radioactive waste disposal. This document reports the results of the IAEA HIDRA (Human Intrusion in the Context of Disposal of RadioActive Waste) project. The document provides input that can be useful to supplement current IAEA Safety Requirements and Guides for geological radioactive waste disposal and near-surface disposal [IAEA SSR-5 (IAEA 2011a), IAEA SSG-14 (IAEA 2011b), IAEA SSG-29 (IAEA 2014)]. The production of this document was coordinated with activities related to the safety case discussed in the PRISM and GEOSAF projects as well as similar projects being undertaken by the European Commission and the Nuclear Energy Agency.

The IAEA has a statutory obligation to establish standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards (Article III of the IAEA Statute). The IAEA also has a statutory obligation to provide for exchange of information among its member states relating to the peaceful uses of atomic energy (Article VI). The development of the safety standards is aided by having a degree of international consensus on the ‘what’ and ‘how’ of waste safety—something that projects such as HIDRA work towards. The results from the HIDRA project will inform the application of the IAEA safety standards by providing foundation material to clarify requirements related to human intrusion and to support expert missions, training events and peer reviews carried out under the IAEA’s Technical Cooperation Fund. Exchange of information among the Member States was also fostered by participating in the various HIDRA meetings and through dissemination of the products developed during the project.

The HIDRA project addressed approaches to consider potential inadvertent human intrusion (IHI) resulting from future human actions in post-closure safety assessment of radioactive waste disposal and the use of those assessments to support decision making within the context of a safety case. Per the IAEA Specific Safety Guide No. SSG-23, The Safety Case and Safety Assessment for the Disposal of Radioactive Waste (SSG-23, IAEA 2012), “Only those human actions that result in direct disturbance of the disposal facility (i.e. the waste, the contaminated near field or the engineered barriers) are considered human intrusion.” Thus, future human actions resulting in disturbances outside the contaminated near field or the engineered barriers are not addressed in this report. Furthermore, SSG-23 states “intentional acts that result in disruption of the facility are not addressed in a safety assessment,” and thus, such deliberate or intentional acts are also not considered in this report.

The results from HIDRA provide insights and general approaches based on the common principles, requirements and recommendations from the IAEA, ICRP and OECD/NEA and experiences in Member States. The intent is to identify and share information related to implementation of activities to develop and meet site-specific requirements for assessing IHI.
2. BACKGROUND

The aim of radioactive waste disposal is to increase the level of safety of the waste by removing it from the human environment. Containing the waste and isolating it from the human environment by burying it, rather than dispersing it in the environment, is generally accepted as the preferred approach for final disposition of solid radioactive waste. When solid waste has been placed in a sealed underground or near-surface disposal facility, the intention is that there will be no further human contact with the waste as disposal facilities are designed for passive safety. However, the concentration and containment of the waste in one location could pose a hazard in the future, if someone were to disrupt the disposed waste.

2.1 SCENARIOS IN THE SAFETY CASE

A safety case for a radioactive waste disposal facility needs to explain how the facility will provide long-term isolation of the waste from the human environment. As the future is uncertain, safety cases typically consider a range of different scenarios involving different types of uncertainties. These uncertainties include, for example, variability in the natural and engineered systems, conceptual uncertainties such as how the disposal system will evolve over time, and future uncertainties regarding how human habits will change over time (Seitz et al. 2011). These scenarios are not attempting to predict the future, but rather to illustrate possibilities that may, or may not, occur in the future. Some of the possible scenarios will be more likely to occur than others.

Scenarios for the evaluation of potential exposures are identified for the purpose of planning or judging protection measures (ICRP Publication 103 (1997), Paragraph 266) with the intent of providing a reasonable representation of the sequence of events leading to potential exposures in the future. Given the uncertainty associated with projections far in the future, a hierarchy of classes of scenarios can be used (IAEA SSG-14, para.II. 32 and 33; IAEA SSG-29, para. 5.18; IAEA SSG-23, paras. 5.38 and 39; and OECD/NEA MeSa Project (OECD/NEA 2012, p.37), for example:

1. central/ base/normal/reference = expected/likely evolution,
2. variant = less-likely but still plausible,
3. extreme = very unlikely,
4. what-if = impossible, implausible, and
5. human intrusion.

The specific terms in the hierarchy are interpreted differently by different regulators, but the concept of a hierarchy with inadvertent human intrusion being considered separately is commonly accepted principle. From the perspective of a design basis commonly applied for operational safety analysis, ICRP Publ.122 (ICRP 2013) classifies the potential future evolution paths into design basis evolution...
(scenario types 1, 2 above) and non-design-basis evolution (scenario types 3, 4, and 5) for geological disposal reflecting the relative potential of the scenario occurring.

The safety case will typically consider a ‘normal evolution’ scenario (sometimes called a central, base, compliance, denominator or reference scenario) that addresses the expected evolution of the facility over time (including changes in the facility and its engineered features and the natural system). In addition, ‘variant scenarios’ may be considered that address possible evolutions, that are considered less likely to occur but nevertheless require consideration for a robust safety case.

Additional scenarios representing more extreme or ‘what-if’ considerations may also be considered to add robustness to the safety case or to address specific requests from interested parties (e.g., a more stylised ‘what if?’ approach to investigate the loss of one or more safety functions of the disposal facility).

The normal evolution and variant scenarios include uncertainties related to variability in the natural and engineered systems and conceptual uncertainties regarding the evolution of the systems over time. The normal evolution and variant scenarios may also include uncertainties associated with changes in human habits over time (i.e. different kinds of land use and human behaviour). Uncertainties associated with the natural and engineered systems are often addressed using a variety of modelling techniques, which may include formal uncertainty analysis using parameter distributions to represent variability and other uncertainties and a collection of different scenarios to address conceptual uncertainties. These analyses can provide quantitative perspectives regarding the range of potential consequences (e.g., using Monte Carlo analysis) and also help to identify the uncertainties that have the most influence on the results (e.g., sensitivity analysis).

2.2 INADVERTENT INTRUSION

The fifth item in the list above, ‘human intrusion’, identifies the class of scenarios to address the potential for IHI into a disposal facility. IHI scenarios are included as an additional indicator for robustness for safety cases for radioactive waste disposal. It is these scenarios and the approach to addressing IHI which are the subject of this report. Human intrusion scenarios consider the possibility that, at some time in the future, knowledge of the disposal facility location and the hazard if presents is lost and future human actions may disturb the facility, e.g. by excavation, drilling etc. This aspect of the future is particularly uncertain over the timescales considered for radioactive waste disposal facilities because of the difficulty in predicting how human society will evolve, when and if knowledge of the facility and hazard will be lost and what future human activities may take place at the location of the disposal facility. Although uncertainties regarding the engineered and natural system can have an influence (e.g., in the context of the durability of barriers to intrusion), human intrusion scenarios tend to be dominated by significant and largely unquantifiable future uncertainties associated with if, how and when the scenario might occur. Thus, IAEA and ICRP recommend that such uncertainties be addressed at each step in the lifecycle of a disposal facility using a more stylized approach. IHI scenarios should be selected from the perspectives of optimization and demonstration.
of the robustness of the disposal system, such that the emphasis on addressing how the potential for and/or consequences of such scenarios can be reduced.

There is agreement that inadvertent intrusion resulting in some disruption to the facility must be considered as part of the overall safety case for a radioactive waste disposal facility (see Chapter 4). International recommendations also state that inadvertent intrusion should be addressed separately from the normal evolution scenarios. However, there is no agreed international position on exactly how to address IHI in a safety assessment, particularly concerning what safety assessments should be performed. There are many factors that could influence the potential impacts of inadvertent human intrusion. The HIDRA project addressed consideration of human intrusion from a variety of perspectives, including:

- the selection of scenarios for assessing the potential impacts of IHI;
- potential measures that could be considered to reduce the potential for¹ and/or consequences of IHI; and
- societal factors of interest when considering IHI in the safety case.

There are many examples of other international projects (e.g., PRISM, GEOSAF, ISAM and the EC PAMINA and BIOPROTA projects) that have addressed inadvertent human intrusion and these were considered during the development of this document. The aim of this document is to build on these previous projects and to provide clarification and support for requirements in existing IAEA Safety Requirements and Guides.

¹ The terms ‘likelihood’, ‘probability’, etc. are used to reflect that it is not certain that intrusion will occur. These terms have similar meanings, but they are quite often used in different contexts. For example, the term ‘likelihood’ is often viewed in a less quantitative perspective in the context of the possibility that HI can take place. On the other hand, the term ‘probability’ is often viewed in a more quantitative manner, concerning the discussion on how probable it is that a specific HI event occurs (e.g., occurrence probability) (see for example PAMINA Handbook D.1.1.3 (2009)). Participants in HIDRA identified challenges with translation/interpretation of these terms in different languages. It was decided for the purposes of this project to use the term ‘reduce the potential for’ as a more general statement to reflect the desire to identify features that will help to delay or reduce the likelihood, probability, etc. of inadvertent human intrusion.
3. PROJECT DESCRIPTION

3.1 OBJECTIVES

The objectives of HIDRA include:

- Share experience and practical considerations for the development and regulatory oversight control of activities to consider potential IHI during development of the safety case
- Provide a structured approach for identifying and selecting protective measures and/or scenarios that are applicable for site-specific safety assessments
- Describe the role of assessments of IHI for decision making throughout the lifecycle of the safety case
- Provide suggestions for communication strategies to describe the rationale for assessments of future human actions and for interpretation of the conclusions of those assessments for the public
- Provide recommendations for WASSC and RASSC, as appropriate, for clarification of existing IAEA requirements and guidance relevant to the consideration of IHI.

3.2 PROJECT SCOPE

The HIDRA project addresses IHI involving a disruption of the disposal facility, occurring after closure and following the loss of institutional control for a properly closed facility. The events are assumed to occur when active and passive controls are no longer deemed effective to prevent IHI. Factors that influence the timing of when intrusion is assumed to occur are also addressed. Potential disruptions that may occur during operations or prior to loss of institutional control are not considered in this project, but are an area that needs to be addressed in the framework of a safety case, for example as accident scenarios. Likewise, as discussed previously, future human actions outside the near-field disposal system and deliberate or intentional acts leading to disruption of the disposal system are not addressed. Human disturbances outside the contaminated near field must be evaluated in the safety case, however, if they potentially modify the natural system so as to degrade system performance.

The HIDRA project considered near surface and geological radioactive waste disposal facilities, including Very Low Level Waste (VLLW) facilities, facilities for Low Level and Intermediate Level Waste (L/ILW), High Level Waste (HLW), Spent Nuclear Fuel (SF) as applicable, and boreholes. Participants have provided experience from regulatory and implementation perspectives for facilities with a broad spectrum of designs, waste characteristics, regulatory frameworks and from differing levels of development of national radioactive waste management programmes. The influence of these different considerations on regulatory and implementation aspects of addressing IHI was a key topic for the project. Approaches for considering inadvertent human intrusion as part of decision-making in the context of the safety
case throughout the lifecycle of a disposal facility (e.g., siting, design, waste acceptance criteria, etc.) have been a particular emphasis of the project.

3.3 PROJECT ORGANISATION

Development of the project started in March 2012 with a small Consultancy to prepare a draft position paper outlining potential concepts to be addressed by a larger working group. A Technical Meeting involving representatives from more than 20 countries was convened in September 2012. At the Technical Meeting, three primary Working Groups were established to address specific topic areas that contribute to consideration of human intrusion for a safety case for a disposal facility. The scope for the three working groups was further refined during a Consultancy in March 2013 that formed the basis for the project organization.

The three Working Groups addressed the following specific areas of interest:

- Societal Factors
- Stylised Scenarios, and
- Protective Measures.

Examples of interfaces between those working groups are illustrated in Figure 3.1. The three specific Working Groups fed input to an integrating function tasked with addressing the overall integration of the different aspects into an approach for identifying scenarios and/or measures that are applicable for including human actions in the safety assessment of a specific disposal facility, and also in decision-making associated with the overall safety case.
3.4 PARTICIPANTS

The project included professionals from Member States who undertake technical activities related to the safety of radioactive waste disposal facilities. They included technical specialists in issues related to safety assessment or the safety case and those responsible for the management and operation or regulation of waste disposal facilities. Between them, they had experience of technical, societal, and design and safety assessment aspects related to human intrusion.

Participants contributed to the project by taking an active part in plenary discussions and Working Group activities, including contributing to project reports. Participants benefited from the exchange of information with experts from different countries and reported on national experience in addressing future human actions, especially human intrusion.
4. IAEA AND ICRP RECOMMENDATIONS AND STANDARDS

Development of a position regarding representation of inadvertent human intrusion in a safety assessment, needs to be undertaken in the context of the concentrate-and-contain strategy that is applied to disposal of solid radioactive waste (see Section 4.1 below). It is also important to understand existing requirements, recommendations and guidance from the IAEA, ICRP, and OECD/NEA related to consideration of inadvertent human intrusion. This section provides information that helps define the basis and expectations for the consideration of future human actions. This information provides context and perspective regarding human intrusion considerations. It is important to communicate such messages with interested parties early and regularly throughout the lifecycle of a disposal facility.

A number of summary recommendations can be made based on these considerations:

- Adoption of the concentrate-and-contain philosophy for radioactive waste management is believed to be the best approach for the long-term management of radioactive waste in terms of protecting people and the environment from the hazard posed by such materials. However, this strategy could result in potentially greater consequences should someone disrupt the disposal system.

- IAEA, ICRP and OECD/NEA agree that some form of inadvertent human intrusion needs to be considered to address the robustness of the facility in the case of a loss of effectiveness of institutional controls (notably, there is also agreement that deliberate intrusion – i.e. knowingly disrupting a disposal facility – should not be considered as part of the safety assessment).

- Consideration of IHI with the assumption that the disposal facility may be disrupted is somewhat unique to radioactive waste disposal (in that it is typically not considered for hazardous or other waste disposal facilities). Consequences from inadvertent intrusion are considered in the context of optimisation rather than being compared with a regulatory dose constraint (i.e., it is typically not a ‘yes or no’ result that could, on its own, disqualify the viability of the disposal facility. However, intrusion has been considered for compliance with a specific performance requirement in some cases.). In general, the intent is to demonstrate and enhance the robustness of the disposal system by considering opportunities to reduce the potential for and/or consequences of inadvertent intrusion. However, for near-surface disposal facilities, quantitative assessments have been used to establish waste acceptance criteria (i.e. to determine whether a given waste stream requires deeper disposal), design criteria and operational practices.

- When considering scenarios for inadvertent human intrusion, one or more stylised scenarios based on current practices near the disposal site (or globally accepted technologies) should be used rather than speculating about future
human behaviour. Protective measures can then be identified to reduce or mitigate the potential for and/or consequences associated with the scenarios.

- The timing of inadvertent intrusion can be determined by active and passive controls or features. Active controls are assumed to preclude inadvertent intrusion. Passive controls can delay the timing of intrusion whilst memory of the facility is retained. Passive safety features (depth, barriers, design) can preclude, delay, and or reduce the consequences of intrusion whilst the features remain effective.

The following sections provide supporting information for these recommendations.

4.1 WASTE MANAGEMENT PRINCIPLES

The production of electricity in nuclear power plants and other uses of radioactive material result in the production of radioactive waste and spent nuclear fuel. The resulting radioactive waste constitutes a potential hazard for man and the environment.

For all hazardous waste (including radioactive waste), there are two basic options for the management of waste for disposal (ICRP 2000, IAEA 2011a):

- dilute and disperse the waste into harmless concentrations, within the biosphere; or
- concentrate and contain the waste, to isolate it from the biosphere.

For solid radioactive wastes there is a generally accepted international consensus that it should be concentrated and contained (IAEA 2011a, IAEA 2006, OECD/NEA 1995a). Further, disposal facilities for radioactive wastes should have passive engineered and natural barriers limiting the dispersion of radiotoxic elements into the biosphere (IAEA 2011a, IAEA 1997). These barriers should act to contain and retain the radiotoxic elements to the extent necessitated by the associated hazard.

An inescapable consequence of the concentration of the waste, and its isolation into a disposal facility, is the potential exposure to concentrated radiotoxic

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2 The terms ‘controls’ (e.g., fences, security, monitoring, surveillance, maintenance) and ‘passive controls’ (e.g., land use restrictions, knowledge management, archives, markers) are used in this report to represent measures that are in place to delay or preclude the potential for someone to inadvertently disturb a disposal facility. The IAEA typically refers to these as ‘institutional controls’ and ICRP Publication 122 (ICRP 2013) has introduced the concept of ‘oversight’ to reflect these types of controls.

HIDRA

FINAL DRAFT JANUARY 2017
material should there be a subsequent disruption to the disposal facility barriers or
direct contact with the waste. The IAEA, ICRP and OECD/NEA agree that both
natural processes and human actions potentially disrupting isolation have to be
considered in the design of a disposal facility as well as in the assessment of its safety
(ICRP 2000). Waste classification systems (IAEA 2009a) generally address concerns
regarding future human actions by recommending deeper disposal of wastes posing
greater hazards.

4.2 PROTECTION OF FUTURE GENERATIONS

There is an international consensus (IAEA 2006, IAEA 1997, OECD/NEA
1995a) that the society that receives the benefits of an activity resulting in waste
should bear the responsibility of appropriately managing the waste. In doing so, the
safety and freedom of action of future generations should be taken into consideration
as far as reasonably possible. However, current society cannot be required to protect
future societies from their own intentional and planned activities, if they are aware of
the consequences. This is valid irrespective of the intent of the planned actions, i.e.
whether they are carried out for benevolent or malicious reasons. Based on this
reasoning, the IAEA, ICRP and OECD/NEA agree that only inadvertent human
actions that may impact the barriers and safety of a repository need to be considered
in its design and in the assessment of its safety. In the document “Future Human
Actions at Disposal Sites” (OECD/NEA 1995b), the NEA working group defined
inadvertent actions as:

"Those in which either the repository or its barrier system are
accidentally penetrated or their performance impaired, because the
repository location is unknown, its purpose is forgotten or the
consequences of the actions are unknown."

Active controls, preventing access to the site and unsuitable actions such as
drilling or rock construction works, are considered to be the most effective protective
measures against inadvertent disruptive actions. These controls are generally
considered sufficient to preclude inadvertent intrusion completely for a specified time
frame, according to the regulations in a given country. A combination of protective
measures, including suitable siting, disposal facility design and active and passive
controls, act to delay the timing, reduce the potential for inadvertent intrusion and also
help to reduce any potential consequences. Examples of controls include restricting
use of the site and preservation of information about the disposal facility, its design
and contents.

However, the IAEA specific safety requirements for disposal of radioactive
waste (SSR-5) (IAEA 2011a) state that the long-term safety of a disposal facility for
radioactive waste must not be dependent on active institutional control. The ICRP,
IAEA and OECD/NEA have recommended that the effects of future human actions in
the form of inadvertent human intrusion scenarios be used in the safety assessment to
identify and mitigate the potential consequences assuming a loss of control at some
time in the future (e.g., IAEA 2011a, ICRP 2000, ICRP 2013). ICRP Publication 81
HIDRA (ICRP 2000) describes human intrusion as a human action affecting repository integrity and potentially having radiological consequences. The NEA working group (NEA 1995b) stated that future human actions can adversely impact radioactive waste disposal systems; these actions must, therefore, be considered both in the siting and design of waste disposal systems, and in assessments of their safety. This requirement is reflected in IAEA SSR-5 in paragraph 1.10:

“The specific aims of disposal are:

(a) To contain the waste;

(b) To isolate the waste from the accessible biosphere and to reduce substantially the likelihood of, and all possible consequences of, inadvertent human intrusion into the waste;…”

4.3 FUTURE HUMAN ACTIONS IN THE CONTEXT OF A SAFETY CASE

As already noted, the requirement to consider a loss of institutional control and subsequent IHI into a repository is somewhat unique for radioactive waste disposal when compared to disposal of other wastes (e.g., chemically hazardous wastes). Although some radionuclides have very long half-lives, the hazard associated with radioactive waste does decrease over time due to radioactive decay, whereas some chemically toxic wastes retain the same hazard potential for all time. It may therefore be regarded as somewhat anomalous that the timescales considered in the safety assessment of radioactive waste disposal are very much greater than those generally considered sufficient for the safety assessment of chemically hazardous wastes. However, assessments over very long timescales (hundreds, thousands, or even hundreds of thousands of years) lead to inevitable uncertainties. One such uncertainty is that future human actions are unknown and cannot be predicted over these timescales. As knowledge of the disposal facility and its associated hazard cannot be assumed to remain on these timescales, this gives rise to the need for a safety case to consider the possibility of various forms of human intrusion into the disposal facility at distant future times.

IAEA SSG-23 provides guidance on implementation of the safety case approach for disposal of radioactive waste, including specific guidance for consideration of human intrusion (para. 6.52 – 6.65). According to SSG-23, the safety case will be developed and refined as the project progresses and will be used as a basis for decision making, for both regulatory decisions and other decisions relating to, for example, the design, supporting research work or site characterization activities. Development of the safety case is also recognized to be “an iterative process that evolves with the development of the disposal facility” (paragraph 4.10, SSG-23). IHI considerations are addressed as part of the basis for decision-making during this iterative process as the safety case matures over the lifecycle of the facility (see SSG-23’s Chapter 6).

SSG-23 is also specific about the role of human actions that do not result in a direct disturbance of the disposal facility (paragraph 6.53):
“only those human actions that result in direct disturbance of the disposal facility (i.e. the waste, the contaminated near field or the engineered barriers) are considered human intrusion. Human actions resulting in the disturbance of the host environment beyond the disposal facility and its immediate proximity are not categorized as human intrusion, since they do not result in direct intrusion into the disposal facility. Such actions should be considered within the scenarios used for the assessment of long-term risks.”

This project considers only actions that would be considered inadvertent human intrusion.

4.3.1 Inadvertent Human Intrusion

IAEA SSG-23 discusses the need to address specifically the impacts of IHI in paragraph 6.56: “In the safety assessment for a waste disposal facility, inadvertent (unintentional) human intrusion should be considered but quantification of the potential risks associated with deliberate intrusion need not be carried out.” An individual or group of individuals inadvertently intruding into the disposal facility (the intruders) could, at least for a short period, be directly exposed to radiation while being unaware of the associated potential hazard. Intrusion may also lead to radioactive material being brought to the surface and mixed with surface soils. This could lead to increased long-term exposure of individuals or groups that may establish a residence above or near the facility.

IAEA, ICRP and NEA are very clear that deliberate intrusion or cases where someone knowingly is exposed to waste are not considered as part of the safety assessment. Whilst recognising that third parties might unwittingly be exposed to radionuclides as a result of deliberate intrusion by others, NEA (1995a) states nonetheless that “intentional disruptive events should not be considered in safety assessments”. In support of this position NEA (1995a) notes that, whilst it is widely accepted that the society that creates radioactive waste should bear the responsibility for developing a safe disposal system that takes into account the needs of future societies, the current society should not be expected to protect future societies from their own actions if the latter are forewarned of the consequences.

Although the definition of ‘deliberate’ and ‘inadvertent’ are relatively clear, it is possible to imagine a situation when inadvertent intrusion becomes deliberate intrusion, i.e. when the intruder realizes that there is hazardous waste and does not stop the action. This is a factor that can be addressed as part of a discussion regarding the use of warning markers or protective measures intended to make it obvious to someone that they are drilling or excavating into something that is not normal soil or rock. This topic is addressed further in Section 7.3.3 of this report.
4.3.2 Use of Stylised Scenarios

The IAEA, ICRP and NEA have all recommended that one or more stylised scenarios be developed to demonstrate the robustness of the disposal system rather than speculating about all types of inadvertent intrusion that could possibly occur, which cannot be known. ICRP Publication 81 (ICRP 2000) states: “Because the occurrence of human intrusion cannot be totally ruled out, the consequences of one or more typical plausible stylised intrusion scenarios should be considered by the decision-maker to evaluate the resilience of the repository to potential intrusion.” In the context of geological disposal, ICRP Publication 122 (ICRP 2013) states: “Therefore, the consequences of one or more plausible stylised intrusion scenarios should be considered by the decision-maker to evaluate the resilience of the disposal facility to potential inadvertent intrusion.” Consistent with ICRP recommendations and SSR-5, if human intrusion cannot be excluded for a certain disposal facility, the consequences of one or more plausible intrusion scenarios should be assessed (SSG-23, Paragraph 6.57). The emphasis for inadvertent human intrusion is on consequences associated with local actions rather than more global human actions such as climate change, which are assumed to be addressed as appropriate in other parts of the safety assessment. However, natural processes such as erosion at the surface or uplift for geologic systems can result in different considerations for intrusion (see discussion in Chapter 7).

It is not possible to predict the evolution of knowledge or society, and thus, the set of future actions we can consider and assess can never be considered fully comprehensive or complete. In the light of this, the analysis of future human actions at the repository site can only be illustrative and never intended to try to be complete (OECD/NEA 1995b). By applying the available knowledge about the site and the repository design and a systematic approach to scenario development, a set of scenarios “describing what can be reasonably contemplated – rather than will be” (OECD/NEA 1995b) can be identified. Future human action scenarios can be regarded as representations of potential realities and the consequence analyses as potential impacts based on a set of assumptions. To avoid speculation about the future, the NEA working group concluded that the scenarios and consequence analysis can “be based on the premise that the practices of future societies correspond to current practices at the repository location and similar locations elsewhere”. Note that this includes the use of globally available technologies that are commonly used for similar geology in other locations, but may not be currently used in a given area.

There are different approaches for considering intrusion. In some cases, probabilities have been considered and the approaches have been accepted by the regulators. However, it is recognised that estimates of the probability of intrusion are highly uncertain. It is generally recommended in ICRP Publications 81 (ICRP 2000) and 122 (ICRP 2013) that quantitative approaches to safety assessment that seek to evaluate the doses associated with human intrusion that may occur should not generally attempt to use a “risk-based” approach (that is consequence multiplied by probability). Nevertheless, risk-based approaches have been used in some safety
assessments. Chapter 7 includes some discussion of approaches to communicate the
relative potential for different scenarios when discussing human intrusion.

### 4.3.3 Inherent Protectiveness of Geological Disposal

This project is considering human intrusion for near-surface and deeper
disposal concepts, including geological disposal. It is important to maintain
appropriate perspective given the inherent level of safety against IHI and other actions
provided by increasing depth of disposal. Deeper disposal is specifically selected as
an option to significantly reduce significantly the potential for IHI. IAEA SSG-23
highlights this distinction in paragraph 6.52: “**human intrusion is particularly
relevant for disposal facilities at or near the surface.**” It is emphasized that most
human activities (e.g. construction operations, farming, etc.) that could lead to
inadvertent human intrusion into a waste disposal facility take place near the surface.
Human activities relevant for deeper disposal (i.e., at depths of a few tens of metres or
more) are much less likely in any given location, especially for geologic disposal.
However, activities may include drilling to geologic disposal depths (e.g. for water,
oil or gas), and may also include surveys for exploration and mining activities,
geothermal heat extraction or the storage of oil, gas or carbon dioxide at shallower
depths.

Thus, the specific development of scenarios and quantitative assessment for
IHI is more targeted towards near-surface disposal. For near-surface disposal, in
addition to design and optimisation considerations, intrusion often contributes to the
development of waste acceptance criteria, determination of the necessary time frames
for institutional controls and determination of whether a specific waste stream
requires deeper disposal. For geologic disposal, the emphasis of intrusion
considerations is the demonstration of robustness of the facility, primarily in terms of
its siting and design.

### 4.3.4 Timing of Intrusion – Active and Passive Controls and Safety Features

An important consideration for addressing IHI is the identification of the time
at which intrusion becomes a possibility. The timing of intrusion is influenced by
societal factors (e.g., institutional controls and oversight) and by the disposal system
(e.g., depth, barriers, design). There is agreement that societal factors are fully
effective with active surveillance/security for some period of time when IHI cannot
occur (this is referred to as active institutional controls or direct oversight). After this
period of surveillance/security, memory of the disposal facility will not be lost
immediately and can be expected to persist without direct surveillance for some
period of time (this is referred to as passive institutional controls or indirect
oversight). A disposal facility may also include concrete, metal or other barriers or
features that will preclude or delay the time at which IHI can occur. For example,
depth of disposal is a very effective means to reduce significantly reduce the potential
for and consequences of IHI. Recommendations and guidance from IAEA and ICRP
are summarised below.
IAEA SSR-5 addresses these concepts in paragraph 1.22(iii), “After its closure, the safety of the disposal facility is provided for by means of passive features inherent in the characteristics of the site and the facility and the characteristics of the waste packages, together with certain institutional controls, particularly for near surface facilities. Such institutional controls are put in place to prevent intrusion into facilities and to confirm that the disposal system is performing as expected by means of monitoring and surveillance.” Further clarification of the role and timing of active institutional controls is provided in Paragraph 4-29 of IAEA SSG-29, “As active means can be relied upon only for a limited period (up to a few hundred years), the possibility of human intrusion into the facility after such a period should be considered when assessing the safety of a near surface disposal facility.”

Although the possibility of intrusion is considered at the end of active control, passive features (institutional controls and the passive safety features in the disposal system) may further preclude or delay the possibility of inadvertent intrusion or certain scenarios. Passive controls (e.g., restrictions on land use, markers, knowledge management) may help to delay inadvertent intrusion. For example, SSG-29, paragraph 4.51 states “The use of passive measures, such as conservation of information in the form of markers and archives, including international archives, will reduce the risk of human intrusion over a longer period than is foreseen for active institutional controls, and should be considered.”

The effectiveness of passive controls and safety features is further discussed in Chapter 7 and as part of the identification and evaluation of protective measures in Chapter 9.

4.4 INTRUSION CRITERIA (OPTIMISATION RATHER THAN A CONSTRAINT)

The overall positive benefits of the concentrate and contain approach are generally expected to outweigh considerations related to potential health effects associated with IHI. Thus, the ICRP and the IAEA have recommended that the consequences of IHI be considered in the context of an emergency and/or existing exposure situation, once the exposure is recognised, rather than as part of the normal evolution scenarios for which consequences are compared with the dose constraint. This also implies that the potential consequences are interpreted in an optimisation context to inform decisions rather than as a strict ‘yes or no’ compliance criterion that could be used to, on its own, to disqualify a site or disposal concept.

Consideration of potential IHI is often different between near-surface and geological disposal, reflecting the fact that by its very nature, geological disposal is selected to reduce significantly reduce the potential for and/or consequences that could result from inadvertent intrusion. For near-surface disposal, intrusion scenarios can be evaluated in a more quantitative manner to establish waste acceptance criteria (e.g., to determine whether a given waste stream would require deeper disposal or disposal at a more favourable or preferable location). In the case of geological disposal, intrusion is generally considered in the context of optimisation of the
disposal approach (siting, selected measures, operational practices, design) recognizing the inherent safety of the choice to pursue geological disposal.

4.4.1 ICRP and IAEA Criteria

The ICRP has addressed interpretation of the assessments of IHI in recommendations for near-surface and geological disposal. For example, ICRP Publication 81 (ICRP 2000)\(^3\) includes the recommendation that:

\[
\text{"In circumstances where human intrusion could lead to doses to those living around the site sufficiently high that intervention on current criteria would almost always be justified, reasonable efforts should be made at the repository development stage to reduce the probability of human intrusion or to limit its consequences."}
\]

In the context of geological disposal, ICRP Publication 122 (ICRP 2013) states that:

"The design and siting of the facility will have to include features to reduce the possibility of inadvertent human intrusion." ICRP, IAEA and NEA identify approaches that can be used throughout the lifecycle of a disposal facility to reduce the possibility of intrusion and limit the consequences should intrusion occur (see Section 4.3).

IAEA SSR-5 (IAEA 2011a) criteria for radiation protection in the post-closure period (para 2.15) include specific guidelines related to IHI:

\[
\text{"(c) In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.}\]
\[
\text{(d) If human intrusion were expected to lead to a possible annual dose of more than 20 mSv (see Ref. [7], Table 8) to those living around the site, then alternative options for waste disposal are to be considered, for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.}\]
\[
\text{(e) If annual doses in the range 1–20 mSv (see Ref. [7], Table 8) are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimisation of the facility’s design."}\]

Item (e) highlights the use of optimisation when interpreting calculated consequences associated with inadvertent human intrusion. In cases where doses are in the range 1 – 20 mSv/yr, emphasis is placed on identifying and implementing

\[\text{\footnotesize Note that the ICRP has formed Task Group 97 to update the recommendations in Publication 81 related to surface and near surface disposal of solid radioactive waste.}\]
measures that can help to reduce the potential for intrusion and/or limit the potential consequences. The identification of measures that can be applied to address such cases is a key component of this project. Note that, in the context of this project, measures are identified that relate to design as well as many other factors that can help to reduce the potential for and consequences of inadvertent human intrusion.

IAEA SSG-23 provides specific guidance related to the application of the dose ranges, primarily applicable for near-surface disposal, in its Paragraph 6.59:

“...“those living around the site” should be considered receptors in human intrusion scenarios. This does not mean, however, that the intruder should be automatically excluded from consideration. A distinction should not be made between the intruder and the residents. Indeed, these could be the same persons in the case of people living on top of a former site about which knowledge has been lost. Instead, a distinction should be made between the normal behaviour of people living near or even on the site, and events with a short duration and/or low probability of affecting a small number of people (such as road construction activities). Regarding the latter as ‘industrial accidents’ would not require application of the same dose criteria to the intruders in these cases as those applied to the residents near or on the site. In accordance with this distinction, the actual contact of the receptor with the waste may be considered in scenarios, and the dose criteria for intrusion, as set out in Ref. [2], may be applied to the resulting exposure if this event is deemed to be possible in a normal residential situation.”
5. GENERAL APPROACH AND LINKS WITH THE SAFETY CASE

A general approach has been developed for the consideration of IHI, consistent with the concept of optimisation as part of a safety case described within the IAEA SSG-23. Section 5.2 includes further information about the role of IHI as part of the different components of the safety case.

5.1 GENERAL APPROACH FOR IHI CONSIDERATION

The general approach described here is to use an optimisation process to identify the stylised scenarios and measures to be considered at each step in the lifecycle for a specific disposal facility. The end result of this ‘optimisation process’ is the selection of scenarios for consideration and the identification of measures that are or are not expected to be effective in reducing the potential for and/or consequences of IHI. Figure 5.1 illustrates the major components of the approach. Note that the approach in Figure 5.1 is designed to be implemented at each ‘key’ step (not necessarily every step) in the lifecycle of a disposal facility, thus a loop is included where measures identified in the assessment at one step in the lifecycle are implemented and included in the safety framework for the next safety case iteration in the lifecycle.

The approach begins with a description of the safety framework for a disposal facility. The safety framework forms the basis for identifying the considerations related to IHI specific to a given facility. The second major component includes specific considerations for the identification of stylised scenarios and potential protective measures associated with IHI that are considered in the safety assessment. These two activities reflect a large part of the scope for participants in this project. As indicated, in Figure 5.1, the societal factors can influence both the safety framework and the selection of scenarios and protective measures considerations. The final steps in the approach address the assessment and analysis activities and how these efforts are used to identify measures that should and should not be recommended for implementation in the safety framework. Any updates to the safety framework are carried forward to the next step in the lifecycle. Each element of Figure 5.1 is described briefly below.
5.1.1 Societal Factors

Societal factors influence the safety framework and the approach to considering IHI. Thus, societal factors are considered throughout the process and hence have been a major working area in the HIDRA project (see Chapter 7). A primary emphasis for Societal factors includes the effective communication of the purpose for considering IHI and the robustness that is added to the safety of a facility by implementing measures to reduce the potential for and/or consequences of intrusion. The general approach is designed to enhance communication by providing a means to document the types of measures that are considered and the benefits to robustness of the safety case that are provided by measures that are implemented. Uncertainties and the approach to managing them are also documented as part of the communications process. Societal factors also contribute to the definition of scenarios that are appropriate for a given site or facility and provide insights regarding approaches for knowledge management that can prolong the time frames over which the memory of the facility can be preserved.
5.1.2 Safety Framework

The safety framework includes three components from the safety case as described in IAEA SSG-23: safety case context, safety strategy and disposal system description. These elements form the basis for identification of the baseline considerations for identification of scenarios and protective measures for IHI. The safety case context (see Section 5.2.1) addresses the basic conditions (e.g., waste to be disposed, purpose of the safety case, regulatory requirements, and interested parties) that must be considered. Clear recognition of the purpose of the assessment at each step in the lifecycle is important. The purpose of the IHI assessment should be aligned with the decisions to be made at the step in the lifecycle for which the assessment is being conducted (see Chapter 6). Regulatory requirements may specify, for example, institutional controls, a disposal concept, stylised scenarios, etc. that must be considered.

The safety strategy (see Section 5.2.2) is consistent with the strategic considerations that have been adopted for the disposal facility and the regulations or national policies. Strategic considerations include, for example, site selection, geologic or near-surface disposal, use of institutional controls, etc. Strategic considerations may evolve over the lifecycle of the facility. The third element of the safety framework is the complete description of the disposal system (see Section 5.2.3). This includes the technical details of the waste forms, disposal facility design and the natural system that can influence the potential for and/or consequences of human intrusion.

5.1.3 Human Intrusion Considerations

This component is a primary focus of the efforts on the HIDRA project. The stylised scenarios (see Chapter 8) and measures (see Chapter 9) elements were specifically addressed by two of the three HIDRA working groups. The first step for addressing IHI is to consider representative classes of events, as identified in Section 8.3. These events may be developed into scenarios to reflect site- and facility-specific considerations (see Section 8.4). Based on these site- and facility-specific scenarios, measures to further reduce the potential for and/or consequences of intrusion are considered (see Section 9.2). The different types of measures that are available are described in Section 9.3. Feedback and iteration between these two activities leads to the identification of site- and facility-specific scenarios and measures that can be considered for further evaluation.

5.1.4 Analysis and Implementation of Measures

The assessment/analysis element includes the efforts to evaluate (qualitatively or quantitatively) evaluate the effectiveness of different measures in respect of reducing the potential for and/or consequences of human intrusion. For near-surface disposal, it is generally expected that a quantitative safety assessment of the potential consequences from an intruder analysis will be conducted. In this case, the intruder assessment is used to identify waste acceptance criteria in addition to addressing the...
effectiveness of different measures. For geological disposal, the analysis may be more qualitative, with an emphasis on demonstrating the added robustness/effectiveness of measures to reduce the potential for and/or consequences of intrusion.

The results of the assessment/analysis step are then used to identify the measures that provide the most benefit from an optimisation perspective. These measures are then evaluated from the perspective of potential conflicts with operational safety, post-closure safety or other safety-related activities. From a communication perspective, it is important to document the added robustness provided by the different measures that are selected. The final output is the identification of measures to be implemented in the safety framework for the next step in the lifecycle and also documentation of the basis for those measures that were considered but not recommended for implementation. (The dashed line in the figure returning to the beginning of the process reflects the restarting of the process for each step in the lifecycle, as discussed in Chapter 6.)

5.2 HUMAN INTRUSION IN THE COMPONENTS OF THE SAFETY CASE

This section follows the alphabetical sequence of components identified in Figure 5.2. Each component is introduced briefly here, followed by a more detailed discussion in the subsequent subsections. As discussed above, the first three components (A. Safety case context, B. Safety strategy, C. System description) provide the overall safety framework that establishes the baseline under which appropriate scenarios and measures are identified. Although the intent is to define the context and strategy to the extent possible at the beginning of the process, it should be recognised that it is likely there will be some evolution, especially in the strategy, as the project matures. Likewise, the system description (especially the waste acceptance criteria, design and/or closure concept) will be expected to evolve over the life of the facility.
In the context of HI, the safety assessment (D.) is the activity in which scenarios and measures specific to a disposal system are identified and evaluated and optimisation is considered. The analysis and assessment in this step can be qualitative or quantitative depending on regulations in a given Member State. The working group activities (Chapters 7, 8 and 9) describe approaches for identifying the scenarios and measures and also highlight societal and communication considerations that are considered during the process.

During the development of the system description and safety assessment, there will also be on-going efforts for optimisation of the strategy and disposal system (E.). This can include consideration of the advantages and disadvantages of implementing different protective measures. Optimisation specific to human intrusion will need to be considered in the context of the overall approach to optimisation for the disposal facility, especially to consider potential effects of measures that may be implemented to address intrusion on the projected consequences from the normal evolution scenario. It is also important to identify and document uncertainties relevant for intrusion and describe how the uncertainties are managed in each step of the process (F.). Documentation of the rigor and thoughtfulness during the process of optimisation and management of uncertainties is an important foundation for building the communication strategy regarding HI.

The result of the safety assessment and optimisation may include identification of measures that can reduce the potential for and/or consequences of HI scenarios and...
can be shown to improve the robustness of the disposal system. The next step in Figure 5.1 is the documentation of limits, controls and conditions (G.), which in the context of human intrusion reflects the formal implementation of protective measures. At this step, it is important to document how the measures identified in the safety assessment and optimisation process will be implemented as part of the context, strategy and disposal system. This is an example of the iterative feedback that will evolve with each step in the lifecycle of a facility.

The end of each iteration is the integration of the safety arguments (H.). This step is the demonstration that regulatory requirements have been met and measures are identified that will be implemented in the safety framework to be used for the next step in the lifecycle of the facility. This is also a key step to develop the description of how the robustness of the facility has been enhanced as a result of the considerations related to human intrusion. For this component, information should also be organised to explain how human intrusion considerations are reflected in decisions that have been made.

Involvement with interested parties is an element that overlaps with all components of the safety case as illustrated in Figure 5.1. This aspect of a safety case is not assigned a letter as a step in the process, but it is a critical consideration throughout and is a focus of the societal factors working group. This reflects the importance of considering societal factors and communication strategies throughout the safety case development process. The following sections provide specific examples of considerations related to human intrusion for each of the components of the safety case identified in Figure 5.1.

5.2.1 Safety Case Context

Each iteration begins with identification of the baseline information or safety context that must be considered for human intrusion (Box A, Figure 5.2). According to SSG-23, the safety case context includes baseline considerations on which the safety case will be developed (Figure 5.3), for example:

![Safety Context]

- Waste to be Managed
- Purpose (Each Step in Life Cycle)
- Regulations
- Roles and Responsibilities
- Interested Parties

Figure 5.3. Examples of Safety Case Context
• defining the purpose for the safety case in the context of a graded approach (note that the purpose may be revised and refined to support decision making at each step throughout the lifecycle (siting, design, construction, operation, etc.),

• identifying roles and responsibilities (government, regulator, operator, public involvement, etc.) and applicable regulations, and

• identification of the waste to be managed, which has a strong influence on the safety strategy.

An important part of developing the safety context is the identification of applicable regulations and guidance for consideration of human intrusion. The regulations comprise the rules and conditions for the treatment of HI in safety cases and what is expected from the implementer in this matter. Furthermore, the regulations serve as the basis for defining the general scope of work for addressing IHI. The context needs to document all specific regulatory information that will impact the selection of scenarios and the safety assessment for intrusion (see examples below).

The regulatory basis differs widely from country to country with some requirements being very prescriptive and others leaving detailed choices (e.g., site specific scenarios, receptors) to the implementer. Regulations often consider recommendations from international organisations and projects, e.g. EU, IAEA, OECD/NEA, ICRP, etc.

In some Member States, scenarios and receptors or a general approach to consider inadvertent human intrusion are specified in regulations or regulatory guidance. Any such specifications would form part of the safety context. Therefore the safety context that has been adopted for IHI varies from one Member State to another and can also be different depending on the waste type for different disposal facilities in a given Member State (e.g., different approaches for LLW, ILW and HLW disposal, respectively).

An important factor to be reinforced for the safety context is that human intrusion scenarios are not meant to convey any authoritative statement about the evolution of the site and future societal activities. As described in Chapter 4, from a safety case context and radiation protection perspective, intrusion is viewed from an optimisation perspective rather than a comparison with a dose constraint and is generally treated separately from the normal evolution scenarios. The intent is to provide added confidence in the robustness of the disposal system and to identify protective measures that can be effective in reducing the potential for and/or consequences of inadvertent human intrusion.
5.2.2 Safety Strategy

According to SSG-23, the safety strategy (Box B, Figure 5.2) refers to the approach that will be taken in site selection and facility design. The safety strategy to comply should reflect the safety objectives, principles and criteria, to demonstrate compliance with regulatory requirements and to ensure that good engineering practice has been adopted and that safety and protection are optimised (Figure 5.4). The potential for human intrusion must also be addressed as part of the safety strategy. The strategy is expected to evolve in an iterative manner as different measures are considered to address the potential for human intrusion.

Safety Strategy
• Site Selection and Disposal Concept
• Defence-in-depth and Safety Functions
• Active and Passive Controls
• Selecting and Updating Protective Measures
• Managing Uncertainty

Figure 5.4. Example of Safety Strategy.

The safety strategy should describe considerations related to the choice of disposal concept (e.g. depth of disposal, use of engineered barriers, remote location), waste classification (e.g. excluding certain wastes from certain concepts), approaches for managing uncertainties, approaches for involvement with interested parties, etc. Specific to intrusion, the safety strategy will need to address how considerations related to intrusion are used to demonstrate and enhance the robustness of the disposal system and also how IHI considerations influence the disposal concept, effectiveness of passive controls and operational decisions (e.g., waste placement, waste acceptance criteria), which may evolve over the lifecycle of the facility. Documentation of how IHI is considered in development of the strategy and how the strategy evolves as intrusion is considered will help with communication of the robustness of the disposal approach with interested parties.

SSG-23 introduces a number of measures that can be considered as part of the safety strategy to reduce the potential for and/or mitigate the consequences of human intrusion into radioactive waste disposal facilities. These measures include active institutional controls and/or a system of durable physical barriers. Furthermore, compartmentalisation of the waste may reduce the consequences of an intrusion event for some disposal concepts. Probably, the most substantial reduction of the potential for and/or consequences of intrusion may be achieved by emplacing the waste at

HIDRA

FINAL DRAFT JANUARY 2017
greater depth. Remote locations and areas lacking resources that may be exploited can
also be advantageous in the context of the potential for and consequences of intrusion.
Although such measures are unlikely to eliminate completely the possibility of doses
to the public from human intrusion, they may reduce the potential for human intrusion
and/or its consequences. Chapter 9 includes a detailed discussion of potential
measures that can be considered, including references to specific topics addressed in
Chapters 7 and 8.

The waste to be managed, as identified in the Safety Context, will have a
significant influence on the choice of disposal concept and the safety strategy. From a
regulatory perspective, there is a distinction in the consideration of human intrusion
for near-surface and geological disposal facilities. For near-surface disposal
facilities, SSG-23 recommends that calculations should be performed to assess the
doses to the relevant potentially exposed persons and results are compared with
specific dose criteria for existing exposures.

However, in the context of geological disposal, SSG-23 recognises that the
strategy to use geological disposal results in the relevance of human intrusion
scenarios being more limited, as the depth and location of such facilities are
specifically selected to make IHI unlikely. Therefore, SSG-23 states that given the
overall robustness of geological disposal against intrusion and the fact that the time
frames of concern are too large to enable meaningful estimates of possible impacts
from intrusion events to be made, a quantitative assessment of IHI is not required.

The most effective measures against inadvertent intrusion involve establishing
the disposal facility in deep geological formations, establishing siting criteria, and
providing for knowledge preservation in the long term.

5.2.3 Disposal System Description

Alongside the context and strategy, the disposal system is the third element of
the fundamental basis on which potential IHI is addressed (Box C, Figure 5.2). The
description of the disposal system should record the information and knowledge about
the facility and surrounding environment in sufficient detail to form the basis for
addressing potential IHI (see Figure 5.5). As for the safety context and strategy,
additional information will be obtained and knowledge about the disposal system will
evolve and mature as the project progresses and assessments are updated. Therefore
there will be significant feedback and overlap between the system description and the
safety strategy as the facility design is a key part of the safety strategy. Likewise,
there will be feedback between the description of the environment around the disposal
facility and the safety context in terms of the conditions to be considered when
identifying IHI scenarios and potential dose pathways and receptors.
Figure 5.5. Examples of Disposal System Description.

The system description should contain the information relevant for HII, and depending on the type of disposal facility, may include information on the following:

- The near field, including: (i) specific information about the waste (e.g. the origin, nature, quantities and properties of the waste and the radionuclide inventory); (ii) system engineering (e.g. waste conditioning and packaging, backfill/buffer materials, layout of disposal units, engineered barriers, cap or cover of the disposal facility); and (iii) the extent and properties of the zone disturbed by any excavation or construction work;

- The far field, e.g. geology (properties of host rock), hydrogeology, hydrology, geochemistry, tectonic and seismic conditions, erosion rates, natural resources;

- The biosphere, e.g. climate and atmosphere, water bodies, the local population, human activities, biota, soils, topography and the geographical extent and location of the disposal facility (also consider how this could change in climate change scenarios for geological disposal).

Depending on the type of disposal facility, the description of the disposal system specific to human intrusion should consider the following:

- A clear specification and description of the components of the facility and natural system and their interfaces and associated uncertainties relevant for human intrusion;

- A description of the overall safety concept and the safety functions with a view towards being able to consider how intrusion could potentially compromise safety functions;

- A discussion of how regulatory or other requirements related to human intrusion have been addressed in the facility design;

- A description of the interactions that may occur between system components (e.g., dependence for safety, redundant or shared safety functions);

- A description of how spatial heterogeneity and distribution of the waste has been taken into account, including associated uncertainties;
• A description of possible time dependent changes in the properties and behaviour of the system components and their interfaces with respect to reducing the possibility or consequences of human intrusion, including how components may degrade or fail, and associated uncertainties; and
• A description of possible environmental changes and their impacts on the human intrusion considerations of the disposal system.

The role of design features should be addressed in the context of assumptions regarding human habits and actions that form the basis for the human intrusion exposure scenarios (consistent with the safety context and safety strategy). This is to address the robustness of the disposal system with a view towards reducing potential consequences should intrusion occur.

5.2.4 Safety Assessment

The term ‘safety assessment’ (Box D, Figure 5.2) is used in SSG-23 to refer to all assessments performed as part of the safety case (see Figure 5.6). This encompasses all aspects that are relevant for the safety of the development, operation and closure of the disposal facility. Thus, the safety assessment also addresses qualitative aspects, non-radiological issues, and organisational and managerial aspects and is therefore referred to as ‘assessment/analysis’ in this document, to reflect the breadth of its scope. In the context of human intrusion, the emphasis is on reducing the potential for and/or consequences of human intrusion following closure of the facility. Nevertheless, it is important to recognise the need to consider potential effects of design or other measures included to address human intrusion in the context of the operational safety assessment. This is an important checkpoint before accepting a given protective measure.

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Figure 5.6. Broad perspective of safety assessment from SSG-23.
As discussed above, for the purposes of human intrusion, the focus will be on potential impacts specifically after an assumed loss of institutional controls. In this document, the emphasis of the safety assessment step is implementation of an iterative approach to identify scenarios and measures to be considered for assessment/analysis (see Figure 5.1). An important initial assessment is a screening step to identify scenarios and measures that are subsumed by others or have trivial impacts. The remaining scenarios and measures would be addressed as part of the assessment/analysis efforts. Considerations for this assessment/analysis step are described in Chapters 7 and 9.

Given the speculative nature of human intrusion and recommendations for the use of stylised scenarios, a key objective of this document is to identify representative classes of intrusion events that will serve as a starting point for context-specific consideration (see Chapter 8). The intent of identifying a few representative classes of intrusion events is to avoid undue speculation about the types of human intrusion that could occur. The assessment/analysis process generally starts with a set of the relevant classes of scenarios, which will be obtained through the approaches discussed in Chapters 7-9 (see Figures 3.1 and 5.1).

5.2.5 System optimisation

Optimisation of protection for a disposal facility is a process that is applied to the decisions made as the safety case evolves throughout the lifecycle of the disposal facility. This step is referred to as iteration and design optimisation in SSG-23 (Box E, Figure 5.2). In line with SSG-23, good engineering and technical solutions should be adopted, and good management principles should be applied to ensure the quality of all safety related work throughout the development, construction, operation and closure of the disposal facility.

ICRP Publication 122 provides a general description of optimisation which can be assigned to different safety issues, including HI:

"'Optimisation has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of protective options, including Best Available Techniques, for enhancing the protective capabilities of the system and reducing its potential impacts (radiological and others).'

The NEA (NEA 2010, Optimisation of Geological Disposal of Radioactive Waste – National and International Guidance, NEA 6836) described optimisation as "the act of choosing the optimal combination amongst several technical provisions for complying with a series of requirements." The NEA considered the process of optimisation in a topical session at the Integration Group for the Safety Case in 2012. The conclusion of this session was that once regulatory safety criteria had been met, optimisation should mean taking steps to proceed with the repository development in the most efficient means, which is likely to mean in the way that reduces time and cost of implementation without reducing safety.
Human intrusion will be a contributing factor to the optimisation process, but is likely to be secondary to considerations related to the expected performance for the normal evolution scenario in particular. Notably, measures adopted to address intrusion should not compromise performance for the normal evolution scenario.

Optimisation should be conducted recognising the importance of effectively communicating the measures against intrusion and robustness of the system. Concepts such as ‘defence in depth’ and ‘passive safety’ are important considerations as part of optimisation and contribute to communications to highlight the robustness of the disposal approach. The selected options for measures in response to human intrusion concerns should be chosen by means of a well-defined, rational procedure. The goal of improved confidence in the selected option is more readily achieved if optimisation includes consideration of alternative options that are presented in the safety case with an assessment of their advantages and disadvantages, and a justification is provided for the preferred option. Further recommendations on decision-making and appraisal of alternative options are provided in IAEA SSG-23, paragraphs 4.64-4.71.

5.2.6 Management of uncertainty related to human intrusion

IAEA SSG-23 refers to The IAEA General Safety Requirements, GSR Part 4, Safety Assessment for Facilities and Activities (IAEA 2009b) for requirements related to addressing uncertainties in safety assessment (Box F, Figure 5.2). IAEA GSR Part 4 states that ‘Uncertainties in the safety analysis have to be characterised with respect to their source, nature and degree, using quantitative methods, professional judgement or both’. Safety assessment for a radioactive waste disposal facility involves consideration of the performance of engineered and natural features over long times and assessment of exposures to humans and the environment far in the future. Given the nature of calculations far in the future, uncertainties that can and cannot be quantified are, and always will be, associated with the confidence in different components comprising the safety case. The need to identify and manage such uncertainties and their potential impact on decisions regarding regulatory compliance of the disposal system has long been recognised [e.g., (Vovk and Seitz 1995; Kozak 1994) and the EC PAMINA project].

Uncertainties related to forecasting human events far in the future (e.g., potential human intrusion) pose challenges to decision makers when explaining the safety of a disposal facility. The management of uncertainty generally is a key aspect of the safety case strategy.

The IAEA PRISM project identified five general categories of uncertainty:

- Data/parameter uncertainty, in terms of inputs, spatial and temporal variability;
- Model uncertainty, in terms of conceptual and mathematical model development;
- Future/scenario uncertainty, in terms of the near-field geosphere and biosphere;
- Resource uncertainty, in terms of financial, human, technological, etc., and
Contextual uncertainty, in terms of the potential for changes in regulations/laws, interested parties, etc. Historically, especially in the context of a post-closure safety assessment, the first three categories of uncertainty are the primary focus. Emphasis on these three categories is reflected in recent safety assessment and safety case reports (e.g., IAEA SSG-23-paragraphs 5.56-5.59, NEA 2012).

Uncertainties associated with inadvertent intrusion are largely dominated by future/scenario uncertainties, which by their nature are not possible to quantify (i.e., for time frames of many decades or hundreds and thousands of years, the future habits and behaviour of people become increasingly speculative). However, there are also technical uncertainties (data/parameter, model) associated with the evolution of the natural and engineered systems that can have an influence on the effectiveness of different measures to reduce the potential for and/or consequences associated with intrusion (e.g., barrier longevity). Given that there are multiple regulatory perspectives regarding consideration of human intrusion, there are also contextual uncertainties that need to be managed (e.g., Are there requirements for quantitative or non-quantitative assessment? Are specific intrusion scenarios identified in national regulations that must be considered?).

During the development of a safety case, it should be expected that a variety of different options will be used to manage uncertainties. In the case of IHI, there is an emphasis on the use of stylised scenarios and current behaviour to represent human actions associated with potential human intrusion in the future rather than trying to quantify, what are largely speculative and unquantifiable uncertainties. One approach to managing uncertainty is by making pessimistic assumptions regarding events and exposures in the context of stylised scenarios (e.g., assuming that there will be a loss of institutional control, assuming intrusion will occur as soon as institutional control is lost, etc.). However, distributions for parameters can be developed and implemented in a formal uncertainty analysis to provide perspective on the range of potential results. When developing input distributions and interpreting results from such calculations, it is important to maintain awareness of the large uncertainties associated with the speculative nature of assumptions regarding future human behaviour. Sensitivity analysis can be a powerful tool in quantitative approaches to identify which uncertainties are important to safety.

5.2.7 Limits, controls and conditions

The safety case and measures identified in the context of IHI should be used to assist in the establishment limits, controls and conditions (Box G, Figure 5.2). Limits, controls and conditions reflect the measures that are implemented for work and activities that have an influence on the safety of the facility. Examples include:

- controls on construction processes (e.g., materials providing a barrier to intrusion);
controls on emplacement operations and backfilling materials and techniques 
(e.g., specific distribution of waste to address IHI);

site specific limits on the types, activities, concentrations and quantities of 
waste that may be disposed of in order to ensure operational and long term safety;
and requirements on surveillance / land use restrictions and on staff training / 
operational procedures (e.g., assumptions regarding active and passive controls).

Limits and conditions of particular importance for disposal facilities 
(e especially near-surface disposal) include the acceptability of the total waste 
inventory. However, in the context of IHI, the acceptable concentration levels for 
specific radionuclides in the waste are typically of greater interest. For near-surface 
disposal, these levels should be defined and/or justified considering the potential for 
human intrusion. The waste acceptance criteria should be established considering the 
design and placement of individual packages and within the context of the entire 
facility, for example by considering operational constraints and the analysis of 
relevant stylised scenarios.

Further details on the derivation of waste acceptance criteria for near- surface 
disposal facilities are provided in the safety guide on waste acceptance criteria and the 
PRISM project report.

5.2.8 Integration of Safety Arguments

As per SSG-23, the safety case should provide a synthesis of the available 
evidence, arguments and analyses (Box II, Figure 5.2). These should explain how 
relevant data and information have been considered, how models have been tested, 
and how a rational and systematic assessment procedure has been followed.

The safety case should acknowledge any limitations of currently available 
evidence, arguments and analyses, and should highlight the principal grounds on 
which a judgement has been made that the planning and development of the disposal 
system should be continued. The safety case should include the approach by which 
any open questions and uncertainties with the potential to undermine safety will be 
addressed and managed.

The safety discussion of IHI will rely substantially on qualitative and semi- 
quantitative information regarding the potential for and/or consequences of 
speculative and uncertain scenarios. In the integration of the safety arguments, it will 
be important to recognise the rather different nature of IHI assessments using stylised 
scenarios compared to the safety assessments of the normal evolution scenarios.

Therefore, generally, it will not be advisable to focus on quantitative arguments 
related to intrusion, but rather to explain the steps taken to present the consideration 
of reducing the potential for IHI and mitigating consequences of IHI as part of the 
overall repository optimisation process. This should include the identification of any 
protective measures that have been selected to contribute to the increased robustness 
of the disposal system.
6. HUMAN INTRUSION CONSIDERATIONS FOR DECISION MAKING IN THE SAFETY CASE

This chapter considers the decision points in the development lifecycle of a disposal facility, from its commissioning, through site selection, construction, operation and closure through to the end of the licensed period. The key HII considerations that need to be taken into account at each decision point are identified. The second section of this chapter focuses on the safety case context and presents a framework for considering HII by suggesting a storyline for the discussion of potential human intrusion activities within the safety case.

The third section brings together the first two sections by indicating the lines along which safety arguments in relation to human intrusion may be developed, i.e. illustrating how good decisions taken during the facility development stages in relation to HII can be presented in the safety case. These safety arguments are then developed in more detail in subsequent chapters of this report.

6.1 HUMAN INTRUSION CONSIDERATIONS FOR DECISION MAKING AT KEY STAGES IN THE EVOLVING SAFETY CASE

The development of a radioactive waste disposal facility involves a number of decisions, typically taken when moving from one stage of the facility life cycle to the next. These decisions are generally supported by the production and examination of a safety case. At each decision stage all factors relevant to the safe development and implementation of a disposal facility need to be considered. This section discusses what human intrusion considerations may need to be considered at each decision stage.

Figure 6.1 (developed in the IAEA PRISM project) illustrates how the safety case evolves over the facility life cycle and indicates (through the colour shading) the relative roles of the operator, regulator and government at the different stages. The following sub-sections discuss the human intrusion considerations that may affect decision making at each of the key stages identified in Figure 6.1.
Figure 6.1. IAEA PRISM project illustration of the evolution of the safety case over the lifecycle of a facility.

6.1.1 Need for Action

At this first stage, the need to act to address the issue of accumulated radioactive waste is likely to be driven by the desire to manage the waste safely. Depending on the type of waste, this may mean conditioning it to a safe state (e.g. vitrifying liquid wastes) and ultimately finding a permanent solution for management of the waste (i.e., disposal). The decision to dispose of waste rather than discharging it to the environment leads to the potential for accumulation of the radioactivity in a single location. Thus, right from the earliest stages of a disposal facility life cycle, considerations of potential human actions for wastes concentrated in a single location can contribute to the decisions that are taken by the key players (proponent, regulator, local communities, other interested parties).

6.1.2 Disposal Concept

IHI considerations play an important role in the development of the disposal concept. In particular, the decision regarding whether deep disposal is required or if near-surface disposal is acceptable will be determined by the waste concentrations and the timescale over which the wastes need to be isolated from the human environment.
A disposal concept will incorporate various barriers and measures to isolate and contain the waste and provide long-term safety for people and the environment. Whilst the primary objectives for human health and the environment must be met, consideration should also be given in decisions regarding the disposal concept to the possibility of IHI and to measures that can be adopted for the disposal concept that could reduce the potential for and/or reduce or mitigate potential consequences of IHI.

For example, a disposal concept may include features that help to make it resistant to intrusion activities, such as a robust engineered cover, container or barriers such as a metal, concrete, or other materials that would make inadvertent intrusion more difficult (see Chapter 9 for details regarding protective measures). Features of different disposal concepts can have competing benefits in the context of reducing the potential for and/or consequences of intrusion. For example, concepts that minimise stacking may also reduce the consequences of an intrusion activity involving drilling, should one occur, by reducing the amount of waste retrieved from a vertical borehole intrusion; however, less stacking could lead to a larger footprint and hence an increased likelihood of intrusion. Potential measures to address IHI need to be considered within the context of the overall optimisation of the disposal concept and should not diminish the safety of the normal evolution scenario.

6.1.3 Site Selection and Design

This is perhaps one of the most important decision stages in terms of consideration of IHI. Sites that have mineral resources, potable water or other resources may be considered more likely to experience future human intrusion activities and therefore may be considered less desirable to host a disposal facility. For example ICRP 122 notes that, “if a site is chosen in an area with no known natural resources, the likelihood for inadvertent human intrusion into the facility may be limited”. However, siting considerations in the context of human intrusion need to be weighed against other factors, including feasibility and operational and post-closure safety considerations and the availability of suitable and societally acceptable sites.

The facility design will be optimised for overall safety under expected or normal activities, but the optimisation process will also address potential measures for reducing the likelihood for and/or consequences of human intrusion and other accident scenarios. Therefore decisions about the facility design, including the types and thicknesses of the various barriers, the layout of disposal vaults or chambers, etc. may be influenced by IHI considerations as part of the optimisation process. A facility may also include design features that aim to warn any potential intruder of the lurking hazard (see Chapter 9).

6.1.4 Construction

The construction phase will start with the decision regarding the granting of a license to construct the facility. Safety, both to workers and the public during facility construction and operation and long-term environmental safety, will be primary
consideration for the decision to grant a license for construction. Considerations related to the potential for IHI are likely to be included in the construction license application, for example, in discussion to support the optimisation of the proposed design and identification of specifications for features that may be added due to considerations related to IHI (e.g., durability requirements for barriers, orientation of disposal units/drifts).

6.1.5 Operation

Once a facility has been completely or partially constructed, depending on the host rock of choice and the disposal system concept, there is likely to be a requirement for a further licence submission to gain authorisation for waste emplacement and operation of the facility. The safety case for this licence submission will incorporate any lessons learned during the construction phase (for example greater knowledge of the rock structure and hydrogeological conditions – relevant for deep geological facilities). In the light of this increased knowledge, it may be appropriate to update the IHI scenarios considered. Throughout the operations phase, it is likely that there will be periodic updates and reviews of the safety case. In particular, if there are any proposed changes to the operational practice or new waste streams (which are to be expected over a period of several decades), their implications for the safety case will need to be assessed and this may include any implications for IHI considerations.

IHI considerations may also be taken into account for the development of the waste emplacement strategy (e.g., a decision may be taken not to dispose of the most active waste packages in the upper rows of a near-surface disposal facility). Another important consideration during the operational phase (and beyond) will be the keeping of accurate records of the disposed wastes. These records need to be clear and accessible not only to the current decision-makers, but also to future generations. The maintenance of accurate records and general public knowledge of the location and type of the hazard is one of the most effective measures that can be taken to reduce the potential for IHI.

6.1.6 Closure

A decision will be taken to close the disposal facility once it has reached its licensed capacity, is full, or if society decides that no further waste should be added. The decision to close a disposal facility should include the requirements for the effective backfilling (if any is needed to provide a safety function) of the waste disposal areas and the sealing of all access-ways, drifts and shafts. These closure requirements should reflect the need to provide barriers to human access to the wastes as well as to control potential preferential release routes from the disposal areas.

The closure decision should also include the policy or procedure for maintaining the disposal facility site records, which should be finalised at this stage.

The decision regarding records management should have regard to the level and type of information that needs to be maintained (for example, individual waste package
contents and location, or the overall inventory and location of each disposal area). As already noted, the maintenance of clear and accessible records and public knowledge of the hazards will be an important control in delaying and/or preventing future IHI.

6.1.7 Post-closure

Following the closure of the disposal facility, there can be a period during which it remains under active controls. During this period of active controls, the disposal facility is likely to be monitored and there will be security at the site that will effectively preclude any IHI. Furthermore, if monitoring reveals any damage to the facility, it can be assumed that this will be remediated. This period is sometimes referred to as ‘post-closure active institutional control’, ‘indirect, regulatory oversight’ or ‘period of restricted use’.

At some point in time a decision will be taken to terminate active control of the disposal facility site. At this point the ownership of the facility site may change: the site operator may relinquish the site to the State, or it may be sold for private or public use. Typically near-surface disposal facilities are relinquished to the State, whereas the land above geological disposal facilities may be returned for alternative use with caveats and agreements that extend land-use controls.

The decision on when to cease active controls is likely to depend on:

- the inventory of the disposal facility (and particularly for near-surface facilities, the time at which the inventory has decayed to an acceptable level);
- the regulatory framework and any regulatory requirements regarding active controls;
- societal factors, for example the wishes of the local community, whether the land is required for any alternative use (for geological facilities) and any political drivers.

6.2 THE SAFETY CASE STORYLINE FOR HUMAN INTRUSION

It can be helpful when discussing the timing of the need to consider future human actions in the context of the safety case to think of the life-cycle of a radioactive waste disposal facility as a storyline, divided into a number of phases with distinct features relating to the potential for IHI. As already discussed, in the context of IHI scenarios for the safety case, it is generally accepted that it is only necessary to consider scenarios where any actions that disrupt the safety functions of the facility are undertaken without knowledge by the intruders of the hazard presented by the disposal facility. We refer to such actions as being ‘inadvertent’. By definition, IHI cannot occur whilst there is general knowledge of the whereabouts of the facility and the nature of its contents. However, it is conceivable that knowledge of the site may be retained by some sectors of society but not others; if the intruder has no knowledge the intrusion would still be classified as inadvertent. Thus, the level of knowledge of
the facility is the key factor in defining the different phases of the safety case storyline, as discussed in the following sub-sections.

6.2.1 Phase 0: Operational Period

This is the period during which the radioactive waste disposal facility is operational. It is the first period during which the site contains hazardous wastes and hence the first period for consideration in the human intrusion safety case storyline. There will be direct oversight (as defined by ICRP 122) of the site as it is licensed as an active facility. This period includes all the time during which waste is emplaced in the facility; there may also be ongoing construction activities during the operational period. This period also includes the time taken by the processes of backfilling, sealing and closing the facility. During this period there is human action at the facility, but it is planned and intentional and suitable protection will be in place for workers, who will be aware of the hazardous nature of the materials with which they are working. By definition, IHI is excluded from this phase of the disposal facility life-cycle.

6.2.2 Phase 1: Post-closure Active Control

This is the period that starts once the facility has been closed and sealed and continues for as long as there is active, physical control of the site. As a minimum this will be a physical fence around the disposal facility site and routine surveillance or similar means of controlling access to the site. In terms of the terminology of ICRP 122, this is the period of indirect, regulatory oversight. The IAEA refers to this as the ‘active institutional control’ period. In this report, it is simply identified as the period of ‘active control’. During this phase, it is anticipated that the facility will be monitored and any identified damage to the disposal facility will be remedied. As there will be security preventing any unauthorised access, it is not possible for IHI to occur during this phase.

6.2.3 Phase 2: Post-closure Passive Control

This is defined as the period that starts immediately following cessation of active control of the site. This phase continues for as long as there is public knowledge of the site and the hazard it presents. In terms of the terminology of ICRP 122, this is the period of indirect, societal oversight. The IAEA refers to this as the period of ‘passive institutional control’. For the purposes of this report, it is simply referred to as the period of ‘passive control’.

It is anticipated that records and controls, such as deed restrictions or drilling/mining permitting requirements, will be maintained for any radioactive waste disposal facility at the local, national and potentially international levels for a period of time up to several decades and even centuries (such timescales may be justified, for example, by considering the UK Doomsday Book created in the 11th century, documenting land use and locations of towns and villages, populations and livestock throughout England, which survives today).
Whilst such records and knowledge of the facility are maintained, it can be considered that it is unlikely that IHI occurs. For example, whilst planning authorities have knowledge of the facility it is highly unlikely there will be any major public works project with authorised large-scale excavations at the site. Whilst the geological and mining communities have knowledge of the facility it is also unlikely there will be any authorised borehole drilling at the site. Markers placed at the disposal facility site may also be considered to contribute to passive control of the site. Such factors can help to limit the need to consider IHI during that time frame or potentially limit the range of possible scenarios that need to be considered.

The extent to which credit can be taken of passive controls is likely to depend on the national regulatory context. At the very least, the safety case should present arguments to explain how passive controls contribute to making any significant IHI event highly unlikely (for example, it would require a major construction without consultation of public records). Section 6.3 discusses the safety arguments that may be considered in this context.

### 6.2.4 Phase 3: Distant Future, Knowledge of Facility Hazard is Lost

This phase begins when there is assumed to be a loss of public knowledge of the hazardous nature of the contents of the disposal facility. In terms of the terminology of ICRP 122, this is the ‘period of no oversight’. It may be possible that there is some knowledge of a feature at the disposal facility location, for example it may present a detectable signature on surface mapping techniques, but there is no knowledge of the potential hazard the facility presents. It is the loss of knowledge of the hazardous nature of the disposal facility that defines this phase.

In this phase there is the potential for inadvertent human intrusion into the disposal facility, or other human actions that could disrupt the safety functions of the disposal facility. Such activities could include drilling into the facility, mining or excavating to the depth of the wastes.

The potential for such IHI will be greatly influenced by several factors, especially the depth of the facility (e.g., it is reasonable to assume a much lower potential for intrusion into a deep geological facility than into a near-surface facility). Siting of the disposal facility away from known resources or populated areas can also contribute to reducing the potential for the facility to be disturbed (e.g. by drilling activities). Probabilities or likelihoods can be difficult to quantify and justify in the case of IHI that may occur far in the future. However, a qualitative discussion of the potential for intrusion can be meaningfully discussed in the safety case and may be important in decisions relating to siting, design and optimisation, for example when discussing the expected effectiveness of different strategies.

The consequence of inadvertent HI will depend on the:

- nature and characteristics of the waste (i.e. the waste form) and its level of radiotoxicity, i.e. how harmful it is;
• timing of the intrusion event, noting that the further into the future the intrusion occurs, the greater the radioactive decay of the radionuclides in the wastes (although for certain radionuclides, such as radium-226, there will be ingrowth from the decay of long-lived parent radionuclides that will lead to an increase in the radiotoxicity);

• amount of radioactivity that is brought into the biosphere;

• nature of the intrusion scenario, i.e. how many people come into contact with the waste or contaminated soil/water and for how long, whether radionuclides are ingested and/or inhaled and levels of exposure to external radiation;

• residual state of the disposal facility following the intrusion event, i.e. the extent to which the intrusion event impairs the isolation of the remaining wastes and whether the disposal facility is repaired following the intrusion event.

This third phase is the phase most applicable to consideration of inadvertent future human actions that have the potential to disturb the disposal facility.

6.3 DEVELOPING HUMAN INTRUSION SAFETY ARGUMENTS

As already noted in Section 6.1, when siting and designing a radioactive waste disposal facility, consideration should be given to reducing the potential for human intrusion scenarios and the potential consequences should they occur. A number of factors can be considered in the context of optimisation, for example:

• selecting a site with characteristics that correspond to a low history of drilling or mining (i.e. there is a low history of excavation activities at the site and all similar sites);

• selecting a site and/or engineered protective layers with a low potential for erosion and/or uplift;

• increasing the depth of waste burial;

• selection of remote locations away from populated areas;

• placing durable markers at the site to increase the length of time before Phase 3 (knowledge of the facility is lost) can reasonably be expected to occur;

• considering the use of engineered barriers above the waste or designing waste containers such that typically applied drilling or excavation techniques would not access the waste (for example, the Yucca Mountain Project safety case (Sandia National Laboratories 2008) took credit in this respect for the role of the titanium drip shields above the waste containers).
However, when considering design features that may make a disposal facility more robust to human intrusion scenarios, it is essential to consider the impact on other aspects of system safety. For example, introducing additional metal to potentially ‘divert’ a drill bit, could lead to the generation of additional gas which may lead to other, more likely, post-closure exposure pathways. If that additional metal is valuable and rising in value, it may entice future human intrusion. Even though such intrusion would not be inadvertent, it is still best to avoid this scenario by using more common, less costly materials to perform barrier safety functions if possible. It will be important not to reduce the overall robustness of the disposal facility in order to mitigate potential, hypothetical future human action scenarios.

Although discussion of inadvertent human intrusion in a safety case is likely to focus on the distant future (Phase 3 above), the earlier periods should not be ignored, as discussion of the length of time during which inadvertent disruptive human actions can reasonably be assumed not to occur helps to build confidence in the safety case. It is one of the goals of disposal to isolate the wastes from the human environment for as long a period as possible. Therefore an important safety argument with regards to the discussion of human intrusion events in a safety case is likely to be the length of time for which any inadvertent human intrusion event can be regarded as being extremely unlikely. Credit can then be taken for the radioactive decay of the wastes, reducing their potential hazard, during the period of isolation.

The safety case storyline can provide a helpful framework for presenting the safety arguments that contribute to robustness of the disposal concept and mitigate against the potential for and/or consequences of human intrusion events. These safety arguments are rooted in the decisions that are taken in relation to human intrusion during the development of the disposal facility.

Potential protective measures that could be taken to reduce or mitigate IHI are discussed in more detail in Chapter 9. It is recommended that the discussion of IHI in the safety case should focus on the measures that have been (or are planned to be) taken to prevent or reduce the potential for a human intrusion event and/or reduce the consequences should intrusion occur. Table 6.1 below summarises the societal controls and design safety features that are relevant to each of the three post-closure phases of active control, passive control and loss of memory. The table indicates the implications for the potential for inadvertent human intrusion in each phase and also highlights that the hazard of the disposal facility is reducing due to radioactive decay, as the potential for intrusion increases with time.

However, the safety case is also likely to need to make some analysis of the potential consequences should an IHI event occur. Chapter 8 presents some suggested stylised scenarios for consideration of human intrusion in the safety case. These should be treated as outside the base scenario or normal, expected evolution of the disposal facility. National regulations may define the extent to which such IHI scenarios require consideration and the level of quantitative versus qualitative analysis expected.
TABLE 6.1. Post-closure Phases in the Disposal facility life-cycle in the context of HI Considerations

<table>
<thead>
<tr>
<th>Time Frames</th>
<th>Active Control</th>
<th>Passive Control</th>
<th>Loss of Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Societal Control</td>
<td>Physical security at site</td>
<td>Knowledge management, records, land use restrictions, site markers</td>
<td>No knowledge of hazardous nature of site</td>
</tr>
<tr>
<td>Design safety features</td>
<td>Depth of disposal, barriers</td>
<td>Depth of disposal, barriers</td>
<td>Depth of disposal, barriers may be degrading</td>
</tr>
<tr>
<td>Implications for likelihood of IHI</td>
<td>No IHI</td>
<td>IHI unlikely – safety case may be able to justify exclusion of major HI scenarios</td>
<td>IHI is a possibility, but may still be mitigated by enduring design safety features</td>
</tr>
<tr>
<td>Hazard of facility</td>
<td>Disposal inventory</td>
<td>Decaying inventory</td>
<td>Decay may be significant for near-surface, low-level waste facilities</td>
</tr>
</tbody>
</table>

Near-surface disposal will generally involve a quantitative assessment from an optimisation perspective involving the potential for exposures associated with waste that is brought to the ground surface and the results will likely play a role in defining waste acceptance criteria and operational and design considerations. For geological disposal, it may be a qualitative or quantitative assessment involving some intrusion in the contaminated footprint of the facility without necessarily directly contacting waste, depending on the facility layout. The purpose for geological disposal will focus on the objective of identifying protective measures that can be beneficial in the context of optimisation of protection.
7. SOCIETAL FACTORS

7.1 INTRODUCTION

Societal factors play an important role when addressing IHI as part of a safety case. Consideration of IHI is relatively unique to radioactive waste disposal, thus it can be an unfamiliar topic to interested parties more familiar with other types of disposal facilities. Effective communication with interested parties is critical to for explaining the basis for including IHI as part of a safety case for a radioactive waste disposal facility and emphasising how IHI considerations are used to improve the robustness of a disposal facility.

When considering how IHI may occur in a given location, societal factors related to current technologies that are used (e.g., drilling, excavation) and human habits help to define specific scenarios that may be considered. Societal aspects may be considered in IHI scenarios in different ways in different projects, since there is no common approach for addressing these uncertainties within a safety case. Differences arise because of different interpretations of different international guidance (IAEA 2011b; ICRP 2013) and national level regulations and also because of other potentially important assessment-specific issues, such as the special interests of particular local interested parties or features of the local geology and geography.

As HIDRA progressed, it became apparent that the most effective enduring defence against the hazards associated with the waste. Examples of how societal factors are addressed in IHI scenario development, the interpretation of the results, and communication of these results to interested parties are discussed in international collaborative work, for example that described in Smith et al. (2012).

However, the annual likelihood of such a scenario occurring is small. For near-surface disposal facilities, IHI is considered more likely to occur due to the increased accessibility (i.e., wastes are closer to the surface), although the type of radioactive waste that is typically managed at near-surface facilities, has a lower dose exposure potential at the time of disposal. If the assessed IHI doses are very large, this could lead to a particular concept for disposal being modified or abandoned in favour of geological disposal (see for example discussion in Smith et al. 2013). However, although IHI assessments may show that the dose consequence from the intrusion may be large, they are often built on a number of cautious assumptions and the potential for an IHI scenario is in many cases very small. For both deep geological and near-surface facilities, societal aspects play an important role in the development of IHI scenarios and interpretation of IHI assessment results. An appropriate communication of the assumptions and results with interested parties is crucial in order to put the human intrusion scenarios and potential consequences into a proper context.
The Societal Factors working group organized its work into three different topics: (1) communication of IHI scenarios; (2) development of IHI scenarios; and 3) knowledge preservation. This chapter is organised as follows:

- Communication of IHI scenarios - how human intrusion scenarios can be used to aid building confidence in the safety and robustness of radioactive waste disposal facilities (section 7.2)
  - Encouraging effective communication between different interested parties during the life cycle of the disposal system (7.2.1)
  - Communication of cautious assumptions (7.2.2)
  - Use of likelihood in communicating results (7.2.3)

- Development of IHI scenarios – how societal factors are considered when generating IHI scenarios (7.3)
  - Technological development of society – global or local, present or future (7.3.1)
  - Human diets, habits and settlement pattern, and political and economical changes influencing scenario selection (7.3.2)
  - Deliberate vs. inadvertent intrusion what distinguishes inadvertent intrusion from deliberate and thereby qualifies the scenario to be included in the IHI assessment (7.3.3)

- Knowledge preservation (Section 7.4)
  - Knowledge preservation during the active control period (7.4.1)
  - Knowledge preservation beyond the active control period (7.4.2)
  - Time frames for the preservation of knowledge (7.4.3)

7.2 COMMUNICATION OF IHI SCENARIOS - HOW HUMAN INTRUSION SCENARIOS CAN BE USED TO EVALUATE AND COMMUNICATE THE INTRINSIC SAFETY OF RADIOACTIVE WASTE DISPOSAL FACILITIES

One of the key purposes of a safety case is to provide a level of confidence to all interested parties that human health and the environment are protected. Confidence in the safety case is strengthened by the use of multiple lines of evidence leading to complementary arguments demonstrating the safety of a disposal facility. IHI is evaluated separately from normal evolution scenarios due to the fact that the potential of occurrence is often very low and uncertain, but it has been decided that IHI needs to be considered as part of a safety case. As stated in Chapter 4, IHI is generally

HIDRA
considered using stylised scenarios with cautious assumptions of what would happen if humans intrude into a disposal facility. The challenge from a communication perspective is that some of these stylised scenarios can lead to calculated doses which can exceed the doses calculated for normal evolution scenarios. Therefore, good communication of the purpose and context for IHI is a key factor to consider when developing and presenting the safety case for a disposal facility. It is important to communicate the context of the scenarios and to provide perspective regarding the cautious assumptions on which the scenarios are based.

It is important to maintain effective communication regarding the role of IHI scenarios with operators, regulators, local communities and other interested parties for the entire life cycle of a disposal facility (see Figure 6.1). In addition to building confidence in the safety case, communication may also contribute to scenario development and help to build the framework for preservation of knowledge of the disposal facility for long time periods and thereby help to reduce the potential for IHI. Considerations for communicating the role of IHI in a manner that builds confidence in the safety case (for example explaining the cautiousness of scenarios, and adding context around the likelihoods) and communication strategies during the life cycle of the disposal facility are discussed below.

7.2.1 Effective communication during the life cycle of the disposal system

Long-term safety of a disposal system is considered from the start of the life cycle of the disposal facility. Different aspects of IHI considerations and different levels of detail should be communicated as throughout the life cycle moves forward. Different communication approaches are often needed for operators, regulators and other interested parties. Communication with international organisations and use of international peer reviews have proven effective to obtain independent feedback that can be used in the development of the safety case for a disposal facility and may also aid in building confidence in the safety case and increase knowledge of the disposal facility. To achieve confidence in the safety case, it is strongly recommended to present a transparent analysis to all interested parties throughout the life cycle of the disposal facility.

Continuous communication and active engagement with interested parties builds confidence and can increase the knowledge and awareness of the disposal facility. This in turn may lead to more effective preservation of knowledge of the site over time (knowledge preservation is further discussed in Section 7.4 and Chapter 9). In addition, a two way dialogue allows the operators (implementers) to take into consideration the concerns of interested parties. For example, early communication may provide feedback on the local site and possible inputs that may be used in the IHI scenario development, such as the drilling technology commonly used at the site. (for For scenario development see Chapter 8). The following are examples of communication during the different stages of the disposal facility life cycle:.
Communication during disposal concept stage

At the disposal concept stage, it is recommended to communicate the story of why a safety case is developed and the purpose of IHI as part of the safety case should be explained to interested parties. Early emphasis needs to be placed on describing the purpose of considering IHI as a means to improve robustness for optimisation rather than trying to address all possible future human actions that may affect the repository. Also, the rationale for selecting a few stylised scenarios to illustrate possible effects of IHI (see Section 4.3) as a means to consider measures to improve safety should also be described. Communication with members of the public could be implemented via public meetings and presentations on measures that will be taken to reduce the potential for IHI (e.g., the depth of disposal facility, its area and type of containment, and/or location away from natural resources). At this stage it is also recommended that operators and regulators begin discussions of possible stylised IHI scenarios that may be assessed in the safety case.

General aspects of IHI can be communicated at this stage. For deep geological repositories, communication should begin with the statement of fact that disposal several hundred metres below the surface is specifically selected to isolate the wastes and make IHI unlikely and to significantly limit potential consequences even if intrusion were to occur. For both geological and near-surface disposal facilities, it is important to communicate all planned measures to show how IHI has been considered in developing a robust disposal facility.

The FSC (Forum on Stakeholder Confidence) of OECD/NEA (OECD/NEA, 2004) emphasises the importance of role clarification at all levels, such that responsibilities are identified, transparent and clear to all interested parties early in the waste disposal facility planning stages. Therefore, it is helpful at the concept stage to start the communication to clarify responsibilities for the disposal facility after closure and establish plans for assured financing for knowledge preservation and institutional control (if such a strategy is intended for the disposal facility).

Communication during site selection and design stage

For the site selection and design stage, communication of IHI considerations and IHI scenarios can be extended to include more details. For site selection, the siting criteria should be clearly communicated including considerations for IHI, such as the potential for valuable resource exploitation at the site. At this stage, the implementer should discuss ways to preserve knowledge of the site and describe how this is expected to contribute to overall safety (see Section 7.4).

In addition to scheduled public meetings and presentations, more detailed discussions between all involved parties are recommended to begin to develop the details of how IHI will be considered. This can be achieved through various fora, workshops, working group meetings including local, regional and national participants. Providing support to the local community to encourage active involvement can be one way to start to build knowledge of the safety case, including
IHI scenarios. One example of support to the local community could be to provide the community with resources and data that allow them to conduct their own study to consider measures that can improve the robustness of the safety case. Local community groups could consist of people representing the local and regional communities, as well as experts selected by them. The local groups could learn more about the project for the disposal facility, understand the underpinning science behind the elements presented to them, and disseminate information to other members of the community. Examples of such groups are found in France (CLIS of Bure), Sweden (Forsmark community), Belgium (Stora and Mona), Canada (Community Liaison Committees) and United States (Site-Specific Citizens Advisory Boards).

Communication of IHI assessments and methodologies in international fora is also recommended as it contributes to sharing of lessons learned and effective approaches to address IHI. In addition, international best practices should be explained when communicating with local, regional and national interested parties at this stage, since international experiences may be used to build confidence in the methodology used.

It can be emphasised in communication that, given the uncertainties regarding future behaviour, stylised scenarios are recommended, i.e. not all possible future human actions can or are intended to be included as part of the optimisation process. Topics of IHI that can be discussed at the site selection and design stage include, as applicable: the distance from urban areas, lack of residents, absence of mineral resources, depth of disposal, etc. Note that natural resources, such as geothermal energy or groundwater, can be present over regional- scale areas. For such large- scale resources, it may be explained that the potential to drill directly through the disposal facility to reach the resource would be low given the actual extent of the resource. It is also suggested to that providing contextual illustrations may help to explain the concept of low intrusion potential.

As specific IHI scenarios are discussed, real life examples could be used to communicate the assumptions made to interested parties. For example, one of the reasons that may be used to support the low likelihood of natural resources could include: archived data from past activities (e.g. drilling) at the proposed facility site and in the areas adjacent to the planned site, as exemplified in Smith et al (1988). When communicating the results of IHI scenarios, the use of comparisons and examples to which the public may be able to relate is recommended, for example by making comparisons of the estimated dose from the disposal facility with doses associated with natural background radiation.

Communication during construction, operation, closure, and post-closure stage

In later stages (construction, operation, closure), the emphasis of communication can shift to address the measures that were considered, and those that are being taken against IHI (e.g., design features, operational approaches, closure plans) (i.e., measures taken (Chapter 9)) and how those measures were selected based
on the ability to reduce the potential for and/or consequences of IHI. The level of caution in the selected IHI scenarios (Section 7.2.2) in the safety case and their low potential of occurrence (Section 7.2.3) can also be emphasised. Moreover, it may be appropriate to show how design of the facility has been optimised to reduce the consequences of any intrusion activity. Such design aspects may be shown to be the results of earlier stage assessments.

Communication with interested parties should continue to emphasise the importance of knowledge preservation and identification of measures to foster enduring knowledge of the disposal facility and hazards. The measures taken to ensure knowledge preservation should be discussed with stakeholders to seek their suggestions and to increase confidence in the safety of the disposal facility.

### 7.2.2 Possible cautious assumptions of IHI scenarios to be communicated

An unavoidable concern arising from considering rather extreme scenarios, not typically considered for other waste disposal facilities, is that some of these stylised scenarios can lead to calculated doses which can far exceed the doses from normal evolution scenarios, especially if the probability or likelihood of a scenario occurring is not considered. For this reason, it is important to consistently communicate the purpose of the IHI scenarios in the context of optimisation and to explain how the evaluation of IHI scenarios is unique to radioactive waste disposal facilities as a means to add further robustness to the safety of the facility. An important element of any part of this communication is to highlight the low possibility for IHI and the measures taken to further reduce the potential for IHI when communicating results from IHI analysis where probabilities of occurrence are not specifically included in the calculations (see Sections 7.2.1 and 7.2.3).

It is important not to over-emphasise numerical analysis of IHI (especially for geological facilities), but rather to provide perspective about the number of cautious assumptions that are often generally built into IHI scenarios. One way to do this is to provide a list of all the assumptions that have been used in the scenario with some explanation of why they are believed to be cautious. Communicating such a list, specific to a given disposal facility, can help interested parties to understand everything that would have to go wrong for IHI to occur. Depending on the site- and facility-specific considerations and assumptions made in the IHI scenarios such a list could include some or more of the following different combinations of:

- Assumed loss of knowledge of the repository;
- Assumption that IHI occurs (even in a remote site with low human activities);
- In some cases, it may be assumed that intrusion occurs immediately following the end of the active control period with no credit for continuing knowledge and passive controls;
- Assumption that intrusion occurs within the disposal facility footprint rather than outside its footprint;
Assumed direct contact by intruders with radioactive waste (typical assumption for near-surface disposal);

- Assumption that that a drill will not be stopped by or deflect around barriers, containers or waste forms, leading to recognition of the anomaly and hazard;

- Assumption that the driller/construction worker will not recognise that something is wrong (e.g., non-soil material in cuttings or excavation);

- Assumption that the drill hole is not closed and sealed after recognition of the hazardous waste;

- Assumed drilling and use of a well for water without considering water quality;

- Assumed residents establishing home/garden on the drill cuttings rather than in an area without cuttings;

- Assumption that some of the cuttings are respirable rather than considering the actual grain sizes;

- Assumption that cuttings will behave like soil with respect to uptake in plants;

- Extreme exposure assumptions for occupancy and local food production and consumption, rather than those relevant to typical situations.

It is not expected that an analysis of a facility would need to detail all the above assumptions, but the list is intended to highlight assumptions that are often made or requested during development of scenarios, perhaps without consideration of their overly cautious nature. Depending on the level of interest, different levels of detail of the assumptions may be discussed. In general, the assumptions are related to either one of:

1) knowledge of the facility and timing of intrusion;
2) occurrence and location of intrusion;
3) recognition of the waste and actions upon intrusion;
4) cautious assumptions regarding potential exposures.; or 5) assumptions regarding the development of society. Some discussion regarding communication of these groups of assumptions is discussed further below.

Assumptions regarding the knowledge of the repository and time of intrusion

Since only IHI is considered, the starting point of scenario analysis is an assumption that there has been a loss of knowledge of the nature and hazard of the disposal facility. A cautious option is the assumption that all knowledge is lost and IHI occurs immediately following the end of the active control period in spite of all of the measures in place to preserve and maintain knowledge of the facility. Approaches for preservation of knowledge and time frames for knowledge preservation are discussed in Section 7.4. The challenge is that people can question the level of certainty associated with preserving knowledge beyond active controls. This highlights the importance of effective communication of measures taken to preserve knowledge. It can be argued in communication that knowledge is likely to be kept...
much longer than is often assumed in the IHI scenarios. For example, it is not realistic to assume an immediate loss of knowledge because of the high level of attention associated with radioactive waste disposal. It is, in fact, difficult to imagine a loss of knowledge of such a highly publicised activity.

There are examples of archives being kept for many hundreds of years (e.g. archive of the Roman Church (Macfarlane 1959, and more widely discussed in Holtorf and Högb erg 2014 and the UK Doomsday book, providing a detailed documentation of land use in the 11th century AD, which still exists today). Actual examples of long-term archives could be used in the safety case communication showing that it is likely that knowledge of the disposal facilities could be kept for very long time frames, even if these time frames are not directly credited in the analysis. All the measures taken to preserve knowledge could be used in communication to build confidence that knowledge will be prolonged for long time frames, e.g. continuous education of current and future generations, long-term plan by implementing passive controls early in the lifecycle (e.g. a national day of recognition), markers. (See Section 7.4 and Chapter 9 for further considerations of knowledge preservation).

**Occurrence and location of intrusion**

It can also be communicated that even if knowledge of the disposal facility is lost, the potential for intrusion at a given time and location may still be very low, especially for disposal facilities in remote, sparsely populated areas without known natural resources. For example, it is possible to communicate the low potential using population density information and data on drilling frequencies in the area based on present and historical data. It may also be reasoned that IHI into the actual disposal facility may be very unlikely by comparing the area of the repository footprint with the surrounding area where drilling or other activities are just as likely to occur. Likewise, and depending on the disposal facility concept, even if drilling within the footprint of the disposal area occurs, the likelihood of actually penetrating a waste canister might be lower than the likelihood of drilling between the radioactive waste canisters, especially for geological disposal facilities with significant spacing between containers/drifts for high-heat-generating wastes. Furthermore, for some kinds of geological disposal facilities, present day information from drillers may indicate that the drilling technique used would make it more likely that the drill would deflect around the waste container rather than penetrating it (the implications of alternative drilling techniques are discussed in some detail in Smith et al. 2013). Thus, whilst there may be pressure to make very cautious assumptions for IHI, it is important to maintain a more realistic perspective when communicating results involving such assumptions. Ideally, the pressure to perform extremely conservative calculations can be deflected by making a reasoned case for a more realistic stylized approach.
Recognition of the radioactive waste and actions that are taken following intrusion

There is often an assumption in IHI scenarios that, if drilling or excavation directly into waste occurs, the potentially hazardous nature of the radioactive waste is not immediately recognised. The degree of caution in this assumption could be discussed, taking into account the type of IHI occurring, and what would be expected to occur given current practices. Indeed, while it is probably reasonable in the case of indirect intrusion (not direct contact with the radioactive waste) to assume that the nature of the materials excavated is not recognised, it is more doubtful that a driller would not recognise that something was wrong in the case of direct intrusion resulting in contact with radioactive waste, for example in a near-surface facility.

The presence of man-made materials may cause some change in the actions taken by the intruder, reflecting present day civil engineering practice on the discovery of the material. Deep drilling IHI implies access to a high level of technology by the intruding society, and in particular, the presence of metals and waste materials, particularly, for example, if found in a salt formation, would be very obvious and quickly recognised as artificial; therefore it is plausible that the hazard would be recognised and appropriate actions taken. Also, for a deep disposal facility, the radioactive nature of the material might be recognised, as when drilling a borehole in a new geological environment, geologists often carry out drill logging using gamma rays in the borehole to characterise the rock or sediments. However, in the case of facilities with large continuous areas of waste rather than dispersed individual containers, unless and until that recognition occurs, the drillers would be at risk of exposure, both from any core material brought to the surface, and from contaminated drilling fluids coming to the surface (Smith et al, 2013). In communication, it can be explained that present day techniques could allow earlier recognition of the nature of the disposal facility than the cautious assumptions that some may want made in the IHI analysis. Early recognition would most likely lead to measures to being taken, such as the intrusion being stopped, and a period of institutional control might be reintroduced, thereby preventing IHI for a period of time afterwards.

Cautious assumptions during scenario development

In some IHI scenarios for near-surface disposal facilities, it may be assumed that the drill hole is utilised as a water resource using water that had been contaminated by earlier leaching from the disposal facility. It may also be assumed that drill cuttings are deposited on the ground surface and mixed with the soil, which may then be used as a vegetable garden plot. In communication, it could be described that based on current practices, when drillers recognise the hazard, they would likely not only to stop the drilling but also to take precautions to prevent others from being exposed. The drill hole would presumably be sealed preventing humans from utilising the water. In addition, it is common practice in many countries to check water quality before utilising a well. If there is an expectation to consider such scenarios for IHI, current practices could be used to highlight the cautious nature of such assumptions used in developing the IHI scenarios.
In communication, it can also be explained that it is unlikely, after recognition of the hazards, that drill cuttings would be left on the ground potentially exposing future inhabitants if the area is used for a vegetable garden plot. For a vegetable garden plot, it can also be discussed that a landfill containing drill cuttings probably would have to be mixed with more suitable soil to be of sufficient quality for the crop growth, since drill cuttings would most likely be composed of coarse material and waste material not suitable for agriculture. Further cautious assumptions that need to be carefully considered for scenario analysis are that the radionuclides in the drill cuttings would be taken into the vegetables in the same way that uptake would occur from soil. However, radionuclides may be sorbed in a different manner bound within the waste cuttings and are unlikely to be easily taken up by the plants. Obtaining actual data for the accessibility of the radionuclides from waste cuttings to the plants may be difficult (and is not required), rather the pessimisms in the scenario assumptions in the scenario should be emphasised as a further line of evidence of the high degree of caution in IHI scenarios.

Assumptions regarding the development of society

As discussed in Chapter 4, it is generally expected that IHI scenarios are developed based on known technology and current practices given that the scenarios are simply assumed to be an indicator of what could happen and recognising that we cannot claim to predict what future technology may be available (see Section 7.3.1). However, in the short term, one can make reasonable extrapolations of current practices (engineering and technology), expert judgments, and social sciences. It can be communicated that development in technology may increase the ability to identify radioactive waste in disposal facilities at great depth but may also lead to identification of other natural resources situated in close proximity. Although identification of resources could increase the potential for intrusion, it can be argued that the potential for IHI would most likely decrease following technological development as the hazardous nature of the material would be more likely to be identified. If a society is capable of finding resources at great depths, for example copper in waste canisters, it is also likely to be able to detect the radioactivity and thus be aware of the potential hazard, and such an intrusion would then be considered as a deliberate intrusion.

7.2.3 Use of probabilities/likelihoods in communication of IHI

Since the consequences from the types of exposures associated with stylised IHI scenarios can be relatively high, they can give rise to concern, if the context and purpose of the calculations are not explained. It is recommended that the actual potential for a given IHI scenario to occur is discussed (see also Section 7.2.2) even if it is not specifically included in any calculations. The potential for intrusion can be addressed using concepts like such as probabilities or likelihoods. Likelihood tends to reflect a more qualitative estimate, whereas probability generally refers to quantitative estimates (e.g. PAMINA 2011). As discussed earlier in this report, for the purposes of the HIDRA project, likelihoods or probabilities are addressed in a general sense with the concept of the ‘potential for’ inadvertent intrusion.
Consideration of the potential for human intrusion into a given disposal facility can help to provide qualitative information to support the inclusion or exclusion of certain human intrusion events from an assessment and also provide quantitative information for risk calculations where it is required. A number of approaches have been used to derive probabilities (e.g. NEA 1989, NEA 1995a, ICRP 2000). There are examples from several countries for deep and near-surface facilities where probability for IHI in certain areas has been calculated based on historical drilling/deep exploration data for that area (see for example, Smith et al. 1988, Smith et al. 2013, Swift 2013, SKB 2010). However, it can be difficult to calculate and justify probabilities (Grimwood and Smith 1989). In fact, the uncertainties are such that several references go as far as stating that it is not possible to derive verifiable probabilities for future human actions, especially for the long time frames relevant for deep geological facilities (e.g. OECD/NEA1995a, PAMINA 2011). It should be recognised that for near-surface disposal facilities at or just below the ground surface, the probability for the assessment of consequences that IHI will occur sometime after the end of active institutional control is often set to 1 as a cautious assumption, implying that it is difficult to completely rule out potential IHI. However, given the cautious assumption that for the purpose of optimization, IHI is generally assumed to happen after loss of memory and controls, the probability of IHI in any given year will be significantly lower than one.

Although it can be difficult to state a specific probability, it is reasonable to communicate the likelihood of intrusion occurring and that certain measures can be taken to reduce the potential for intrusion. From this perspective, it is useful to explain that the potential for IHI is one consideration early in the life cycle of a disposal facility, for example when developing site selection criteria or deciding between near-surface or geological disposal for a given waste stream. The potential for IHI may decrease by locating a disposal facility away from known natural resources (IAEA 2011b), e.g. several countries aim to minimise the potential for IHI by avoiding areas where there has been a history of drilling or where there are exploitable resources (e.g. Switzerland -NAGRA 2002, UK – Siting criteria, 2014, Sweden -SKB 2010, Finland-Smith 2013). Locating near-surface facilities in remote areas can also decrease the potential for human intrusion. Typically, radioactive waste disposal facilities are sited away from population centres for public-acceptance reasons, not just to lower the IHI potential. Other examples of measures against intrusion are passive in nature such as markers or anti-intrusion barriers. These can, further reduce the likelihood for IHI (see Chapter 9 for more examples of such measures).

In cases where it is deemed too difficult to derive and justify probabilities, it is possible to provide information to demonstrate that the measures adopted for development of the facility can make the potential for IHI very low. If quantitative doses from intrusion are calculated, those results should always be directly qualified with a discussion of the relative potential for a given IHI scenario to actually occur.
Assumptions regarding future human actions need to be defined and justified consistent with societal norms. No one is able to predict with any certainty the future evolution, behaviour, and actions of humans. Nevertheless, it is possible to describe different possible societal contexts based, for example, on the assumed level of societal development (SKI/SSI/SKB, 1989). IAEA (2003b) notes that the types of societal assumptions needed to support the assessment are dependent on the degree of conservatism or realism desired in the analysis and the end points to be considered. It is reasonable and consistent to select IHI human habits which are consistent with societal assumptions used to support other safety assessment scenarios. Societal factors can also play a role in defining mitigation measures against IHI.

When generating IHI scenarios both technological and societal factors should be considered. According to OECD/NEA (1995a) the scenarios “can be based on the premise that practices of the societies correspond to current practices at the repository location and similar locations elsewhere”. The Societal Factors working group identified several potential factors to consider during development of IHI scenarios:

- Technological development of society – global or local, present or future
  (Section 7.3.1)
- Human diet and habits, political, economic, environmental and other changes, which may influence scenario selection and measures (Section 7.3.2)
- Recognition of the hazards of a disposal facility. Although the definitions of deliberate and inadvertent are very clear, it is possible to imagine a situation when inadvertent intrusion becomes deliberate intrusion as the intruder gains knowledge of the hazard (Section 7.3.3).

7.3.1 Technological development of society - global or local, present or future

The technological status of a society can significantly affect the potential for IHI into a disposal facility. For near-surface disposal facilities, the capability to intrude into the facility does not require sophisticated technology. However, intrusion into a geological disposal facility requires more sophisticated technology (i.e., the capacity for deep drilling or deep mining). With the availability of sophisticated technology, there would also be an increased likelihood of recognising the hazardous waste and in turn this decreases the potential for IHI, a fact that is valid for both near-surface and geological disposal facilities. It is of course true in general, for both near-surface and geological disposal facilities, that the more technologically advanced a society, the greater the chance that the nature of the hazard would be detected following any intrusion event.

Over the long time spans of a disposal facility, the technological status of society is likely to change. Technological status has grown at a rapidly increasing rate in the recent centuries and it is likely to increase further in the future with new techniques becoming available to society. However, although an increase in
technological development is expected, there are large uncertainties associated with the development of technology and society. Thus, to avoid speculation, several sources (NEA 1995a, Wilmot et al 1999, SSI 2005, IAEA 2014) recommend that IHI scenarios be developed based on present-day social structures and technological capabilities consistent with protecting future generations at a level consistent with current generations (see also Section ‘Assumptions regarding the development of the society’ in 7.2.2). Access to technology is not the same worldwide. However, information exchange and collaboration worldwide are increasing and thus also developing countries are often using advanced technology.

The general knowledge level of the society is important since it will determine whether future generations will be able to interpret available information on the radioactive waste disposal facility. If the detailed information on the radioactive waste characterisation and/or the function of the radioactive waste disposal facility has been partially lost and the disposal facility is rediscovered, the general knowledge level determines whether people will recognise what they have found. In addition, it will affect whether they will be able to restore those functions of the disposal facility that may have been impaired. The knowledge level of the society is linked to technical development and for scenario development (see Chapter 8) it is recommended to assume that an intruder would have the same ability to recognise the hazard of the radioactive waste as present day people.

7.3.2 Human diets, habits and settlement pattern, and political and economical changes influencing scenario selection

Human diets and physiological needs

When quantitative approaches are used to address the potential consequences of IHI, the choice of diets and other exposure model assumptions for IHI scenarios should generally be consistent with assumptions for the rest of the safety assessment, as applicable, given the nature of the IHI scenarios relative to the normal evolution scenarios. It is recognized that habits will change for future generations, but there is no basis for speculating about what changes will occur in the context of a safety case. Thus, it is generally accepted to calculate doses to future generations using assumptions based on habits of the current generations, implying maintaining the same level of protectiveness. Physiological needs are assumed to remain constant and as today (e.g., Information on metabolic data and models consistent with the most recent recommendations of ICRP and other international and national organisations).

Human habits and settlement pattern, environmental change

Human habits and settlement patterns could affect the potential for IHI. Facilities are often located in less populated areas to reduce the potential for IHI. Although measures can be taken to prevent human migration into the area, depending on the suitability for human development, with time these areas may become more densely populated which, depending on the depth of the facility, may increase the potential for IHI to occur. Although likelihood for IHI in disposal facilities at or near
the surface may increase if local population increases, the likelihood for IHI into geological disposal facilities may decrease since deep drilling usually does not take place in densely populated areas. However, this may not be true for drilling involving geothermal energy, as the boreholes aiming at hot water aquifers need to be located as close as possible to the populated areas and perhaps directly under them. Remote areas (e.g. desert settings away from populated areas), where there are limited resources, are not likely locations for current settlement and would pose the same challenges for future settlement (e.g., availability of sufficient drinking water).

However, it is not possible to ensure that such areas will not be populated in the future. Therefore, although it can be credited as a safety advantage to situate disposal facilities in remote areas, this consideration cannot solely be used to justify that IHI will not occur in the future and the potential for and/or consequences of IHI are still considered.

In general, environmental change may make an area more or less attractive for living. For example, no humans are assumed to inhabit glaciated/submerged areas during glaciations and ice retrieval phases. Likewise, areas that today are not suitable for living due to overly dry or cold conditions may become wetter and/or warmer due to climate change and thereby more suitable for living. Climate change is generally considered in other areas of the safety case and does not specifically have to be treated in the IHI scenarios. However, change in the climate may be taken into account in IHI scenarios as a factor that could influence the potential for intrusion to occur in the area.

Disposal facility sites may be modified due to a variety of processes such as climate change and landscape evolution that may change the nature of the biosphere and its habitability (as will have been discussed in the wider safety case). Erosion of coastal sites or land-rise in areas subjected to de-glaciation is also possible. This may have an effect on the type and potential for IHI to occur.

**Political, economic and other changes**

A potential concern for maintaining records is political and economic disturbances that may occur over time frames associated with a disposal facility. These factors could be taken into account in consideration of the length of the effective control period, i.e. the time frame for which memory of the disposal facility is kept (see Section 7.4.3). However, there are good examples of records that have survived for many hundreds of years in spite of dramatic political and economic changes. For example, there have been many societal changes in Europe over the past hundreds of years and many records have survived (e.g., the Doomsday Book in the UK). Keeping records in more than one central archive, i.e. at regional, national and international levels, may lead to more chances of memory of the disposal facility being retained.
7.3.3 Deliberate vs inadvertent intrusion - what distinguishes inadvertent from deliberate intrusion?

IHI is considered for the safety case (i.e. it can only occur because of loss of knowledge of the disposal facility, the location of the disposal facility is unknown, its purpose is forgotten, or the possible consequences of the intrusion are unknown). This implies that an individual or group of individuals are exposed to the radioactive waste whilst being, at least initially, unaware of the associated potential hazard. Such inadvertent intrusion could occur for a number of reasons, but it is only possible after a loss of knowledge and land-use control.

Although the definitions of deliberate and inadvertent intrusion are reasonably clear, it is possible to imagine a situation when inadvertent intrusion becomes deliberate intrusion (e.g., when the intruder realises that there is hazardous waste but does not stop the action). An inadvertent intrusion might become deliberate very soon (e.g. as soon as one recognises something is not correct). However, even if future humans realise something is unusual about the site, they might not immediately recognise the degree of hazard related to the materials they have encountered.

Even though there might be abnormalities or markers warning the future humans, it is not certain that they will understand the warning signs. The problems of effectively communicating over thousands of years have to be acknowledged and have been discussed in Mann (1986) and in Appendix B of Jensen (1993). Thus, even if there are measures taken to make the intruder aware of the hazards, IHI scenarios may be identified as inadvertent at the beginning of an intrusion, and are analysed up to the point when the intruder is assumed to recognise the hazard. The potential for an early recognition of the hazard leading to the intruder to stop their actions can be used in communications to illustrate low potential for a fully inadvertent exposure and thereby help to further support the robustness of the waste disposal facility (see Section 8.2.3).

7.4 PRESERVATION OF KNOWLEDGE

Given the dependence of IHI on an assumed loss of knowledge of the disposal facility, it becomes clear that the most reliable measures against IHI are those directed at preserving knowledge of the disposal facility. The longer the knowledge of a disposal facility system is maintained, the longer IHI into the disposal facility may be avoided. In order to build the necessary framework for long-term preservation of knowledge of the facility, it is recommended to start building memory of the disposal facility during the early phases, design and planning stages, and to continue during the construction, operational, closure and active post-closure control phases of the disposal facility.

After closure, a period of active control may contribute to the safety of certain disposal facilities, but due to uncertainties regarding the future, the active control period is limited for a certain period of time (IAEA 2012 section 6.62, 6.73).
Examples of active measures are a presence at the site, physical protection of the site, and surveillance (see Section 7.4.1 and Chapter 9).

There exist opposing views on whether active controls are preferable or not. In one view, the statement of “not imposing undue burdens on future generations” implies that the long-term safety of such a facility shall not rely on human actions, such as an extended active control period. For geological facilities, such an approach may be considered as achieved due to of the inherent isolation of the facilities from the surface environment. Another view is that active institutional control is a fundamental element of the lifecycle of a disposal facility to allow for maintenance and confirmation of performance beyond closure and to provide for extended protection from inadvertent intrusion – this is especially important, for near-surface facilities.

Regardless of the period of active control, it is suggested to build long-term relationships with different interested parties including, operators, regulators, local communities, national and international societies and experts (e.g. resource-geologists). It is noted that knowledge of the facility will be best preserved if the local public is involved and understands that it is in their interest to help to preserve knowledge and to start preserving knowledge early. Passive or indirect controls can contribute to the preservation of knowledge well beyond the end of active controls. These could include, for example, ensuring that public records on the disposal facility are kept and restrictions on land use and permitting requirements for mining or drilling are in place (see section 7.4.2 and Chapter 9).

In recognition of the importance of knowledge preservation, there is an ongoing NEA project entitled, “Preservation of Records, Knowledge and Memory (RK&M) across Generations”, that includes discussions of effectiveness of different measures aimed at knowledge preservation (OECD/NEA 2015). This project plans to create maps of potential components of a systemic approach to RK&M preservation that considers the different timescales and that relies upon a number of inter-related communication mechanisms. Examples of communication mechanisms include national archives, markers and time capsules, international frameworks and the "Key Information File" (KIF). The KIF work will provide an international, standardised structure for synthesising key information about each national repository. In addition, the RK&M project will co-operate with the NEA Radioactive Waste Management Committee’s Regulators' Forum on the issue of transfer of responsibilities from today's oversight bodies to future bodies at some point in time.

This section includes a discussion on how measures can be taken to help reduce the potential for IHI by building knowledge during the active control period and preserving that knowledge beyond the active control period. In addition, time frames of knowledge preservation in IHI scenarios are discussed.
7.4.1 Knowledge preservation during the active control period

In the safety case, it must be demonstrated that a variety of appropriate controls and measures are maintained during an active control period to ensure that human actions do not adversely impact the safety functions of the disposal facility. This means that there must be an organisation and resources available to maintain active controls as required during the specified time period. In addition to funding, it is necessary to maintain specialised technical competence and staff able to implement controls for long periods of time. In addition to maintaining controls, the active control period should also be used to continue to enhance the approaches to preserve knowledge of the disposal facility with a large number of people.

Effective ways to build, maintain and promote knowledge during the active control period can include:

- Layering and redundancy of control measures to carry out roughly the same function. For example, several entities could be responsible for keeping knowledge of the disposal facility (e.g. ministries responsible for planning, national geological societies, public school systems).
- Monitoring of the disposal facility and its environment and routine reporting to confirm the assumptions used in the safety case.
- Implementing a reliable financing and administrative management system.
- Updating the safety case periodically throughout the life-cycle of the disposal facility. It is a good practice to make the safety case a ‘living document,’ to keep memory, and to maintain expertise for both operators and regulators.
- Promoting the presence of the facility (e.g., community and public school tours, inclusion of information about the facility in public school studies, regular events recognising the facility).

7.4.2 Knowledge preservation beyond the active control period

The potential for IHI increases when active controls are no longer in place. Passive controls (e.g. archives and restriction of land-use) may also prevent or delay the potential for IHI but have weaknesses in terms of long-term reliability (U.S. National Research Council 2000). Nevertheless, passive controls are expected to prolong the knowledge of the disposal facility significantly and decrease the potential for IHI well beyond the active control period.

Passive control systems ought to be developed early in the life-cycle of a disposal facility. To maintain the necessary knowledge, a suitable mechanism may need to be developed for the transfer of responsibility from one generation to the next, using organised systems of information conservation. The benefits of encouraging passive control early and maintaining the controls are the increased longevity of the passive measures in combination with the experience gained through development and
implementation of the controls. Considerations for passive control measures that can be used to help preserve knowledge of the disposal site are briefly discussed below.

**Land use restrictions**

A system of passive control measures, expected to restrict activity in and around a disposal site would be expected to be effective for some time after the end of the active control period (NEA 1995a). As such, restrictions of land-use (both on the surface and underground) or designating areas as prohibited zones can be implemented in planning laws with the aim to not allow land use development at or near the disposal facility site. Administrating such restrictions on land-use will act to prevent IHI and also aid in preserving memory of the disposal facility. Such restrictions can be expected to be especially effective against major public works involving excavation or mining exploration activities because of requirements to gain the necessary approvals before proceeding with such work. Thus, land use restrictions can be a justification for further delaying the time frame for scenarios where such permitting would be a general expectation prior to major activities that could result in IHI.

**Archives and documentation (Item C3 in measure database, see Chapter 9)**

The preservation of archived records aims at providing information about the location, contents and hazards of the repository to future generations (Jensen 1993). There are several examples of archives that have survived for centuries, e.g. archive of the Roman Church and archives about mining activities, the UK Doomsday Book). However, there is a limit for how long archives can be relied upon. Nevertheless, it is a good practice to keep local, regional, national and international archives about the radioactive disposal facilities. The use of archived information may be improved by introducing some types of key words (like disposal facility, radioactive waste) at prominent locations in the archives.

In addition to setting up archives, it is also necessary to ensure that they will be accessible and usable in a distant future society. As such, it should be verified that the relevant information is properly selected, understandable and easily accessible. To do so, a good practice is to let people without knowledge of the disposal facility regularly test and make use of these archives as soon as this information starts to be gathered. This kind of archive testing has been carried out at the Centre de la Manche in France where a group people unfamiliar with the disposal facility were asked to find information necessary to treat fictitious events that were assumed to have occurred at the disposal facility site. Results from such tests are very useful to improve the quality of archives. However, since languages and institutions change with time, archives are likely to be limited in terms of the time-span over which they can help reduce the likelihood of IHI.
Markers and monuments

A system of durable, physical, surface and subsurface warning markers could be used to warn of the presence of, and potential hazard associated with, the repository. Markers may be left on site to warn a future society of the potential danger of intruding. Markers should be understandable to most people no matter how the society develops. As such, they may include a variety of languages. A symbol could also be used to avoid specific languages issues. IAEA has developed the a ‘universal symbol’ intending to indicate possible dangers from radiation (see Figure 7.1)

Figure 7.1. Example warning sign.

Monuments could also be considered as markers. They could be internationally developed and the same monument could be used at each site around the world so that, in case of memory loss in one country, the monument might still be recognised internationally and the memory could be restored. On the other hand, there are examples from history in the form of symbols, inscriptions and ancient writings which can no longer be interpreted with any certainty. The Nazca Lines in Peru are one of those unresolved mysteries. In fact, it is unknown what these geoglyphs mean and who created them. It is believed that the Nazca Lines were created by the Nazca culture between 800 BC and 200 BC [Beuth and Navarro 2010], but that is by no means certain, and their intended message is a complete mystery.

The pros and cons of the usefulness of markers and monuments to prevent IHI are still under discussion. Some people argue that markers and monuments are good for keeping memory and by using widely known markers or monuments knowledge of the disposal facility could be kept for a long time. Durable markers could be retained even if local knowledge were lost for some reason. However, an alternative view is that it might be wiser not to leave any markers to prevent intrusion into the disposal facility out of sheer curiosity, should the warning not be understood. This alternative view is not gaining much traction, however, and the IAEA (2011b) SSG-14 Specific Safety Guide states: “It is likely that passive institutional controls, such as the use of markers and control on land use, will be implemented and maintained, at least for a certain period immediately after closure.”
Additional measures to preserve knowledge

Other ways to preserve the memory of a disposal facility could be to use education, to build a durable visitor center or even to set up a commemorative day to mark anniversaries of the closure of the facility.

Continuous sharing of knowledge with of current and future generations of the local people would help preserve the knowledge about the location of the repository and its hazard potential. This kind of information sharing could start early in the lifecycle of the facility and continue for as long as the community exists (e.g., at site selection and could be routinely passed on and acquired via tours for local schools reaching the younger members of the site’s community).

A visitors centre could also be built to contribute to maintaining knowledge nationally and internationally. A visitor’s centre may include mock-ups of the disposal facility and reinforce measures taken to establish high levels safety for the facility. Organising routine tours of the visitor centre for selected ages of children at local schools and also for members of the community and national and even international visitors could enhance knowledge preservation of the site.

E-learning tools and internet can also be used to share information and knowledge about the disposal facility.

The establishment of a day commemorating the ‘site’ could be used to help preserve knowledge of the site. This should be inaugurated early in the process in order that the community becomes familiar with it and a tradition established to continue passing the information from one generation to the next. This concept could be established when thinking about closure of the radioactive waste disposal facility. Therefore, when the facility is closed, there could be a ceremony to commemorate the day and to remember its existence on an annual or other routine basis.

7.4.3 Timeframe of the preservation of knowledge

The timeframe over which knowledge can be assumed to be maintained as a deterrent to IHI is site specific and will depend upon factors such as the nature of the disposal concept (e.g., deep, near surface), the features of the disposal site, the relevant regulatory criteria, nature of the waste, timeframe of active institutional control, passive measures against intrusion and societal factors. An important function of the safety assessment will be to discuss the earliest time at which IHI could occur, using this information to judge, for instance, the adequacy of the duration of the period where knowledge can be assumed to be preserved.

When considering IHI scenarios, one consideration is how widely known the facility has to be in order to avoid intrusion. Different situations regarding knowledge of the disposal facility are imaginable, that is: the disposal facility might be widely known or known to a small number of people. The disposal facility could be known only locally (i.e., the local population retains knowledge (even ‘rumour’ or ‘myth’ of
the disposal facility as a part of its local culture) or the knowledge might be totally lost. For the purpose of scenario development (Chapter 8), in some cases it is cautiously assumed for near surface disposal facilities that intrusion may occur once the active control period is terminated. This approach completely ignores the effectiveness of preservation of knowledge. Time frames of a few hundreds of years following active controls can be justified for the effectiveness of passive controls and preservation of knowledge as a deterrent to IHI (IAEA 2012 para 6.62).

Geological disposal facilities should be designed to be passively safe following closure, therefore active control is not considered a requirement for all deep geological disposal facilities. Nevertheless, knowledge may still be assumed to remain for some time after closure and measures to promote preservation of knowledge should be considered. Some countries assume that knowledge remains for some hundreds of years after closure of a geological disposal facility (e.g. Canada - Quintessa and SENES 2011, Finland - Smith et al. 2013, Sweden - SKB 2010). However, these assumptions may not account for the fact that local less formal rumours or myths may nonetheless prolong that knowledge for even longer time spans.

In IHI scenario development, the timeframe for preservation of knowledge should be justified. This justification can be based on known past experience (e.g., use of archives and land use control like such as the German drilling permit system), measures taken to preserve knowledge, and available provisions for funding for knowledge preservation.
8. STYLISED SCENARIOS

8.1 INTRODUCTION

It is not possible to predict specific future human actions, especially far in the future (on timescales of hundreds or thousands of years). The possibility that future human actions, and specifically IHI, might interfere with the performance of disposal facilities can never be ruled out entirely. When considering IHI, it is necessary to consider potential ‘scenarios’ that could result in disturbance of the facility. As defined in IAEA SSR-5:

“'Human intrusion’ refers to human actions that affect the integrity of a disposal facility and which could potentially give rise to radiological consequences. Only those human intrusions that result in direct disturbance of the disposal facility (i.e., the waste, the contaminated near field or the engineered barriers) are considered.”

Due to the unavoidable uncertainty associated with human intrusion, it may be unjustified to develop very detailed human intrusion scenarios. IAEA SSG-23, 6.61 states

“Human intrusion scenarios should be developed on the basis of stylised representations of the nature of the intrusion and the actions of the intruder, and it should be recognised that there is an unavoidable uncertainty associated with human intrusion. Human intrusion scenarios are not meant to convey any authoritative statement about the evolution of the site and future societal activities, but are designed to provide illustrations of potential impacts of human intrusion. If stylised scenarios are being used, they should be based on the assumption of present day technologies and procedures.”

ICRP Publication 81 (ICRP 2000) notes the difficulties of estimating probabilities of IHI, and that its occurrence cannot be entirely ruled out. ICRP therefore recommends (§ 62) that “one or more typical plausible stylised scenarios” should be considered by the decision-maker to evaluate the resilience of a repository to postulated events or scenarios.

This section provides a general method for identifying, developing, and customising site- and facility-specific IHI scenarios. These scenarios may be used in a quantitative framework or can be used in a more qualitative manner to illustrate the measures that have been included in the disposal facility to address potential intrusion. Figure 8.1 provides a high-level overview of the method. Consistent with the approach described in Chapter 5, the first step is to consider the safety context, safety strategy, and disposal system description. The safety context will include regulatory requirements that address IHI. Depending on the national regulatory approach, the safety context may identify requirements to address with IHI scenarios or may go as far as specifying the representative scenarios that must be considered to address IHI.
The safety strategy and disposal system description include identification of the type of disposal system (e.g., near surface disposal, geological disposal) and attributes of the system description including characteristics of the radioactive waste disposal system (e.g., facility design, waste forms, canister materials) and the natural environment (e.g., geology, hydrology, biosphere). Often for disposal facilities, these attributes are consistent with features, events, and processes in the normal evolution scenario (e.g., if there is a long time before intrusion occurs, the canister materials may corrode, as they would in the normal evolution scenario). It is valuable to identify any specific safety functions associated with the system that may be challenged by considerations related to IHI. This information can help to reinforce the measures that are considered to improve the robustness of the facility against intrusion.

The third phase involves identifying and screening the representative human intrusion events and resultant stylised IHI scenarios. Examples of stylised IHI scenarios are provided that are representative of human intrusion scenarios most commonly used by Member States, for applicability to the specific circumstances described above.

The fourth phase customises the stylised IHI scenario (e.g., drilling methods, equipment) and for quantitative approaches identifies the impacts of the representative human intrusion event (e.g., transport pathways, exposure, indicator performance). The final phase reviews the outputs and identifies whether additional iterations of this process are warranted. These additional iterations may result in the incorporation of protective measures. The figure also highlights the importance of communication and documentation through the entire process of considering human intrusion.
The objective of this section is to provide information to assist in developing human intrusion scenarios at the level of detail appropriate for the purpose of the analyses (e.g., less detail may be needed for the siting phase compared to the licensing phase). The specific scope includes:

- Provide a set of stylised human intrusion scenarios, including both near-surface and geological disposal, based on representative human intrusion events

- Provide a method to be used to assist in modifying the stylised human intrusion scenario to capture site-specific details

FIG. 8.1. Methodology for developing site-specific stylized scenarios. For each step, the number in parentheses identifies the section where the step is described in further detail.
The scope of this section is to provide representative human intrusion scenarios. The considerations provide an overview of topics that may need to be addressed to develop a site-specific human intrusion scenario. Note that the intent is not to provide a comprehensive list.

8.2 RADIOACTIVE WASTE DISPOSAL SYSTEMS

As defined in the IAEA RWM glossary (IAEA 2003a), a waste disposal system “refers to the disposal environment as a whole, including the geological surroundings, the engineering system of a repository (e.g. barriers) and the waste packages.” SSR-5 notes “within any State or region, a number of disposal facilities of different designs may be required in order to accommodate radioactive waste of various types.” The typical components of a disposal system are described in section 5.2.3.

Given that long term safety of a disposal facility essentially relies on the features of the multiple barrier system proposed (such as the choice of: a specific disposal site, a given host geology at a certain depth, specific features of the engineered and natural barriers and the absence of known mineral resources near the disposal facility location), it is important to ensure that the relevant characteristics are documented.

SSR-5, 1.14d characterises low level radioactive waste disposal facilities in the following way:

“Disposal in a facility consisting of engineered trenches or vaults constructed on the ground surface or up to a few tens of metres below ground level is considered near surface disposal. Such a facility may be designated as a disposal facility for low level radioactive waste.”

Near surface disposal has been practised in a number of countries, covering a wide variation in site features, types and amounts of waste inventory and facility designs. A hypothetical near surface disposal facility is shown in Figure 8.2, although it should be noted that specific near surface disposal facilities could vary significantly in waste content, natural, and engineered features.
FIG. 8.2. Hypothetical Near Surface Radioactive Waste Disposal Facility. The scale bar is of the order of tens of metres. Note that near surface disposal facilities may be located on the ground surface.

SSR-5, 1.14d characterises high level radioactive waste disposal facilities in the following way:

“Disposal in a facility constructed in tunnels, vaults or silos in a particular geological formation (e.g., in terms of its long term stability and its hydrogeological properties) at least a few hundred metres below ground level is considered geological disposal. Such a facility could be designed to receive high level radioactive waste, including spent fuel if it is to be considered waste. However, with appropriate design, a geological disposal facility could receive all types of radioactive waste.”

A hypothetical geological disposal facility is shown in Figure 8.3, though it should be noted that there could be a wide variation in site features, types, and amounts of waste and facility designs. The greater depth of geological disposal facilities is required to provide the long term containment and isolation needed by long-lived waste, and that depth is a significant protective measure against human intrusion.
FIG. 8.3. Hypothetical Geological Radioactive Waste Disposal Facility. The scale bar is of the order of hundreds of metres.

Near surface and geological disposal generally capture the range of depths commonly considered for disposal of radioactive waste. SSR-5 (paragraph 1.14) provides a brief description of additional disposal options such as specific landfill disposal for very low level waste, options for disposal of radioactive waste at depths from tens to hundreds of metres, borehole disposal at a range of depths, and disposal of mining or mineral waste near or on the surface. IHI considerations for disposal at intermediate depths would be more similar to geological disposal than to near-surface disposal. The human intrusion scenarios presented in the next section can be used to identify and develop specific human intrusion scenarios. A wide range of radioactive waste disposal facilities can be imagined, though the depth, content, and configuration are all important factors.

8.3 STYLISED SCENARIOS BASED ON REPRESENTATIVE HUMAN INTRUSION EVENTS

Various approaches can be used to develop human intrusion scenarios. For the purposes of this report, three representative human intrusion events have been identified (Table 8.1):

- Drilling
- Excavation
• Mining

Consideration of these three representative human intrusion events results in six stylised human intrusion scenarios (Table 8.1). These representative human intrusion scenarios are described with potential transport pathways and receptors in Sections 8.3.1 – 8.3.6. They can be adapted to alternative disposal systems (see section 8.6).

The intent is not to provide a comprehensive list of scenarios, but to highlight how the illustrative scenarios discussed in this document can be used to inform the development of site-specific IHI scenarios for presentation in a safety case. The scenarios do not include every potential consideration. One can envision an almost unlimited number of deviations from these scenarios, but the intent is not to comprehensively describe all possible situations that could be imagined. The intent is to provide a reasonable suite of scenarios that are sufficient to provide an indication of the robustness of the disposal facility against IHI and to identify and test measures to improve the robustness of a disposal facility.

Section 8.4 provides considerations to assist in customising the human intrusion scenarios and some ideas for consideration of the potential impacts identified. Also note that for a site-specific system, there may be aspects of one or more of the scenarios listed below that could be considered in the IHI analysis (e.g., there may be a drinking water receptor from a plume that is contaminated by road excavation into a near surface disposal system). Note that exploratory drilling is often the first step in each of the six representative scenarios (e.g., exploratory drilling prior to construction, excavation, or mining).

Near Surface Disposal Facility:

Human intrusion scenarios for near surface disposal can have a greater relevance to and impact on the safety case relative to the lower likelihood of human intrusion into properly sited geological disposal facilities (primarily due to the depth of the repository). The scenarios for near- surface disposal will generally have to be sufficient to support a quantitative analysis of potential exposures, which is not essential for geological disposal. In near- surface disposal facilities, particularly in the more shallow options, the waste is relatively close to the ground and thus is more susceptible to being breached via IHI. Unlike geological disposal, IHI for near-surface disposal generally considers the possibility of waste being brought to the surface because of the nature of the disposal system.

The actual likelihood of intrusion is dependent on a number of factors, such as the intensity of human activity in the area where the repository is located, the design features of the repository (e.g., depth of disposal units, presence of protective measures) and the length of time covered by the assessment. Since human intrusion cannot be excluded for near- surface disposal, most safety assessments assume that at some time following the end of institutional controls human intrusion occurs. Commonly considered generic intrusion events include drilling and some form of excavation.
Geological Disposal Facility:

The most commonly considered generic intrusion event for geological disposal facilities located in insoluble host rocks is exploratory drilling. It is assumed that waste isolation and containment could be disturbed by drilling through the footprint of the facility and creating a direct pathway to the waste or by a borehole intersecting a contamination plume in the near-field. The plume could have been formed due to the interaction between the waste and groundwater after breaching of the engineered barriers by natural processes and/or human intrusion. In both cases, the borehole may present a pathway to the biosphere resulting in exposure of humans.

Given the nature of geological disposal, especially for disposal facilities where there is significant spacing between containers, less emphasis is placed on quantitative assessment of very low probability scenarios involving waste being brought to the surface.

Another generic intrusion event considered in some assessments is inadvertent mining through the geological disposal facilities. For geological disposal facilities in soluble rock formations, events that include access of water to the disposal zone and dissolution mining of the host rock may be part of the assessment.

### TABLE 8.1. GENERIC HUMAN INTRUSION EVENTS AS A FUNCTION OF THE TYPE OF DISPOSAL FACILITY

<table>
<thead>
<tr>
<th>Disposal facility type</th>
<th>Human Intrusion Event</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Near surface disposal facility | • Drilling  
• Residential excavation  
• Roadway excavation | There are many variations of near surface disposal facilities, which may be either above or below the surface. Roadway is used to represent a larger scale surface excavation. |
| Geological disposal facility | • Drilling  
• Conventional mining  
• Unconventional mining | Unconventional mining includes techniques such as solution mining and hydraulic fracturing. |

### 8.3.1 Near Surface Disposal – Drilling

**Scenario Description:**

This scenario involves human intrusion into a near-surface disposal facility (Figure 8.4). The intrusion event involves drilling a borehole through the near surface disposal facility into an underlying aquifer (darker line). Radioactive cuttings and/or drill core are brought to the surface. The primary worker receptor is likely to be a borehole driller. Other exposed workers could be the drill crew, consisting of workers and field scientists, as well as laboratory staff investigating the cuttings and/or drill core. The primary public receptor is likely to be a nearby resident farmer. Other exposed public receptors could be resident farmers living further down gradient of the aquifer. Although this description focuses on water, such a scenario is also intended to
be representative of drilling that could be for any number of other purposes (i.e., it is
assumed that someone could inadvertently drill and bring waste to the surface).

FIG. 8.4. Hypothetical Near Surface Disposal Drilling Scenario.

Potential Transport and Exposure Pathways:

The primary transport pathways for the worker are likely to be direct
exposure to the cuttings or drill core and inhalation of the dust. Other transport
pathways could include ingestion of contaminated particles. The exposures for the
worker are expected to be relatively short-term. The resident receptor could ingest
contaminated food due to waste being mixed with surface soil (vegetables, milk or
meat from cattle eating contaminated grain or grass) and may also ingest or inhale soil
with radionuclide contamination and receive external exposures. There can also be
exposures from drinking groundwater obtained from the aquifer that has been
contaminated by previous releases from the disposal facility. Contaminated water may
also be used for agriculture or livestock (ingestion). The exposure to the resident
farmer is expected to be relatively long-term.

8.3.2 Near Surface Disposal – Excavation (Residence)

Scenario Description:

This scenario involves human intrusion into a near surface disposal facility.
The intrusion event involves excavation into a near surface disposal facility to
construct a residence (Figure 8.5). Radioactive materials are exposed at the surface
during excavation and radioactive materials surround the basement foundation of the
residential building. The primary worker receptor is likely to be an excavation worker. Other exposed workers could be the surveyors, field scientists, constructions workers building the residential building. The primary public receptor is likely to be the occupant of the residential building.

**FIG. 8.5. Hypothetical Near Surface Disposal Excavation (Residential) Scenario.**

**Potential Transport and Exposure Pathways:**

The primary exposure pathways for the workers are likely to be direct exposure to the radioactive material and inhalation of the dust, when actually working in the waste. Other transport pathways could include ingestion of contaminated particles. The exposures for the primary worker are expected to be relatively short-term. The primary exposure pathways for the resident receptor would be similar to the drilling scenario, but may also include exposures associated with the basement floor proximity to the waste and a mixture of excavated waste and soil that would be used as backfill around the basement walls (e.g., external exposure). Note that this scenario is often mitigated by including sufficient clean cover over the waste material to preclude a basement reaching the depth of the buried waste.

**8.3.3 Near Surface Disposal – Excavation (Road)**

**Scenario Description:**

This scenario involves human intrusion into a near surface disposal facility. The intrusion event involves excavation into a near surface disposal facility to build a
road (Figure 8.6) and could also include other larger scale public works. Radioactive materials are exposed at the surface during excavation and materials on the roadside remain exposed after the road is constructed. The primary worker receptor is likely to be an excavation worker. Other exposed workers could be the surveyors, field scientists, constructions workers building the residential building or any laboratory staff investigating the excavated material. The primary public receptor is likely to be the occupant of a nearby residential building. Note that scenarios like this involving major public works projects could potentially be considered less likely during the time frame that public records and permitting requirements are assumed to remain.

FIG. 8.6. Hypothetical Near Surface Disposal Excavation (Road) Scenario

Potential Transport and Exposure Pathways:

The primary transport pathways for the primary worker are likely to be direct exposure to the radioactive materials and inhalation of the dust. Other transport pathways could include ingestion of contaminated particles. The exposures for the workers are expected to be relatively short-term. The potential exposure pathways for the resident receptor would be similar to those considered for the drilling scenario. The exposure to the public receptor is expected to be relatively long-term.

8.3.4 Geological Disposal – Deep Drilling

Scenario Description:
This scenario involves human intrusion into a geological disposal facility. The intrusion event involves drilling a borehole near or through the footprint of a geological disposal facility (darker line in Figure 8.7). Directly contacting a container is considered highly unlikely for high-level waste disposal involving dispersed containers. Cuttings that have been contaminated by radionuclides released from the facility may be brought to the surface and radionuclides may also contaminate an aquifer. The primary worker receptor is likely to be the borehole driller. Other exposed workers could be the drill crew, consisting of workers and field scientists, as well as laboratory staff investigating the cuttings or cores. The primary public receptor is likely to be a nearby resident farmer. Other exposed public receptors could be resident farmers living further down gradient of the aquifer. Note that drilling to such depths generally suggests a relatively major programme (e.g., mine or other resource exploration) that would be likely to require permitting and approvals from the authorities. Thus, such activities could potentially be considered unlikely during the time frame when public records are assumed to exist.

**FIG. 8.7. Hypothetical Geological Disposal Drilling Scenario.**

Potential Transport and Exposure Pathways:

The primary exposure pathways for the workers are potential direct exposure to contaminated soil brought up during drilling and inhalation of the dust during drilling. Other transport pathways could include ingestion of contaminated particles. The exposures for the worker are expected to be short-term. The primary transport pathway for the public receptor is likely to be ingestion from drinking water from a contaminated well. Other transport pathways could include ingestion if the water is used for crops or livestock. Radionuclides may be transported down gradient in the...
aquifer to impact other wells, but the impacts would be likely to be lower. The exposure to the primary public receptor is expected to be relatively long-term.

8.3.5 Geological Disposal – Subsurface Mining

Scenario Description:

This scenario involves human intrusion into a geological disposal facility. The intrusion event involves underground excavation into a geological disposal facility (Figure 8.8). The intrusion continues until a waste canister is uncovered. The primary worker receptor is likely to be the underground excavator. Some programmes assume that the workers will reseal the mine shaft. The primary public receptor is assumed to be a nearby resident farmer. Other exposed public receptors could be resident farmers living further down gradient of the aquifer. Note that excavations to such depths generally suggests a relatively major programme that would be likely to involve permitting and approvals from the authorities. Thus, such activities could potentially be considered unlikely during the time frame when public records are assumed to exist.

Potential Transport and Exposure Pathways:

The primary exposure pathway for the primary worker is likely to be direct exposure to the sealed waste canister before it is recognised. The exposures for the underground excavator are expected to be short-term. The primary exposure pathway...
for the public receptor is likely to be ingestion from drinking water from a
contaminated well. Other exposure pathways could include ingestion if the water is
used for crops or livestock. Radionuclides may be transported down gradient in the
aquifer to impact other wells, but the impacts would be likely to be lower. The
exposure to the primary public receptor is expected to be relatively long-term.

8.3.6 Geological Disposal – Unconventional Mining (Soluble Rock)

Scenario Description:

This scenario involves human intrusion into a geological disposal facility. The
intrusion event involves solution mining a soluble rock, disrupting the geological
disposal facility (Figure 8.9). Radioactive solution may be brought to the surface. The
primary worker receptor is likely to be the borehole driller. Other exposed workers
could be the drill crew, consisting of workers and field scientists. The primary public
receptor is assumed to be a nearby resident farmer. Other exposed public receptors
could be resident farmers living further down gradient of the aquifer or consumers of
salt. Note that drilling to such depths generally suggests a relatively major programme
(e.g., mine or other resource exploration) that would be likely to involve permitting
and approvals from the authorities. Thus, such activities could potentially be
considered less likely during the time frame when public records are assumed to exist.

FIG. 8.9. Hypothetical Geological Disposal Solution Mining Scenario.
Potential Transport and Exposure Pathways:

The primary exposure pathway for the primary worker is likely to be direct exposure to the radioactive solution. Other exposure pathways could include ingestion or inhalation of contaminated particles from the evaporation process. The exposures for the driller are expected to be relatively short-term. The primary exposure pathway for the public receptor could include ingestion or inhalation of contaminated particles from the evaporation process. Other exposure pathways for the public receptor could include ingestion from drinking water from a contaminated well, ingestion if the water is used for agriculture or livestock, or ingestion of the salt.

8.4 CUSTOMISATION OF A REPRESENTATIVE HUMAN INTRUSION SCENARIO

Described below are some potential considerations related to the impacts from a generic human intrusion event. The considerations are followed by a few examples. These examples are not intended to be a comprehensive list, rather, they are intended to provide additional context to the specific considerations for developing IHI scenarios. These considerations provide aspects that may be considered when developing a human intrusion scenario and they allow the flexibility for organisations to determine how to consider them (e.g., some organisations may seek feedback from interested parties). Note that these considerations are not intended to be comprehensive.

8.4.1 Identify the Disposal System

The first subtask is to identify the type of disposal facility. This is a high-level concept of the facility. Concepts are discussed in more detail in section 8.2.

Considerations:

- Is it a near surface disposal system?
- Is it a geological disposal system?
- Is it some other disposal system configuration (e.g., borehole, intermediate-depth disposal system)?

The second subtask is to identify attributes of the system description. The level of detail used to describe the system depends on the safety considerations and assessment context (e.g., siting phase, licensing phase, regulations). Components of the disposal system include:

- The near field, including: (i) the types of waste (e.g. the origin, nature, quantities and properties of the waste and the radionuclide inventory); (ii) system engineering (e.g. waste conditioning and packaging, backfill/buffer materials, layout of disposal units and spacing of the waste containers,
engineered barriers, cap or cover of the disposal facility); and (iii) the extent and properties of the zone disturbed by any excavation or construction work;

- The far field, e.g. geology (properties of host rock), hydrogeology, hydrology, geochemistry, tectonic and seismic conditions, erosion rates, natural resources;

- The biosphere, e.g. climate and atmosphere, water bodies, the local population, human activities, biota, soils, topography and the geographical extent and location of the disposal facility (also consider how this could change in climate change scenarios for geological disposal).

Some additional considerations include:

- What are the safety functions of the different components of the disposal system (e.g., waste container may delay release or serve as a deterrent to IHI)?

- What is the expected state of the disposal system and how does it change (including uncertainties associated with the different components of the disposal system at the time of human intrusion (e.g., degradation of the cap, degradation of the waste container, stability of natural environment))?

### 8.4.2 Screen the Representative Human Intrusion Scenarios

The third subtask is to identify the applicability of the representative future human intrusion scenarios. For example, representative human intrusion scenarios for excavation into a near surface disposal system would likely not be applicable for geological disposal systems and could therefore be screened out from more comprehensive analysis. Considerations include:

- What is the purpose and/or scale of the human intrusion scenario (e.g., testing specific design measures in a qualitative context, quantitative calculations to establish waste acceptance criteria)?

- What are the safety functions of the different components of the disposal system – are they assumed to mitigate or delay intrusion (e.g., waste containers may serve as a barrier to delay the timing of intrusion, depth of disposal in a near surface facility may preclude inadvertent excavation of waste)?

- What uncertainties may be associated with the different aspects of the IHI scenario (e.g., receptor habits (would typical drilling methods penetrate the facility?), is excavation likely in the location of the disposal facility?)?

- Is one scenario already encompassed by the definition of another scenario or are the consequences of a scenario bounded by another scenario, i.e. is it possible to subsume one or more scenarios?
8.4.3 Define the Human Intrusion Event Characteristics

The fourth subtask is to identify the attributes of the human intrusion event. There are three typical methods of human intrusion: drilling, excavation and mining. Many characteristics may be considered when identifying the attributes associated with the identified method of intrusion. The specific human action resulting in human intrusion will influence the migration pathways and potential exposure to the representative person. Local engineering firms and universities may be a useful resource for identifying the technical characteristics of the postulated human intrusion and disruption of the disposal system. As noted in IAEA SSG-23, 6.61, the intrusion characteristics “should be based on the assumption of present day technologies and procedures.”

Considerations:

- Is there anything about the site that may make human intrusion more likely (e.g., presence of natural resources)?
- Are there any characteristics of the disposal system that make human intrusion less likely (e.g., short-lived waste, remote location, very deep emplacement)?
- What is the purpose of the intruding action (e.g., drilling for resources or exploration, building development, mineral extraction, hydraulic fracturing)?
- What is the human intrusion method (e.g., drilling, excavation, mining)?
- What are the technical characteristics of the intrusion method (e.g., auger, rotary or percussion drilling, mechanical excavation, target depth)?
- What types of equipment are being used during the intruding action (e.g., borehole drilling machines, heavy loading equipment)?
- What are the dimensions of the intrusion (e.g., area and/or depth of the impacted area, volume of the waste)?
- Is there a specific portion of the disposal facility where intrusion occurs (e.g., emplacement drift, waste container or adjacent barriers, near-field contaminated zone, what is the distribution of higher or lower activity material in the potential intrusion area, what is the likelihood of hitting waste or a specific waste container if drilling occurs in the disposal facility)?
- Are there any radioactive waste materials associated with the intrusion (e.g., drill cuttings, waste excavation materials)?
- What is the impact of timing of the human intrusion event (e.g., radioactive decay, timing of container or barrier degradation, gas generation, erosion)?
• What uncertainties may be associated with the human intrusion characteristics (e.g., ranges of possible equipment characteristics, ranges in time of intrusion, location of intrusion)?

• Are there any characteristics of the normal evolution scenario that may have changed (e.g., has a geologic barrier function been adversely affected by the intrusion)?

8.4.4 Identification of Potential Impacts of the Human Intrusion Event

The fifth subtask is to identify the potential impacts of the IHI event. These impacts may be analysed through the evaluation of human exposures or intermediate safety indicators of the disposal system (e.g., radionuclide fluxes). The analysis may be either quantitative or qualitative.

Transport of Radionuclides:

This describes the potential migration of radionuclides from the disposal facility, through the natural system, to a representative human receptor. The transport of radionuclides is likely to be consistent with transport in the normal evolution scenario, although the location of exposure may be different and, depending on the regulatory framework, the migration pathways may be different for the intrusion scenario (e.g., waste cuttings brought to the surface). [SSG-23] provides guidance for conducting a radiological impact assessment.

Considerations:

• What is/are the dominant transport pathway(s) (e.g., gaseous, aqueous, particulate)?

• What inventory is being transported (e.g., amount of radioactive materials, long or short-lived, radioactive or irradiated material)?

• Is the inventory transported by the human intrusion event (e.g., via borehole cuttings or cores, excavated material)?

• Is the inventory transported naturally (e.g., advection or diffusion through water, movement of particulates).

• How long does the inventory take to reach the representative human (did the human intrusion event cause the migration to occur faster than otherwise expected, was a natural barrier compromised or adversely impacted)?

• What are assumptions about remediation strategies (e.g., resealing a borehole or mine shaft if intrusion was recognised)?
What are the uncertainties associated with the impacts of the human intrusion event (amount and timing of material exhumed, range of transport rates, quality of remediation strategies)?

Are there any characteristics of the normal evolution scenario that may have changed?

**Safety Indicators:**

The safety indicators (e.g., radionuclide concentrations, radionuclide fluxes) show how the components of the disposal system or the disposal system as a whole fulfill their safety functions and how their performance may be impacted by the human intrusion event. It is possible certain components may mitigate or delay the impacts, while certain components may be compromised by the human intrusion event. The indicators provide input into identifying potential protective measures that may be used to optimise the performance of the disposal system. Measures are described in more detail in Chapter 9.

**Considerations:**

- Is transport enhanced as a result of human intrusion (e.g. pressurised aquifer/fast flow path for deep disposal, waste material brought to and mixed on the ground surface for near surface disposal)?

- Are there components of the disposal system that prevent transport of inventory or compensate for lost safety functions (e.g., minimal water available for transport, waste forms that are not readily dispersed, other components of the disposal system)?

**Human Exposure:**

This describes how the representative human comes into contact with the radioactive material. Radionuclides that have been made available as a result of intrusion can be inhaled, ingested, or come into direct contact with the representative human. Note that there may be several representative individuals in each human intrusion scenario (e.g., worker, resident). The concentration and type of radionuclides, along with the duration of exposure, determine the doses received and are considered. In general, specific assumptions about human habits should be consistent with the normal evolution scenario.

**Considerations:**

- Who is the representative person (e.g., borehole driller, excavator, local resident)?

- How is the representative person exposed (e.g., inhalation, ingestion, direct exposure)?
What is the source of the radioactive material (e.g., contaminated drinking water or agriculture, cuttings or dust mixed with surface soil, direct exposure to waste, accumulating radioactive gases)?

What are the concentrations of the radioactive material (e.g., aqueous radionuclides may concentrate in some agricultural products, averaged concentration in cuttings or excavated material mixed with surface soil, gaseous radionuclides may disperse in the atmosphere)?

How long is the representative person exposed (e.g., a worker may only be exposed for a short time, a resident may be exposed for the duration of living at the site)?

How are uncertainties associated with human exposure managed (radionuclide concentrations, range of exposure times, likelihood of the intrusion scenario)?

8.4.5 Incorporating Measures

This section considers the effectiveness of potential measures to reduce the possibility for or potential impacts of a human intrusion event. Measures are described in more detail in Chapter 9. There also may be some inherent measures related to the waste disposal system such as waste acceptance criteria or depth for geological disposal systems. Note that due to the iterative nature of these assessments, the effectiveness of potential measures is typically assessed and documented at each step to help demonstrate how IHI scenarios are used to consider and select measures to improve the robustness of the disposal system. The applicability of the human intrusion scenario and incorporated measures should be assessed.

Considerations:

Are there any measures available to delay or mitigate the consequences of the human intrusion event specific to drilling, excavation, and mining (e.g., deeper disposal, alternative engineered materials, robust barriers, pre-emptive removal of nearby resources)?

What positive influence does the measure have on the safety of the system (e.g., enhances performance of the components/system such as delaying timing when intrusion can occur, reduces human exposure)?

Do the measures negatively influence the normal evolution scenario (e.g., decreased system safety, increase in human exposure)?

How do these measures impact the system description (e.g., do design considerations need to be modified)?

Does the measure contribute to defence-in-depth by improving robustness of the safety functions of the disposal system as a whole?
Measures may also impact the decision to include certain scenarios in the assessment, at least for some timeframes. For example, the decision to use a thicker cover for a near-surface disposal facility may prevent the occurrence of an excavation human intrusion scenario for some time while the thickness is maintained. For geological disposal, use of a non-local backfill material may be used to alert future inadvertent intruders (e.g., exploratory drillers) to some unnatural occurrence.

8.5 DOCUMENTATION AND COMMUNICATION

The information and potential impacts obtained by following the human intrusion scenario development method can be used to enhance confidence related to the human intrusion inputs into the safety case. Once the impacts are identified, measures can be assessed to see if they offer the system any additional protection. Also, providing clear justification for decisions made throughout the human intrusion scenario development method can help build interested parties’ confidence through transparency.

Clear documentation of the decisions made while developing a human intrusion scenario is important. Documentation facilitates clear communication with the relevant stakeholders and helps to build confidence in this aspect of the safety case. Additional information related to communications is available in Section 7.4.

Considerations:

- Are there aspects of the safety case context that have a significant influence on the disposal system (e.g., requirements in regulations, waste forms that dictate a specific disposal method)?

- How were the scenarios identified (e.g., what scenarios were considered, why were the specific scenarios chosen)?

- Was the selection of measures and customisation of scenarios appropriately documented (e.g., are decisions transparent and justified, is the level of detail appropriate for the analysis)?

- Are the sources of uncertainty captured (e.g., are the magnitudes of uncertainty identified; was any analysis qualitative, deterministic, or probabilistic)?

8.6 ADAPTATIONS OF THE HUMAN INTRUSION SCENARIOS

The scenarios provided above are representative of a reasonable range of human intrusion scenarios. They can be adapted for alternative human intrusion scenarios and alternative disposal systems, i.e. it is generally believed that drilling, excavation and mining can accommodate a reasonable set of IHI scenarios. A few examples are provided below.

Alternative Human Intrusion Scenarios
Geothermal Heat Extraction:

Geothermal heat extraction involves drilling for geothermal resources and utilising those resources for heating (e.g., drilling for hot water and pumping that into radiators or heat exchangers). Exposure to a driller would be similar to the near surface and deep-drilling scenarios for the workers. Exposure to a member of the public would be similar to the excavation scenarios, although the specific pathways would depend on how the geothermal resources were utilised.

Storage of Oil, Gas or Carbon Dioxide:

Storage of these materials involves drilling a borehole into an appropriate geological unit and either creating a storage area through solution mining, or directly pumping material into the geological unit. The exposure scenarios would be similar to the geological disposal scenarios for different rock types. That is, storage in non-soluble rocks would result in scenarios similar to those of non-soluble rocks and storage in soluble rocks would result in scenarios similar to those of soluble rocks.

Alternative Disposal Systems

Intrusion into Borehole Disposal Systems:

The burial depth of the radioactive waste influences the human intrusion scenario, (e.g., drilling, excavation, mining) while the activity content of the waste and half-life of the radionuclides influences the human intrusion exposure assessment. Note that due to the smaller cross-sectional area of boreholes compared to other disposal facilities, the likelihood of direct intrusion is substantially lower than it would even be for geological disposal facilities. Additional guidance on boreholes is provided in SSG-1, “Borehole Disposal Facilities for Radioactive Waste.”

Intrusion into Uranium Mill-tailings Disposal Systems:

Uranium mill-tailings disposal systems can be considered a form of near surface disposal facility, although some Member States are considering geological disposal. Human intrusion scenarios would be similar to other near surface disposal facility human intrusion scenarios. The differences in types of waste (long-lived) and the physical dimensions of the disposal facility are aspects to be considered.
9. Potential measures

There are many different approaches to reduce the potential for and/or consequences of IHI. In the HIDRA project, such approaches are referred to as "potential measures". Potential measures are considered with the stylised scenarios (Chapter 8) and societal considerations (Chapter 7) to formulate the facility-specific scenarios and measures that will be considered at a given step in the lifecycle for a disposal facility. Figure 9.1 shows schematically the element "potential measures" of the general approach discussed in Section 5.1. Based on the evaluation, protective measures are identified that are then implemented as part of the safety framework for the next step in the lifecycle.

This chapter includes the background and rationale for the concept of measures (see Section 9.1), an approach for the derivation of protective measures for implementation for a specific disposal facility (see Section 9.2) and a general discussion of categories of potential measures that can be considered (see Section 9.3). Annex A includes a current version of the database of potential measures for consideration to reduce the potential for and/or consequences of IHI.
9.1 BACKGROUND AND RATIONALE

The term “measures” can be described in a more general sense as provisions/precautions that are taken to comply with a certain purpose. In terms of radioactive waste disposal, the purpose is focused on both reducing the potential for and/or the consequences of IHI [IAEA 2012]. Consideration of such measures directly addresses the ICRP recommendations to consider features to reduce the possibility of IHI when considering design and siting of the facility (see Section 4.4.1). It is further stated, that appropriate countermeasures\(^4\) can be implemented to avoid significant impacts [ICRP 2013]. However, there is a general consensus, that any measures taken to reduce the potential for IHI should not compromise the safety performance of the normal evolution of the disposal system (i.e., considerations related to IHI should never be placed before other safety considerations). Appropriate measures have to be evaluated and identified to contribute to the optimisation of the disposal system against IHI. This is already a requirement in some regulations as part of the optimisation process [UK EA 2009, BMU 2010]. ICRP Publication 122 describes optimisation in a manner that reflects the approach for consideration of potential measures: “Optimisation has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of protective options, including Best Available Techniques, for enhancing the protective capabilities of the system and reducing its potential impacts (radiological and others).”

This optimisation framework (see Section 4.4) provides the rationale for the selection of appropriate measures for implementation at a given disposal facility. The main task is therefore the derivation of “protective measures” which will contribute to the objectives of reducing the potential occurrence of IHI and/or reducing the radiological consequences if IHI should occur, in the context of optimisation rather than to meet a dose constraint. In this context, the HIDRA project developed a systematic approach to evaluate potential measures and identify the protective measures to be implemented in a safety case (see section Section 9.2).

Different protective measures may be considered at different stages of the life cycle of the disposal facility. They can be categorised as passive or active measures and can reflect a wide variety of safety functions, as discussed in the forthcoming sections. Examples of safety functions for measures might include: warning, informing, preventing, delaying, impeding and controlling. In this context several main categories for measures were identified for consideration (see Section 9.3).

When protective measures are derived and implemented, there is no intent to imply a prediction of how future generations will act when respective measures are encountered/detected (for example, in the case of site markers, will future generations avoid the facility or explore it?). Rather, the intent is to make reasonable

\(^4\) The term counter-measure is used in ICRP [1] and can be considered as a synonym for the term protective measure in this report.
improvements to the system on the basis of our current understanding. It has to be further noted that the selection of measures is site and facility specific. It is expected that some measures will be inappropriate for some facilities and may be ideal for another facility, depending on the design and safety context.

9.2 APPROACH FOR THE DERIVATION OF PROTECTIVE MEASURES

A general approach has been developed for the process of identifying potential measures and evaluation of their effectiveness, leading to the selection of specific protective measures to be implemented as part of the optimisation of protection process. The general approach consists of four steps, as illustrated in Figure 9.2. The first step is defining the framework, followed by the compilation of general measures, identification of potential measures and finally the derivation of protective measures in the context of optimising the disposal facility.

Figure 9.2. Schematic illustration of the four steps to derive protective measures

Each of the four steps requires different data and input and provides output for the succeeding steps. The approach for deriving protective measures includes several types of measures with different status and meaning. The terminology used for the HIDRA project is listed in Table 9.1.
Table 9.1. Description of different types of measures considered in the HIDRA approach

<table>
<thead>
<tr>
<th>Type of measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measures</td>
<td>is the generic term for all measures considered in this report</td>
</tr>
<tr>
<td>General measures</td>
<td>includes the overall list of measures which are considered in the process of deriving potential measures (compiled in step 2 and input for step 3)</td>
</tr>
<tr>
<td>Potential measures</td>
<td>are those measures which might be appropriate candidates for the ultimate protective measures (identified in step 3 and input for step 4)</td>
</tr>
<tr>
<td>Inherent measures</td>
<td>are already part of the site, disposal concept, disposal design/layout etc. For example, the location of the disposal facility in deep geological formations which reduces the potential or possible radiological consequences of HI (identified in step 3 and input for step 4)</td>
</tr>
<tr>
<td>Protective measures</td>
<td>are those measures which meet the technical criteria and regulatory requirements and are recommended for implementation (derived in step 4 and input for a possible iteration of optimisation)</td>
</tr>
</tbody>
</table>

9.2.1 Step 1: Definition of the framework

The initial step of the approach of deriving protective measures refers to the definition of the framework. The defined framework is the underlying safety basis for the further steps. For the definition of the framework, each country has to consider the respective national regulatory basis (e.g. acts, regulations and ordinances and possible conditions and provisions) and the safety strategy to be taken into account when dealing with IHI (See Chapter 5).

9.2.1.1 Regulatory basis

Dealing with IHI in the safety case requires the consideration of the underlying regulations of the respective country. The regulatory framework may include specific requirements related to IHI that will have to be considered. Some examples of regulations from different countries are listed below.

According to the Regulatory Code of the Swedish Radiation Safety Authority [SRSA 2008] measures can be adopted to make intrusion into the repository difficult or to caution against intrusion. The safety analysis report for the facility has to prove that these measures either have a minor and negligible impact on repository safety, or that the measures result in an improvement of safety, compared to the situation that would arise if the measures were not adopted.
The relevant UK environmental regulations are set out in Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation [UK EA 2009]. This includes some specific guidance and a regulatory requirement in relation to the consideration of human intrusion, namely. Requirement R7 states that: “The developer/operator of a geological disposal facility should assume that human intrusion after the period of authorisation is highly unlikely to occur. The developer/operator should consider and implement any practical measures that might reduce this likelihood still further. The developer/operator should also assess the potential consequences of human intrusion after the period of authorisation.”

Design modifications to reduce the potentials of inadvertent intrusion have to be undertaken according to the Canadian Regulatory Guide [CNSC 2006]. This may include the site selection for the facility (where site selection options are feasible), siting the facility at a depth that discourages intrusion, incorporating robust design features that make intrusion more difficult, and implementing active or passive institutional controls, as appropriate.

In the case of the regulations for the United States, (Swift, 2013) there are two different approaches to evaluating IHI mandated by the regulations. One approach, for the formerly proposed Yucca Mountain repository in hard rock, was to select a time when the waste packages had degraded to the point where current drilling technology could penetrate it, and analyze the effects on the natural system barrier from an intrusion that entrained waste and moved it unhindered into the underlying aquifer. This was a prescribed stylized test of system robustness. Only one occurrence needed to be demonstrated and evaluated against the same prescribed dose performance measure as had to be met by the undisturbed system.

The other US approach (Swift, 2013) was prescribed by the regulator for the Waste Isolation Pilot Plant in deep bedded salt deposits in the New Mexico portion of the Permian Basin. Because there is resource extraction nearby (in particular oil and gas drilling and extraction at a level well below the repository), a law was passed forbidding resource extraction in a large area within which the repository is located. Although the law has no time limit, the regulator stipulated that no credit can be taken for this law, or for active controls, after 100 years post-closure. In addition, a formula was prescribed for calculating the frequency/probability of an intrusion borehole over the next 10,000 years. A 10,000-year performance calculation typically has about 8 such intrusions. The results of these IHI events are part of the performance measure prescribed for the system. IHI events cause the only releases from the system. There has been discussion of pre-emptively removing the oil and gas from beneath the repository to lower—but not eliminate—future IHI probability.

Guidance concerning future human intrusion is given in the German “Safety requirements Governing the Final Disposal of Heat Generating Radioactive Waste” [BMU 2010]. It is stated that “the optimisation of a final repository with regard to reliable isolation of the radioactive materials in the final repository from future human activities shall be carried out as a secondary priority to the optimisation of...”
The final repository shall also be continuously optimised in accordance with the principles of radiation protection and from a safety management point of view. As future human activities cannot be predicted, a variety of reference scenarios for inadvertent human intrusion, based on common human activities at the present time, shall be analysed. Within the context of such optimisation, the aim shall also be to reduce the potentials of human intrusion and its radiological effects on the general public.”

These examples show that international recommendations have common views regarding the consideration of measures to reduce the potential for IHI and with the optimisation of the disposal facility. However, there are also some differences in specific details that might have some effects on the derivation of protective measures.

For example, certain measures are excluded due to specific regulations. There are countries, for example, which do not intend to adopt active institutional controls after repository closure or place markers at the disposal site (e.g. Germany, Sweden) [OECD/NEA 1999]. In such cases potential measures regarding controls and markers would not be considered.

In other countries, especially in the case of near-surface disposal, consideration of measures and institutional controls play a much more important role. Time frames for institutional controls can extend to hundreds of years depending on country-specific policies. With respect to timescales and the safety case, the main issues of concern are:

- How long should active measures, including monitoring, be maintained?
- What credit if any can be taken for both active and passive measures in the safety case?

There are differences in the degree to which national regulations address these questions. In some cases, regulations indicate the time frame over which monitoring, control and record keeping should be maintained, and/or the time frame over which IHI can be excluded in a safety case as a result of such actions [OECD/NEA 2006]. A question of particular importance for the safety case is the timeframe over which passive or indirect controls can be credited to eliminate the possibility of IHI or to eliminate certain scenarios from consideration (e.g., large public works or mining activities).

Therefore, it is essential to be aware of specific regulatory restrictions, limitations etc. in the safety context of IHI.

9.2.1.2 Conditions and Provisions

In addition to the regulatory basis, further conditions and provisions for the study of IHI in the safety case may need to be addressed. This can be done for different reasons (e.g. managing uncertainty).
Such conditions and provisions are important for providing a reasonable framework in which to consider IHI without becoming overly speculative about future activities. Furthermore, any such conditions and provisions need to be in line with the relevant regulatory basis. Commonly accepted conditions and provisions were identified in Section 5.2.2, as follows:

- only IHI has to be considered
- current and past technologies in the region have to be taken into account when identifying relevant human actions
- IHI has to be considered separately from the systematic scenario development process
- IHI considers stylised scenarios rather than implying a prediction of future behaviour.

9.2.2 Step 2: Compilation of general measures

The development and compilation of a list of general measures is a key step to provide a starting point for the identification of potential measures in step 3 of the approach. Step 2 does not require specific information about the detailed disposal concept and design and layout of the disposal system. It is however helpful to have general information about the envisaged area for the disposal system e.g. the intended host rock, the repository concept and the types and amount of waste which have to be disposed. The more information about a specific site and concept that is available, the better the initial situation for the identification of suitable measures.

The HIDRA project considered a variety of different sources for the compilation of general measures which are described in the following subsections. The output of step 2 is a set of general measures to be considered when identifying potential measures.

9.2.2.1 Database

A key product of the HIDRA project is the development of a generic database of measures that can be used as a starting basis when considering the mitigation of IHI. The measures in the database were collected from former or current IHI evaluations and general brainstorming [GRS 2014]. This database is expected to continue to develop with time. The intent is for the database to serve as a reference for the different types of measures that can be considered based on conditions at a given site and facility.

This database, which was drawn up on the basis of a collection of ideas, the outcome of discussions and several references contains not only the compilation of general measures but also a range of attributes e.g. type of measure, effectiveness and use, effort involved, and action (passive, active) required. It was believed that such
characterisation of each general measure would be helpful in step 3 for the
identification of potential measures.

The database is included in an Excel file. This Excel file consists of the
following two worksheets:

- a) Description_Database_Entries and
- b) Database_Collected_Measures.

The worksheet a) contains a list of attributes associated with the data for each
identified measure. These attributes are explained in the worksheet and an example of
a general measure is provided (Figure 9.3 shows an example of Worksheet a)).
Worksheet b) lists the measures and includes a specific characterisation for each
measure according to its attributes (an example worksheet b) is shown in Figure 9.4).
Annex A provides the current contents of the attributes and a list of the general
measures in the database.
**Table: Measures with Focus on a Specific Objective**

<table>
<thead>
<tr>
<th>Entry (No.)</th>
<th>Reference</th>
<th>Explanation</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>1.1 Reduction of the possibility of intrusion</td>
<td>Measures with focus on a specific objective</td>
<td>Institutional control</td>
</tr>
<tr>
<td>1.2</td>
<td>1.2 Reduction of the radiological consequences</td>
<td></td>
<td>Waste separation, compartmentalisation, encapsulation</td>
</tr>
<tr>
<td>2.1</td>
<td>2.1 Institutional control</td>
<td>Reference on measures outside the disposal system or be applied</td>
<td>Waste separation, compartmentalisation, encapsulation</td>
</tr>
<tr>
<td>2.2</td>
<td>2.2 Waste management</td>
<td>Restriction of use, development freeze</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>2.3 Active measures</td>
<td>Restriction of use, development freeze</td>
<td></td>
</tr>
<tr>
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**Figure 9.3.** Detail of the worksheet “Description Database Entries”

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**FINAL DRAFT JANUARY 2017**

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**Page**: 94
<table>
<thead>
<tr>
<th>No.</th>
<th>Possible optimisation measures</th>
<th>Sub-category</th>
<th>Reference</th>
<th>Relates to a specific disposal facility</th>
<th>1. Objective</th>
<th>2. Position</th>
<th>3. Action</th>
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<td>Waste types and characteristics</td>
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<td></td>
<td>D3 Choose underdeveloped regions, rough terrain</td>
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<td>D4 Locating disposal boreholes at a site with an existing security infrastructures, e.g. at an existing NMP (Ref. S36G-1)</td>
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Figure 9.4. Detail of the worksheet “Database_Collected_Measures”
To illustrate the use of the database, an example is provided from which specific information and characterisation of the included measures can be obtained. The example refers to the measure B7 “Construction of a drift backfilled with robust material/rock”.

The measure B7 is assigned to the category “B) Design of disposal facilities and engineering barriers” and the sub-category “BII Increasing Resistance”. This kind of measure might reduce the potential of IHI and is characterised as an internal, passive and constructive measure. It has the function (characteristic) to delay, prevent and hinder an inadvertent intrusion. Furthermore, this measure is not tied to any specific human action such as drilling and mining and is therefore assigned as a general measure for the identified IHI technologies. The other characteristics in the table such as “benefit/cost”, “effort” and “availability” can be evaluated at the earliest in step 3 when detailed information is provided (e.g., for the site, disposal concept and design and layout). The entries for the attribute “Optimisation conflict” can only be given after the analysis of the measures regarding optimisation conflicts in step 4.

9.2.2.2 Literature/Projects

Another resource for the compilation of general measures is the study of existing literature or projects regarding IHI. Such resources will be an important source reflecting practical experiences. The literature and projects can be both national and international. Relevant examples include:

- Information preservation
  - Bibliographies (e.g. RK&M [OECD/NEA 2013a])
  - Catalogues (e.g. RK&M [OECD/NEA DRAFT])
  - Loss of information (e.g. RK&M [OECD/NEA 2014])

- Markers and monuments
  - Marker studies (e.g. RK&M [OECD/NEA 2013b])

- Existing safety cases
  - Stylised IHI scenarios
  - Assumptions for human actions

The output of the project and literature study can be used in turn as an input for the database (see Section 9.2.2.1).
9.2.2.3 Consulting experts

Another supporting feature for the identification of general measures can be consultation with technical experts (e.g. expert elicitation). Site specific information can be obtained regarding current practices and perspective about the effectiveness of different barriers (e.g., drillers and miners) (see section 9.2.3.5).

The technical experts can provide additional information regarding possible circumstances that might be undesirable or abnormal when performing a specific action. This can be, for example in the case of an exploratory drilling, the loss of drilling fluid, uncommon slow drilling heading, strong deflection or borehole inclination and damaged drill-bits.

Furthermore, the description of a specific technique, including working steps from the first planning, preparatory work, respective action with accompanying measurements and concluding work can also be worthwhile when identifying and evaluating general measures.

Finally, the information provided by the technical experts can be useful when considering the implementation and development of respective measures that lead to undesirable effects and/or facilitates the possible detection of an abnormal situation. Those noticeable problems or uncommon features might lead to further investigations by the staff performing the specific action.

9.2.3 Step 3: Identification of potential/inherent measures

The potential measures, those measures identified as relevant for a specific disposal system, are analysed in Step 3. This requires inter alia the consideration of specific information of the waste characteristics, site, disposal concept, and design/layout of the facility. Beyond that, the relevant human actions (see Section 8) considered for development of the stylised IHI scenarios have to be taken into account (see section 9.2.3.5).

Before any potential measures are selected, it is essential to identify the “inherent measures” that are already in place in the disposal system. This is required for understanding the capabilities of the disposal system and, where applicable, modifying inherent measures for increasing its effectiveness. The intent is to document all measures that contribute to reducing the potential for and/or consequences of IHI. Thorough documentation helps to better explain all the provisions being taken against IHI.

For various reasons, some of the general measures may not be considered as suitable potential measures. For example, if national regulations prohibit marking the disposal site, any general measures regarding markers and monuments would be excluded from.

Finally, a list of potential measures constitutes a pre-selection of candidates for further analysis, from which the protective measures can be derived. Therefore,
the potential measures have to be selected or identified on a reasonable basis by taking into account the following aspects:

- Measures must not compromise the safety of the disposal facility.
- Measures must not lead to other undue hazards to people and the environment.
- Measures have to follow the principle of proportionality regarding benefits, efforts and costs, which will be considered as part of optimisation.

The following subsections provide more detailed information and examples regarding potential/inherent measures from different perspectives such as site, disposal concept, design/ layout and waste characterisation, as well as the underlying stylised scenarios. The examples were chosen for the most part from the database of collected general measures (see Section 9.2.2.1 and Annex A).

9.2.3.1 Site

The site for a specific disposal facility for radioactive waste plays a major role in a safety case. In particular, site selection, site characterisation and site evolution in the post-closure phase are all elements which have to be considered in the context of the safety of disposal facilities.

The objective of site selection is to ensure that the site has natural properties to provide adequate containment of the waste from the environment in conjunction with the engineered barriers of the disposal facility. As engineered barriers cease to function, the site characteristics should provide sufficient retention capabilities to maintain the potential releases of radionuclides from the disposal system within acceptable levels.

The following list includes some examples of beneficial characteristics that are not essential, but may be considered [Cooper et al. 2010, IAEA 1984, IAEA 2014]:

- arid climate
- deep groundwater table below the base of the disposal facility, with groundwater not suitable for human consumption
- geologic structure with high absorption/ion exchange properties which retard radionuclide migration;
- geologic strata of low permeability
• simple geologic structure to permit modelling of groundwater and radionuclide migration patterns

• located away from any known or anticipated seismic, tectonic or volcanic activity

• suitable geochemical and geotechnical properties

• area free from flooding

• slow wind and water erosion rates

• no potentially valuable mineral deposits or construction materials unique to the local area

• topography suitable for easy movement of heavy machinery

• low population, remote area

• land unsuitable for agriculture

• absence of special environmental attractiveness

• absence of any known rare species or ecosystems

• absence of sites of special cultural or historical significance

• social acceptance by local communities

The criteria in the list refer to different safety, technical and societal-acceptance issues relevant to long-term safety, operational safety, feasibility, costs, future human actions and human intrusion. It is evident from the list above that it is not realistic to find a site with all the desirable aspects. Therefore, the site selection process will inevitably include a balance between the desirable and the less desirable aspects. For the balancing process it is essential that in particular there can be a reasonable expectation that long-term safety requirements will be met. That is, those aspects which might reduce the potential of IHI are suitable attributes of the site but they are of secondary importance compared to long-term safety and operational...
safety. The experience of several Member States has also shown that societal
acceptance is a key ingredient in the successful selection of a site.

It should finally be noted that those aspects of the site which, for example,
make it difficult to intrude or make the location less attractive for any economical and
non-commercial reasons are inherent measures. Some of the inherent measures can be
modified to promote their potential effectiveness. There may be cases in which the
likelihood for IHI increases over the time period during which the repository is
operating. This could happen if a known resource such as oil and gas beneath or
beside a repository in salt, for example, becomes more commercially attractive. In
such a case it may be appropriate to remove the resource from beneath and near the
repository with careful extraction techniques that are mindful of the repository and do
not disturb its natural barriers. In addition to site selection, consideration of the post-
closure phase is also essential when identifying potential measures. In particular, site
alteration might be a basis for potential measures. The database of collected general
measures (see Section 9.2.2.1 and Annex A) includes some examples which refer to
the alteration of the site after the closure of the disposal facility. These examples
include

- Alteration of the landscape (difficult to develop)
- Pre-emptively extracting potential resources, or rendering the resources
  unattractive
- Development of the site as a recreational area that might be preserved by
  future generations

Some more details to potential measures in conjunction with siting are given
in Section 9.3.4.

9.2.3.2 Disposal Concept

The disposal concept varies from country to country and facility to facility,
depending on the types of wastes and the safety framework. Generally, the disposal
concept involves the following components, which often constitute protective
measures (i.e. inherent measures of the disposal concept):

- Types of disposal facility: near surface, borehole, and deep geological:-
each type has different human intrusion potentials and consequences;
- Design: layout configuration, footprint shape and size, and depth. While
  the layout configuration, footprint shape and size can affect the potentials
  and consequences of human intrusion, the facility depth has the greatest
  influence on the potential for IHI and its consequences. Generally
  speaking, the deeper a repository, the lower the potential for and
consequence of human intrusion, but optimisation needs to be achieved based on the specific circumstances;

- Waste types and forms: e.g. used fuel bundles, or solidified high-level wastes from reprocessing: will affect the intrusion consequences as well as the potential for IHI;

- Containers: different types of material (steel, copper, titanium, etc.), size, shapes and thickness, and corrosion properties;

- Disposal rooms or near surface units: vertical and horizontal arrangement of waste, footprint shape and size, etc.; IHI needs to be considered along with other factors for the design;

- Engineered barriers: features of vaults, covers and other barriers that can influence IHI;

- Sealing: shaft and tunnel seal, plugs, backfill material and container buffer. Of relevance are the types, properties and the thickness of sealing materials;

- Surrounding and overlaying media: types, geological, hydrogeological, geotechnical properties of rock/soil.

9.2.3.3 Design/ Layout

For the derivation of protective measures, information on design and layout plays a key role in the screening of the general measures in terms of conceptual appropriateness, feasibility of implementation, and availability. Final judgment for the adaptation of the identified potential measures is carried out in step 4 through an iterative process considering all aspects which can affect the long-term safety and robustness of the disposal facility.

The depth of the disposal facility and the emplacement of different wastes in different areas or locations etc., which are conceptually established on the basis of waste characteristics, are classified as inherent measures. Since designing the disposal facility is an iterative process, these inherent measures can be modified in the early stage of the design process for optimisation regarding IHI. As the design process approaches the detailed design, additional measures may be identified to complement the inherent measures to reduce the potential for and the radiological consequence of IHI.

Potential measures to be identified in step 3 depend significantly on the design and layout of the disposal facility. Furthermore, a potential measure can have some effects on other safety issues. For example, near surface disposal facilities are generally accepted for disposal of VLLW and LLW. The potential measure to increase the depth of the disposal facility could lead to undesired side effects for the
disposal facility accommodating LLW and VLLW. For example, the containers for these types of waste may have in general a thin wall thickness, whereby a greater depth of the facility can cause damage to the containers due to the larger overburden. In contrast, the disposal canisters for HLW or spent fuel have in general a sufficient wall thickness to resist ambient pressure from the host rock and swelling pressure of the buffer.

Further examples of potential measures are the installation of reinforced concrete vaults in the near surface, construction of a drift backfilled with a robust material and rock for geological disposal, boreholes plugged with impermeable material and/or insertion of a layer of rubble or tyres, which may be difficult to drill through. Whether or not such potential measures are appropriate depends on the design and layout of the disposal facility. Markers such as colour indicators, chemical indicators, biological indicators, etc. listed in the database of collected general measures (see also Section 9.2.2.1 and Annex A) can be appropriate potential measures for both near surface disposal facilities and deep geological disposal facilities.

Potential measures such as increased vault or cask wall thickness and rubble layers in covers or insertion of a drift backfilled with a robust material have a function to reduce the possibility of IHI. Whereas potential measures such as waste separation or placement of higher activity wastes deeper in a near surface facility, installation of indicators, etc. play an important role in reducing radiological consequences. In most cases, potential measures derived in the category “design/layout” are installed during the construction of the repository and would be considered passive measures which do not need further update and maintenance to address intrusion considerations after closure.

9.2.3.4 Waste Classification and Characterisation

There exists internationally a broad range of waste classification and disposal methods. Quantitative regulations are typically used when classifying the radioactive waste which can be accepted in disposal facilities. These quantitative regulations include, for example, the limits of concentrations of radioactivity, maximum inventories of radioactivity and dose rates. The limits for radioactivity are usually defined for each radionuclide or for total radioactivity in order to identify low (LLW), intermediate (ILW) and high-level waste (HLW) according to the IAEA waste classification scheme [IAEA 2009]. Some examples of potential measures (see Section 9.2.2.1 and APPENDIX) which refer to waste reduction, mitigating the toxicity and compilation of appropriate regulations are as follows:

- reducing the waste volume
- waste conditioning (general)
The potential measures regarding waste characterisation refer primarily to waste management and waste processing techniques prior to the waste’s disposal.

9.2.3.5 Stylised Scenarios/ Human activities

The general consensus is that there is limited benefit in considering a wide range of speculative IHI scenarios when optimising the disposal facility with regard to the potential for IHI. Rather, the emphasis is placed on current practices and one or more stylised scenarios. Therefore, human activities as practiced today in the local area of the site and showing a potential for intrusion into the disposal facility with regard to the associated technologies or courses of action have to be identified. On this basis, a set of stylised scenarios are generally provided for further analysis (see Chapter 8).

Stylised scenarios have to be considered both to evaluate the effectiveness of potential measures and to identify where and how specific measures should be implemented in the disposal system. For the aim of deriving protective measures in connection with stylised scenarios it is essential to know about current common human activities with respect to their practical execution and application.

Human intrusion scenarios will be based on human actions that use technology and practices similar to those that currently take place or that have historically taken place, in similar geological and geographical settings. The assumed habits and behaviour of people will be based on present and past human habits and behaviours that have been observed and are judged relevant [UKEA 2009].

For example, there is no need to consider solution mining as a basic human action if the underlying geology of the disposal facility is not composed of soluble substances such as rock salt or potash salt. The same applies in general to human actions at the surface or near the surface and past technologies that have no impact on a geological disposal facility. On the other hand, actions that relate to the deep underground (such as mining) also have to be taken into account for near surface disposal facilities.

9.2.4 Step 4: Derivation of protective measures

Derivation of protective measures is the last step. The potential measures identified in the preceding step are analysed using qualitative and, if feasible and appropriate, quantitative assessments. The analysis is performed in close connection to the provided stylised scenarios from chapter 8 (i.e., the relationship between the...
scenario and assumptions regarding the effectiveness of different measures (timing
and mitigation). The main objective of the analysis is evaluation of whether the
potential measures are in conflict with the primary safety targets. A further objective
refers to the consideration of the feasibility and effectiveness of a specific potential
measure. The evaluation of the effectiveness can be done, for example, by discussing
and/or calculating the cases before and after implementing the specific potential
measure.

Those potential measures which do not compromise the primary targets and
which are found to be feasible and effective against IHI in the optimisation
framework, are designated the derived protective measures, which are recommended
for implementation.

9.2.4.1 Facility Safety Objectives

The development of a disposal system is in general an iterative process taking
into account specified objectives, which in this document are referred to as primary
targets. The facility safety objectives can differ from country to country dependent on
the respective regulatory basis. Some examples of primary targets which are relevant
in most of the countries dealing with disposal systems for radioactive wastes, include:

- Radiation protection for the operating phase
- Long-term safety
- Reliability and quality of long-term waste containment
- Technical and financial feasibility

The optimisation of the disposal system in terms of IHI is a lower priority with
respect to the primary targets. This means that potential measures from step 3 must
not be in conflict with the above-mentioned primary targets. A conflict is given when
the potential measure compromises one or more of the primary targets. For example,
it has to be checked whether the identified potential measures regarding IHI may
initiate or favour processes or create circumstances that will have adverse effects on
operational or long-term safety. In such cases, the potential measure has to be
modified or excluded.

9.2.4.2 Analysis and additional considerations

The identified potential measures from step 3 (see Section 9.2.3) of the
approach constitute the input for the analysis. In the analysis and additional
considerations, the potential measures will be discussed to identify any possible
conflicts with primary targets, feasibility and effectiveness (see figure 9.5). If
required, a quantitative assessment of the IHI scenario before and after the
consideration of potential measures can be modelled and analysed. The comparison of the calculated results should give information about the benefits and effectiveness of a specific potential measure.

The first step is to confirm that the potential measures are not in conflict with the primary targets (see Section 9.2.4.1). This evaluation can be an inter-disciplinary process and require information and specialists from different scientific fields (e.g. geologists, physicists, chemists, engineers etc.). Stylised scenarios may be used to identify for each potential measure whether the objectives of the primary targets could be compromised.

The following virtual example provides some perspective on the evaluation process. For example, the implementation of rubber mats as a resistance to drilling might be identified as a potential measure at step 3 of the approach. Rubber mats installed as a ceiling in emplacement drifts, tunnels or chambers could resist a drill-bit and could therefore prevent further drilling activities or make it at least difficult to proceed, whilst keeping the facility relatively intact. On the other hand, the rubber consists of organic material which is subject to bacterial degradation [26]. The rubber degradation process generates gas which might compromise the sealing of a disposal system. The gas produced might also act as a transport medium for radioactive wastes. Both issues can affect the primary targets “long term safety” and “reliability and quality of long-term waste containment”. As a consequence, the protective measure of the rubber mats should be modified in such a way that no compromising effects occur, otherwise the measure should be excluded from further consideration as a protective measure.
Potential Measures \rightarrow \text{Analysis} \rightarrow \text{Primary Targets}

- **Exclusion**: No → Modifiable
  - **Conflict**: No → Additional Considerations
    - Feasible: No → Effective: No
      - Decision for implementation
    - Feasible: Yes
      - Effective: Yes
      - Decision for implementation

Potential measures which are not in conflict with the primary targets should be assessed in terms of their feasibility and effectiveness. These additional considerations can be undertaken in a qualitative and/or quantitative way. When discussing the feasibility of potential measures, the effects, efforts, and possible costs of the adequate implementation or establishment have to be considered along with practical considerations related to effectiveness of the measure. In terms of the costs for providing a specific potential measure the asset costs, installation costs, and the
possible follow-up costs (e.g., maintenance and monitoring) should be taken into account.

The assessment of the effectiveness of a potential measure could consider many factors, for example:

- internal or external measure,
- passive or active measure,
- type and characteristic of the measure,
- dependent or independent of a specific human action or IHI scenario,
- availability and effectiveness of the measure (material degradation, functionality).

The database (see 9.2.2.1 and Annex A) includes for each measure a summary of the above mentioned factors, which is intended to support the evaluation of effectiveness.

Referring to the above mentioned example of the use of rubber mats, it can be envisioned that for other environmental conditions this potential measure might be useful for providing resistance to drilling. However, it is stated that a specific rubber material, such as vulcanite, becomes brittle in chemically aggressive pore-water and furthermore it may be technically difficult to introduce such materials into a disposal tunnel of several hundred metres in length and some metres in diameter [Buser 2013]. In this case the feasibility and the effectiveness of the potential measure rubber mats will be estimated as low. However, it should be noted that this estimation can vary depending on the conditions e.g. disposal concept, site and waste characteristics.

In some cases the specific potential measure can be modelled and considered in quantitative calculations. The effectiveness can then be evaluated by comparing the calculations with and without a specific potential measure in place or active. The calculated values should be seen as indicators for comparison. An indicator might be, for example, the extracted quantity of radioactive waste in a particular stylised IHI scenario.

Finally, it has to be decided if the identified potential measures warrant implementation. It is anticipated that the decision for accepting a potential measure as a protective measure to be implemented will be a balancing process where all the information, assessments and evaluations are consolidated in an optimisation framework.
As already mentioned, there are different types of measures with different intentions and purposes. Some measures are geared towards constructive or indicative provisions and some are based on regulatory provisions. Some measures are passive and some rely on active intervention. Others in turn are already part of the disposal concept such as the location of the disposal facility in deep geological formations. These measures are known as inherent measures and will be identified for each individual disposal facility as a potential basis for further optimisation. There are quite a number of possibilities. In order to allow a systematic compilation and classification of potential measures, the following categories were defined for the database:

A) Monitoring/ Surveillance

B) Design of disposal facilities and engineering barriers

C) Knowledge management

D) Siting

E) Waste types and characteristics

The characteristic of each category and some respective examples of types of measures are described below. Annex A (database of collected measures) includes the current list of collected measures, organised into specific categories.

### 9.3.1 Monitoring/ Surveillance

The category “Monitoring/ Surveillance” is a generic term and comprises a number of measures predominantly focused on preventing, delaying, warning and controlling the potential for IHI. Examples of such measures are:

- fences and security at a site
- satellite based surveillance controls on land ownership and restrictions on land use and
- monitoring.

Information preservation and archives are often discussed in connection with active and passive controls. In this document these issues are assigned to the category “Knowledge management” (see section 9.3.3) due to their close relation to information and knowledge conservation.

The IAEA Safety Glossary “Terminology Used In Nuclear Safety And Radiation Protection (IAEA 2007 Edition)” defines institutional control as follows:
“Control of a radioactive waste site by an authority or institution designated under the laws of a State. This control may be active (monitoring, surveillance, remedial work) or passive (land use control, information preservation) and may be a factor in the design of a nuclear facility (e.g. near surface repository).”

The majority of the measures involve active engagement. Only a few are of a more passive nature, for example restrictions on land use, markers and monuments. Both active and passive measures are discussed on a national and international level.

Regarding the active measures, it is argued that disposal facilities in deep geological formations are designed to be passively safe in the post-closure phase. Therefore, active support is not essential. Furthermore, active measures need to be balanced with the principle of avoiding undue burdens on future generations. For near surface disposal, active measures are more commonly considered, since active institutional controls are seen as an effective way to prevent IHI. In the context of near surface disposal the IAEA Specific Safety Requirements (SSR 5) [IAEA 2011] state:

“In near surface disposal facilities are generally designed on the assumption that institutional control has to remain in force for a period of time. For short-lived waste, the period will have to be several tens to hundreds of years following closure. Such controls will be either active or passive in nature. For near surface disposal of waste from mining and mineral processing that includes very long lived radionuclides, and which generally comprise large volumes, activity concentrations have to be limited so that ongoing active institutional control does not have to be relied on as a safety measure. Waste with activity concentrations above the limitations has to be disposed of below the ground surface.”

In terms of passive measures, especially with regard to markers, it is argued that warning messages could be misunderstood or neglected. Moreover, markers can have a reverse effect, that future generations might be attracted to the site out of curiosity. Otherwise, markers or other features to enhance awareness of the disposal facility can be an important safety element, depending on the disposal facility, disposal concept, and the waste category.

If markers for disposal sites are planned, a globally standardised form of the marker system might be useful (e.g. design, size, durable material etc.)\(^5\). The reason is that if IHI with perceived radiological consequences does occur, then the societies at other similarly marked places will be warned and may act accordingly to prevent IHI at their locations. This implies inter alia a functioning information system between societies.

\(^5\) [Foote 1990, BMI 1984] Describe the creation of a universal biohazard symbol as a two-fold aid to communicational durability.
There is wide consensus that measures from the category “Monitoring/ Surveillance” e.g. institutional controls, can be effective to prevent IHI for a certain period of time but should not to be relied upon for the safety of the disposal facility into the far future after closure [IAEA 2011a, IAEA 2011b, IAEA 2012].

It is often conservatively assumed that IHI can occur immediately after the end of active institutional control. There is no international consensus on the period of time beyond active control over which passive controls would be effective to preclude intrusion. There can be a general perspective that the end of institutional control is connected to the loss of knowledge about the disposal facility and the hazard of the site from the perspective of when IHI can occur [IAEA 2012, IAEA 2001].

9.3.2 Design of disposal facilities and engineering barriers

In contrast to the other categories, the category “Design of disposal facilities and engineering barriers” includes measures that are focusing both on reducing the potential for and the radiological consequences of IHI. This category comprises a wide spectrum of different types of measures with different intentions that are dependent on the specific design of the disposal facility.

Certain measures are aimed at warning those acting in the future that there is an abnormal situation so that they will take due care. Examples of such measures are the implementation of indicators with fluorescent colours and the use of unusual and unexpected substances as backfill material in excavations of the disposal facility. However, there seems to be a similar situation to the issue of markers (see 9.3.1) that such indicators might attract rather than deter intruders. The rationale here is that these indicators might warn intruders to act with increased care by giving them the knowledge that they are encroaching into something unusual.

Other measures are directed at increasing the chances of the nature of the hazard being detected before, during and after an intrusion into the waste emplacement area has taken place. These measures can include all types of indicators, e.g. optical, acoustic and magnetic, that might facilitate the detection of the disposal facility and the potential recognition of its hazard potential.

Another type of measure in this category refers to physical provisions against human activities. The physical provisions act as a robust barrier against potential techniques used by potential intruders. As a result, the intruder might investigate the causes of the situation or at least will be sensitised for their next actions. Examples of such measures are an increased wall thickness of waste containers, cover thickness of near surface facilities and the use of resistant materials for additional barriers. In such cases a drilling of a borehole, for example, might be deflected and/or the drill bit may be damaged.

Design measures of the disposal facility can also contribute to the reduction of IHI potentials and radiological consequences, for example: the separation,
compartmentalisation and encapsulation of the emplaced waste might reduce the amount of affected waste in the instance of an intrusion. Therefore, these measures are targeted on the reduction of potential radiological consequences from an IHI event.

The waste emplacement strategy can also be influenced by human intrusion considerations. For example, the most active waste packages are often placed at greater distances from potential intrusion routes. For example, in a near surface repository the most active waste packages are often emplaced at the bottom of the stacks in order to reduce the potential for intrusion into those particular waste packages.

Another design measure refers to the reduction of the footprint of the disposal facility in order to reduce the potential for IHI. In this context the disposal facility might be designed in such a way that the required area for the waste emplacement is minimised. The adjustment of several layers of drift emplacement is an example of reducing the footprint of a disposal facility. However this measure has a counter argument that drilling in the space of the reduced area of a disposal facility the borehole might cross all of the designed layers and hence breach a larger volume of waste. A very small footprint is associated with deep borehole disposal and this can reduce the potential for IHI. This might be valid in the case of specific future human actions such as vertical drilling from the surface; but for other techniques such as mining there is no evidence that the potential for crossing the boreholes with disposed wastes will be reduced.

Another design and safety strategy related measure is related to the depth of the disposal facility in a geological formation. The envisaged depth of such disposal facilities especially for HLW is in general about several hundred metres. Some near surface facilities may also include excavations to depths exceeding 10 metres. These design options limit IHI by reducing the number of:

- types of basic actions e.g. drilling, leaching and excavation;
- motivations e.g. exploration, exploitation, mining, disposal;
- individuals who have the intention, means and resources for such an endeavour.

It is generally accepted that sufficient depth of the disposal facility is one of the most effective measures against IHI. The depth required will depend on the waste properties, the design of the disposal facility, characteristics of the host rock, etc.

9.3.3 Knowledge management

The category “Knowledge management” refers to measures that encourage the transfer of information and knowledge about disposal facilities and their inventories to future generations. Some examples of such measures are...
• information collection and preservation, e.g. keeping copies of records at different locations,

• creation of information centres, e.g. at disposal sites,

• establishing archives on a local, regional, national and global level and

• educational programmes, e.g. radioactive waste disposal as a subject in schools, colleges and universities.

The rationale behind these measures is to keep future generations informed regarding hazardous sites and to provide them with all necessary information for a considerate management of such sites. Along with depth of disposal, knowledge management is viewed as one of the most effective deterrents for IHI.

There is general consensus that the potential for inadvertent human actions can be essentially eliminated or significantly reduced if future generations are aware of existing disposal sites and of the potential hazard posed by the disposal facilities. However, from a safety point of view this can only be assumed for a limited period of time. This timescale may be sufficient for significant hazard reduction (through radioactive decay) of the inventory in a near surface disposal facility, but will be relatively short compared to the timescale over which higher activity wastes remain hazardous. The timeframe required for information preservation and the earliest possible intrusion time cannot be determined on a scientific basis and are therefore generally a subject for regulatory provision. A common approach is the assumption that IHI can occur after information and knowledge of the site are lost [IAEA 2012, PAMINA 2011]. The preservation of information on the other hand has to be achieved for as long as possible. Since this is an undefined specification, some countries take into account historical documents e.g. maintained by archives, registers or national libraries. These documents demonstrate that information can be preserved for more than several hundred years [OECD/NEA 2006].

In conjunction with information preservation it is also crucial to decide, what kind of information has to be preserved and in which form. There are lots of recommendations from national and international studies that relate to these issues (see Section 7.4). Therefore, this subject will not be further discussed here but it has to be noted that appropriate arrangements have to be met in order to establish a sustainable basis to preserve the necessary information. This includes, for example, sophisticated technical solutions, methodologically sound concepts, secured funding, and stable organisational structures [Beuth and Navarro 2010] (see Section 7.4)

Another aspect relates to the question of the appropriate organisational environment for a database with relevant information to be accommodated. It might be conceivable that in the future nuclear technology plays a minor role for whatever reason. In this context, it will be worthwhile to consider the integration of the radioactive waste subject in a more super-ordinate system such as a global
environmental database. Such a database could include all information of hazardous disposal sites for radioactive and non-radioactive toxic waste e.g. chemical, biological and mixed waste. It is likely that the public would have an ongoing interest in data and information for such sites. The radioactive waste issue might have a better chance of remaining in the awareness of future societies if there existed such an environmental database of global concern.

In summary, efforts have to be undertaken to establish and maintain knowledge management systems at several levels as long as possible to deter the occurrence of IHI.

9.3.4 Siting

The category “Siting” refers mainly to measures which focus on sites for disposal facilities that are less attractive for settlements and economic reasons. For example:

- avoiding resources, e.g. minerals, groundwater, crude oil and historical places
- preference of particular regions e.g. low population density, underdeveloped areas, lack of or difficulty obtaining potable water, and rough terrains
- reshaping the landscape, e.g. creation of an inhospitable area that is difficult or costly to redevelop.

The initial motivation for future human actions at a disposal site could be the exploration of exploitable resources. Therefore, it seems reasonable that one consideration is to consider sites for radioactive waste disposal away from such resources from a current perspective. As a consequence the potential for IHI is reduced. However, there are some concerns as to whether the potential can be significantly reduced over the timeframes considered in safety assessments. Reducing the potential for IHI by avoiding sites with valuable resources includes the assumption that future generations have the same requirements about needs and crude materials as the present and past generations. This may not necessarily be the case given the long timescale for the isolation period of HLW.

There are examples that materials which were considered as valueless in the past are seen nowadays as precious or exploitable materials and vice versa. The element wolfram and also pitchblende were considered in the 16\textsuperscript{th} century as mine spoils from the mining of silver and tin in the Erzgebirge. Other substances were used as fuel in the past (e.g. turf) have become less important in present times. Therefore, the assumption of reducing the potential for IHI by avoiding natural resources is a reasonable consideration, but should not in itself be a deciding factor for siting of a disposal facility.
An actual example of a repository located near active resource extraction areas is the Waste Isolation Pilot Plant in New Mexico, USA. There were no oil wells in the area when the repository was sited and very few while it was constructed. A federal law was passed forbidding resource extraction on the designated site. Nevertheless, WIPP’s regulatory authority, the US Environmental Protection Agency, required the drilling of boreholes through the repository to be considered in system safety assessments as soon as 100 years after repository closure, whilst also requiring a passive marker and information retention system to be in place. The regulator prescribed a 100-year rolling average to be used to calculate 10,000-year drilling rates in the area, to be re-calculated for every 5-year compliance recertification. The only mode of release for the system is through IHI scenarios, of which there are approximately eight in every compliance calculation. With the increase in the resource’s value and the enhancement of extraction efficiency over the last decades, oil wells have now surrounded much of the legally defined site. Drill rates have fallen again due to the reduction in the resource’s value, underscoring the wisdom of using the 100-year running average, since there will be ups and downs in the market and eventually the resource will no longer be commercially viable in this location.

Removal of the resource from beneath the site without disturbing the natural barriers is an option that has been considered, but is not likely to be implemented in the foreseeable future.

Another aspect refers to a geology that mainly consists of materials occurring in large amounts even near the surface. For this reason, it can be expected that an intrusion into the deep underground with the intention of material extraction is less rational [Beuth and Navarro 2010, Buser 2013].

There are some discussions that the waste and the waste containers themselves could become a resource. From a present day perspective, the spent fuel and also some used or envisaged container materials are already regarded as precious materials (e.g. copper). However, it is generally expected that any such intrusion to retrieve these materials would be deliberate, so these considerations are not a consideration for IHI.

Finally, there are some thoughts of reshaping the landscape or topography of a given disposal site in such a manner that might deter future societies from any plans of site development or other actions. An illustrative example is the use of the site as a dump. The restoration of the site would imply high costs and efforts. An exact opposite example is the conversion of the site into a recreation area, so that future generations may decide to preserve the area without any changes. A more practical example in the case of a level site with no serious expectations of flooding and high erosion is to construct surface mounds or berms using durable but readily available materials (e.g., the proposed berm of rock outling the underground facility at the surface of the Waste Isolation Pilot Plant repository in the US.
9.3.5 Waste types and characteristics

This category of measures is aimed at reducing the radiological consequences of IHI by controlling the level of radioactivity, inventory, and/or radio-toxicity of radioactive waste source to be disposed at a facility. Radiological waste characteristic measures may also be used to select appropriate disposal procedures (e.g., disposal of highly radioactive sources and long-lived radionuclides at the bottom of disposal cell or trench) to minimise the impact of IHI. The aim is to ensure that while the waste is at its most radiotoxic, the disposal facility is sufficiently robust; as robustness decreases (for example, through the degradation of engineered barriers), so does the radiotoxicity of the waste (through radioactive decay) [OECD/NEA 1995]. Examples of such measures are:

- selection of compatible waste form and packages
- selection of radionuclide waste inventory.

The selected host rock, engineered barriers, and immobilisation matrix can preserve some properties of confinement in case of intrusion. The waste form selected might help to reduce the impact after the intrusion occurs. For that matter, the integrity of waste materials will be maintained intact and chemical and leaching properties will not cause disruption of barriers. Special packaging, encapsulation, containment, and disposal procedures appropriately selected based on waste characteristics can also serve to reduce the potential for and/or consequences of IHI.

Realising that radioactive waste disposal usually requires long-term reliable processes to contain the waste, IHI is considered when institutional controls and knowledge of facility hazard are somehow lost. Therefore, in the case of near-surface disposal or any other disposal options that are suited for short-lived radionuclides, the waste acceptance criteria and the selection of the waste stream allow the repository to be adjusted and optimised in order to reduce the impact of an intrusion. Assuming that human intrusion was ruled out during the institutional control period, the short-lived radionuclides have sufficient time to decay before intrusion occurs and most of the impact will be caused by the remaining long-lived radionuclides. Therefore, the content of long-lived radionuclides has to be limited by both appropriate selection of the waste inventory and waste acceptance criteria.

Waste acceptance criteria may, by themselves, constitute a measure geared at reducing the potential impact of human intrusion. They may include requirements on the radiological content of the waste, but also on its physical form (solidified waste vs. dispersible materials) as a result of which the transfer of activity (into the air, into plants etc.) can be reduced.

Waste acceptance criteria and institutional controls have a close relationship. So it is stated that assumptions concerning the duration of institutional control play a major role in defining waste acceptance criteria, particularly for near surface disposal facilities [IAEA 2012].
Nevertheless, the existence of waste acceptance criteria is, especially for facilities at or near the surface, only one aspect to be considered in reducing the potential impact of IHI. For such facilities, it is important to cautiously select/establish the final inventory in the facility. Waste packages consuming a large fraction of the facility’s total activity limit for one or several radionuclides are avoided, if other options are available, or special containers are developed hence reducing the potential impact of a localised intrusion.

Optimisation of a disposal facility related to IHI could also be performed from the early stage of facility development. In this regard, a variety of measures could be considered with regards to the waste characteristics and waste conditioning producers to decrease the radiotoxicity of the waste produced in an operating facility via, fuel fabrication procedures, packaging, and containment. An integrated approach to the overall fuel cycle, including options such as partitioning and transmutation (P&T) and pyro-processing, to reduce long-lived radionuclide and total inventory for disposal, is also a measure to reduce the radiotoxicity of the waste. However, it has to be noted that techniques related to waste treatment and manipulation could cause exposures to workers and therefore their introduction should comply with the radiological principles of justification.

9.4 SUMMARY

The evaluation of the effectiveness of a single protective measure is difficult and can be somewhat speculative. However, the implementation of a set of complementary protective measures can contribute to confidence building. Since a set of protective measures increases the chance that future generations might recognise the rationale behind detected and encountered provisions or at least warn them against further actions. Again, any predictions regarding the actions of future generations with respect to protective measures are arbitrary.

As a consequence, the establishment of a multi-measure system that considers different kinds of protective measures from all the discussed categories above seems to be an appropriate strategy in the context of IHI.

The radioactivity of the emplaced waste decreases markedly with time due to the radioactive decay. However, the half-lives of the radionuclides in the radioactive waste vary widely. Although many radionuclides decay substantially early in the evolution of a disposal facility, others will persist for much longer. In either case, a delay of IHI can contribute to the reduction of radiological consequences. Figure 9.6 shows an example of the decrease of the radioactivity over time after emplacement, using different loads of a waste cask. It is obvious that especially over the first 1,000 years the decrease of the radioactivity is considerable, with the activity decreasing disproportionately in the initial phase. The longer the delaying protective measures are effective, the less is the activity of the radionuclides remaining in the repository, and hence the lower the radiological consequences should inadvertent human intrusion occur.
Figure 9.6 Double-logarithmic chart of the decrease of the specific activity of different loads of a POLLUX cask, with an inset for the POLLUX-10 (PWR-UO2) cask with linear scale of the axes [GRS 2014]

There are some protective measures that are considered generally as effective. Those protective measures are the construction of disposal facilities in deep geological formations; preservation of information and knowledge of the facility and its hazard; and providing for active and passive institutional control.

Institutional controls represent an essential line of protection for most near surface disposal facilities. Performing institutional controls should be supported by establishing strong conditions. Each responsible organisation should take the appropriate steps to ensure that financial provision is made which will enable the appropriate institutional controls and monitoring arrangements to be continued for the period deemed necessary following the closure of a disposal facility. The organisation which will be responsible for performing or maintaining institutional controls needs to have the power, competence and capability to follow the given mandate.

Finally it has to be re-stated that IHI is a key concern for near-surface facilities. Compared to deep geological disposal, near-surface facilities are more vulnerable for IHI. However, near-surface facilities are predominantly designed for the disposal of radioactive waste with less radioactivity such as very low level waste and low level waste. Deep geological disposal, on the other hand, is conceived on the principle of containing and isolating the waste, where isolation means keeping the
major part of the waste and its associated hazard away from the biosphere, making IHI to the waste difficult.

Nevertheless, the possibility of IHI can never be completely eliminated for either type of facility, due to the uncertain evolution of human societies, but protective measures can be taken to reduce both its potential and consequences. These protective measures are determined as part of the wider process of optimisation, optimisation being an integrative process covering all aspects of the development of a disposal facility (site characterisation, design, RD&D and safety assessment).

Some protective measures might be straightforward to apply since they have little impact on other aspects of the facility. Some, on the other hand, are less straightforward because they impact directly on other factors that are considered in the optimisation process (including the overall safety, feasibility and effectiveness). The boundary conditions for the optimisation process also need to be taken into account, these include, for example, socio-economic factors, including policy decisions and societal acceptance issues (see section 7).

Due weight should be given to each of these interrelated factors so that optimisation can proceed and a successful final outcome be obtained that addresses the input from all interested parties.
10. CONCLUSIONS

Disposal of radioactive waste aims to protect people and the environment from the potential hazards of the materials by removing the wastes from the human environment. This approach is considered desirable in comparison to the dispersal of the waste in the environment. However, the waste becomes concentrated in one location, which poses potential hazards should the waste become disturbed at a future date. For radioactive waste, it is generally expected that in preparing safety cases for such disposal facilities, the possibility of the wastes being inadvertently disturbed at some point in the future and the potential consequences of such an intrusion need to be considered.

The IAEA, ICRP and OECD agree that only inadvertent human actions that may impact a disposal facility need to be considered. This is because today’s society cannot be expected to protect future societies from their own intentional and planned activities if they are aware of the consequences. This is valid irrespective of the intent of the planned actions, i.e. regardless of whether they are carried out for benevolent or malicious reasons. International recommendations and national regulations generally state that in the safety case human intrusion scenarios should be considered separately to the normal evolution scenarios. In particular, and especially for geological disposal facilities, it may not be required to demonstrate compliance with any dose constraints for the human intrusion scenarios. Rather, the potential consequences arising from human intrusion are considered in the context of identifying opportunities to reduce the potential for and/or consequences of human intrusion and, where appropriate, for opportunities to enhance the robustness of the disposal facility.

The HIDRA project has developed a general approach for the consideration of inadvertent human intrusion in the safety cases for radioactive waste disposal facilities, addressing both geological disposal facilities and near-surface disposal facilities. The project specifically addressed differences in the approaches for addressing intrusion for the two general classes of disposal. The approach developed to consider inadvertent intrusion is intended for application in an iterative manner that supports decision-making throughout the lifecycle of a disposal facility. The general focus of the approach is to identify and consider the effectiveness of different measures that may be adopted to reduce the potential for and/or consequences of human intrusion to improve the robustness of the disposal facility.

Geological disposal, at depths of several hundred metres, is typically selected as the preferred route for those wastes that require long-term isolation from the human environment, typically higher activity and long-lived wastes (including spent nuclear fuel, high-level waste and long-lived intermediate-level wastes). Disposing of such wastes at depth is the most effective means of ensuring that these materials are not inadvertently disturbed at some future point. The choice of a geological disposal facility substantially reduces the potential for and/or consequences of intrusion into the facility.

Near-surface disposal, at depths of maybe a few tens of metres, is typically selected for low-level wastes. Some low-level wastes can pose significant hazards
should intrusion occur in the first hundreds of years. Generally, waste acceptance
criteria are applied to determine whether wastes are suitable for near-surface disposal.
For these wastes, the aim is to remove the materials from the human environment for
a sufficient length of time until the natural process of radioactive decay has reduced
the level of radioactivity in the wastes to acceptable levels. Thus the strategy for
mitigating the potential hazard of human intrusion into a near-surface facility is to
implement measures to preclude scenarios or delay the time at which an intrusion
event could occur for sufficient time to ensure that the consequences of any intrusion
would be acceptable. This is achieved by the application of appropriate waste
acceptance criteria and operational controls and by maintaining institutional controls
at the near-surface disposal facility after closure.

The HIDRA project included direct ties to the lifecycle considerations for a
safety case as discussed in the IAEA PRISM project. The potential for human
intrusion is one of the considerations that need to be addressed as part of decision-
making and development of the safety case throughout the lifecycle of a disposal
facility. This starts with the choice of facility concept, dependent on the waste type
and the length of time for which the waste needs to be isolated and contained. Human
intrusion considerations play a role in the siting of a disposal facility, with locations
where the waste is less likely to be disturbed being favoured where possible. For
geological disposal this will typically mean siting the facility away from potential
mineral resources that could lead to drilling or mining into the facility. For near-
surface disposal, remote locations away from populated areas will be favoured to
reduce the potential for inadvertent intrusion. Human intrusion considerations may
also influence the design and operation of a disposal facility, for example the layout,
choice of engineered barriers and emplacement strategies for certain waste-streams.

After the depth of disposal, the most effective means for reducing the potential
for inadvertent human intrusion is to maintain control and knowledge of the facility
and the potential hazard it contains. Active controls of the disposal facility are
assumed to preclude inadvertent intrusion. Active controls (sometimes referred to as
institutional control or oversight) mean the facility is managed securely such that any
access to the site is controlled. Active controls will be in place during construction,
operation, sealing and closure of all disposal facilities. Following closure of the
facility, especially for near-surface disposal, there is also likely to be a period of
further active control when access to the site is controlled. (This may also be
associated with a period of monitoring of the facility.) For near-surface disposal
facilities, the period of post-closure active control may be defined in the disposal
facility licence or permit and may be linked to the waste acceptance criteria. For
geological disposal facilities, regulations generally require demonstration of passive
safety, i.e. the facility must be demonstrated to be safe without the reliance on any
ongoing human management or intervention. However, there can also be a period of
post-closure institutional control for which credit may be taken in the safety case.

After active controls have been withdrawn there may be a further period where
passive controls are still effective. Passive controls typically include land use
restrictions and institutional memory and knowledge of the facility and its potential
Such passive controls can further delay the timing until inadvertent human intrusion becomes credible. Knowledge of the disposal facility is generally expected to be maintained through local, national and international records. The HIDRA project considered a number of approaches for extending the time frame where knowledge of the facility is maintained. Assumptions regarding the effective duration of passive controls is one area where approaches vary in different countries. Suitably designed markers at the site may also act to warn future generations of the potential hazard. However there is also a school of thought that believes such markers could have the reverse effect of arousing curiosity about the site.

Safety arguments regarding the discussion of human intrusion events in a safety case are likely to focus on the length of time for which any inadvertent human intrusion event can be regarded as being extremely unlikely. Credit can then be taken for the radioactive decay of the wastes, reducing their potential hazard, during the period of isolation. Passive controls may also be more effective in precluding certain scenarios that would require permitting or other regulatory approvals (e.g., road construction or major public works, mine development). The ways in which societal control of a disposal facility and the design safety features of the facility operate through the period of active control, passive control and eventual loss of memory of the hazardous nature of the site are summarised in Table 10.1.

<table>
<thead>
<tr>
<th>Time Frames</th>
<th>Active Control</th>
<th>Passive Control</th>
<th>Loss of Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Societal Control</td>
<td>Physical security at site</td>
<td>Knowledge management, records,</td>
<td>No knowledge of hazardous nature of site</td>
</tr>
<tr>
<td></td>
<td></td>
<td>land use restrictions, site</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>markers</td>
<td></td>
</tr>
<tr>
<td>Design safety</td>
<td>Depth of disposal, barriers</td>
<td>Depth of disposal, barriers</td>
<td>Depth of disposal, barriers may be degrading</td>
</tr>
<tr>
<td>features</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implications for</td>
<td>No IHI</td>
<td>IHI unlikely – safety case can</td>
<td>IHI is a possibility, but may still be mitigated</td>
</tr>
<tr>
<td>potential for IHI</td>
<td></td>
<td>justify exclusion of major IHI</td>
<td>by enduring design safety features</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scenarios</td>
<td></td>
</tr>
<tr>
<td>Hazard of facility</td>
<td>Disposal inventory</td>
<td>Decaying inventory</td>
<td>Decay may be significant for near-surface, low-level waste facilities</td>
</tr>
</tbody>
</table>

TABLE 10.1. Summary of time frames and different considerations related to inadvertent intrusion.
After presenting safety arguments for the low potential for inadvertent human intrusion into a disposal facility, the safety case will nevertheless generally be required to give consideration to the possible consequences should human intrusion occur.

It is generally internationally accepted (e.g. IAEA SSG-23 para 6.61) that human intrusion should be addressed by considering stylised scenarios. These stylised scenarios should be based on current practices and present day technologies and procedures to avoid the need to speculate about possible future human behaviour and technology. Such stylised human intrusion scenarios are therefore not intended to convey any statement about the evolution of the site or future societal activities, they are merely designed to provide illustrations of potential impacts of human intrusion.

The HIDRA project has identified the following human intrusion scenarios for consideration:

- For geological disposal facilities: deep drilling, sub-surface mining, unconventional (solution rock) mining;
- For near-surface disposal facilities: drilling, excavation (residence), excavation (road).

For near-surface disposal facilities, quantitative assessments of the consequences of human intrusion scenarios may also be used to establish waste acceptance criteria (i.e. to determine whether a given waste-stream requires deeper disposal), design criteria, operational practices and the necessary time frames for institutional controls.

The use of stylised scenarios also provides a basis for the identification of potential measures that could be considered to mitigate the potential for and/or consequences associated with the human intrusion scenarios.

The HIDRA project has identified a framework for considering the benefits of potential protective measures to mitigate against the potential impacts of inadvertent human intrusion. The following criteria have been identified for the consideration of any measures:

- Measures must not obviously compromise the safety of the disposal facility (i.e. they must not compromise the primary safety targets for the disposal facility).
- Measures must not lead to other undue hazards to people and the environment.
- Measures have to follow the principle of proportionality regarding benefits, efforts and costs, which will be considered as part of the overall optimisation of the disposal facility.

In particular, when considering a potential protective measure against human intrusion it should be considered whether it would cause any negative impacts on the
normal evolution scenario. For example, the introduction of metal barriers above the wastes in a near-surface disposal facility may reduce the potential for inadvertent human intrusion by diverting any excavation tools, however potential disruptions to safety functions resulting from expansion or gas generation from the corrosion of the metal may need to be considered. In all cases, the primary focus of the safety case is on the normal evolution scenarios and optimisation with regard to human intrusion impacts is considered secondary to optimising the safety of the normal evolution of the facility.

In summary, the most effective measures against inadvertent human intrusion involve establishing the disposal facility in deep geological formations, establishing suitable siting criteria, providing for long-term knowledge preservation regarding the hazard at the site and implementing design measures that reduce the potential for human intrusion without negatively impacting the normal evolution of the disposal facility.
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HIDRA

FINAL DRAFT JANUARY 2017


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ANNEX A. Database on possible protective measures

Worksheet a) Description of Database of Entries

<table>
<thead>
<tr>
<th>Entry (No.)</th>
<th>Reference</th>
<th>Explanation</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Objective</td>
<td>Reduction of the possibility of intrusion</td>
<td>Measures with focus on a specific objective</td>
</tr>
<tr>
<td>1.2</td>
<td>Reduction of the radiological consequences</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Position</td>
<td>External measures</td>
<td>Reference on measures outside the disposal system or be applied</td>
</tr>
<tr>
<td>2.2</td>
<td>Internal measures</td>
<td>Reference on measures inside the disposal system or be activated</td>
<td>Inserting of resistances against tunneling/mining techniques</td>
</tr>
<tr>
<td>3.1</td>
<td>Action</td>
<td>Passive measures</td>
<td>Reference on measures which need no further actions and maintenance if they are once</td>
</tr>
<tr>
<td>3.2</td>
<td>Active measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Type</td>
<td>Regulative measures</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Constructive measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Planning measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Conceptual measures</td>
<td>Measures which require a planning realisation regarding implementation and place of installation</td>
<td>Placement of the repository (repository depth)</td>
</tr>
<tr>
<td>5.1</td>
<td>Delaying</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Characteristic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>Indicating, informing, warning</td>
<td>Measures which can have a respective effect</td>
<td>Optical indicators (fluorescent colours, phosphorescent materials)</td>
</tr>
<tr>
<td>5.4</td>
<td>Aggravating, hindering, defending</td>
<td>Increase of the cask wall thickness</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>Controlling, guarding</td>
<td>Safeguards</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Dependence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Depending on the specific human action</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>Basic action</td>
<td>Borehole drilling</td>
<td>Reference to a specific basic action</td>
</tr>
<tr>
<td>7.2</td>
<td>Construction of a mine</td>
<td>Creation of a cavern</td>
<td>Usage of difficulty soluble fixtures</td>
</tr>
<tr>
<td>7.4</td>
<td>Excavation/ Blasting/ Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.1</td>
<td>Assessment: benefit/ cost</td>
<td>Medium</td>
<td>Evaluation of the effectiveness of respective measures</td>
</tr>
<tr>
<td>8.2</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.1</td>
<td>Assessment: effort</td>
<td>Great</td>
<td>Evaluation of the expected effort in conjunction with respective measures</td>
</tr>
<tr>
<td>9.2</td>
<td>Medium</td>
<td>Construction of a drift backfilled with robust material/rock</td>
<td>Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, uranium</td>
</tr>
<tr>
<td>9.3</td>
<td>Little</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.1</td>
<td>Assessment: availability</td>
<td>Long-term</td>
<td>Evaluation of the temporal availability of respective measures (for deep geological disposal e.g. from few thousand years to the demonstration period and longer)</td>
</tr>
<tr>
<td>10.2</td>
<td>Medium-term</td>
<td>Evaluation of the temporal availability of respective measures (depending of the disposal facility e.g. from loss of the memory to several hundred years up to a few thousand years)</td>
<td>Inserting of rubber mats in the emplacement drifts</td>
</tr>
<tr>
<td>10.3</td>
<td>Short-term</td>
<td>Monitoring of the environment</td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>Optimisation conflict</td>
<td>Existing</td>
<td>Assessment of the measure regarding optimisation conflicts (e.g. the measure might compromise the safety of the disposal system)</td>
</tr>
<tr>
<td>No.</td>
<td>Possible optimisation measures</td>
<td>Sub-category</td>
<td>Reference</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------</td>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Waste types and characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Waste conditioning (general)</td>
<td>E1 Waste reduction</td>
<td>No Relation</td>
</tr>
<tr>
<td>E3</td>
<td>Transmutation (general)</td>
<td>E8 Mitigate toxicity</td>
<td>No Relation</td>
</tr>
<tr>
<td>E4</td>
<td>Waste acceptance criteria (general)</td>
<td>E8 Regulations</td>
<td>No Relation</td>
</tr>
<tr>
<td>E5</td>
<td>Waste recycling (general)</td>
<td>E8 Mitigate toxicity</td>
<td>No Relation</td>
</tr>
<tr>
<td>E6</td>
<td>Selection of radioactive waste inventory</td>
<td>E8 Regulations</td>
<td>No Relation</td>
</tr>
<tr>
<td>E7</td>
<td>Waste employment strategy</td>
<td>E8 Mitigate toxicity</td>
<td>No Relation</td>
</tr>
<tr>
<td>D</td>
<td>Siting</td>
<td>D1 Site Alteration</td>
<td>No Relation</td>
</tr>
<tr>
<td>D2</td>
<td>Select regions with sparse population</td>
<td>D1 Site Conditions</td>
<td>No Relation</td>
</tr>
<tr>
<td>D3</td>
<td>Choose underexploited regions, rough terrain</td>
<td>D1 Site Conditions</td>
<td>No Relation</td>
</tr>
<tr>
<td>D4</td>
<td>Locate disposal boreholes at a site with an existing security infrastructure, e.g. at an existing NPP (Ref. SSG-1)</td>
<td>D1 Site Alteration</td>
<td>No Relation</td>
</tr>
<tr>
<td>D5</td>
<td>Avoiding of resources (minerals)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D6</td>
<td>Avoiding of resources (groundwater)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D7</td>
<td>Avoiding of resources (crude oil)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D8</td>
<td>Avoiding of resources (gas, shale gas)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D9</td>
<td>Avoiding of resources (geothermal energy)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D10</td>
<td>Avoiding of resources (natural mineral deposits)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D11</td>
<td>Avoiding of resources (biodegradable materials)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D12</td>
<td>Avoiding of resources (area of outstanding natural beauty)</td>
<td>D1 Avoiding Resources</td>
<td>No Relation</td>
</tr>
<tr>
<td>D13</td>
<td>Selection of host rocks (geological formations) with self-healing properties</td>
<td>D1 Site Conditions</td>
<td>No Relation</td>
</tr>
<tr>
<td>D14</td>
<td>Adding substances to potential resources to make them useless</td>
<td>D1 Site Alteration</td>
<td>No Relation</td>
</tr>
<tr>
<td>D15</td>
<td>Development of the site as a recreational area that might be perceived by future generations</td>
<td>D1 Site Alteration</td>
<td>No Relation</td>
</tr>
<tr>
<td>D16</td>
<td>Avoiding sites which are prone to erosion</td>
<td>D1 Site Conditions</td>
<td>No Relation</td>
</tr>
<tr>
<td>C</td>
<td>Knowledge management</td>
<td>C1 Preservation and archiving</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C2 Establishment of an information center at the site</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C3 Archiving and documentation (local, regional, national, global)</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C4 Implementation of a commemoration day</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5 Adoption of the issue in the education programme</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6 Creation/maintenance of stringent conditions for the preservation of information and knowledge (organisational structure, financing requirements, national agreements, int. agreements)</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C7 Verify preserved information regarding potential changes in language and provide a translation document</td>
<td>C1 Preservation and Archiving</td>
</tr>
<tr>
<td>No.</td>
<td>Possible optimisation measures</td>
<td>4. Type</td>
<td>5. Characteristic</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------</td>
<td>---------</td>
<td>------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1 Regulative measures</td>
<td>4.2 Constructive measures</td>
</tr>
<tr>
<td>E1</td>
<td>Reducing the waste volume</td>
<td>No Relation</td>
<td>X</td>
</tr>
<tr>
<td>E2</td>
<td>Waste conditioning (general)</td>
<td>No Relation</td>
<td>X</td>
</tr>
<tr>
<td>E3</td>
<td>Transformation (general)</td>
<td>No Relation</td>
<td>X</td>
</tr>
<tr>
<td>E4</td>
<td>Waste acceptance criteria (general)</td>
<td>No Relation</td>
<td>X</td>
</tr>
<tr>
<td>E5</td>
<td>Waste recycling (general)</td>
<td>No Relation</td>
<td>X</td>
</tr>
<tr>
<td>E6</td>
<td>Selection of radioactive waste inventory</td>
<td>No Relation</td>
<td>X</td>
</tr>
<tr>
<td>E7</td>
<td>Waste emplacement strategy</td>
<td>No Relation</td>
<td>X</td>
</tr>
</tbody>
</table>

**D**

| D1  | Alteration of the landscape (difficult to develop) | No Relation | X | X | X |
| D2  | Choose regions with sparse population | No Relation | X | X | X |
| D3  | Choose underdeveloped regions, rough terrain | No Relation | X | X | X |
| D4  | Locating disposal boreholes at a site with an existing security infrastructure, e.g. at an existing NPP (Ref. SSG-1) | Borehole Disposal | X | X | X |
| D5  | Avoiding of resources (minerals) | No Relation | X | X | X |
| D6  | Avoiding of resources (groundwater) | No Relation | X | X | X |
| D7  | Avoiding of resources (crude oil) | No Relation | X | X | X |
| D8  | Avoiding of resources (gas, shale gas) | No Relation | X | X | X |
| D9  | Avoiding of resources (geo-thermal energy) | No Relation | X | X | X |
| D10 | Avoiding of resources (natural mineral deposits) | No Relation | X | X | X |
| D11 | Avoiding of resources (pure mineral ores) | No Relation | X | X | X |
| D12 | Avoiding of resources (area of outstanding natural beauty) | No Relation | X | X | X |
| D13 | Selection of host rocks (geological formations) with self-healing properties | Underground Disposal Facility | X | X | X |
| D14 | Adding substances to potential resources to make them useless | No Relation | X | X | X |
| D15 | Development of the site as a recreational area that might be preserved by future generations | Underground Disposal Facility | X | X | X |
| D16 | Avoiding sites which are prone to erosion | No Relation | X | X | X |

**C**

<p>| C1  | Preservation of information and knowledge | No Relation | X | X | X |
| C2  | Establishment of an information center at the site | No Relation | X | X | X |
| C3  | Archiving and documentation (local, regional, national, global) | No Relation | X | X | X |
| C4  | Implementation of a commemoration day | No Relation | X | X | X |
| C5  | Adoption of the issue in the education programme | No Relation | X | X | X |
| C6  | Creation/maintenance of strong conditions for the preservation of information and knowledge (organisational structure, financing, requirements, national agreements, int. agreements) | No Relation | X | X | X |
| C7  | Verify preserved information regarding potential changes in language and provide a translation document | No Relation | X | X | X |
|-----|--------------------------------|-----------------|----------------------------|----------------------|
|     |                                | 7.1 Borehole drilling | 7.2 Creation of a cavern | 7.3 Construction of a mine | 7.4 Excavation/ Blasting/ Others | 7.5 General (no reference to a specific basic action) | 8.1 High | 8.2 Medium | 8.3 Low | 9.1 Great | 9.2 Medium | 9.3 Little |
| E   | Waste types and characteristics |                |                            |                      |                                  |                                    |            |            |         |          |            |            |
| E1  | Reducing the waste volume | No Relation | X | X | X | X | X |
| E2  | Waste conditioning (general) | No Relation | X | X | X | X | X |
| E3  | Transformation (general) | No Relation | X | X | X | X | X |
| E4  | Waste acceptance criteria (general) | No Relation | X | X | X | X | X |
| E5  | Waste recycling (general) | No Relation | X | X | X | X | X |
| E6  | Selection of radioactive waste inventory | No Relation | X | X | X | X | X |
| E7  | Waste emplacement strategy | No Relation | X | X | X | X | X |
| D   | Siting |                |                            |                      |                                  |                                    |            |            |         |          |            |            |
| D1  | Alteration of the landscape (difficult to develop) | No Relation | X | X | X | X | X |
| D2  | Choose regions with sparse population | No Relation | X | X | X | X | X |
| D3  | Choose underdeveloped regions, rough terrain | No Relation | X | X | X | X | X |
| D4  | Locating disposal boreholes at a site with an existing security infrastructure, e.g. at an existing NPP (Ref. SSG-1) | Borehole Disposal | X | X | X | X | X |
| D5  | Avoiding of resources (minerals) | No Relation | X | X | X | X | X |
| D6  | Avoiding of resources (groundwater) | No Relation | X | X | X | X | X |
| D7  | Avoiding of resources (crude oil) | No Relation | X | X | X | X | X |
| D8  | Avoiding of resources (gas, shale gas) | No Relation | X | X | X | X | X |
| D9  | Avoiding of resources (geothermal energy) | No Relation | X | X | X | X | X |
| D10 | Avoiding of resources (natural mineral deposits) | No Relation | X | X | X | X | X |
| D11 | Avoiding of resources (petroleum deposits) | No Relation | X | X | X | X | X |
| D12 | Avoiding of resources (area of outstanding natural beauty) | No Relation | X | X | X | X | X |
| D13 | Selection of host rocks (geological formations) with self-healing properties | Underground Disposal Facility | X | X | X | X | X |
| D14 | Adding substances to potential resources to make them useless | No Relation | X | X | X | X | X |
| D15 | Development of the site as a recreational area that might be preserved by future generations | No Relation | X | X | X | X | X |
| D16 | Avoiding sites which are prone to erosion | No Relation | X | X | X | X | X |
| C   | Knowledge management |                |                            |                      |                                  |                                    |            |            |         |          |            |            |
| C1  | Preservation of information and knowledge | No Relation | X | X | X | X | X |
| C2  | Establishment of an information center at the site | No Relation | X | X | X | X | X |
| C3  | Archiving and documentation (local, regional, national, global) | No Relation | X | X | X | X | X |
| C4  | Implementation of a commemoration day | No Relation | X | X | X | X | X |
| C5  | Adoption of the issue in the education programme | No Relation | X | X | X | X | X |
| C6  | Creation/maintenance of strong conditions for the preservation of information and knowledge (organisational structure, financing, requirements, national agreements, int. agreements) | No Relation | X | X | X | X | X |
| C7  | Verify preserved information regarding potential changes in language and provide a translation document | No Relation | X | X | X | X | X |</p>
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<th>No.</th>
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<th>10. Assessment: availability</th>
<th>11. Optimisation conflict</th>
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<td>10.1 Long-term</td>
<td>10.2 Medium-term</td>
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<td>Waste types and characteristics</td>
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<td>Selection of radioactive waste inventory</td>
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<td>E7</td>
<td>Waste emplacement strategy</td>
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<td>D</td>
<td>Siting</td>
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<td>D1</td>
<td>Alteration of the landscape (difficult to develop)</td>
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<td>D2</td>
<td>Choose regions with sparse population</td>
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<tr>
<td>D3</td>
<td>Choose underdeveloped regions, rough terrain</td>
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<td>D4</td>
<td>Locating disposal boreholes at a site with an existing security</td>
<td>Borehole Disposal</td>
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<td>infrastructure, e.g. at an existing NPP (Ref: SSG-1)</td>
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<td>D5</td>
<td>Avoiding of resources (minerals)</td>
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<td>D6</td>
<td>Avoiding of resources (groundwater)</td>
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<td>D7</td>
<td>Avoiding of resources (crude oil)</td>
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<td>D8</td>
<td>Avoiding of resources (gas, shale gas)</td>
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<td>D9</td>
<td>Avoiding of resources (geothermal energy)</td>
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<td>D10</td>
<td>Avoiding of resources (natural mineral deposits)</td>
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<td>D11</td>
<td>Avoiding of resources (historical places)</td>
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<td>D12</td>
<td>Avoiding of resources (area of outstanding natural beauty)</td>
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<td>D13</td>
<td>Selection of host rocks (geological formations) with self healing</td>
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<td>properties</td>
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<td>D14</td>
<td>Adding substances to potential resources to make them useless</td>
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<td>D15</td>
<td>Development of the site as a recreational area that might be</td>
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<td>preserved by future generations</td>
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<tr>
<td>D16</td>
<td>Avoiding sites which are prone to erosion</td>
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<td>Knowledge management</td>
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<td>C3</td>
<td>Archiving and documentation (local, regional, national, global)</td>
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<td>C4</td>
<td>Implementation of a commemoration day</td>
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<td>C5</td>
<td>Adoption of the issue in the education programme</td>
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<td>C6</td>
<td>Creation/maintenance of strong conditions for the preservation of</td>
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<td>information and knowledge (organisational structure, financing,</td>
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<td>requirements, national agreements, int. agreements</td>
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<tr>
<td>C7</td>
<td>Verify preserved information regarding potential changes in language</td>
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<td>and provide a translation document</td>
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Worksheet b-2) Database of Collected Measures (Category A and B)

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<th>Sub-category</th>
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<th>1. Objective</th>
<th>2. Position</th>
<th>3. Action</th>
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<td>B1 Designing</td>
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<td>B4</td>
<td>Inserting of resistances against tunnelling/mining techniques</td>
<td>B8 Increasing Resistance</td>
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<td>X</td>
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<td>B5</td>
<td>Increase of the cave wall thickness</td>
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<td>Inserting of a multi-layered concrete slab near surface</td>
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<tr>
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<td>Construction of a shaft backfilled with robust material/silts</td>
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<td>X</td>
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<td>B8</td>
<td>Inserting of indicators for attracting attention, pointing at existing anomalies, sensitizing</td>
<td>B8 Using Indicators</td>
<td>no Relation</td>
<td>X</td>
<td>X</td>
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<tr>
<td>B9</td>
<td>Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, urine</td>
<td>B8 Using Indicators</td>
<td>no Relation</td>
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<td>Chemical indicators (colouring/chemical reaction in the air, e.g. indigo)</td>
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<td>no Relation</td>
<td>X</td>
<td>X</td>
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<td>B11</td>
<td>Biological indicators</td>
<td>B8 Using Indicators</td>
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<tr>
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<td>Chemical indicators (fluorescent colours, phosphorescent materials)</td>
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<td>no Relation</td>
<td>X</td>
<td>X</td>
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<tr>
<td>B13</td>
<td>Acoustic indicators (set off upon contact with fluids, light, touch, etc.)</td>
<td>B8 Using Indicators</td>
<td>no Relation</td>
<td>X</td>
<td>X</td>
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<td>B14</td>
<td>Magnetic indicators</td>
<td>B8 Using Indicators</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>B15</td>
<td>Optical indicators (luminous-organic compounds, mecoprop, a.g. vapourisation of volatile substances)</td>
<td>B8 Using Indicators</td>
<td>no Relation</td>
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<td>Seismic indicators</td>
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<td>Construction of a borehole top seal, borehole plug made of robust material</td>
<td>B8 Increasing Resistance</td>
<td>no Relation</td>
<td>X</td>
<td>X</td>
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<tr>
<td>B18</td>
<td>Inserting of rubber mats in the emplacement drifts</td>
<td>B8 Increasing Resistance</td>
<td>no Relation</td>
<td>X</td>
<td>X</td>
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<td>B19</td>
<td>Warnings, labelling in the emplacement area</td>
<td>B8 Using Indicators</td>
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<td>Specific shaped casings which might deflect borehole driftings</td>
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<td>Inserting a layer of rubble</td>
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<td>Inserting a layer of layers</td>
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<td>Barrier Mounts</td>
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</table>

A) Monitoring/ Surveillance

<p>| A1 | Institutional control | A1 Control and Surveillance | no Relation | X | X | X | X |
| A2 | Surveillance (site inspection, satellite-based) | A1 Control and Surveillance | no Relation | X | X | X | X |
| A3 | Monitoring of the environment | A1 Control and Surveillance | no Relation | X | X | X | X |
| A4 | Restriction of land use, development freeze | A2 Restriction | no Relation | X | X | X | X |
| A5 | Designation as prohibited zone | A2 Restriction | no Relation | X | X | X | X |
| A6 | Safeguarding | A2 Control and Surveillance | no Relation | X | X | X | X |
| A7 | Control of land ownership | A2 Restriction | no Relation | X | X | X | X |
| A8 | Markers and monuments | A2 Marking | no Relation | X | X | X | X |
| A9 | Sights, fences and gates at sites | A2 Marking | no Relation | X | X | X | X |
| A10 | Small number of large rocks | A2 Marking | no Relation | X | X | X | X |
| A11 | many small markers | A2 Marking | no Relation | X | X | X | X |</p>
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<th>4.1 Regulative measures</th>
<th>4.2 Constructive measures</th>
<th>4.3 Planning measures</th>
<th>4.4 Conceptual measures</th>
<th>5.1 Delaying</th>
<th>5.2 Deterring, preventing, restricting</th>
<th>5.3 Indicating, informing, warning</th>
<th>5.4 Aggravating, hindering, defending</th>
<th>5.5 Controlling, guarding</th>
<th>6.1 Depending on the spec. human action</th>
<th>6.2 Independent of the spec. human action</th>
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<td>Repository dimensions (reduction of spatial expansion)</td>
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<tr>
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<td>Inserting of resistances against tunneling/mining techniques</td>
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<td>Inserting of a reinforced concrete slab near surface</td>
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<td>X</td>
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<td>Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, X</td>
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<tr>
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<td>Acoustic indicators (set off upon contact with fluids, light, touch, etc.)</td>
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<tr>
<td>B15</td>
<td>Olfactory indicators (sulphuric-organic compounds, mercaptane, e.g. odourisation of natural gas)</td>
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<tr>
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<td>Construction of a borehole top seal, borehole plug made of robust material</td>
<td>Borehole Disposal</td>
<td>X</td>
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<td>Inserting of rubber mats in the emplacement drifts</td>
<td>Underground Disposal Facility</td>
<td>X</td>
<td>X</td>
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<td>Warning, labelling in the emplacement area</td>
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<td>Usage of difficulty soluble materials</td>
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<td>Inserting of a reinforced concrete slab near surface</td>
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<td>Construction of a drift backfilled with robust material/rock</td>
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<td>Inserting of indicators for attracting attention, painting at existing anomalies, sensing</td>
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<td>B9</td>
<td>Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid,</td>
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<td>Chemical indicators (colouring through oxidation with oxygen in the air, e.g. indigo)</td>
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<td>Optical indicators (fluorescent colours, phosphorescent materials)</td>
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<td>Acoustic indicators (set off upon contact with fluids, light, touch, etc.)</td>
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<td>Olfactory indicators (sulphur-organic compounds, mercaptane, e.g. odoration of natural gas)</td>
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<td>B17</td>
<td>Construction of a borehole top seal, borehole plug made of robust material</td>
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<td>Inserting of rubber mats in the emplacement drills</td>
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<td>Usage of difficulty soluble fixtures</td>
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<td>Specific shaped casings which might deflect borehole drillings</td>
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<td>Inserting a layer of rubble</td>
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<td>B1</td>
<td>Design of disposal facilities and engineering barriers</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B2</td>
<td>Placement of the repository (repository depth)</td>
<td>Underground Disposal Facility</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B3</td>
<td>Repository dimensions (reduction of spatial expansion)</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B4</td>
<td>Waste separation, compartmentalisation, encapsulation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B5</td>
<td>Inserting of resistances against tunnelling/mining techniques</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B6</td>
<td>Increase of the cask wall thickness</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B7</td>
<td>Inserting of a reinforced concrete slab near surface</td>
<td>Underground Disposal Facility</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B8</td>
<td>Construction of a drift backfilled with robust material/rock</td>
<td>Underground Disposal Facility</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B9</td>
<td>Inserting of indicators for attracting attention, pointing at existing anomalies, sensitising</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B10</td>
<td>Colour indicators that react upon contact with a liquid and cause e.g. colouring of the fluid, scannine</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B11</td>
<td>Chemical indicators (colouring through oxidation with oxygen in the air, e.g. indigo)</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<tr>
<td>B12</td>
<td>Biological indicators</td>
<td>No Relation</td>
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<tr>
<td>B13</td>
<td>Optical indicators (fluorescent colours, phosphorescent materials)</td>
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<td>No Relation</td>
<td>No Relation</td>
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<td>B14</td>
<td>Acoustic indicators (set off upon contact with fluids, light, touch, etc.)</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B15</td>
<td>Magnetic indicators</td>
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<td>B16</td>
<td>Olfactory indicators (sulphuric-organic compounds, mercaptane, e.g. odourisation of natural gas)</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B17</td>
<td>Emittting indicators</td>
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<td>B18</td>
<td>Construction of a borehole top seal, borehole plug made of robust material</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B19</td>
<td>Inserting of rubber mats in the emplacement drills</td>
<td>Underground Disposal Facility</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B20</td>
<td>Warnings, labelling in the emplacement area</td>
<td>No Relation</td>
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<td>B21</td>
<td>Usage of difficulty soluble fixtures</td>
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<td>B22</td>
<td>Specific shaped casings which might deflect borehole drillings</td>
<td>No Relation</td>
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<td>B23</td>
<td>Inserting a layer of rubble</td>
<td>Underground Disposal Facility</td>
<td>No Relation</td>
<td>No Relation</td>
<td>No Relation</td>
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<td>B24</td>
<td>Barrier Mounds</td>
<td>Underground Disposal Facility</td>
<td>No Relation</td>
<td>No Relation</td>
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**Monitoring/ Surveillance**

| A1  | Institutional control                                           | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A2  | Surveillance (site inspection, satellite-based)                 | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A3  | Monitoring of the environment                                   | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A4  | Restriction of land use, development freeze                     | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A5  | Designation as prohibited zone                                  | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A6  | Safeguards                                                      | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A7  | Controls of land ownership                                      | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A8  | Markers and monuments                                           | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A9  | Signs, fences and guards at sites                              | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A10 | Small number of large rocks                                    | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |
| A11 | Many small markers                                              | No Relation       | No Relation       | No Relation     | No Relation   | No Relation |