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Developing, Using and Modifying a Requirements Management System for Implementing a Disposal System

(DS-RMS)

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Executive summary

Within Work Package 12 (Guidance) of EURAD (European Joint Programme on Radioactive Waste Management), activities aim to develop a comprehensive suite of instructional guidance documents that can be used by EU Member States with radioactive waste management programmes, regardless of their phase or level of advancement with implementation of geological disposal.

In the course of EURAD, based on a review made by Work Package 12, it was decided to develop guidance on requirements management, because requirements management is recognised to be a very important activity for implementing waste management programmes / systems. The work package board together with the WP12 editorial board agreed to develop such guidance in a process with active involvement of end-users through a number of workshops and a training event. In this process, it was decided to develop three documents:

- a guidance document for generic waste management systems (EURAD 2024a),
- a document describing in more detail the development of requirements for disposal systems with a discussion of the post-closure safety case and its interaction with requirements management (this document),
- a guidance document for specific waste management programmes and with their different systems, taking the stepwise implementation of these systems into account (EURAD 2024b).

As all three documents are 'stand-alone' documents and each of them describing the same methodology ('the way of thinking') but each of them looking from a slightly different angel, there is some overlap between them on the more basic issues related to the requirements management methodology.

This document is for disposal systems with mainly looking at a deep geological repository for high-level radioactive waste as an example. Here, one of the key issues discussed is the interaction between the safety case (especially performance assessment) and the development of requirements related to post-closure safety. As in the other two guidance documents, the main emphasis is on methodological aspects ('*the way of thinking*') and describes the basic thoughts to be made when developing a disposal system.

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1. Introduction

1.1 Aims of the document

In **EURAD** (European Joint Programme on Radioactive Waste Management) it was decided to develop guidance on requirements management, because requirements management is recognised to be an important activity for implementing waste management programmes / systems. It was agreed to develop this guidance in a process with **active involvement of end-users** through a number of workshops and a training event. In this process, it was decided to develop **three documents**:

- a guidance document for generic waste management systems (EURAD 2024a),
- a document describing in more detail the development of requirements for disposal systems with a more extensive discussion of the post-closure safety case and its interaction with requirements management (this document),
- a guidance document for waste management systems, taking their stepwise implementation into account (EURAD 2024b).

As all the three documents are **'stand-alone' documents**, each of them describing the same methodology ('the way of thinking') but each of them looking from a slightly different angel, there is some overlap between them on the more basic issues related to the methodology.

The development of these documents profited very much from the lively interactions during the workshops and the training event and from the feedback through reviews of the draft versions of the reports. The document related to disposal systems was also shared with an NEA/IGSC 'Ad-hoc Group' on updating the 'Methods for Safety Assessment for Geological Disposal Facilities for Radioactive Waste (MeSA)'[1] with some of the members providing very valuable detailed comments. As discussions continue in applying requirements management in waste management programmes, most likely the EURAD documents will see some further updates – thus, the EURAD documents should for the time being seen as **'living documents'**.

This document '**Developing, using and modifying a requirements management system for implementing a disposal system**' (DS-RMS) has the purpose to provide guidance on requirements management, on the structure of requirement management systems and on developing, using and modifying a requirements management system. Its focus are **disposal systems,** mainly deep geological repositories (DGR). The document puts much emphasis on the **interaction between requirements management and the post-closure safety case**. This document is mainly for programmes working on disposal.

The target audience of this document are mainly the organisations that are in charge of **developing a disposal system**[2]. However, the document also considers the needs of all other stakeholders – thus, this document should be of main interest for the implementer / waste management organisation (WMO), but also interesting for all other stakeholders (regulator and the technical support organisation, responsible government agencies, civil society, etc.).

The document '**Guidance on Developing, Using and Modifying a Requirements Management System for Generic Waste Management Systems – G-RMS**' (EURAD 2024a) is for a generic system. The main aim of this guidance document is to **make the reader familiar with the key characteristics of requirements management** independent of what the reader wants to use the requirements

[1] In the meantime published (NEA, 2025).

[2] The words/terms 'disposal system' and 'repository' are interchangeable and are both used in this document.

management system for. Therefore, it contains no details about any system. As an appendix, it also contains a **literature review on requirements management**.

The guidance document '**Guidance on Developing, Using and Modifying a Requirements Management System for Waste Management Programmes with their Different Systems – WMP-RMS**' (EURAD 2024b) has also the purpose to provide guidance on requirements management, on the structure of requirement management systems and on developing, using and modifying a requirements management system but **with a clear focus on an overall waste management programme and on the different waste management systems**.

The two latter documents may be of special interest when not addressing disposal systems.

1.2 Introduction to requirements management and the aims of the document

Disposal systems are systems that consist of many elements that need to properly interact to make the systems functioning properly. Furthermore, most of the elements of disposal systems have several life cycle stages that need to be considered with some information in earlier stages not yet being fully defined. The **implementation of disposal systems** is thus a process that covers a broad range of interrelated issues involving a range of different disciplines; the corresponding disposal programme is thus a challenging process. Based on the positive experiences in many other complex projects (e.g., aerospace, aviation, communication, computer, energy (nuclear, other), defence, software development, etc.), **systems engineering** is considered to be a key element for being successful with such complex projects. Systems engineering can be defined as follows (quote from INCOSE, 2015):

"Systems engineering is an interdisciplinary approach and means to enable the realisation of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal[3]. Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation."

There is broad agreement in **systems engineering** (see e.g., INCOSE, 2015; NASA, 2020) that **requirements management** is an important element to support the implementation process of complex (interrelated) systems such as disposal systems. The view that requirements management is a key element to support the implementation of a disposal system is also shared by waste management organisations that are advanced in implementing their HLW repository (e.g. (in alphabetical order) Finland, France, Sweden, Switzerland and the UK).

The brief discussion of requirements management above indicates that the activities needed when planning, implementing and using waste management systems are essentially the same activities as performed in systems engineering and requirements management. Therefore, it is **recommended and justified** for waste management organisations (the **implementers**) to **develop and use a requirements management system.** This has been done by the waste management organisations with advanced HLW programmes, as using a requirements management system does not require additional activities but supports the systematic way of working with all the benefits mentioned above.

[3] In our terminology, this corresponds to managing the 'end-of-life'.

Good practice in systems engineering and requirements management requires to **work systematically in a structured manner and with discipline** according to the rules defined by the specific requirements methodology applied.

A systematic approach is essential, as it ensures several important issues, and thus, **requirements management** will create a range of **benefits**, e.g.:

- Ensuring **completeness and consistency** of the **information** needed, and of the **decisions** to be taken in the stepwise approach of developing and implementing a disposal system.
- Early detection of **wrong, conflicting and/or missing information** and **decisions**.
- Development of a **common understanding** of all the persons working in a disposal programme and supporting the structured interaction between them.
- Providing **transparency** at each stage of the project (‘*why, what, when, by whom, for whom, how, influenced by whom, …*’), with transparency helping to maintain an overview, and thus supporting **daily management**,
- Providing easy access to the **currently accepted ‘oversight’ information** as it replaces numerous individual documents by one system and thus **increases efficiency**,
- Providing **traceability** now and in future. Traceability is needed to manage **refinements and changes that are the rule** and not the exception for long-lasting projects such as disposal projects. Traceability allows to identify the features that need to be changed to cope with the refinements and changes needed. Traceability is also needed to investigate the overall effects of suggested / needed refinements and changes before their actual implementation. This allows to make some adaptions to the proposed refinements / changes, if needed.

  Traceability is also important for keeping a record of important decisions made as part of **knowledge management for future generations** to understand the ‘know why’, the ‘know what’ and the ‘know how’ these decisions were taken.
- Requirements management is a prerequisite for periodically assessing the **performance and the implementation feasibility** of the proposed waste management system and to assess the importance of remaining **uncertainties and risks**.
- Supporting the **setting of priorities,**
- Providing the means to **identify the needed capabilities** (either internally within the disposal programme or through support by ‘external’ service providers) for the successful implementation of the disposal system,
- Requirements management also provides a proper basis for **estimating development effort and cost**.
- etc.

As requirements management is a **mature methodology** that is broadly used in many applications, and as a lot of literature exists on requirements management methodology, this guide takes advantage of **this broad body of knowledge.** Thus, the text in this document relied wherever possible on the literature of that community (see reference list) that has been consulted (in limited depth) when preparing this document.

For developing this guidance document, the information available mainly from the ‘International Council on Systems Engineering – INCOSE’ (see e.g., INCOSE, 2022a), but also from other literature is used, taking the experience made in several waste management organisations into account.

Requirements management supports effective leadership and efficient management (as defined e.g., by Drucker, 2001) in developing the disposal system and its implementation (as defined e.g. in INCOSE, 2022b) by addressing the following two issues:

- *'Do the right things'* (a key element of leadership) and develop *'the right products'* and implement them at the *'right time'*.

  In other words, doing *the right things* starts with defining ***'why'*** is ***'what'*** wanted by ***'when'***. The *'why'* consists of the high-level goals, needs and expectations on the disposal system as defined by the external stakeholders that initiate the development of the disposal system. The *'what'* results from decomposing / breaking down the *'why'* into more detailed and tangible requirements. Then, it is defined by *'when'* the *'what'* must be available.

- *'Do the things right'* (a key element of management) to arrive at *'the right product design'* with the *'product being implemented right'*.

  In other words, *doing the things right* consists of specifying ***'who'*** (the needed elements of the disposal system) must be implemented ***'how'*** to fulfil the *'what'.*

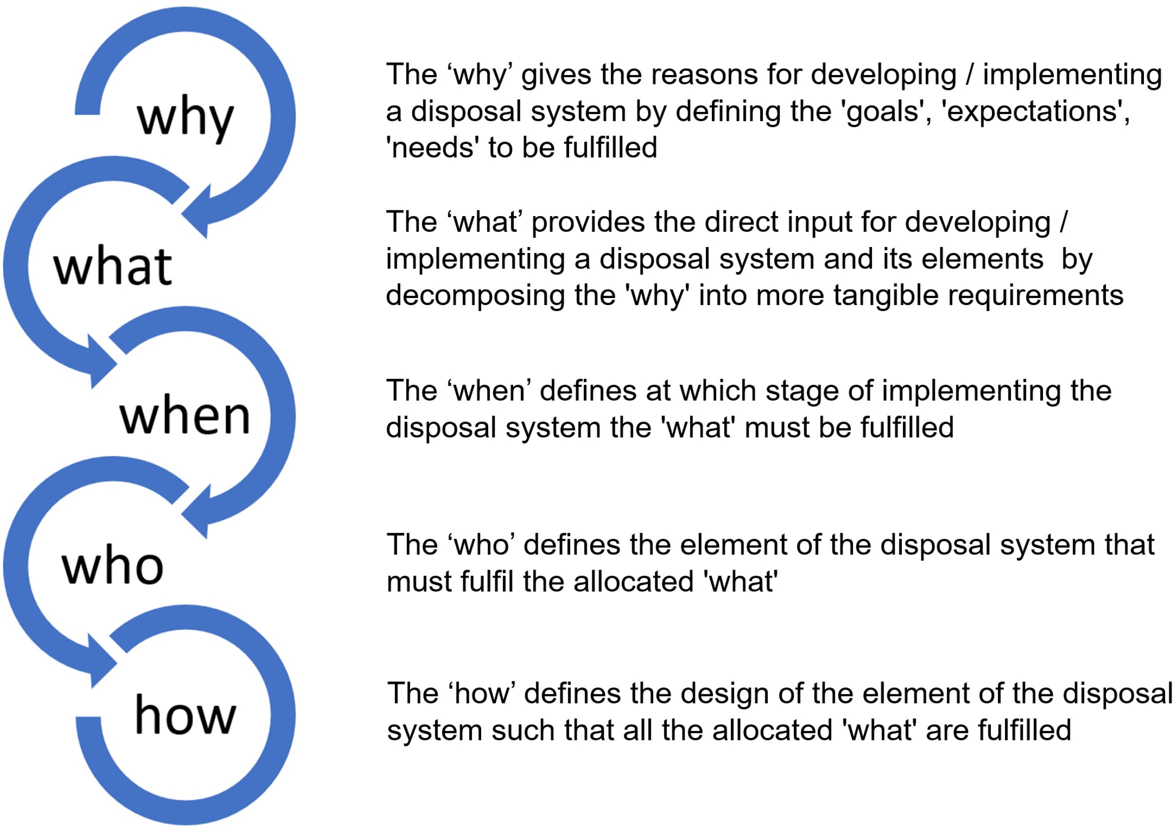

Figure 1 – The cornerstones of requirements management: the sequence of issues that need to be addressed.

The *'why'*, *'what', 'when', 'who'* and *'how'* are the **cornerstones** of the requirements management process documented in a requirements management system, as briefly described below:

- The ***'why'*** gives the reasons and the justification for the planned disposal system by defining the goals of the disposal system, the needs the disposal system has to fulfil and the expectations on the disposal system that need to be met. The dominating 'why' is achieving the endpoint of the disposal project: a sufficient level of safety of the closed repository with all foreseen waste being emplaced.
- For developing the disposal system, the goals, needs and expectations have to be decomposed / broken down into more tangible descriptions on ***'what'*** the disposal system and its elements have to fulfil by ***'when'***.
- The *'what'* is mainly about the goals to be reached with the final product – the **closed repository** with **all wastes being emplaced** has to **provide sufficient safety** for the period of concern by using passive barriers. The final product has to be complemented with the *'what'* for the supporting products that are needed to achieve the final product as wanted (e.g., RDD, planning / design, licensing with the subsequent construction, operation / waste emplacement and closure).
- The disposal system and its development and implementation will require of many elements, including temporary support elements – the ***'who'*** that is needed by *'when'* to fulfil the *'what'*. To maintain an overview on all the (temporary) elements needed, they are put as 'black boxes' into a so-called **'functional architecture'** that captures all the elements and their interactions that are needed for implementing the disposal system – the closed repository with the waste emplaced providing the needed level of safety after closure.
- Finally, for each element, a specification has to be developed that describes ***'how'*** the element must be implemented to fulfil the *'what'*.

  The *'how'* should in sufficient detail define the key characteristics and properties of the final product (the closed repository) and of the needed supporting products (e.g., information, documents, decisions, licenses, supporting infrastructure, etc.) and may also need the definition of working procedures. This also includes the definition of *'who'* (*'together with whom'*) ensures that the goals are met.

The sequence of issues is briefly summarised in a simplified manner in Fig. 1. This description is also the basis for the structure of requirements management system shown in Fig. 2 (for an **early-stage programme** with only broad concepts being defined) and in Fig. 6 in chapter 5.4 (for an **advanced programme** with all elements being defined and some elements already being implemented and used).

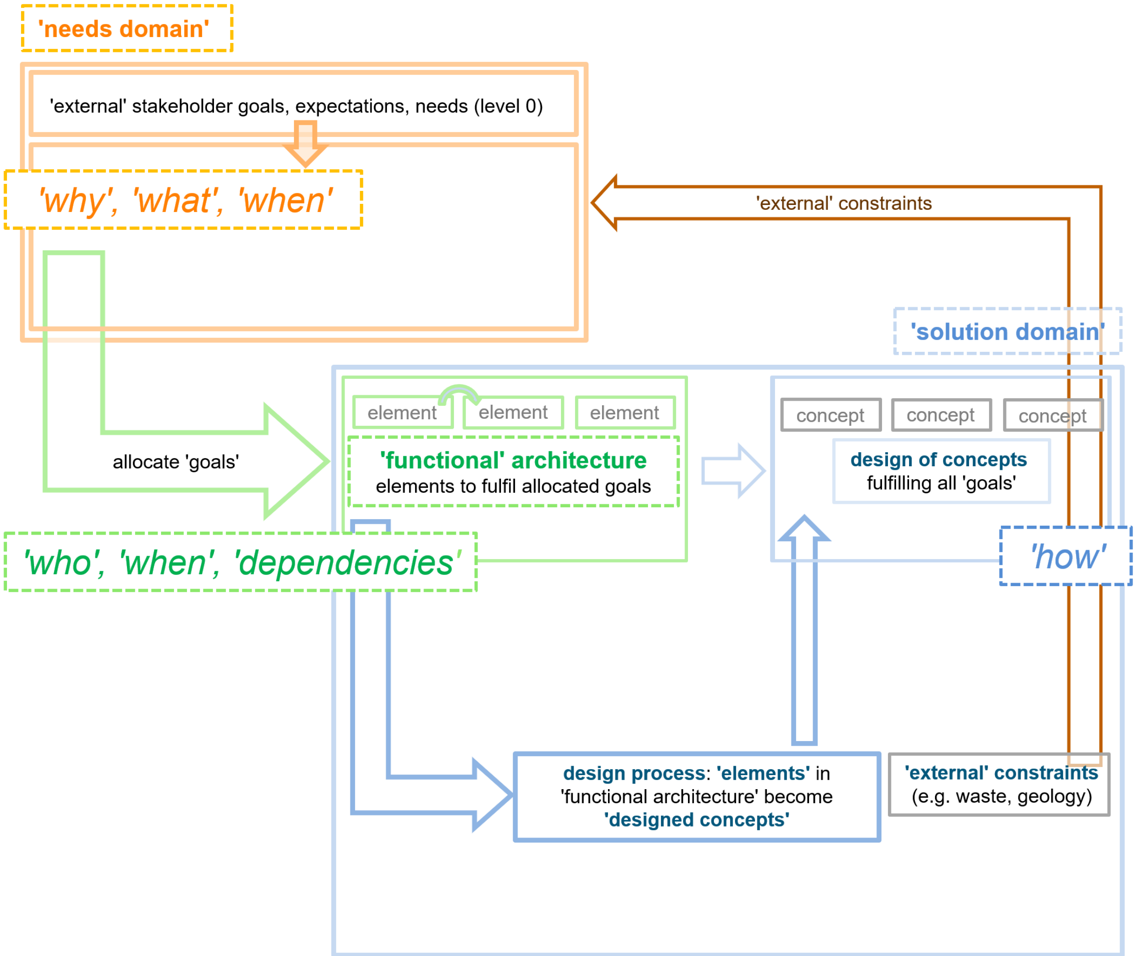

Figure 2 – A scheme with the domains of the requirements management system (the 'needs domain' – describing the 'why', 'what', 'when'; the 'functional architecture' – capturing the 'who', 'when' and dependencies; the 'solution domain' – defining the 'how') and the flow of information and the workflow (arrows).

The scheme shows the elements of a programme at an early stage, where the main aim for the 'needs domain' is on the goals, needs and expectations of the 'external' stakeholders and where the 'functional architecture' only contains high-level elements and the 'solution domain' only concepts for the high-level elements. However, 'external' constraints (e.g. waste foreseen for disposal, geological options / geology of the site selected) need to be considered from the beginning on.

It is important to note that the requirements and the corresponding planning and design will evolve with progress of the disposal programme – at an **early stage,** only higher-level requirements are available, the 'functional architecture' has no details, and the planning of future activities and the design of the objects will only be at the conceptual level (see Fig. 2). The work can initially concentrate on those elements that need work in the planning horizon; the work on the other concepts can wait until they get closer to the planning horizon and need attention. As the disposal programme progresses and reaches an **advanced stage**, more detailed requirements will be derived, the architecture will become more detailed and planning and design will get more refined and eventually, stepwise implementation will start (see Fig. 6).

As the waste management programmes and their boundary conditions (waste, geology, legal / regulatory framework, stage of programme) in the different countries differ to some extent, also the requirements management systems with the specific requirements for the programme-specific disposal systems will differ. Thus, each programme will need its **own requirements management system** (newly developed or adapted from an existing requirements management system), containing the programme-specific information (including requirements).

Requirements management for a disposal system can take advantage of the information available on many issues already worked on by well-established processes in the disposal programme looked at, independent of requirements management. Thus, an **important task of implementing a requirements management system** is to take advantage of the **existing information** and the **corresponding work-processes** available in the disposal programme looked at (and also taking the experience made in other disposal programmes into account, as far as applicable) and to **integrate them into the overall structure of the used requirements management system** and to **complement this structure** with missing elements and information to arrive at a requirements management system that ensures the successful implementation of the planned disposal system.

The main **aim of this document** is to provide an overview on the issues to be considered when (i) using requirements management (the **process**) and (ii) the corresponding requirements management system (the **platform to work in**), and (iii) using the corresponding requirements management **workflows** to support the successful implementation of a disposal system.

Thus, the main emphasis of this document is on **methodology** (**'the way of thinking'**[4]**) for developing and using a requirements management system** and not on the details of the disposal system and on the requirements and other information as such. Thus, the document mainly describes **the issues to be thought about** and not the issues themselves. This document is **rather detailed** about the issues to think about – many of them apply to advanced disposal programmes and need not yet to be considered by programmes in an earlier stage.

Groups such as the **NEA's Integration Group on Safety Case (IGSC)** or **IAEA's GEOSAF project**[5] **and other projects** are working on the scientific-technical content of requirements and on the detailed procedures to develop them. Thus, there is no need to cover these aspects in detail in this document.

Nevertheless, to make the text better understandable, many specific examples are given in the document. However, these **examples** should be seen as **illustrations**[6] and **not as recommendations** as the requirements are specific for the system looked at.

This document 'Developing, using and modifying a requirements management system for implementing a disposal system' (**DS-RMS**) is in principle **applicable to all disposal systems** (surface disposal or near-surface disposal for (Very) Low-Level Waste (VLLW, LLW), disposal at shallow or intermediate depth in mined repositories for Low-/Intermediate Level Waste (L/ILW), disposal at greater depth in mined repositories for Spent Fuel (SF), Vitrified High-Level Waste (HLW) and Long-Lived Intermediate Level Waste (LL-ILW), borehole disposal at limited depth for disused sealed radioactive sources or at greater depth for SF and HLW – the main emphasis is, however, on deep geological disposal of SF, HLW and LL-ILW.

[4] There are several other documents that also address 'the way of thinking' (e.g., IAEA, 2020).

[5] International Project on Demonstrating the Safety of Geological Disposal aiming at harmonising the demonstration of safety of geological disposal facilities during and after their operation.

[6] Some more illustrations are given in EURAD (2024b).

1.3 Content and structure of this document

This document consists of a number of sections, with all the sections being relevant for a requirements management system for disposal systems, putting significant emphasis on reaching an adequate level of post-closure safety. The order of the sections should help the reader to get familiar with requirements management for disposal systems. However, the sections are made such that each of them can be read as 'stand-alone' text.

Each section starts with a paragraph with an introduction / overview and is then followed by one or more somewhat larger paragraphs on 'the issues' (things to be aware of) and ends with a paragraph summarising the section. There is some overlap between the sections to get the connection between them well established. Thus, sometimes there is some repetition in the text.

The remainder of the text of this section 1.3 is a **very condensed summary** of the whole document; it can be skipped by those readers that will go through the full document.

The document consists of the **following sections:**

- An **introduction** (section 1), consisting of:
  - a description of the **role and importance of requirements management** and the **aims** of the document on the development and the use of a requirements management system for disposal systems (sub-sections 1.1 and 1.2),
  - a description of the **content and structure** of the document (this sub-section – sub-section 1.3).
- A brief description of the **key themes of relevance for a disposal programme with the aim to implement a closed repository** with all wastes emplaced that provides the needed level of safety in the **post-closure phase.** These themes will define the overall system (and its boundaries) that will be addressed with the requirements management system for implementing a closed repository. The text contains also a brief description on how to manage the interfaces to the 'outside world' – in short: it is about the **disposal programme** to implement the **disposal system** and the **management of its interfaces** to other systems (section 2).

  Section 2 also explains why it is considered useful to include four different high-level themes[7] in the requirements management system for implementing a disposal system: (1) ensuring post-closure safety of the closed repository; (2) implementing / building the repository, emplacing all waste and closing the repository; (3) preparing the implementation of the closed repository and (4) interacting with society. With the exception of (4), these themes are the equivalent of the **stages of the life cycle** of the elements of the waste disposal programme.
- A description of the **stakeholders** to be considered in requirements management and their roles and their input (section 3).

[7] The themes used in this document are not the same themes as used in the EURAD roadmap although there are some similarities.

- A description of the requirements for implementing a disposal system (section 4):
  - An introduction (sub-section 4.1)
  - A description of the **'needs'-related requirements** (sub-section 4.2) defining the 'needs domain' (***why*** is ***what*** *wanted by* ***when****?*), with sub-sections on:
    - a description on how the 'needs'-related requirements are **derived**, see sub-section 4.2.1,
    - the 'needs'-related requirements for the **closed disposal system ('as built') to ensure an adequate level of post-closure safety**, see sub-section 4.2.2,
    - the 'needs'-related requirements to ensure the correct **implementation of the closed disposal system**, see sub-section 4.2.3,
    - the 'needs'-related requirements to ensure the correct **preparation of the implementation** of the closed disposal system, see sub-section 4.2.4,
    - the 'needs'-related requirements related to **interacting with society** during the full duration of implementing the closed disposal system – from the start of the disposal programme until its end, see sub-section 4.2.5.
  - A description of the **'solution'-related requirements / specifications** (section 4.3) defining the 'solution domain' (***who*** has to fulfil ***what*** by ***when***, and ***how*** *is this achieved?*), with the sub-sections on:
    - a description on how the 'solution'-related requirements are **derived**, including the definition of the needed elements of the disposal programme to fulfil all the 'needs'-related requirements, see sub-section 4.3.1,
    - the 'solution'-related requirements to ensure an adequate level of **post-closure safety of the closed disposal system** ('as built'), see sub-section 4.3.2,
    - the 'solution'-related requirements to ensure the correct **implementation of the disposal system**, see sub-section 4.3.3,
    - the 'solution'-related requirements to ensure the correct **preparation the implementation** of the disposal system, see sub-section 4.3.4,
    - the 'solution'-related requirements related to the **interaction with society**, see sub-section 4.3.5.
- A description of the **structure** of the hierarchically organised **requirements management system** that contains the different **levels of requirements** of the disposal programme (covering the 'needs' and the 'solution' domain) that are used to design and implement the different **elements of the disposal system** (leading to specifications for these elements and a documentation of the implemented system elements) together with **key links / dependencies** (section 5).
- A description of the **evolution** of the requirements and the corresponding requirements management system for the design and the implementation of the disposal system in the **stepwise approach** of repository implementation (section 6).
- The process **steps to implement** the requirements management system (section 7).
- The process **steps to use** the requirements management system (section 8).

- The process **steps to manage the evolution** of the requirements for the disposal system and the evolution of the design of the disposal system in the stepwise implementation process (section 9).
- Finally, the appendix contains:
  - **Schemes** with short explanatory texts that illustrate the different steps in developing / using a requirements management system (Appendix A).
  - A **glossary** for key terminology (Appendix B).
  - A list of **abbreviations** used with explanations (Appendix C).
  - Lists of **key references:**
    - References related to requirements management used for specific applications (Appendix D).
    - References related to 'needs'-related requirements (Appendix E).

2. The system covered with requirements management and the treatment of its interfaces to other systems

2.1 Definition

The **disposal system** and the elements needed for its implementation (the disposal programme) need to be captured by the requirements management system. Thus, it has to contain all the **elements** (objects, activities and other measures) of **relevance for implementing the closed repository,** including their life cycle.

The **boundaries of the disposal programme** covered by the requirements management system delineate this system from the 'outside world' (e.g., interim storage). The requirements management system also includes a description of how the **interfaces to the other systems** at the different boundaries are managed.

2.2 The scope of the requirements management system and its boundaries

To define the scope of the requirements management system and its boundaries, it is important to be aware of the main goals of implementing the disposal system and the corresponding disposal programme and on what can directly affect these goals. Although **post-closure safety** is undoubtedly the **key objective** of a disposal system, there are also other issues of importance when implementing a disposal system. Thus, the following aspects need to be considered in the requirements management system for implementing a disposal system (see also Fig. 3):

- The 'starting point' to discuss post-closure safety is the **closed repository** with all wastes emplaced ('as built'). The closed repository consists of the **geology** (host rock, geological situation (today and its future evolution)), the **waste** to be disposed (encapsulated in disposal canisters[8]), and additional elements of the system of **engineered barriers** (buffer, backfill, seals), with all these elements being part of the system to be developed with the help of the requirements management system. The **requirements** developed **for the closed repository** must ensure that the closed repository with the emplaced waste **will be safe** for the period of concern. **'Ensuring post-closure safety of the closed repository'** is sometimes also called theme 1, see e.g. Figure 3. This theme corresponds in principle to the life cycle stage '*using the repository'* because theme 1 is the main objective of and motivation for the disposal system.
- The closed repository is the endpoint of a lengthy **implementation process** with site selection / site characterisation, construction, operation (including the emplacement of the encapsulated waste and of the engineered barriers) and closure of the repository, with implementation potentially having a significant impact on the properties of the closed repository. Thus, a strong interface exists between the implementation process of the repository and its final product – the closed repository. Therefore, repository implementation is also included in the requirements management system for implementing a disposal system. **'Implementation of the closed repository with all wastes emplaced'** is sometimes also called theme 2, see e.g. Figure 3. This theme corresponds to the **life cycle stage** '*implementing the repository'*.
- A significant part of ensuring **post-closure safety** is related to the **safety case** that has to collect the evidence that the planned closed repository 'as built' will be **safe for the period of concern**, taking its evolution into account. The safety case is also part of the systematic approach of developing the repository design (**'design for safety'**) and provides through the

[8] For LL-ILW, L/ILW and LLW, the waste is loaded into disposal packages.

periodic safety assessments feedback to the development of the disposal system (improve the scientific-technological basis through RDD[9], provide input to site selection, refine the design of the disposal system, etc.). Thus, there is a strong interface between this iterative **development of the safety case** and the **development of requirements** for the design and implementation of the final product – the closed repository with all waste emplaced.

As the implementation of the repository is a lengthy and complex process, it requires **good preparation and planning** to ensure that the implementation is done in a safe, reliable and sustainable manner. Furthermore, implementation takes place in a strict **licensing regime** that requires the needed documentation to be sufficiently comprehensive and of sufficient quality and to be available in time. Thus, also here there is a strong interface between planning / licensing and the final product – the closed repository.

Thus, the preparation of repository implementation, including the necessary development work (studies (incl. RDD), planning (incl. requirements management), design and licensing) and developing and using the safety case to guide implementation (by 'design for safety')) is also included in the requirements management system for implementing a disposal system. **'Preparing the implementation of the closed repository'** is sometimes also called theme 3, see e.g. Figure 3. This theme corresponds to the **life cycle stage** '*planning the repository'*.

- Finally, **societal support** is very important and requires adequate interaction between those formally involved in developing the disposal system, those responsible for licensing and decision-making and society. Thus, also here important interfaces exist and therefore, the interface with society is also mentioned in the requirements management system for implementing a disposal system. **'Interaction with the society'** is sometimes also called theme 4, see e.g. Figure 3**.** This theme, however, is not addressed in much detail in this document as it is specific and different for each country.

In reality, the **sequence of work** starts with **preparing the implementation** (theme 3). This provides the basis for the **stepwise implementation of the repository** up to the point of closure of the repository with all the waste being emplaced (theme 2). **Post-closure safety** (theme 1) is the key driver for both the planning of implementation (site selection, design of engineered barriers, periodic post-closure safety-cases to provide input and feedback, post-closure safety as key issue in the licensing process) and for the implementation of the system up to closure of the repository (waste encapsulation and emplacement, emplacement of the remaining engineered barriers). Finally, from the very beginning of the waste disposal programme up to its end, **interaction with society** will be a high priority issue to be able to implement the disposal system in agreement with society (theme 4). Theme 1 as the key driver (operationally addressed with theme 3) ensures that **themes going in parallel,** will **properly interact** with each other (providing feedback, information exchange, etc.).

Finally, it is important to note that in the early stage of a programme not all the themes have to be included in full detail – the awareness that the themes exist may be enough when starting.

The requirements management system has thus to include the **full life cycle** of the elements of the disposal system, including the elements needed for its implementation[10]. This includes preparation (incl. site selection, design, licensing, etc.), construction, use / operation (besides emplacing the encapsulated waste and the remaining engineered barriers also maintenance, renewal, modification), decommissioning and closure of the disposal system to arrive at the final product – the safe closed

[10] It does not only include the closed repository but also all other issues that are needed for the implementation of the closed repository and covers all the themes / life cycle stages mentioned above. It thus includes the objects, the activities with their deliverables and other issues needed; see chapter 4 for more details.

repository with all waste emplaced. Thus, it is important that the requirements management system captures what needs to be achieved in the different **phases of repository implementation**. The relation between the themes / life cycle stages mentioned above and the phases is illustrated in Fig. 3.

To keep this document focussed, **site selection** is in this document only mentioned in context of important properties of geology and its impact on safety and design of the disposal system. The detailed process of site selection is not addressed as this is done in different ways in the different countries with the 'volunteering'- approach being one possibility and 'looking for the most suitable site' - approach being an other possibility with possible stages in between.

Looking at the **overall waste management system** the following **boundaries** must be considered when implementing a disposal system:

- **pre-disposal activities** (waste conditioning (treatment, solidification, packaging), handling, transportation, storage, …) with the corresponding pre-disposal infrastructure (conditioning equipment / facilities, transportation, storage facilities, …),
- **on-going disposal activities** (e.g. for L/ILW) in existing disposal systems, and
- other **planned disposal systems**.

These **boundaries and interfaces** can be managed e.g. by waste acceptance criteria (WAC) that are imposed as constraints (requirements) on each respective system; some of them actually must be treated as constraints (e.g., already conditioned and packaged waste).

Then, for disposal, besides pre-disposal and disposal – ideally one should also look at and **interact with the front end** (where the radioactive material enters the system) as it impacts disposal. Such interactions aim at avoiding unnecessary complications.

When discussing the boundaries of the disposal system and their management, one also has to acknowledge the importance of service providers, suppliers and the supply market (summarised as the **supply chain**) as being outside of the system boundaries and not being under direct control until binding contracts are made. Thus, the interface with and the management of the supply chain is of critical importance. In a broad sense, this may also include shared solutions.

2.3 Summary

Fig. 3 summarises the key elements of the system to be captured with the requirements management system for implementing a disposal system. To **reach the overall goal** – the closed repository that ensures the safety of the disposed waste in the post-closure phase (arrow G (in red) in Fig. 3) – four broad themes (T-1 to T-4 in Fig. 3), with the first three being **stages of the life cycle** of the elements of the disposal programme, are essential in the phased (stepwise) implementation of a disposal system, with the phases being P-1 to P-5 in Fig. 3, with the activities occurring and the products developed in these four phases together often being called the 'disposal programme'. Each of the themes / stages of the life cycle has to address different goals in the different phases (text boxes in Fig. 3) and for these goals, requirements must be defined. Each of the themes / stages of the life cycle has its distinct overall goals, see below:

- Theme 1 (T-1): **Ensure post-closure safety of the closed repository** that contains all wastes foreseen for disposal. This corresponds to the **life cycle stage** '*using the repository*'. *'Using'* here means providing safety for the waste disposed in the closed repository until its radiotoxicity has decayed to a level where it will not cause significant harm to people and the environment also in case that the barrier functions have degraded.

- Theme 2 (T-2): **Implement the closed repository** (construction, operation / emplacement of waste and engineered barriers, dismantling / closure / sealing) such that all requirements related to post-closure safety as defined under theme 1 above as well as other requirements essential for implementation (e.g. related to safety, environmental protection, etc.) are fulfilled. This corresponds to the **life cycle stage** '*implementing the closed repository'*.
- Theme 3 (T-3): **Prepare the implementation of the closed repository with all waste emplaced** (planning, design, analyses / modelling and (stepwise) licensing),
  - providing input to the development of the requirements for the closed repository as needed in theme 1 above, e.g., with the help of periodic updates of the safety case,
  - ensuring that the requirements of the closed repository with all waste emplaced as defined in theme 1 above are fulfilled,
  - ensuring the safe, reliable and sustainable implementation of the repository as defined with the requirements for theme 2 above,
  - ensuring adequate interaction with society as defined with requirements for theme 4 below.

  This corresponds to the **life cycle stage** '*planning the implementation of the closed repository'*.
- Theme 4 (T-4): **Interact with society** to ensure that the disposal programme with the implementation of the closed repository finds the needed societal support. In Fig. 3, as part of meeting societal expectations, when closing the repository, an institutional programme is implemented that is kept in operation as long as society wants to have it – although there is no need for this to ensure post-closure safety, and thus, this is not required in all countries. This theme has in a strict sense no corresponding life cycle stage, but it is much more a part of all life cycle stages mentioned before.

These overall goals can be decomposed (broken down) for **each of the themes** / **life cycle stages** into **goals for each of the phases** of implementing the repository; for illustration, in Fig. 3 the phases are 'initiation' (P-1), 'site selection' (P-2), 'construction' (P-3), 'waste emplacement & closure' (P-4), and the 'post-closure phase' (P-5).

With respect to the **boundaries of implementing the disposal system**, the following issues are important:

- The **system boundaries** (as a disposal system normally covers only a part of the overall waste management system) have to be **explicitly considered** as boundary conditions (constraints) that are either already initially fixed or that still need to be negotiated.
- The **boundary conditions** are important as they can have a big **impact on implementing the disposal system** looked at; thus, the boundary conditions should be clarified early enough (e.g., through waste acceptance criteria).
- The **supply chain** is often on the 'free market' and thus **not directly under control** and thus outside of the boundaries of the disposal system. This needs adequate consideration (e.g., be prepared to make design changes when a supply market disappears). This could be an issue because repositories have specialities for which there is not a big demand and that makes the supply chain vulnerable.

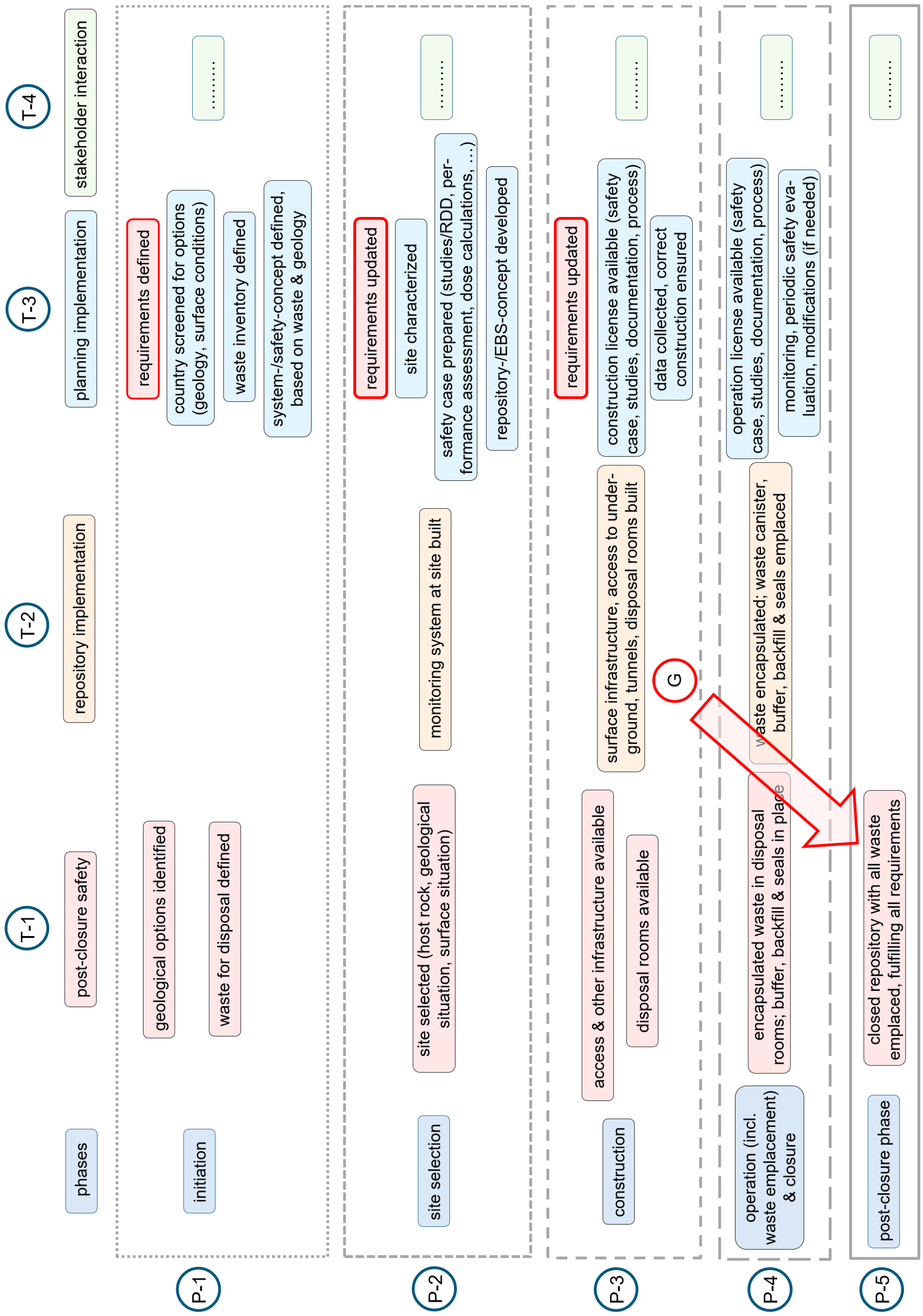

Figure 3 – The requirements management system for implementing a disposal system: elements / products and dependencies of the corresponding disposal programme.

The endpoint and the overall goal of a disposal programme is the closed repository with all foreseen waste being emplaced that fulfils all post-closure safety requirements (point G). To achieve this overall goal, in each of the phases needed for implementing the closed repository (rows P-1 to P-5), goals / products (fields with text) have to be achieved for each of the life cycle stages (also called themes) needed for implementing the closed repository (columns T-1 to T-4 in different colours). For more details, see text.

3. Stakeholders formally involved and their roles and activities

3.1 Definition

A stakeholder is for this document defined as a person, a group or an organisation that **influences the requirements** to be met by the disposal system and its implementation or that is **impacted by the disposal system and its implementation**.

3.2 Issues to be considered

In this guidance document, stakeholders are divided into three groups:

- '**External' stakeholders** are external of the operational work on the waste management system (no direct involvement in the development of the of the waste management system) but are decisive by providing the high-level overall goals of the waste management system under consideration. They have a strong interest in the success of the waste management system and are often involved in the initiation of the corresponding programme.
- The **'internal' stakeholders** are in charge of developing the waste management system under consideration and thus directly influence / control the development of the system-specific requirements, that have to fulfil the high-level goals of the 'external' stakeholders. These are then used by the internal stakeholders in the design of the waste management system and become fully effective after its implementation.
- Finally, there are a range of **stakeholders** that are **formally not directly involved in the development** of the waste management system but need to be informed and may be involved through consultation – this includes the public at large that is not directly affected by the waste management programme / system.

Below, the 'external' and 'internal' stakeholders are discussed in somewhat more detail.

- The **'external' stakeholders** see a strong 'need' to find a 'solution' for the disposal solution under investigation and often also initiate the corresponding implementation process. They are, however, **external** of the operational work of implementing the disposal system (no direct involvement in the development of the disposal system; and there are also no or only limited possibilities for the 'internal' stakeholders (see below) to influence / control the 'external' stakeholders), but they are decisive by providing the overall **goals** (and/or: **needs and expectations**) that must be met by finding a 'solution' – the so-called 'high-level' – requirements. Sometimes these 'high-level' - requirements are constraints (e.g., existing / expected waste foreseen for disposal, prescribed site selection process / site chosen).

  Not all input by the 'external' stakeholders is necessarily at a high level; the input that is at a lower level is considered in the process of decomposing the high-level requirements by the 'internal' stakeholders discussed just below.

  The **'external' stakeholders** include, e.g.:

  - **Policy makers**, issuing nuclear and other legislation that needs to be considered as requirements in implementing the disposal system,
  - **Licensing body / decision-maker**, using their power provided by nuclear and other legislation to impose requirements on the considered disposal system and its implementation as part of their decision-making authority, though still maintaining its independence.

 – **Regulators / regulatory support**, with requirements as documented in their regulations related to the implementation of disposal systems,

   Regulators / regulatory support, with requirements according to their findings from their reviews directly related to the considered disposal system and its implementation. though still maintaining its independence.

   Furthermore, most likely, regulators will review the requirements management system of the implementer and through the review comments influence the requirements management system of the implementer.

 – **Waste generators** having in some countries the legal obligation to manage their radioactive waste in a safe and sustainable manner at their own cost without, however, being directly involved in the development and implementation of the repository. With their overall responsibility for disposal, they also define parts of the 'high-level' requirements (e.g., with imposing the overall waste volume planned for disposal as a 'high-level' constraint).

 – **Local municipalities** potentially hosting a repository, with requirements related to their needs and expectations. In some programmes with 'voluntarism' being the approach for site selection or when having the veto-right, the **municipalities** play a decisive role in site selection. Thus, their goals, needs and expectations must be included in requirements management.

- The **'internal' stakeholders** (the implementer) have the task to develop a 'solution' that fulfils the goals of the 'external' stakeholders. As a first task, the 'internal' stakeholders have to **decompose** the 'high-level' requirements provided by the 'external' stakeholders into the **goals for the themes / life cycle stages** described in section 2. These goals are further decomposed into so-called **functions**[11] and **quality characteristics** with corresponding **performance targets** and/or **quality targets**. These requirements together with the 'high-level' - requirements form the so-called **'needs domain'.**

  In a next step, the 'internal' stakeholders develop in a first step a **'functional architecture'** of the system with all elements that are needed to meet the functions and characteristics with their targets. In a second step, the functions and characteristics of the 'needs domain' are **allocated** to a specific element of the 'functional architecture'. In a third step, for each element a **system-specific specification of the product** to be implemented (in short: **product specification**) and a **production specification** is developed through an adequate design-process. These system-specific specifications form the so-called **'solution domain'**[12] and are the basis for the actual implementation.

  This shows that the '**internal' stakeholders** are involved in and directly control the development of the detailed requirements up to the disposal system-specific specifications for the actual implementation – they have the **full responsibility** for these tasks.

  The product specifications become fully effective after the **implementation** of the specified products and become constraints for all future activities.

[11] As equivalent to the 'function', the terms 'behaviour' or 'task' can also be used if more appropriate.
[12] The 'solution domain' describes / specifies the solution (the disposal system) that meets all the goals, needs and expectations and the corresponding functions and characteristics with their performance-/quality-targets as described in the 'needs domain'.

The **‘internal’ stakeholders** include, e.g.:

- **Operator and developer** having the mandate (e.g. given by the state) to develop a solution (through coordination of and involvement in the design and the eventual implementation) of the disposal system, in waste management often called the ‘waste management organisation’ (WMO), relying on:
  - its own **in-house competencies**
  - **service providers**: developing the conceptual design (incl. the underlying safety-case), the system design and the design of specific elements of the disposal system (incl. system of engineered barriers) with additional requirements related to their **standards, codes, guidance documents** (e.g. by national / international organisations) that define ‘good engineering practice’ / state-of-the-art:
    - internal within the implementer organisation,
    - external to the implementer supporting the implementer.
  - **supply market** (contractually bound) delivering system-elements / products / objects with additional requirements related to their **standards, codes, guidance documents** that define ‘good engineering practice’ / state-of-the-art.

or:

- **‘Large’ waste generators** / **consortium of waste generators** being the owners and implementer of the repository through their responsibility to find a solution for disposal – with the tasks and the organisations similar as described above.

Developing and using a requirements management system by the **implementer** is a very important process; this issue is discussed in somewhat more depth in chapter 3.3.

To summarise, the ‘external’ stakeholders and the ‘internal’ stakeholders have **different roles and responsibilities**:

- **‘External’ stakeholders** provide input to develop the **requirements** related to the **‘needs domain’** *(‘why do we need a disposal solution?’)*,
- **‘Internal’ stakeholders** are in charge to **decompose the high-level requirements** into theme-specific / life cycle stage specific goals and these goals into functions and characteristics with their corresponding targets (all being part of the ‘needs’ domain) and then develop the ‘functional architecture’ with all elements of the disposal system needed to fulfil the ‘needs’ with their implementation. Taking the requirements of the ‘needs domain’ as input, this then requires the development of **product and production specifications for the system-elements** that form the **‘solution domain’** *(‘how is it achieved?’)*.

  The ‘needs domain’, the ‘functional architecture’ and the ‘solution domain’ are discussed in more depth in section 5.
- It is important to be fully aware that **the implementer and the regulator** have different roles. The requirements management system of the regulator (if available) should be independent of the requirements management system by the implementer; however, the regulatory requirements must be included in the requirements management system of the implementer.

Furthermore, most likely, the **regulator will review** the requirements management system of the implementer and through his review comments and through the review of licence applications, the regulator will have an impact on the requirements management system of the implementer.

- To address the 'needs' and 'expectations' of the 'external' stakeholders and to manage the decomposition of the higher-level requirements (goals) into lower-level requirements (functions and characteristics and their targets), it may be useful to develop a **'map' of the 'external' and 'internal' stakeholders and their documents** also capturing the relationship and interdependences between these stakeholders and their documents.

3.3 Requirements management - working as a team

Successful implementation of disposal systems is a **team effort** by the 'internal' stakeholders (the waste management organisation) that relies upon both the technical development of the products needed and the project management supporting the technical development process:

- The **technical development** of the products is done by:
  - **Systems engineers**, responsible for the process of correctly populating the overall requirements management system with information (incl. design input requirements and design output specifications) and the correct use / application of the information. For this, the system engineers have to organise and oversee the design process and thus need to have a good understanding of the system to be developed, but they do not need to understand all the details about each product – they are 'generalists'.

    The system engineers are also responsible to **manage the requirements management process**. That includes the development of workflows and keeping them up-to-date as well as ensuring that they are applied whenever needed; thus, they ensure that the status of the information in the requirements management system is at all times is clearly visible and that only 'cleared' information is being used for developing the projects.
  - **Subject matter experts**, responsible for the scientific-technological details of the different products, with also having a good understanding about the context of the products they are responsible for. They also have to be able to decompose the goals into functions / characteristics with their targets.

    Some of the subject matter experts **oversee the RDD** for the different products and provide the corresponding information, while the other subject matter experts are the **specialists for the design** and the development of the product specifications and production specifications and oversee implementation, use and 'end-of-life' of the product. Then, some subject matter experts **oversee implementation**, **use** and **'end-of-life'**, also to keep track of the detailed verification and validation.
- **Project management** for the work to be carried out **supports** the efficient technical development of the products and includes the management of the following issues:
  - activity lists, bar charts, network diagrams,
  - resources needed / available,
  - cost / budget available,
  - organisational framework of the project,
  - etc.

Thus, there are **strong interdependencies between systems engineering, using and maintaining the scientific-technological basis and design, requirements management and project management** that must also be considered when setting up the requirement management system – what should be included and what not? At a high level, it is considered worthwhile to **include also** the project management issues. This also needs to be considered when organising the team; it is essential that the **team works as an integrated unit** well together without any administrative / organisational hurdles.

At an early stage, the **team will be very small,** with one person having several of the responsibilities mentioned above; the **team will grow** as the programme advances.

3.4 Summary

The following issues are of importance:

- Stakeholders are an important **source of information** for developing requirements.
- Thus, it is very important to **identify** all relevant stakeholders and/or their information. If needed, the stakeholders should be involved in the extraction of relevant information related to requirements to ensure that nothing gets lost.
- Stakeholders have **different roles and responsibilities**: 'external' stakeholders provide input for developing the **high-level requirements** related to the **'needs domain',** whereas 'internal' stakeholders are in charge of decomposing the input of the 'external' stakeholders into more detailed requirements of the 'needs domain' and then to develop the 'functional architecture' and derive from the requirements of the 'needs domain' the **product and production specifications** for the elements of the disposal system (defined with the 'functional architecture') that are part of the **'solution domain'**.
- Due to the long duration of disposal programmes, **potential changes** in the stakeholder 'landscape' (map of stakeholders and their documents) must be carefully monitored to ensure that at all times the relevant stakeholders are known and involved as far as needed.
- As the nature of the disposal programme changes from one phase to the next, the nature and the level of detail of the requirements needs to be adapted. This also has an **impact on the 'external' stakeholders to be involved**.
- The 'external' stakeholders provide the **'raw data'** that may need interpretation, discussion and negotiation with proper documentation of (interim and) final results, and this may require interaction with the 'external' stakeholders that provided the original information. This should ensure that their input is adequately reflected.
- The **different roles and responsibilities** of the different (formal) actors / stakeholders within each country must be acknowledged. In the elicitation / extraction of the input by the stakeholders it is important to keep their specific roles and responsibilities in mind in populating the requirements management system with their information.
- Finally, the work of the implementer related to requirements management is an important issue. This requires the **work of a team of both generalists and specialists**, having clearly defined roles and responsibilities.

4. Requirements for a disposal system and its implementation

4.1 Introduction

4.1.1 Overview

The requirements for implementing a disposal system are organised within the different disposal programmes in a hierarchical manner, often in a structure similar as described in this chapter.

The starting point are the overall **goals of the disposal programme** – the so-called 'level 0' - requirements, e.g.:

The overall goal of the disposal programme is the disposal of all envisaged waste in a disposal system in a manner that ensures the protection of people and the environment against the radiological hazards of the wastes disposed for the period of concern without creating any undue burdens on future generations by using a disposal system with passive barriers.[13]

The needed disposal system shall be implemented in a safe and sustainable manner within reasonable time, at affordable cost and in agreement with society.

In a next step, the requirements for the four broad themes / life cycle stages as described in sub-section 2.2 must be defined:

1. At the highest level, for each of the broad themes / life cycle stages, the broad **goals**[14] (the so-called 'level 1' - requirements) to be reached must be defined. When the goals for all the four themes / life cycle stages are reached, then the overall goals of the disposal programme (as mentioned above) will also be reached.
2. To ensure that the broad goals for each of the themes / life cycle stages are achieved, **functions**[15] (the so-called 'level 2' - requirements) are defined. These functions can be informed by more detailed sub-functions. A function is directly related with a purpose that supports a goal.

   Besides the functions, also **characteristics**[16] contribute to achieving the goals of the themes / life cycle stages. The characteristics are equally important as the functions, but in the design process they come second to the function as they often are related to the (quality) characteristics of the process / object that has to fulfil the corresponding goals.
3. For the functions / sub-functions, **performance targets** and for the quality characteristics **quality targets** (the so-called 'level 3' - requirements) are defined such, that – if the functions and the characteristics with their underlying targets are met – the broad goals of the themes / life cycle stages are reached and with this, also the overall goals of the disposal programme are fulfilled.

The requirements described above (the 'level 1 to level 3' - requirements) are the result of decomposing the **goals, needs and expectations of the external stakeholders** (the 'level 0' and 'level 1' - requirements) into more detailed requirements.

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13 This obviously does not apply to surface or near surface disposal of LLW.
14 Instead of 'goal', sometimes the term 'objective' or 'principle' is used.
15 In some cases, the terms 'task' or 'properties' / 'behaviour' are more appropriate / precise than 'function'.
16 Sometimes also called non-functional requirements.

Then, there is an additional issue to be considered, the **constraints**. These are facts, e.g. the waste to be disposed (existing, expected in future), geology (possibilities in country or site selected) and facilities already implemented. The constraints act at the level of functions / targets, and have often also an impact on the 'functional architecture' (see below).

It is important to note that most themes / life cycle stages (as described in section 2) have specific **(sub) goals** and corresponding functions / characteristics with their targets for the different **phases** of implementing the disposal system.

With the **design process** by the internal stakeholders the functions and characteristics with their targets are developed into **product specifications** for the disposal system such that the resulting disposal system with its elements fulfils all 'level 1 to 3' - requirements when implemented. The design process includes the following steps:

4. At the interface between the 'needs domain' and the 'solution domain', the **'functional architecture'** is defined that includes all elements of the disposal programme (objects, activities and other measures with their products) needed for implementing the closed repository. This 'functional architecture' also includes the 'functional' interactions / dependencies between the different elements of the disposal programme.

5. Next, for each of the functions and characteristics, an **object**, an **activity** (with its deliverable) or an **other measure** (with its achievement) as described in the 'functional architecture' of the disposal system (including its implementation measures) is **identified** that – when properly designed / planned and implemented – will fulfil the functions and characteristics with their performance / quality targets.

   Then, the actual **design process** for each element of the 'functional architecture' starts. This process leads to the specification of the **objects** (material and corresponding properties, dimensions and – whenever appropriate – with the loads and conditions acting on the element of the disposal system as considered in the design), of the **deliverables** (e.g. documents) of the activities and of the **achievements** of the other measures. Their required key characteristics (e.g., properties / behaviour) ensure that the corresponding functions / tasks and characteristics with their performance / quality targets allocated to the different elements of the disposal programme are met. The specifications of the products are the **product specifications** (the so-called 'level 4' - requirements).

   The 'level 4' - documents can especially for objects be **divided into two parts**: (1) the **design input requirements** ('level 4a') with a compilation of all functions / characteristics with their targets that an object or a product based on an activity or an other measure has to fulfil, with a definition of the spectrum of loads and conditions the object[17] has to withstand, and the results of a conceptual design of the object with defining the types of material to be used and a pre-design to give the approximate dimensions of the object, and (2) the detailed **design output specifications** ('level 4b') with detailed material specifications and detailed dimensioning and the demonstration of compliance with all requirements through modelling and analyses[18]. In the remainder of this document these two parts are normally **summarised as product specifications.**

[17] In how far the issue of loads and conditions for an object also applies to activities and other measures needs to be decided on a case-by-case basis.

[18] In Posiva & SKB (2017) the 'level 4a' - requirement is called 'design requirements' and the 'level 4b' - requirement 'design specifications'.

Then, specifications may be needed to describe the details on how to arrive at the required product (production process, work process). The prescriptions of the production processes (incl. the demonstration that all requirements are met – verification and validation[19]) form the **production specifications** (the so-called 'level 5' - requirements).

Finally, the **implemented products** (objects, deliverables by the activities, achievements by other measures) are **documented**, with the results / findings of the planned demonstration of having met all requirements being included in the documentation (at the so-called 'level 6').

Item 1 to 3 are the so-called 'needs'-related requirements (covering the 'needs domain' – consisting of the 'level 1 to level 3' - requirements) and are discussed in **section 4.2**, **items 4 and 5** are the so-called 'solution'-related specifications (consisting of the 'level 4 to level 6' - requirements) and are discussed in **section 4.3**. The 'functional architecture' as the interface between the 'needs domain' and the 'solution domain' is also described in section 4.3. Fig. 6 (scheme) in chapter 5.4 illustrates the relation of the different levels of requirements / documentation.

To summarise: The development of requirements is divided into two major steps:

- It starts with defining of ***'what is wanted (what, when, why)'***, based on an analysis starting with the input by the 'external' stakeholders with their goals, needs and expectations ('level 0'), followed by the definition of the goals for the four themes / life cycle stages ('level 1') in the different phases of implementation, and of the functions and characteristics ('level 2') with their performance/quality targets ('level 3') needed to fulfil these goals – see the sub-sections in section 4.2 with a discussion for each of the four themes / life cycle stages to be addressed in the requirements management system for implementing a disposal system.
- This is followed by defining of ***'who'*** and ***'when'*** by identifying the elements within the 'functional architecture' that have to ensure that the ***'what'*** will be fulfilled. The design process describes ***'how'*** this is achieved (***'by whom and when'***) by system-specific *'actions'* in the format of specifications for technically feasible objects, activities and other measures – the product and production specifications. This is discussed in more depth in the sub-sections of section 4.3 for each of the four themes / life cycle stages to be addressed in the requirements management system for implementing a disposal system.

[19] Verification of 'having done the things right' and validation of 'having done the right things' are in the literature sometimes represented as the 'V-model', where each verification-step and each validation-step is linked to the corresponding requirement as defined at the outset of the process. As this gives the impression that the requirements will not change during the implementation process, the 'V-model' is not described in this document because disposal programmes are developed in a stepwise manner over a long period of time, where many requirements will experience some changes as part of the stepwise refinement and because of new information becoming available in the lengthy process of implementation, see e.g., EURAD (2024a, chapter 2.7).

4.1.2 Requirements for the repository to ensure post-closure safety – the special role of functional analyses and modelling as part of safety assessment

The special nature of evaluating and demonstrating post-closure safety through functional analyses and modelling of the long-term evolution of the closed repository has a direct impact on the development of the requirements for the closed repository at the start of the post-closure phase (the 'initial state' just after reaching the 'closure situation'[20]). This development process is briefly described in this sub-section:

- It is important to note that the requirements for post-closure safety address the **initial state of the closed repository** (initial state at the time of closure), but they have to take into account that some of the conditions and properties of the disposal system **will evolve** in the period to be analysed and will thus be significantly different from the initial state – this evolution has to be considered in the requirements for the initial state. However, this evolution can only be **captured through functional analyses and modelling** and thus, to define these requirements one has to use the corresponding results[21] – this is done through an iterative process.

- The development and refinement of the **disposal system** and the **safety concept** and the development of **requirements** is based on the **interaction** between **performance assessment** (as part of assessing post-closure safety), **site selection** (with assumed properties based on an evaluation of the siting possibilities) or **characterisation of the site selected** and the **design process** of the repository and of the **system of engineered barriers**, taking the **properties of the waste** into account.

  To develop / refine the **system** that should fulfil the high-level post-closure safety objectives, the different safety-relevant elements of the disposal system are listed and the current understanding on the contribution of the different barrier elements to post-closure safety is described (the so-called **safety concep**t – the 'functional architecture' of the barrier system). This is then the basis to address the following issues, e.g.:

  – for **each barrier element**, identify which **safety functions** it must fulfil; when considered appropriate, the safety functions are complemented by **quality characteristics** to specifically describe the expected quality of the safety function that the barrier element must fulfil (e.g. reliability of fulfilling the safety function),

  – for each safety function and quality characteristic, describe and quantify the **corresponding performance and quality target** that must be met by the corresponding barrier element to achieve sufficient safety. To ensure that the safety functions and (quality) characteristics are fulfilled, and the performance / quality targets are met, the performance / quality targets of these barrier elements must have the characteristic that they are either measurable or assessable by modelling,

  – the **investigation goals** have to be derived for the field programme to evaluate whether the **geology** of the site selected / under investigation has the **expected properties and performance**, and

[20] E.g., for the waste canister, when the canister is emplaced in its final position and the buffer surrounding the canister is emplaced and the disposal room closed. Thus, reaching the 'initial state' of the closed repository is not for all individual elements of the disposal system the same point in time.

[21] This points to the importance to use materials that allow their evolution to be bounded with adequate bandwidths and sufficient reliability.

  - the **properties and performance of the waste** must be analysed to ensure that the expectations are met, and whether there is a need to take specific measures in encapsulating the waste (to be defined in the waste acceptance criteria and / or the canister loading concepts / plans for spent fuel).

- This process requires in the initial phase of a disposal programme **several iterations** until a satisfactory situation is achieved with having a **balanced contribution of the different barrier elements to safety**, taking the local **geological properties and conditions**[22] and the **waste properties** into account. With the required performance of the barrier elements being defined, the part of defining the requirements of the 'needs domain' is completed.

- It is now the task of the **design process** to develop these functions and characteristics into **product specifications**:

  - The design process starts with an evaluation on **how the site chosen is best used** – which system elements of the 'functional architecture' should be allocated where. This includes – most important – the **disposal rooms,** taking also the other infrastructure (surface facilities, the access to underground, the connection to the disposal rooms) into account.

  - The results of the **design** of the **disposal rooms and the elements of the engineered barriers** to fulfil the allocated functions and characteristics with their targets defined above are documented in the format of product specifications. To develop the design (as part of the design process, see sub-sections 4.3.4), the **initial state** and the resulting **loads and conditions** acting in the disposal system have to be defined and their **temporal evolution** has to be considered for the full period of time where the functioning of the barrier elements with the required quality is relied upon – thus, the conditions most important for the design can be different from those at the initial state.

  - Finally, the **construction / production process** of the disposal rooms and the elements of the engineered barriers will be defined, and the vulnerability of this process will be evaluated with respect to **undetected deviations** of the products from their specifications that could endanger the performance of the barrier elements (as part of the design process, see sub-section 4.3.4). If needed, this may require some adaptations in the design / production or the consideration of these deviations in assessing post-closure safety (with the post-closure safety case being part of the modelling and assessment process, see sub-section 4.3.4).

    In case of **heterogeneous host-rocks**, the so-called 'rock suitability classification'[23] instrument is a similar approach as the specification of the production process. Also here, undetected deviations are an issue.

The **process** of developing the 'solution'-related requirements for the closed repository ('initial state' at the stage just after closure) with respect to post-closure safety with the help of performance assessment (as part of the safety case) is discussed in more detail in section 4.3.2.

[22] Depending upon status / maturity of the disposal programme, the geological properties are either broad expectations, or siting criteria, or information based on a first site screening (with existing data), or the result of a comprehensive site characterisation programme for the selected site.

[23] See e.g., Posiva, 2012.

4.2 Requirements for the disposal system related to the 'needs domain'

4.2.1 Developing the 'needs'-related requirements – introduction

As mentioned in section 3, the source of the **higher-level requirements** are the external stakeholders. Their objectives, needs and expectations address the overall disposal programme ('level 0' - requirements), sometimes also expressed as the mission of the disposal programme. They are thus highly relevant for the four themes / life cycle stages of relevance for implementing a safe disposal system as described in sub-section 2.2.

The objectives, the needs and the expectations for the overall disposal programme leading to the implementation of the closed repository are then **decomposed** for the **four themes / life cycle stages** mentioned above into **goals** (as far as needed), into **functions** and sub-functions and **characteristics** with a **performance target** / **quality target** for the different phases of implementing the disposal system. This decomposition of the higher-level requirements (goals) has to ensure that – with all requirements being fulfilled at the lower level (functions and characteristics with their targets) – also the requirement at the higher level (goals) is fulfilled.

As mentioned in the introduction, all the information that follows below should be seen as examples that **illustrate 'the way of thinking'** to develop and use a requirements management system and not as detailed input about requirements to be 'blindly' used; there may be other alternatives for the issues described below.

4.2.2 'Needs'-related requirements for the closed repository to ensure post-closure safety

4.2.2.1 Goals for the closed repository related to post-closure safety

In this sub-section the goals related to the safety of the closed repository in the post-closure phase are discussed.

Overall goals

At the highest level, e.g., the following goals should be achieved:

- *Disposal of all foreseen wastes in a closed repository that ensures the protection of people and the environment against the radiological hazards of the wastes disposed for the period of concern without the need for any other measures after closure.*

  The closed repository also provides protection against diversion of fissile material[24] *and sabotage.*

This overall goal can be decomposed into the following objectives[25]. The closed repository should:

- allow the **disposal of all foreseen wastes** (fulfilling the corresponding waste acceptance criteria derived within the requirements management process),
- ensure the **protection of people and the environment** against the radiological hazards[26] due to the waste disposed, now and in future,

[24] This applies only to a repository that has such material (e.g. spent fuel).
[25] The terms 'objective' and 'goal' are interchangeable.
[26] In some countries also the protection against chemo-toxic hazards is an issue that also needs to be assessed.

- rely on **passive safety** by taking advantage of multiple safety functions being provided by several passive barrier elements (multi-barrier system, consisting natural and engineered barriers), with the barriers requiring no maintenance / repair[27],
- have taken advantage of **optimisation of protection**, taking social and economic factors into account,
- ensure **safeguards** (preventing diversion of fissile material) and provide **protection against misuse of radioactive material** as long as this is of concern.

These high-level objectives are achieved through post-closure safety functions and quality characteristics to be provided by the different elements of the barrier system of the repository, see the sub-section below.

4.2.2.2 Post-closure safety functions and post-closure characteristics

The broad post-closure **safety functions** and post-closure safety **characteristics** to be provided by the **passive barrier elements of the disposal system** (wastes encapsulated / packaged in suitable canisters surrounded by suitable engineered barriers emplaced in disposal rooms with closed / sealed access routes in a suitable host rock at adequate depth and in a suitable (and stable) geological environment) need to be defined. The definition of the **barrier elements of the disposal system** and the **allocation of the different safety functions** and **safety characteristics** to the different barrier elements of the disposal system is discussed in more detail in section 5.

However, to define the safety functions and characteristics, it might in practice be worthwhile to think already now 'in parallel' also about the broad nature of the barrier elements of the disposal system to ensure that reasonable safety functions and safety characteristics are defined. This is considered justified because the broad properties of the host rock envisaged / chosen as defined by the **geological situation in a country** is a constraint for developing the disposal system and normally has a significant impact on the post-closure safety functions and safety characteristics with performance / quality targets that the system of engineered barriers have to fulfil[28].

With the safety functions and safety characteristics showing adequate performance and quality, post-closure safety will be ensured. The broad safety functions include, e.g.:

- **Isolation** of the waste from the surface environment,
- **Full containment** of the radionuclides for a defined period of time (especially for spent fuel and vitrified high-level waste).
- **Retention** (incl. immobilisation) and **retardation** of radionuclides (slow transport) after breaching of the containment.
- **Long-term stability** of the geological barrier and the system of engineered barriers, taking the evolution of the geological environment and of the climate into account (long-term stability related to external FEPs[29] acting on the barrier system). This issue must be considered in the site selection process.

[27] This does not apply to surface or near-surface disposal of LLW.

[28] According to the general literature on requirements management, the safety functions and safety characteristics with their performance / quality targets should be defined independent of the system chosen – this rule is here not obeyed for good reasons.

[29] FEPs: features, events and processes

- Long-term stability ensured through the **compatibility of the different barrier elements**, including the waste (long-term stability of the barrier system related to internal FEPs acting on the barrier system, taking the evolution of the barrier system into account). This also includes e.g. criticality safety for disposal of spent fuel. This is thus an issue that must be considered in the design process.
- **Capacity of the disposal rooms for the disposal** of the envisaged wastes[30]. This can have an impact on site selection (needed size of suitable host rock blocks at the selected site).

Each of the broad safety functions is informed by more detailed sub-functions that ensure that the broad safety functions with their performance targets will be fulfilled. Also the safety characteristics with their quality targets need to be met. This is discussed in the next sub-sections.

4.2.2.3 Performance targets for the post-closure safety functions

To apply the safety functions, their **effectiveness** needs to be specified – this is done by defining a so-called **performance target** for each of the post-closure safety functions.

To derive these performance targets, the overall system concept with the more detailed design concepts for the different elements of the disposal system needs to be developed / refined and some indicative safety analyses need to be done. Thus, it is useful to coordinate the process of deriving performance targets with the development / refinements of the safety concept that relies on the **interaction between performance assessment, the analysis of geological information based on site selection / site characterisation and the design process, taking the properties of the waste into account** as discussed in sub-section 4.1 and explained in more depth in the sub-sections 4.3.1 and 4.3.2.

As mentioned before, **site selection** has a strong interface with defining the post-closure safety functions and safety characteristics and their performance / quality targets. In the phase of screening the geological options, it is important to evaluate **the potential contribution of the different types of host rocks** available in a country to the different post-closure safety functions.

For the example of **fractured hard rocks** with no self-sealing capacity with some fast transport pathways, those parts of the rock with such fast pathways are not an efficient transport barrier. If these parts of the host rock cannot be reliably detected and avoided by the disposal rooms, the role of retention and retardation of the host rock is assumed to be limited (at least for some of the waste canisters) and thus, a **long-lived canister** may be needed as part of the safety concept.

For the example of **clay stones of low permeability** with good self-sealing properties, no fast pathways exist, and transport is diffusion dominated. For such host rocks, the canister has not to provide full containment for very long times.[31]

A few examples of typical performance targets for some of the safety functions are given below as illustrations; these should be used with care as they are heavily dependent upon the specific conditions / properties of the repository looked at (performance targets in bold):

- Full containment of the radionuclides for a defined period of time (for spent fuel and vitrified high-level waste): **duration of full containment** (e.g., 10’000 years).

[30] This could also be called a ‘disposal’ function.

[31] However, for criticality safety it may be necessary that the canister provides sufficient geometrical stability for the time needed.

- Retention (incl. immobilisation) and retardation of radionuclides after breaching of the containment, e.g.:
  - for the waste matrix (e.g. UO_2-matrix) low dissolution rates are possible in an adequate environment; thus, a porewater chemistry in the nearfield (buffered by the **mineralogy of the buffer material**) that is favourable for low dissolution rates is important. Thus, the buffer mineralogy is the target (preferred range of (in %-weight) of specific minerals).
  - for slow transport (retardation) through the buffer reasonably low **effective diffusivities** (preferred range of diffusion constants) of the buffer material are the target.
  - for retention / retardation, **favourable porewater chemistry** and **mineralogy** for good sorption in the buffer and low solubilities in the nearfield (with the porewater being buffered by the **mineralogy of the buffer material**) are important[32]. Thus, the buffer mineralogy is (again) the target (preferred range of (in % -weight) of specific minerals).
  - for slow transport (retardation) through a homogeneous non-fractured host rock (with good self-sealing properties), reasonably low **permeabilities** are the target as input for site selection, if compatible with the geological options available (preferred range of permeabilities).
  - for slow transport (retardation) through a fractured host rock without self-sealing, reasonably low (equivalent) **transmissivities** of the flow paths are the target as input for site selection, if compatible with the geological options available (as preferred range of transmissivities).
  - for retention / retardation, favourable **porewater chemistry** and **mineralogy** (expressed as preferred range of pH, Eh and ionic strength, and of porewater concentrations for key species and preferred content of key minerals) for good sorption in the host rock are the targets (as input for site selection, if compatible with the geological options available).
  - for retention / retardation in a fractured host rock without self-sealing, favourable **properties of the rock matrix for matrix diffusion and sorption within the rock matrix** are important. Thus, sufficiently high diffusion constants, rock porosity, favourable mineralogy and porewater chemistry are the targets as input for site selection, if compatible with the geological options available.
  - etc.
- **Long-term stability** of the geological barrier (as input for site selection), e.g.:
  - **avoidance** of geological structures prone to differential movements of more than a manageable **maximum displacement** (rate) by the system of engineered barriers is the target.
  - **avoidance** of sites with **significant exploitable natural resources** of **national importance** is the target.
  - etc.

[32] As the buffer may have limited buffering capacity, the targets for the porewater chemistry of the host rock may also be relevant and thus be used.

- Long-term stability ensured through compatibility of the different barrier elements, e.g.:
  - limitation of maximum temperatures at certain points within the disposal system by limiting the **radiogenic heat output** of the waste canisters as the target. To limit temperature, there are also other factors, e.g., the emplaced buffer will need to have certain thermal properties (**heat conductance, heat capacity**) as target; in some cases, also enlarged **distances** between canisters (with corresponding targets) can mitigate heat effects.
  - limitation on the **amounts / concentrations of certain types of material** (e.g. construction material (e.g. grouts) or stray material by construction / operation) prone to dissolution in the porewater that could negatively affect some safety functions are the targets.
  - etc.
- Capacity for disposal of the envisaged wastes: **volume of encapsulated / packaged waste** in e.g., as number of waste canisters / packages (as a constraint by the 'external' stakeholders) is the target.
- etc.

4.2.2.4 Quality targets for the safety characteristics

In addition to the safety function performance targets, also quality targets need to be defined for the safety characteristics. These address e.g. questions like *'how reliable?'*. This is just an illustrative indication and needs to be complemented for the systems looked at.

4.2.3 'Needs'-related requirements for implementing the closed repository

4.2.3.1 Goals of repository implementation

In this sub-section the requirements related to the implementation of the closed repository at the selected site (monitoring (establish baseline, detect changes and evolution and assess findings, underground geological characterisation, testing of procedures, construction, operation / waste emplacement, monitoring of performance, closure) are discussed.

Overall goals

For the life cycle stage 'implementation of the closed repository', at the highest level e.g. the following goals should be achieved:

- *Implementation of the repository is done such, that all requirements defined for post-closure safety for the closed repository are met.*

  Furthermore, the construction and the use of the facilities for investigations, monitoring, waste emplacement, emplacement of the engineered barriers, and the closure goes according to plan in a safe, reliable and sustainable manner meeting the corresponding requirements at affordable cost, within reasonable time and in agreement with society.

These overall goals are **decomposed** into *'functional goals related to implementation'*, '*ensuring compliance with the post-closure goals'* and *'goals related to 'operational' issues during implementation'*, see descriptions below.

Functional goals related to implementation

For the decomposition of the high-level goal described above, it is important to identify and describe the **phases** needed for implementing the repository with their related **goals** / **basic functions (or tasks)**, as described below (with the assumption that a site has been selected and that the conceptual design of the repository is available):

- After having selected the site, **monitoring** at the site should start early enough to reliably determine the baseline conditions (incl. natural variability, trends) and continue monitoring to detect any changes of the baseline and assess the importance of detected changes.
- Perform underground **investigations**
  - to collect additional data to assess / confirm site suitability and to acquire additional information for the design of the repository,
  - to perform tests related to the construction (and operation) of the repository,
  - etc.
- **Construction** of the repository.
- **Operation** of the repository:
  - **encapsulation** of the waste in disposal canisters,
  - **emplacement** of the encapsulated waste and the other elements of the system of engineered barriers,
  - in parallel, **extension of the repository** with additional disposal rooms (if planned).
- **Closure** of the repository.
- Dedicated monitoring related to **system performance** and to the potential impact of the repository on the **environment** (in the different phases mentioned above, if planned).

Ensure compliance with the (functional) post-closure goals

To ensure that the **closed repository will fulfil all the requirements** defined for post-closure safety (see section 4.2.2) are met, additional goals apply, e.g. such as:

- the **disposal rooms** must be placed in the desired position (and the information must be available to demonstrate this) and excavations and implementation of rock support is carried out as planned,
- the **engineered barriers** (canister / waste package, buffer, backfill, seals) as emplaced must have the desired properties,
- the **impact of the underground openings** needed for construction, operation and closure on the barrier efficiency of the overall barrier system for post-closure safety must be acceptable,
- the **impact of the operational phase** with the open (not yet backfilled) openings on the surrounding hydrogeological system must be acceptable for post-closure safety.
- etc.

For all these issues, the information must be available that clearly demonstrates that all requirements are met.

Goals related to 'operational' aspects of the implementation process – goals related to the 'characteristics of implementation'

Besides ensuring that the goals and requirements related to **post-closure safety** are met (addressed above), goals and requirements must be defined to ensure that the **implementation process** is done in a **safe, sustainable and reliable manner**, at affordable **cost** and within reasonable **time** and that it is in accordance with a range of other issues / requirements all of them related to the so-called **'implementation (quality) characteristics'.** These ensure that the 'hands-on' work has to be done in a safe, reliable and efficient manner using adequate working instructions and suitable installations / equipment with safety of persons and protection of the environment has to be ensured also in case of incidents and accidents through corresponding administrative measures and safety installations. Furthermore, it also ensures the reliability of all installations, provides flexibility to implement changes if needed, etc.

The goals related to **'implementation (quality) characteristics'** include e.g.:

- ensuring **nuclear safety** (e.g., defence in depth),
- ensuring **radiation protection** goals during repository operation / waste emplacement (e.g., limiting nuclide releases into the environment, limiting contamination / airborne radioactivity, limiting direct radiation / apply sufficient shielding for workers and population, restricting access to places with relevant dose rates, etc.),
- ensuring **security** (protection against misuse of radioactive material and sabotage (including cyber security) and **safeguards** (diversion of fissile material) during repository operation (during and after waste emplacement),
- ensuring **worker's safety and health** during all phases (e.g., ensure adequate working conditions; prevent mishaps / incidents and accidents, allow for escape / rescue / evacuation, etc.),
- ensuring the **protection of the population and the environment** during all phases in relation to conventional (non-nuclear / non-radiological) and nuclear / radiation hazards,
- ensuring the compatibility of the facilities and activities with land-use planning and **environmental impact** legislation as a pre-requisite to achieve **agreement with the local population** during all phases,
- ensuring **reliability** (including reliability of (non-destructive) testing of materials/products)**, availability, maintainability and repairability / exchangeability of components** of the system elements needed for the implementation of the closed repository during all phases,
- providing **flexibility to allow for changes,**
- ensuring the possibility to implement **corrective actions** during all phases (if needed), including retrieval of waste disposed, if needed,
- etc.

As already discussed in connection with post-closure safety, these **broad goals related to 'functions' and 'characteristics'** are **achieved through functions** (or properties / behaviour, tasks) with corresponding performance **targets** and through **(quality) characteristics** with corresponding quality **targets**, see below.

4.2.3.2 Implementation functions and characteristics

The implementation functions and characteristics are derived by decomposition of the implementation goals described in section 4.2.3.1. Thus, the goals are broken down into the needed implementation functions to be performed and implementation characteristics to be met to reach the goals in the different phases.

This has to be done for the *'functional goals related to implementation'*, for *'ensuring compliance with the post-closure goals'* and for *'goals related to 'operational' issues during implementation'* mentioned above. This results in a large number of functions and characteristics, too many to discuss all of them in this document.

As an example, the goal of 'construction of underground openings' is broken down into different **functions** / tasks[33], e.g.:

- excavation of the rock (loosening of the rock in the cross-section and removal of the rock),
- installation of the rock support,
- construction of the tunnel lining,
- installation of the carriage way,
- installation of the equipment (cables, light, sensors, …),
- commissioning of the underground opening (testing, …).

with the **characteristics** related to these tasks / activities being related e.g.to, safety, environmental impact, accuracy, reliability, possibility for correction, flexibility to adapt, cost effectiveness, etc.

The **level of detail** in defining these functions and characteristics will depend upon the stage of the programme; in an early stage, not that many details are needed – in the stage of implementation, more details are needed (see discussions 4.2.4.1).

A similar process as described here for the functional goals of 'construction of an underground opening' has to be applied to all functional goals of implementation that have been listed above. This shows that some specific **expertise** is needed to define the functions and characteristics (not necessarily available in each organisation) and may thus need some external support.

4.2.3.3 Performance targets for the implementation functions

In a next step, the performance targets for each function must be defined. For the functions defined above, some examples are given below:

- excavation – minimum **speed** (m' per day),
- rock support – maximum rock **deformation** (m'),
- etc.

This is done in a similar manner for all the implementation functions. This again needs sufficient specific **expertise** (not necessarily available in each organisation) and may thus need some external support.

[33] As said earlier in the text, for specific aspects the term 'task' is more appropriate than 'function' – the 'task' is in its impact in the requirements management system the same as a 'function'.

4.2.3.4 Quality targets for the implementation characteristics

Finally, quality targets for the implementation characteristics must be defined, where this is needed. For the function of excavation, a typical quality characteristic with its target would be the accuracy of the profile excavated – maximum over-profile (in % of diameter).

For operations, a typical characteristic is availability of an installation – hours per day available for operations (with the rest being used for maintenance, etc.).

This is done in a similar manner for all the implementation functions with quality characteristics and for all non-functional characteristics. This again needs sufficient specific **expertise** (not necessarily available in each organisation) and may thus need some external support.

4.2.4 'Needs'-related requirements for preparing the implementation of the closed repository

4.2.4.1 Goals for preparing the implementation of the closed repository

In this sub-section the goals related to preparing implementation (planning, modelling (including the development of the safety-case for post-closure safety), the design of processes and facilities (incl. equipment) needed for implementation, decision-making and the licensing process (including the interaction with the regulator, policy maker / government and the public)) are discussed.

Overall goals

At the highest level, e.g. the following three goals for preparing implementation should be achieved:

- *Planning of the **closed repository** to ensure that an **adequate level of post-closure safety** is achieved with the use of periodically updated safety-cases, developed in high quality and in a reliable and robust manner with the following aims:*
  - *provide input to site selection and repository design, with defining adequate criteria for site selection and suitable requirements for the design of the repository with its system of engineered barriers based on a convincing safety-case and through assessing the performance of the barrier system (geology and engineered barriers) and its elements,*
  - *assess the level of safety for the post-closure phase with a reliable safety-case as input to decision-making and licensing.*
- *Planning the **implementation of the closed repository** to ensure that the closed repository is implemented according to the plans, with clear demonstrations that all **requirements** for **post-closure safety** and for the **implementation process** are met. This requires:*
  - *for each milestone in the implementation process of the disposal system (internal decisions, licensing steps, etc.), the needed products (documents, etc.) must be prepared in time with the necessary quality, and the subsequent use of these products and the corresponding discussions must be accompanied in an adequate manner and meet all applicable requirements in a demonstrable manner.*
  - *the products and the underlying material (e.g. studies, RDD, investigations) must ensure and demonstrate that the implementation of the disposal system is safe, technically feasible, reliable and sustainable and can be implemented at reasonable cost and within reasonable time and meet all applicable requirements in a demonstrable manner.*
- *Planning the **preparation of the implementation** of the closed repository (planning of the planning) to ensure that the preparations of implementation will meet all applicable requirements in a demonstrable manner.*

Functional goals related to the post-closure safety case

The functional **overarching goals** as described below must be fulfilled.

- The safety-case has to:
  - **provide guidance and feedback** to the further development of the closed repository (site selection, safety strategy (with a corresponding safety concept), conceptual design of the disposal system, etc.), including involvement in developing the corresponding requirements; with the aim to *'design for safety'* (including site selection) as discussed in section 4.1.
  - **assess the level of safety** for the disposal system according to the status of planning as input to decision-making / licensing (status of site selection / site characterisation, status of design of disposal system, etc).
- The development of a safety-case should be **started very early** in the implementation process to ensure that the feedback and corresponding guidance takes place from the beginning on.
- The safety-case has to be **'fit-for-the-purpose'**. This requires that a corresponding scientific-technological basis is available. Thus, the RDD programme, the site-investigation programme and the development of the design must be coordinated with the needs of the safety-case.
- The safety-case has to be **periodically updated** to be available in a level of detail that is in line with the needs of the actual phase of the disposal programme.

Functional goals related to preparing the implementation

The functional **overarching goals** as described below must be fulfilled:

- The following **elements (tasks) needed for implementation** need to be planned (incl. periodic update):
  - definition / characterisation of the **inventory of radioactive wastes** to be disposed (existing waste, waste expected in future): volumes, waste conditioning (for L/ILW and LL-ILW), nuclide inventory, key properties, etc.; including an assessment of uncertainty in the information,
  - safety assessment / safety case for **post-closure safety** providing feedback and input to each decision-point (e.g. site screening / site selection, developing the conceptual design, construction license, operation license, etc.),
  - **selection of the site** (host rock, geological situation, situation at the surface) based on a process with involving all relevant stakeholders and with acquiring / developing the necessary information,
  - development of the **conceptual design of the repository** (incl. the system of engineered barriers), tailored to the properties of the host rocks / geological environments considered, taking the properties of the wastes to be disposed into account. This also includes the development of the system of engineered barriers. The following **life cycle stages** and themes have to be considered to ensure implementation feasibility:
    - **construction**
    - **operation** (emplacement of waste canisters / waste packages and engineered barriers)
    - **closure**

- **site characterisation,**
- safety assessments / studies related to **construction safety and operational safety** (conventional, nuclear, radiation protection) providing feedback and input to each decision-point (e.g. developing the conceptual design, construction license, operation license, etc.),
- interaction with **society** (for all phases),
- **management** of the overall programme in all phases,
- etc.

Functional goals related to planning the preparations

Planning the activities needed for all the tasks of preparing implementation (what must be done in the current project phase, incl. the refinement of the requirements management system) must be **in line with the phase under investigation**. Thus, the **level of detail** for the issues mentioned above will evolve with moving from one phase to the next, e.g. as follows (see also chapter 6):

- first ideas (and assumptions based on analyses of analogue projects),
- conceptual thoughts,
- preliminary plans / documents / descriptions,
- plans / documents / descriptions for submitting the permit / licence applications for the work / implementation,
- plans / documents / descriptions sufficiently detailed to get clearance for and to start the work / the implementation (including tendering the construction work, etc.).

- The following **sequence of activities and decision-points** (the phases of implementation) has to be addressed in planning:
  - initiating the disposal programme (based on an up-to-date waste management strategy),
  - site selection,
  - construction license,
  - construction of the repository,
  - operation license,
  - operation of the repository with waste emplacement and – if planned – in parallel with the extension of the disposal rooms.
  - as far as planned, dedicated monitoring activities
    - to assess the impact of the repository on the environment,
    - to assess system performance,
    - to ensure compliance with internal and regulatory requirements (e.g., being within ‘operating window’).
  - closure of the repository.

- Planning has to ensure that the **needed scientific-technological basis** is in line with the phase under investigation:
  - The necessary **'science readiness levels**' and '**technology readiness levels'** must be defined and the measures to be taken that they are achieved. This must be planned – see also the requirements for the safety case discussed above.
  - This requires that the corresponding **studies and investigations** (incl. RDD) are conducted in time to achieve the 'science-' and 'technology readiness levels'.

4.2.4.2 Functions when preparing the implementation of the disposal system

The functions (or – more precise: the tasks) for preparing the implementation of the disposal solutions include:

- Compilation of **radioactive material information** for developing disposal concepts & analyses of safety:
  - compile / update of (model) waste inventory (existing waste, expected waste, reserves), including waste characterisation.
  - develop loading concepts / plans for the canisters for spent fuel.
- Perform **geological investigations**, incl. evaluations and syntheses (e.g. through site descriptive models) to produce the geological information bases for:
  - identifying siting possibilities and conducting site selection,
  - developing disposal concepts (system concept and safety concept),
  - assessing post-closure safety,
  - or – in later phases – performing the design work (allocation of underground structures, excavation of the different structures (rock support, excavation method, etc.)).
- Perform safety analyses for post-closure safety:
  - performance assessment to understand and quantify the behaviour and performance of the specific barrier elements (also as input for updating the requirements management system),
  - provide input to the site selection process as part of the requirements management process,
  - provide feedback to design (e.g. through modified requirements) to modify individual barrier elements,
  - assess the expected levels of safety for a given barrier system.
- Perform the **design work**:
  - develop / update the disposal concept, incl. architecture: allocation of the different structures needed,
  - develop the design of the system of engineered barriers that takes the results of site selection into account – *'tailoring the design to the properties of geology, taking the properties of the wastes to be disposed into account'* – with geology and the waste being constraints,
  - develop operational schemes (processes, equipment, facilities, workforce, etc.),
  - develop the design of the facilities (disposal rooms, all other facilities needed for implementation).

- Perform safety analyses for the different phases of implementation:
  - perform analyses related to conventional (occupational) safety (protection of persons and the environment), also for the 'non-nuclear' phases, including construction,
  - perform analyses related to nuclear safety (for those phases where this is relevant),
  - perform analyses related to radiation protection (for those phases where this is relevant),
  - provide feed-back to design (facilities, operational schemes, construction procedures, administrative measures, etc.) based on all the analyses done on the safety issues mentioned above.

4.2.4.3 Performance targets for preparation functions

The performance targets for the functions (tasks) mentioned above are related e.g. to the needed level of detail and the time schedule to complete the work. It is beyond the scope of this document to go into more detail.

4.2.4.4 Quality characteristics and quality targets for preparing implementation

The preparation functions are complemented by quality characteristics and their quality targets to specifically describe the expected quality of the preparations if this is considered to be necessary. This is related e.g. to the completeness and reliability of the information provided, taking uncertainties into account. It is beyond the scope of this document to go into more detail for this issue.

4.2.5 'Needs'-related requirements for interacting with society

Overall goal:

The overall goals of interacting with society can be, e.g.:

- *Building up a relationship with members of the public that allows a constructive dialogue to provide input to the definition of the path forward to develop and implement a disposal solution for the wastes under discussion. This requires a common understanding (communication in understandable language of the issues), listening to the concerns of the citizens and addressing their needs and concerns in an open manner.*

Appropriate interaction with all relevant stakeholders is crucial for the success of a disposal programme. The stakeholders involved may change from one phase to the next. Thus, as a starting point, one can take the typical phases with their key goals (see e.g. list with sequence of activities and decision-points in section 4.2.4) and evaluate the key stakeholders that are affected and need to be involved in the respective phases.

This needs a good understanding of the societal and political structure and culture of a country and of the siting region. This is then the starting point to define requirements for each of the phases related to stakeholder interaction and to identify the type of interactions and the people needed to interact with society. This area needs special know how and expertise and is thus beyond the scope of this document.

4.3 Requirements for the disposal system related to the 'solution domain'

4.3.1 Developing the 'solution'-related requirements – introduction

Below, the steps to derive the 'solution'-related requirements are briefly summarised.

- The **input** for deriving the 'solution'-related requirements are the 'level 0 to level 3' - requirements of the 'needs domain', see section 4.2.
- As a first step, the disposal system to be analysed needs to be roughly defined, as far as existing information allows this. Based on the **system concept** available (in an early stage e.g. based on an analogy to existing concepts of other programmes), first a '**functional architecture'** of the disposal system is developed.

  The 'functional architecture' consists of all elements of the disposal programme that are necessary for the planning, the implementation and the use of disposal system to function (fulfilling all requirements); with the implementation including all activities up to the closed repository with all wastes being emplaced, and 'using' the disposal system having the purpose to protect persons and the environment against the radiological hazards of the waste in the post-closure phase (the 'use' phase). The 'functional architecture' thus includes **all the 'means' / elements needed** for implementing the closed repository and for the safe and reliable functioning of the closed repository in the post-closure phase; this has also to consider the needed (quality) characteristics. The 'means' include all the **objects**, the **activities** with their deliverables (e.g., documents, decisions, experiments with their results, etc.) and the **other measures** with their achievements needed for implementing the disposal system. In the 'functional architecture' these elements of the disposal programme act as 'black boxes' that perform specific processes, have specific properties / a specific behaviour or fulfil specific functions / tasks. When defining the 'functional architecture', all the **phases of repository implementation** must be considered with the full **life cycle of each element** of the disposal programme. Finally, the functional **interactions** needed between the different elements of the disposal programme (including the elements needed for its preparation and its implementation) must be defined. Thus, the '*who needs to support whom'* needs also to be captured by the 'functional architecture'.

  Often, the **development of the 'functional architecture'** starts with defining the overall process needed to achieve the overall goals for each of the themes / life cycle stages (as described in section 2) in each phase. This allows then to identify the different sub-processes needed that are supported by the corresponding elements of the disposal programme and to define how they interact.

  The 'functional architecture' provides the **interface** between the 'needs' domain (the 'level 0 to level 3' - requirements) and the 'solution domain' with the 'level 4 and 5' - requirements (the specifications).

- Then, the **functions** and **characteristics** ('level 2' - requirements) with the corresponding performance-/quality-**targets** ('level 3'- requirements) are **allocated** to the corresponding **elements** of the disposal programme according to the 'functional architecture'.

- Then, the **'constraints'** need to be considered. This concerns geology and the waste to be disposed, and other issues as far as applicable:
  - The geological properties are determined by the **geological options available** in a country and by **selecting a site** out of these options. The selection depends upon the site selection approach and thus, on the criteria used. Once a site has been selected, the geological properties are given and 'dictate' the boundary conditions for the design the repository and of the system of engineered barriers. Site selection is influenced by the site selection criteria, but these are by the (limited) geological possibilities of a country more constrained than the requirements used for the design of the engineered systems.
  - The situation for the **wastes** is like the situation for geology. Also the properties of the waste (especially the nuclide inventory) are given by their use (e.g., irradiation of the fuel); for L/ILW, some modifications of the properties are possible through treatment / conditioning. Thus, the properties of the waste 'dictate' to some extent the needed properties of the site / geology (mainly for the needed long-term stability) and those of the engineered barriers.
  - To summarise, the disposal rooms with the system of engineered barriers are **tailored to the properties of geology**, taking the **properties of the waste** into account.
- Next, the design process starts where each element of the disposal programme according to the 'functional architecture' is designed such, that all the functions and characteristics with their performance-/quality-targets allocated to this element are fulfilled. If the requirements allocated to an element lead to conflicts, and no satisfactory solution can be found, **negotiations** have to start to resolve these conflicts. This can also lead to a **change** in the functional architecture.

  In the design, the **in-situ conditions and loads** (e.g. geochemical environment, temperatures, stresses, etc.) acting on the elements of the disposal system (objects) must also be taken into account.

  The design process for the different elements is conducted in two steps:
  - In a first step, the so-called **'design input requirements**' for an element are developed. This includes the consolidated list of all requirements to be fulfilled by the element, the loads and conditions acting on the element (mainly for objects) and the results of a pre-design that define the broad characteristics of the element (for objects: types of material to be used, broad dimensions, etc.).
  - In a second step, the so-called **'design output specifications'** for an element are developed based on the 'design input requirements'. This consists of the detailed design (with all considerations being documented) of the product to be implemented and leads to two document types to be used for the implementation process, the **'product specification'** and the **'production specification'**.

More details are given in the sub-sections below.

4.3.2 'Solution'-related requirements for the closed repository to ensure post-closure safety

In this sub-section, the development of the **product specifications** for the elements of the closed repository are discussed. It complements the overview already given in section 4.1.2.

- First, the **host rock and the geological situation** at potential sites (if site selection has not yet occurred) or at the site selected must be described. For the geological properties / characteristics, in the strict sense one cannot talk about requirements, although site selection criteria are most likely used for selecting the site. Having **selected the site,** the geological properties / characteristics are given and are **constraints** that need to be considered.

  The **host rock and the geological situation** (including the surface conditions / climate) are important for two things:

  - first, they strongly influence the 'level 1 to 3' - **requirements** for the system of engineered barriers as discussed in section 4.2.2.
  - then, they have a very strong impact on the **in-situ conditions and loads** acting on the system of engineered barriers.

- Next, the development of the **product specifications for the elements of the closed repository** at the start of the post-closure phase (the **'initial state' after closure**) are discussed. It is important to note that the product specifications address the initial state of the repository, but they have to take into account that some of the loads and conditions acting in the disposal system and the properties / the behaviour of the host rock, the geology surrounding the disposal rooms, the engineered barriers and the surface environment **will evolve** in the period to be analysed and may thus for some of the barrier elements be significantly different from the initial state – this evolution needs to be **captured through modelling** and has to be considered in the product specifications for the initial state.
- The development and refinement of the design of the disposal system is based on the **interaction** between **performance assessment** (as part of assessing post-closure safety) and the **design process**, taking the properties of geology and of the waste to be disposed into account.
- In a first step, the **conceptual understanding** on how the disposal system and its evolution will look like must be described. For this, in a first step the '**functional architecture'** of the disposal system is defined (what are the barrier elements of the disposal system and how do they interact). The description of the conceptual understanding has to address the key processes and their effectiveness as well as perturbing effects, etc. For this, geology and its impact on in-situ loads and conditions and their evolution are also broadly described.
- To develop the disposal system that should fulfil the high-level post-closure safety objectives, the elements in the 'functional architecture' are screened to identify those elements that are essential for post-closure safety (the **barrier elements**). For the safety-relevant barrier elements, the current understanding on their contributions to post-closure is safety is then described (the so-called **safety concept**). This is then the basis to address the following issues:
  - For **each barrier element** (being mapped by the functional architecture), identify which **safety functions** and **quality characteristics** it must fulfil in the period it must function,
  - For each safety function and quality characteristic, take note of the **corresponding performance / quality target** that must be met by the corresponding barrier element to achieve sufficient safety and be aware of the **in-situ loads and conditions** that act on the

barrier element. To ensure that the safety functions and quality characteristics are fulfilled, and the performance / quality targets are met, the performance / quality targets of these barrier elements must either be measurable or be assessable by modelling,

- Define the **investigation goals** of the field programme to evaluate the understanding of the **geology** of the site selected / under investigation and to check whether the site has the expected **properties and performance** and whether the **loads and conditions** acting on the system of engineered barriers and their evolution due to the evolving geological environment are as expected – if the loads and conditions have changed, make the necessary changes in the design input parameters of the system of engineered barriers,
- Based on the information from waste characterisation, define the expectations on the **properties and the behaviour of the waste** under disposal conditions and define its encapsulation (e.g. to be defined in the waste acceptance criteria) and develop corresponding canister loading concepts / plans for spent fuel (including the specification of measurements, as far as needed). It is again important to note that the properties of the waste are constraints that need to be considered.

- This process requires in the initial phase **several iterations** until a satisfactory situation is achieved with having a **balanced contribution of the different barrier elements** to safety (especially the system of engineered barriers),

  With the expectations on the safety-relevant properties and performance of the **host rock and geological situation** and safety-relevant properties of the **waste** being described, and the required performance for the elements of the **system of engineered barriers** being defined, defining the requirements is completed.

- It is now the task of the design process to transform these requirements into specifications of the products to be implemented ('product specifications'):
  - As **input** for the detailed design of a barrier element, **'design input requirements'** are developed that consist of:
    - the **description of all functions and characteristics** with their targets to be fulfilled by the barrier element, with the compatibility of the requirements resulting from the functions and characteristics having been confirmed. This will sometimes require discussions / negotiations between 'owner / operator' and the design team (incl. subject matter experts) that may lead to some modifications of the system,
    - the **conceptual design** of the barrier element, providing input on the types of materials to be used and on the broad dimensions of the element,
    - the description of the initial state, the interactions and the resulting **loads and conditions** acting on the barrier element and **their temporal evolution** for the full period of time where the functioning of the barrier element with the required performance / quality is relied upon – thus, the loads and conditions most important for the design can be different from those at the initial state.
  - Based on these 'design input requirements', the detailed **design** of the barrier element is developed – the **'design output specification'** with the detailed specification of the **materials** (incl. detailed properties) to be used, the detailed **dimensions**, the **loads and conditions** considered in the design, etc. The documentation has also to contain a description of the design methodology and of the verification methods used that provide convincing information and results (e.g., from experiments, etc.) that the barrier element will

reliably fulfil the allocated functions and characteristics defined above. This will then lead to the needed **product specifications**.

   - Finally, the **construction / production process** will be defined, and the vulnerability of this process will be evaluated with respect to **undetected deviations** of the barrier element from the specifications that could endanger its performance. If needed, this may require **some adaptions** in the production process or in the design or the consideration of these deviations in assessing post-closure safety.
   - To go through all these steps may require **several iterations.**

- To analyse the **performance of the design** developed, different steps are needed that use different types of tools to address the following questions:
   - Are the **needed elements of the disposal system** with the needed details included in the system concept (described as 'functional architecture') to cover all the required functions / characteristics and are they **understood** and described in sufficient detail for assessing their performance?
   - For the different elements of the disposal system, is the **temporal evolution** of the loads and conditions they are exposed to adequately captured for the period they need to function?
   - Will the elements of the disposal system **perform as needed** under the expected conditions with the design as specified (materials with their properties, dimensions, etc.) and thus fulfil their functions and characteristics with the required performance (and quality) and meet the corresponding performance / quality targets, taking the evolution / degradation of the barrier elements into account?
   - Are the **uncertainties and risks** for the different issues mentioned above adequately described and captured in sufficient detail?
- To address these questions, the required performance assessment
   - has to take the **constraints / boundary conditions** of the disposal programme into account (geology available, waste to be disposed, legal and regulatory requirements, decisions already taken, elements already implemented, etc.),
   - will use the **results of earlier analyses** (or earlier thoughts based on analogies from advanced programmes) as an important source of information as a starting point,
   - will complement this information with **findings from recent progress** in science, from specific investigations made and from the experience made in other programmes, etc.
- This leads to a (updated) system concept / safety concept (described as 'functional architecture') in which the **role of the important barrier elements** and their contribution to safety are adequately described. This includes:
   - the **geological barrier** (host rock and geological situation) with its contribution to safety and its respective safety relevant properties,
   - the **waste to be disposed** (existing and expected in future) with its impact on performance of other barriers (chemical constituents, physical properties (e.g. heat output, radiation, …)) and its safety relevant properties (e.g. nuclide inventory, longevity of waste matrix, instant release fraction, etc.),

  - the different elements of the **system of engineered barriers** with their contribution to safety and their respective safety relevant properties.

- Then, with the help of performance assessment tools, the **behaviour and performance** of the different **barrier elements** and their **temporal evolution** is assessed in detail, e.g. by looking at the features, events and processes (FEPs) that are expected to act in the disposal system and influence the initial state, the loads, the interactions and the resulting conditions for the different barrier elements, including the future evolution of each of the different barrier elements and its corresponding impact on the performance of the overall disposal system. Once a sufficient understanding on the safety relevant properties of the system is available, **release calculations** can be made to check whether sufficient safety is achievable. In this iterative process, the design of the barrier elements is assessed and improved if needed until a satisfactory situation is achieved and the **design** of the disposal system can be '**frozen'**. This is then also the basis to **'freeze'** the corresponding **performance / quality targets**.
- In the case of a **heterogeneous geological environment**, as an equivalent to performance targets, host-rock and site-specific criteria can be used to assess the **quality of the geology** found. If needed, these criteria allow to avoid those parts of the host rock with the disposal rooms that are considered to have less favourable properties (e.g., by using the so-called 'rock suitability classification' method). The rules on **avoidance of less suitable parts of the host rock** will also be 'frozen'.
- In **advanced programmes** where the site has been selected and characterised in detail and that have gone through several safety cases, this point with the clearly defined disposal system and its functions and characteristics being 'frozen' is normally achieved with limited effort, taking the information and experience from earlier assessments into account.
- This is then the **starting point for the safety case**, where the **uncertainties and risks** related to the initial state of the repository and its future evolution are considered, again e.g. by the use of FEPs. The detailed analysis of the system with its uncertainties and risks with the help of performance assessment tools will lead to a clear understanding on the **spectrum** of initial states, loads, interactions and of the resulting conditions that operate in the system that is used to describe the future evolution and the likelihood of occurrence of the resulting **different possible (abstracted) variants of the evolution of the disposal system** with their changing safety relevant properties.

  Besides the uncertainties in initial state and future evolution, the issue of verification needs also to be addressed – the reliability of the testing performed during the production process to detect **non-conformities in the production process**. If there are some uncertainties in this testing, this also needs to be considered in the overall performance evaluation ('acceptability of non-detected deviations').
- This is then the basis to define the **'expected evolution' variant** with the design basis initial state, loads, interactions and resulting conditions that also takes the uncertainties and risks into account that are broadly associated with the expected evolution with its changing safety relevant properties.

  It also allows to define the **'unlikely evolution' variants** or even hypothetical variants that are beyond the design basis (in analogy to reactor design) with their changing safety relevant properties that will also be analysed.

Then, it may be worthwhile to evaluate in how far some of the **less likely variants** can be covered by the design with minimal changes or even without any changes, just by using more refined resistance models, by defining some acceptable tolerances and/or by slightly adjusting of some safety factors – with all these modifications being justified and explained. Thus, it may at the end well be the case that the **design of the disposal system** can cope with a **broader range of evolutions and loads and conditions** than originally anticipated when defining the design basis – thus, it can happen that for some system elements the **final design basis is broader** than originally planned.

- If the results of the corresponding consequence analyses show some weaknesses for some of these variants, **additional iterations** may be needed to make some modifications to the system or – if this is not feasible or desirable – to improve the understanding and reduce some of the critical uncertainties through focused RDD. This will finally lead to an **optimised system**.

The requirements related to the planning and modelling activities mentioned in the process described above are also briefly discussed in section 4.3.4.

Summary

Fig. 4 illustrates the whole process to **ensure post closure safety** and thus covers not only the issues raised about the 'solution'-related requirements (section 4.3), but also those discussed in sections 4.2.1 and 4.2.2 when defining the 'needs'-related requirements. This is done because of the **iterative nature of the process** that covers both the 'needs'-related and the 'solution'-related requirements / specifications. The overall process includes the following steps:

- The starting point (step No 1) is an update of the documentation of the current status of the disposal system under investigation with:
  - an evaluation of the **current understanding** of the disposal system, especially also the understanding about the geology at the site selected / at the (types of) sites envisaged with the basic conceptual design of the engineered barrier system, taking geology and the properties of the waste into account – with geology and the waste being **constraints** that need to be captured in the 'needs domain' and in the 'functional architecture',
  - a description of the **system concept** that describes all elements of the disposal system of potential relevance for post-closure safety,
  - the definition of the current **safety concep**t that describes the broad expectations on the contribution of the different barrier elements to safety (isolation, stability (external and internal FEPs), full containment, retention and retardation after breaching of the containment).

  This provides the basis for the subsequent requirements management process.
- The definition / update of the **goals** ('level 1' - requirements), **safety functions and (quality) characteristics** ('level 2' - requirements) and **performance and quality targets** ('level 3' - requirements) related to post-closure safety – step No 2. In this process, it is important to ensure that the **constraints** about geology and waste are adequately captured by the 'level 1 to 3'-requirements.
- The definition / update of the 'functional architecture' and the **allocation** of the **safety functions** and **(quality) characteristics** with their performance and quality targets to the **different barrier elements** (geology, engineered barriers) of the 'functional architecture' – step No 3.

- The **design process** (step No 4), that uses for each of the **barrier elements** (defined in No 3) the allocated requirements (defined under No 2) and the expected loads and conditions (incl. their future evolution) acting on them to define the key characteristics of each of the barrier elements – the products defined by the **product specifications** ('level 4' - requirements, consisting of the 'design input requirements' (level 4a) and 'design output specifications' (level 4b)) that are complemented with the **production specifications** ('level 5' - requirements).
- The analysis of the **performance** of the different **barrier elements** in their environment, recognising the evolution of the **loads and conditions** and taking uncertainties and risks into account – the so-called performance assessment. The results of performance assessment are analysed. This includes the comparison with performance and quality targets and **giving feedback** to design and / or the definition of the 'level 2'- and 'level 3'- requirements (red arrows) – step No 5.
- Based on the results of performance assessment, the **most likely evolution** (with the possibility to include also some alternative evolutions, if reasonable) is identified (design basis) and described as well as **alternative evolutions** (beyond design basis – alternative scenarios, conceptualisations, parameters). These are then analysed, and **doses calculated,** again with the possibility to **give feedback** (red arrows) – step No 6.

This scheme reflects the parallel, but strongly interactive work of requirements management, design and performance assessment.

The process described above and the corresponding scheme in Fig. 2 is in line with the process described by Posiva and SKB (Posiva and SKB, 2017) e.g. with the oversight-scheme in Fig. 2-1 of that report.

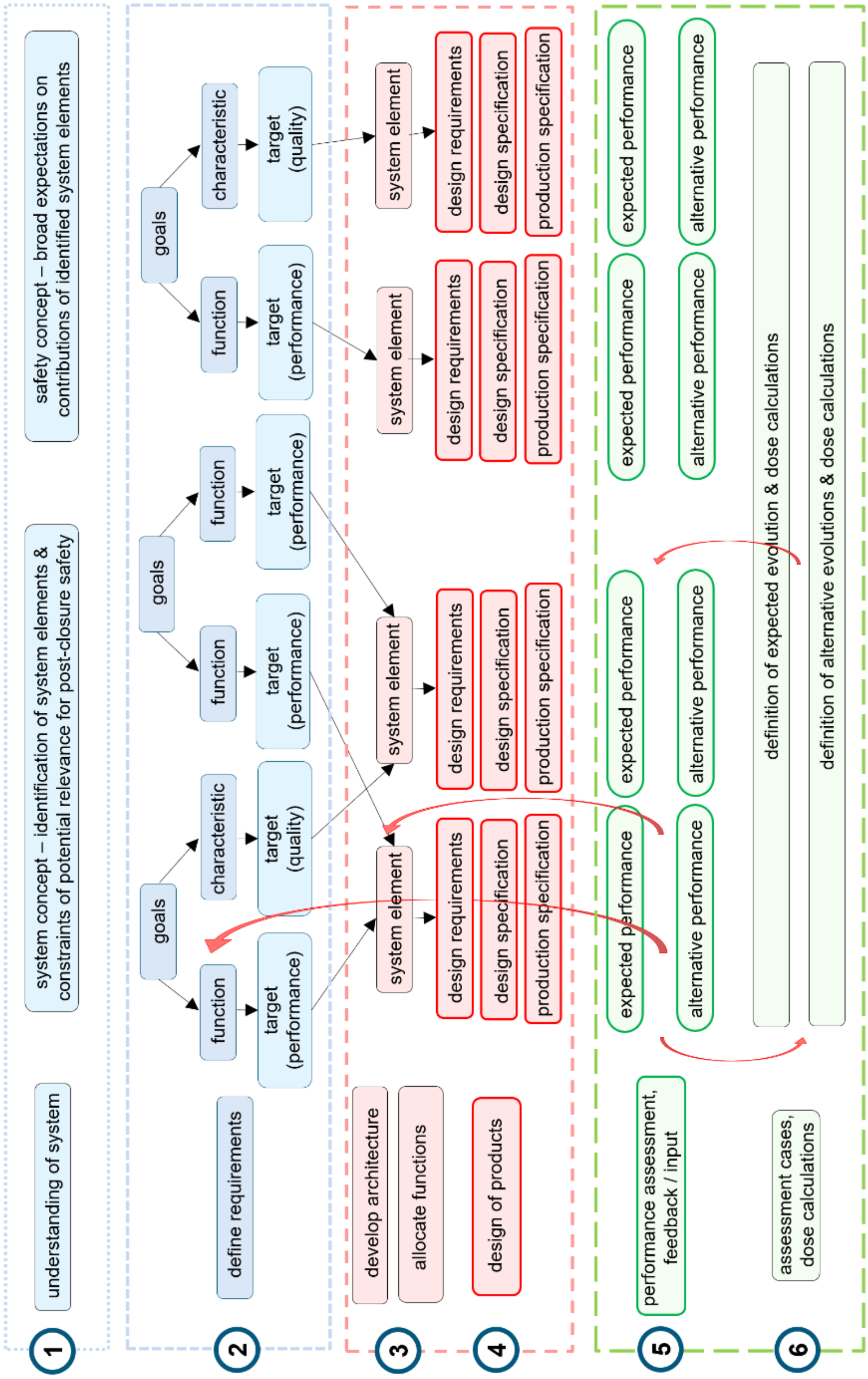

Figure 4 – Schematic presentation of the different steps (1 to 6) of developing the post-closure requirements and the post-closure safety case.

For more details about the different steps, see text on previous page.

4.3.3 'Solution'-related requirements for implementing the closed repository

In this sub-section the development of the **product specifications** needed for the implementation of the closed repository are discussed. This includes all **elements of the disposal system** that are needed to successfully **implement the closed repository** with all envisaged waste being emplaced and fulfilling all requirements related to post-closure safety. For this, **all phases** of implementation must be considered with the different elements of the disposal system needed in the different phases.

For implementation, it is often worthwhile to first **define the broad processes** that are needed in each of the phases to fulfil the functions / tasks and characteristics required in that phase (as part of the life cycle stage 'preparing the implementation', see section 4.3.4). The corresponding **process design** then provides the input about which objects (including equipment and object overarching systems), which activities and which other measures are needed for which function / characteristic in each phase of implementation. These objects, activities and other measures are discussed below.

- The **goals, functions** and **characteristics** with their corresponding **performance and quality targets** as discussed in sub-section 4.2.3 are **fulfilled by**:
  - specific **objects** (in bold) with an indication of the goals and functions / characteristics they fulfil, e.g.:
    - **surface infrastructure for monitoring** to define the base line, to detect and analyse deviations from the base line,
    - **surface facilities** for construction, operation, closure including waste encapsulation, preparing the engineered barriers, managing material for operating and closing the repository and logistics in general, maintenance / repair, for interacting with society, etc.,
    - **access to the disposal rooms** for construction of the disposal rooms, for emplacement of the encapsulated waste and the engineered barriers and for emplacing the closure barrier elements,
    - **disposal rooms** with the encapsulated waste and the engineered barriers emplaced,
    - **auxiliary rooms** to allow and support the needed activities / processes during construction, rock characterisation / testing, operation / emplacement of encapsulated waste and engineered barriers, performance monitoring (if planned), closure, etc.
    - with the corresponding **systems** that overarch several of the objects mentioned above, such as:
      - transportation of persons, waste packages, material, rock spoil, etc. (often by different transportation systems)
      - ventilation / cooling
      - energy supply
      - water and wastewater management
      - communication and control
      - escape, evacuation, rescue
      - etc.
  - specific **activities** (with their deliverables) needed to monitor / investigate, construct, operate and dismantle / close the facilities and to interact with all relevant stakeholders.

  - specific **other measures** (with their achievements), e.g., insurances (to cover some risks), etc.

- Based on the requirements for **each of the phases** defined above in sub-section 4.2.4, for **each requirement** (function / task and characteristic with their performance / quality targets) the **needed element of the disposal system** (object, activity or other measure as described above) is identified that has to fulfil this requirement.

  Then, the design process starts that has to ensure that the **final design** of each element of the disposal system (as documented in the product specification) **fulfils all requirements** (functions and characteristics with their performance-/quality targets) allocated to the element designed, taking the **surrounding environment** (loads and conditions) into account.

  During the process design, **conflicts** may arise – the requirements to be fulfilled by a system element are not compatible, and no suitable design can be found. This then needs some **negotiations to find a solution**; in some cases, this can lead to a modification of the functional architecture with adding one or more new elements to the disposal system. This process is done in an iterative manner to improve the system as far as needed.

  An issue of importance are those system elements that **change their function** when moving from one phase to the next – this then may require some modifications of one or more (parts of the) elements. If the changes are too big, a change in the 'functional architecture' may be needed that can lead to additional system elements.

- In a next step, **uncertainties and risks** (including those resulting from the surrounding environment (e.g., flooding of surface facilities / construction site, loss of external power, impact of earthquakes on facility and safety systems, etc.) are analysed and the **reliability** of the different systems and processes evaluated. If necessary, measures are defined to keep the consequences of uncertainties, risks and limitations in reliability / availability at an acceptable level. This process is again done in an iterative manner to finally arrive at an optimised system.

  The design process occurs in two steps:

  - In a first step, the so-called **'design input requirements**' are developed. This includes the consolidated list of all requirements to be fulfilled by an element, the loads and conditions acting on that element (mainly for objects) and the results of a pre-design that define the broad characteristics of the element (for objects: types of material to be used, broad dimensions, etc.)

  - In a second step, the so-called **'design output specifications'** for an element are developed based on the 'design input requirements'. This includes the detailed design to be implemented and consists of two parts, the **'product specification'** and the **'production specification'**.

- In this area, the allocation of the **responsibility** for the different requirements (at the different levels) is an important issue and will also need the involvement of subject matter experts and needs also to consider the peculiarities of the **external supply chains** in implementing a disposal system, see also section 4.3.4. Here, the **availability of qualified suppliers / support** can become a critical issue.

The requirements related to planning and the design process described in the three bullet points above are briefly discussed in section 4.3.4 below.

4.3.4 'Solution'-related requirements for preparing the implementation of the closed repository

The 'solution'-related requirements for preparing the implementation of the closed repository apply again to two elements:

- The development and the periodic update of the **safety case** to:
  - provide input to site-selection,
  - provide feedback to the further development of the disposal system with respect to post-closure safety,
  - assess the level of post-closure safety for the envisaged disposal system.
- **Planning** the implementation of the closed repository (incl. site selection and design of the repository, incl. the system of engineered barriers), including decision-making and licensing and **developing the needed products**.

The 'solution'-related requirements for preparing the implementation of the closed repository are mainly related to develop the **needed documentation** and to **provide the scientific-technological basis** to be able to produce this documentation. Then, also the process of using this documentation for **decision-making** and for the different **licensing-steps** must be considered in planning.

The 'level 4'- requirements are **specifications for the products** (documents, documented decisions, etc.) to be produced. Such specifications contain, e.g.:

- The topics and questions to be addressed,
- The nature of investigations & developments (studies, measurements, modelling, demonstration experiments, etc.) to be performed,
- etc.

The 'level 5'- requirements are **specifications for the production** (on how the work should be done), e.g.:

- Types of procedures / tools to be used (e.g. detailed protocols)
- QA-measures to be taken (independent measurements, peer review, etc.)
- etc.

Based on the **goals** to be achieved in each **phase**, the products to be developed include e.g.:

- Planning documents covering RDD, developing / updating waste inventory, site selection, geology (field work, syntheses), safety analyses (post-closure, operational), design, etc.,
- Documentation of the stepwise site selection process,
- Developing / updating waste inventory
- Field work and developing / updating geological information (e.g. through site descriptive model),
- Design documents,
- Results / conclusions (documented) from the safety-case for post-closure safety,
- Results / conclusions (documented) from assessing the safety and environmental impact during construction, operation (incl. nuclear safety, radiation protection), and closure,

- Results / conclusions (modelling studies, measurements / experiments / RDD) in support of the issues mentioned above and needed for internal decision-making,
- Documents / material needed for license applications and licensing interactions,
- Legal agreements,
- QA-documents,
- etc.

The **planning and development of the needed products** in these phases mentioned above is e.g. done by the following disciplines/activities:

- Maintaining the radioactive waste inventory (incl. characterisation and RDD)
- Geoscience (field work, studies, RDD, syntheses, etc.)
- Analyses of post-closure safety (development of methods / tools, development / refinement of the safety concept (incl. RDD), development / update of the safety case, etc.)
  - to provide feedback to the design of the facilities, the systems, the operation procedures, etc.
  - to develop the needed safety documentation for decision-making and licensing
- Design of the repository (RDD, studies, demonstration experiments, prototyping, etc.)
  - to develop the system of engineered barriers
  - to develop the overall implementation process with the needed processes in each of the phases, the corresponding design of the equipment and of the needed surface and underground facilities
- Assessment of safety / risks during construction, operation (including emplacement of waste) and closure and their management (development of methods / tools, identification of risks, risk analyses (understanding the risks, etc.), risk evaluation (actions needed, etc.), documentation)
  - to provide feedback to the design of the facilities, the systems, the operation procedures, etc.
  - to develop the needed safety documentation for decision-making and licensing
- Assessment of reliability, availability, maintainability / repairability and possibility for corrective actions of the facilities and processes needed for implementation. This may require some feedback to the design of the facilities, the systems, the operation procedures, etc. to ensure the quality of the 'operational' aspects of construction, operation and closure.
- Overall management (strategy, business processes, QA, etc.)
- Interaction with stakeholders / interest groups
- etc.

Also here, the role of **uncertainties and risks** needs to be assessed and countermeasures planned, if needed (e.g., mistakes in data management, loss of key personnel, delays due to misjudgement of time needed, etc.). This will finally lead to the more detailed **requirements / specifications** for each of the disciplines / activities in each of the phases for developing the needed products. As already mentioned earlier, in the early phases the level of detail (and the working load) for planning of the later phases will be rather limited and getting more detailed with progress of implementation.

For each of the products mentioned above the responsibilities (which of the different disciplines / activities mentioned above) for developing them are defined. Then, the ‘level 4’ - and ‘level 5’-requirements / **specifications** are developed that again occurs in two steps:

- In a first step, the so-called **‘design input requirements**’ are developed. This includes the consolidated list of all requirements to be fulfilled by a product, and the broad characteristics of the product are defined (literature studies, experiments, modelling, etc.)
- In a second step, the so-called **‘design output specifications’** for the product are developed based on the ‘design input requirements’. This includes the detailed programme of work, with milestones (with goals), etc.

4.3.5 ‘Solution’-related requirements for interacting with society

In this document, no details on the ‘solution’-related requirements for interacting with society are given. These depend upon the detailed situation in each **disposal** programme / country and require special expertise and knowledge about the national and local situation.

5. Structure of the requirements management system for a disposal system and its implementation

5.1 Introduction

The purpose of the requirements management system is to **store the information** developed in the processes as described in section 2 to section 4 in a suitable manner **for further use**. Furthermore, the requirements management system has to provide traceability (to understand the reasons and give confidence in planning and in the decisions) and should allow easy checks for **completeness and consistency** of the information, to make evaluations (based on the current configuration of the system) and to provide the **needed information to the users** in a suitable format. Furthermore, **managing changes and refinements** must be supported, including periodic assessments and updates (if needed), e.g., when moving from one phase to the next. Finally, it provides a platform to assess the importance of **uncertainties and risks** and may also be used for the transfer of knowledg**e**. For all these activities, **workflows** are developed for the requirements management process.

5.2 Structure of the requirements management system and its population

Below, the key elements of the requirements management system for implementing a disposal system are briefly described:

- The requirements management system has **three hierarchically organised domains** that address different but strongly interlinked parts of the requirements management system (see Fig. 5):
  - ***'Why'*** is ***'what'*** wanted by ***'when'*** is the focus of the **'needs domain'**: it starts with the (high-level) **goals, needs and expectation** of 'external' stakeholders about the system to be implemented (the closed repository with all the waste emplaced, implemented in a safe, reliable, timely and cost effective manner) form the **'level 0' - requirements.**

    The 'level 0' - requirements are then decomposed in / complemented by **more detailed goals** for the **different themes / life cycle stages** in the **different phase**s that need to be fulfilled for implementing the disposal system – the so-called **'level 1' - requirements**.

    At 'level 0' or 'level 1', also the **'external' constraints** (e.g. waste, site chosen with its geology and situation for the surface infrastructure, constraints resulting from the interfaces to other systems, etc.) must also be considered.

    These issues may require some documentation showing that the decomposed 'level 1' - requirements actually cover all constraints and all 'level 0' - requirements.

    The 'needs domain' also includes the results of decomposing the 'level 1' - requirements into the **'level 2 and level 3' - requirements** – the **'functions'** and '**characteristics'** with their **performance-** and **quality-targets**. This may again need some documentation that shows that the decomposed 'level 2 and 3' - requirements actually cover all the 'level 1' - requirements.

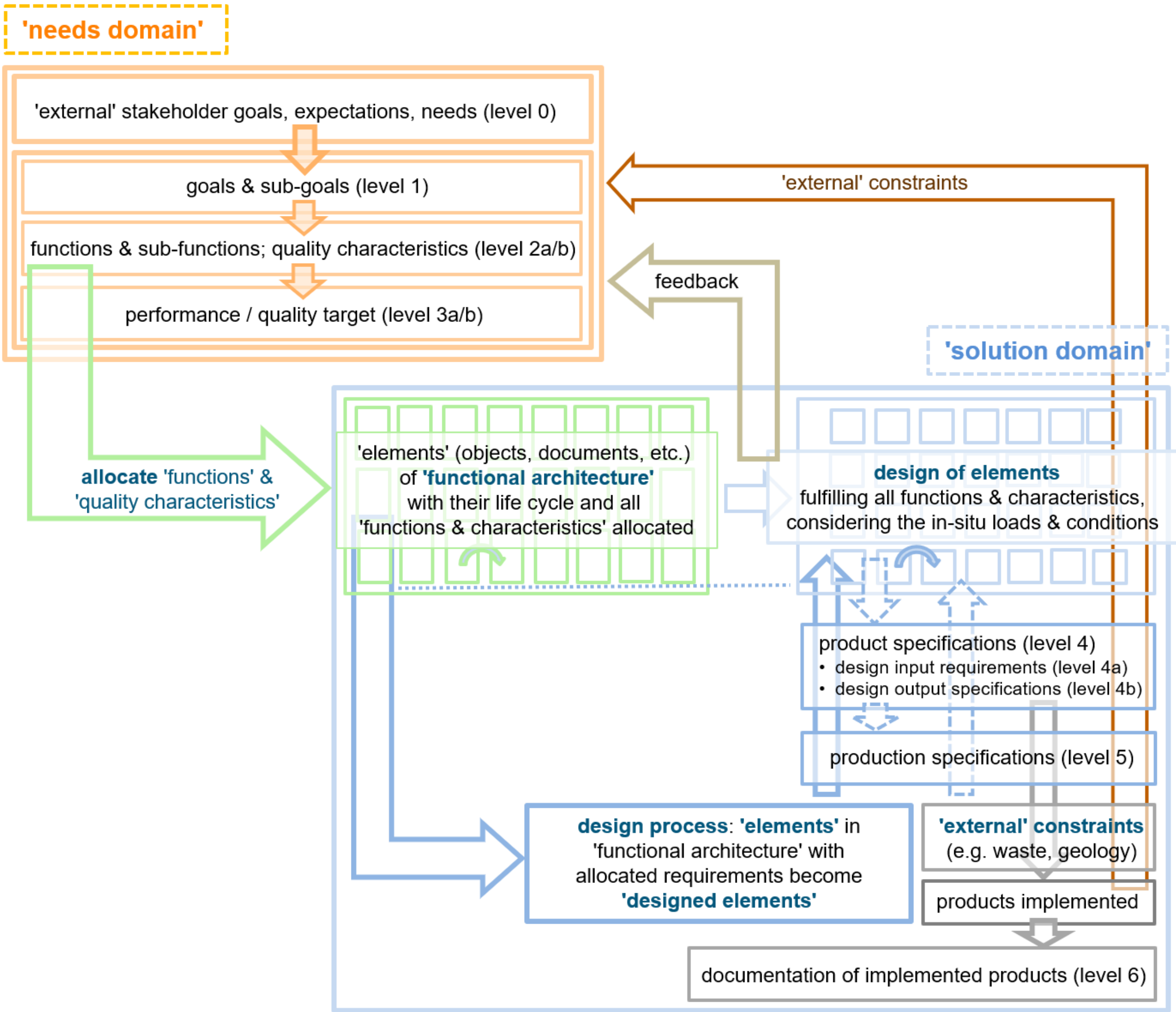

Figure 5 – Scheme showing the fundamental structure of a requirements management system with the 'needs domain', the 'functional architecture' and the 'solution domain.

– ***Who'*** has to fulfil ***'what'*** by ***'when'*** is the focus of the '**functional architecture'** that forms the **interface between the 'needs domain' and the 'solution domain'**: the 'functional architecture' is used to define the 'means' (objects, and deliverables / achievements from activities and other measures) – the so-called (system-)elements) of the disposal programme to fulfil the requirements of the 'needs domain'. The 'functional architecture' also includes the elements resulting from the **constraints** mentioned above.

  The 'functional architecture' is then used to **allocate each function / characteristic** with their **performance / quality targets** of the 'needs domain' to an **element of the disposal system** and to describe the relevant **interactions** between the different elements of the disposal programme.

  If in the process of allocating the requirements no appropriate element can be found, then the 'functional architecture' is most likely incomplete / incorrect and must be revised.

The allocation thus allows to broadly **assess completeness**, e.g. by using the following simple questions: Do elements exist that have no function allocated to them? → is the element not needed or is a requirement missing? Do requirements exist that (through the corresponding function / characteristic requirement ('level 2')) are not allocated to a element? → is the requirement not needed or is an element missing?

- ***'How'*** to achieve the ***'what'*** is the focus of the **'solution domain'**: solutions are developed for all elements of the disposal programme, including the elements needed for its implementation), and also consider all stages of the life cycle of each element. In the detailed **design process** of an element, the allocated functions / characteristics with their performance / quality targets are the basis to develop the **specifications for each element,** taking the surrounding environment (with the loads and conditions) into account (the 'level 4' - requirements). This is done in two steps: first, the '**design input requirements'** ('level 4a') are developed; these define the detailed requirements for the design and also the design concept. This input is then used to develop the '**design output specification'** ('level 4b') – the **product specification**, see the more detailed description in section 4.3.2.

  Finally, for each element the **production process** is defined that ensures that the product specification is put 'in real life' in the correct manner and also includes the needed verification and validation activities (the 'level 5' - requirements).

- This then leads to the **stepwise implementation** of the repository – the final goal of the disposal programme with the different elements implemented and used in the **different phases**. This includes facilities for underground characterisation and experiments, facilities for construction, facilities for disposing the waste (disposal rooms, access to disposal rooms, handling the waste and engineered barriers) and closure structures. Successful implementation of the individual system elements and the overall system is **documented** in dedicated documents ('level 6' - documents).

Below, the **stepwise approach** and the **temporal aspects** are discussed in somewhat more depth:

- Both the 'needs domain' and the 'solution domain' have to include the **different stages of the life cycle of the system elements** that consists of …
  - **planning** (including also studies / investigations, development (incl. RDD, site investigations, etc.), design, etc. leading to
    - **documents** as products as input for the implementation of the closed repository (product specifications, production specifications),
    - **internal decisions** related to the implementation of the closed repository.
  - **licensing steps** leading to documented **decisions** that then become constraints (requirements) for all future steps / activities.

  These two elements provide the **basis for implementation** of the remaining stages of the life cycle:

  - **construction** (with characterisation and monitoring in parallel),
  - **operation** with emplacing the encapsulated waste and the engineered barrier elements, that ensure post-closure safety (in combination with the geological environment), often combined with some monitoring,

  - **decommissioning / dismantling / closure**, leading to the closed repository – the final goal of the disposal programme.

  The different stages of the life cycle of the elements of the disposal programme must be explicitly made visible in the requirements management system.

- The life cycle is connected to a time schedule that consists of **specific phases**, with each phase …
  - being delineated by specific **milestones** with clearly defined **goals** (achieved with the corresponding products) – the **roadmap**,
  - with the start of the phase being determined by the milestone of completion of the preceding phase, and the end of the phase by the successful completion of all activities needed to produce the needed products to reach the goals of the phase considered, and each phase being connected to a **work breakdown structure** defining the activities needed to produce the products to achieve the goals (decisions based on documents, building objects, etc.),
  - with an anticipated **duration** of the phase based on an estimate of the time needed to perform all activities needed as described above.
- Thus, the **structure** of the requirements management system has also to consider the **phases** of repository implementation:
  - the 'needs domain' has to identify the milestone (goal) and/or the phase to which a **requirement** applies.
  - the requirements in each phase have to be **allocated to an element** of the 'functional architecture' in the same phase and this again needs to be documented in the requirements management system.

    This allocation should also reflect the **hierarchical nature** of the 'needs domain', the 'functional architecture' and the 'solution domain' – the high-level requirements are related to the high-level system-elements with a solution at the high (conceptual) level.
  - the 'solution domain' has to identify for each **element** in which phase the element has to reach what **stage of its life cycle** (with **fulfilling** the corresponding requirements of the 'needs domain'), with the typical stages being 'planning', 'construction' and 'modification', 'use / operation (including waste emplacement)', 'decommissioning / dismantling / closure'.

Then, there are several other issues to be considered when developing a requirements management system, e.g.:

- For **evaluating the correctness** of the information in the requirements management database, 'meta-data' (including attributes) must be included in the database to make the structure and the relation of the information included in the requirements management system visible in a suitable manner.
- Then, there is a need to **ensure traceability** to be able to properly **manage refinements / changes.**

  Traceability includes:
  - **Backward traceability**: What was the origin of a certain requirement? Which sources (stakeholders (legal / regulatory, other), documents, other systems) were used for deriving that requirement?

- **Forward traceability**: Where is a requirement used? The design of which element of the disposal system is based on it?
- Traceability of **dependencies between requirements**, e.g.:
  - Which 'needs'-related item defines the broader scope of a specific 'solution'-related item? The scope of 'solution'-related items (their scope) is defined by which specific 'needs'-related item?
  - Do requirements rely on one another? (e.g., requirements related to design do rely on requirements related to acquisition of the data needed for the design),
  - Which requirements are equal with respect to some characteristics (e.g., being relevant for the same phase; being relevant for the same element but in different phases, etc.).

- Furthermore, a range of attributes will be needed to make the necessary **evaluations / reports** for the different uses of the information in the requirements management system.
- Finally, a practical advice: when starting the development of the requirements management system, take the **information and experience** in the respective disposal programme into account to develop a hierarchically organised system – start with the high-level elements and complement them with more detailed information and pay sufficient attention to dependencies.

5.3 Some details about post-closure safety and site selection

For developing the requirements to ensure post-closure safety, some specific issues must be considered, as there are some high-level constraints that must be observed:

- the **waste to be disposed** (already existing or committed due to the planned future use of radioactive materials),
- the **geological options** available in the country (spectrum of geological options) or the **geology** and the surface situation at the s**ite selected**.

The requirements related to the design of the repository (system of engineered barriers, location of the disposal rooms and other elements of the facility at the chosen site) have to ensure that the design is tailored to the properties of the geological situation at hand, taking the properties of the waste into account. Thus, these two issues must be **integrated as constraints** (externally imposed boundary conditions) into the requirements management system, taking into account that at least in the early phases there may be some **uncertainties in these constraints**.

In an early-stage programme, one has thus in a first step to make some **working assumptions** about:

- the **waste to be disposed** with its key characteristics (e.g., the longevity of nuclide-inventory to derive an estimate on the period of concern),
- the **spectrum of geological situations** available with their key characteristics (long-term stability, barrier properties (including heterogeneity of the barrier properties) as a basis to decide on the target properties to be used in the site selection process,

For more advanced programmes, the situation is as follows: With having the **site selected** – the (expected) properties of the site (based on the actual stage of site characterisation) and for heterogeneous rocks, taking the rules of the rock suitability classification into account, the uncertainties on the geological situation are limited and a more solid basis exists to derive the requirements for the engineered barriers, tailored to the properties of the geology at hand and taking the waste properties into account.

Thus, when defining the ‘level 1 to 3’ - requirements and the ‘functional architecture’, it is important to include the existing constraints for some of the system elements into the requirements management system, see Fig. 4 and corresponding text in summary of chapter 4.3.2. In that sense, the description of populating the requirements management system is for the requirements for the system of engineered barriers not fully accurate – here, one does not start with the ‘level 1 to 3’- requirements but with the constraints that provide input to define some of the ‘level 1 to 3’- requirements for e.g. for the system of engineered barriers to capture the constraints resulting from the properties of the waste foreseen for disposal and the geological environment of the site selected.

5.4 Summary

The representation of the **structure of the requirements management system** depicted in Fig. 5 is shown again in Fig. 6 with numbers for the **workflow** and **information flow** described in the figure caption. The key points are summarised below:

- The structure of the requirements management system has to include both the ‘**needs domain**’ and the ‘**solution domain**’ – the ‘needs domain’ with the requirements (‘level 0 to 3’ - requirements) and the ‘solution domain’ with the ‘product specifications’ and the ‘production specifications’ (‘level 4 / level 5’ - requirements) and the documentation of the successful implementation / delivery of the products (‘level 6’ - documents) and the ‘**functional architecture’** providing the interface between the ‘needs domain’ and the ‘solution domain’.
- The requirements management system supports and documents the **allocation** of the requirements (functions and characteristics with their performance / quality targets) of the ‘needs domain’ to the different elements of the disposal programme captured in the ‘functional architecture’.
- The ‘functional architecture’ is also essential for developing the post-closure safety case as it defines the different barrier elements needed to ensure post-closure safety and thus reflects the **safety concept** – the conceptual description of the functions / characteristics that each barrier element has to fulfil in the post-closure phase. Thus, the development of the ‘functional architecture’ and the allocation of the safety functions / characteristics to the different barrier elements is an iterative process that is heavily influenced by the host rock options considered during site selection or the site selected with its properties acquired in detail during site characterisation (partially in parallel to repository construction).
- The **‘external’ constraints** (e.g., the waste to be disposed, the site / geology selected) are an important issue as they directly influence the ‘needs domain’ – e.g., the requirements of the system of the engineered barriers are dependent upon the properties of the waste and the properties of the geology.
- The requirements management system structure has also to capture all **dependencies** (hierarchical and links).
- The requirements management system structure has to support the **workflows** of **populating** the requirements management system and of **managing** the requirements, including the stepwise refinement and iterative improvement (including change management).

As mentioned in chapter 1, the sequence of schemes in Appendix A provides some more insight in the process of developing and using the requirements management system.

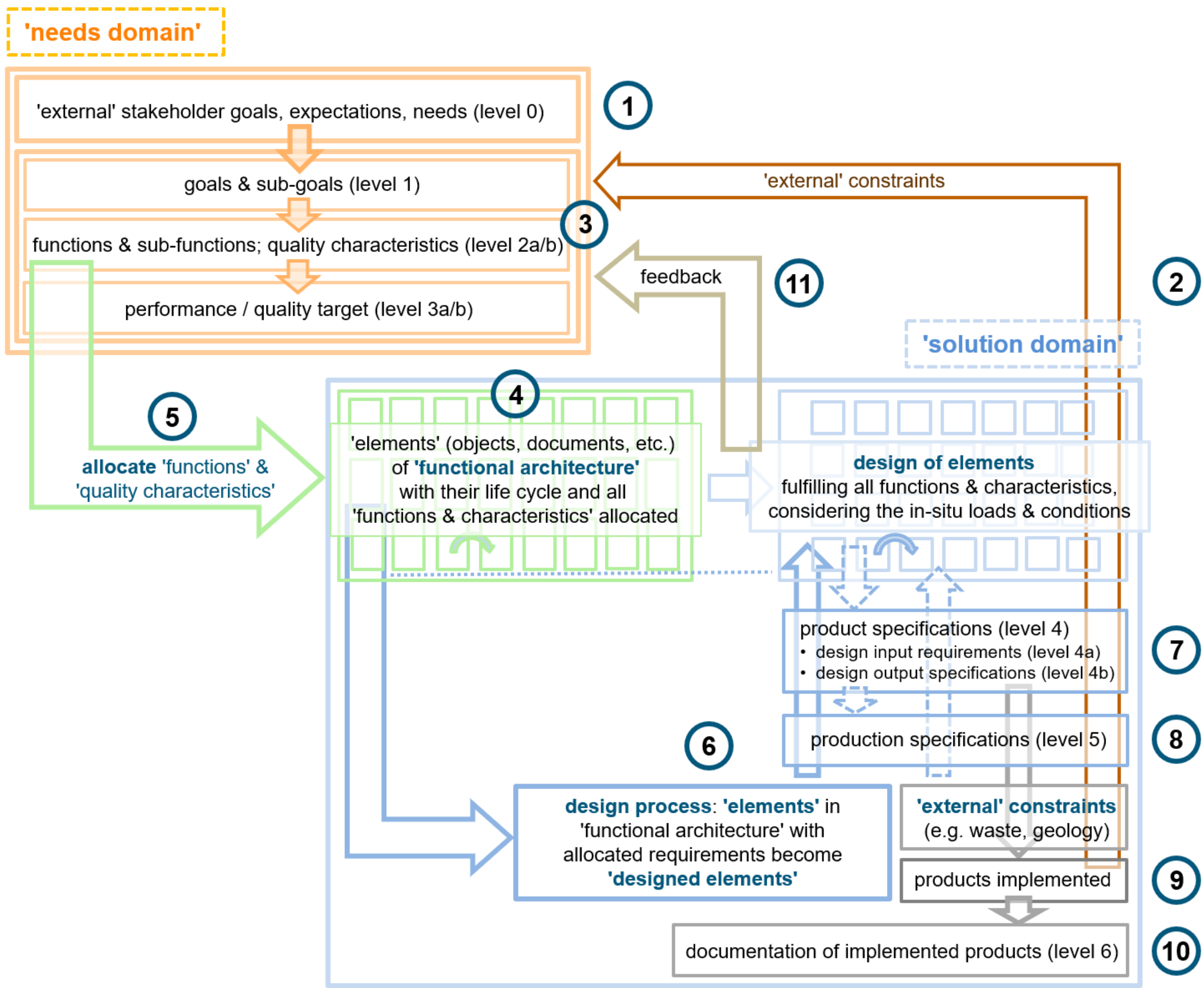

Figure 6 – Scheme with the detailed structure of the requirements management system with the 'needs domain', the 'solution domain' and the 'functional architecture' as interface and with the key dependencies and the flow of information between them.

Explanation: 'needs domain' (orange) with: (1) high-level requirements of the 'external' stakeholders with external constraints (2) that directly affect the 'needs'; (3) decomposition of 'external' stakeholders requirements into goals/sub-goals with the corresponding functions/sub-functions and characteristics with their performance/quality targets; (4) the 'functional architecture' of the disposal system (green) with the system elements providing the 'means' (objects, other products (documents, decisions, etc.)) to fulfil the requirements of the 'needs domain' with taking note of the dependencies between some of the system elements and with (5) allocating the requirements of the 'needs domain' to the elements of the 'functional architecture' (green); the 'solution domain' (blue) with: (6) the design process that develops the design for each of the system elements, taking the allocated requirements and the loads & in-situ conditions into account, leading to (7) product specifications and (8) production specifications; (9) implementation of products (objects, documents, decisions, etc.) with some of them becoming constraints (2), and (10) documentation of the implemented products (grey). The overall process involves (11) iterations / refinements throughout the whole implementation process with possible changes in the requirements (orange) and the 'functional architecture' (green) and the design / specifications (blue).

The 'needs domain', the 'solution domain' and the 'functional architecture' must contain all information related to requirements management for all the themes / life cycle stages and elements in the different phases needed for the implementation of the closed repository.

6. Evolution of the requirements management system in the stepwise approach of implementing the disposal system

6.1 Introduction

The evolution of the requirements management system and the requirements included in the system considers the typical phases of system development and implementation; thus, the **stepwise approach** in developing and implementing the system is considered in the requirements management system with the help of updates. The update of the requirements management system when **moving from one phase to the next** has to consider the 'needs domain', the 'solution domain' and the 'functional architecture'. Typical phases are described e.g. in section 4.2.4.

The **stepwise updating** of the requirements management system (as part of the stepwise approach) has to acknowledge that the level of 'ambition' of requirement management changes from one phase to the next.

- In the **early phases** of developing a disposal system, the requirements management system helps not to overlook something important at a reasonably high level (aim for completeness, not for details), as the requirements management system provides a good framework and a suitable working process to check for completeness and to make updates when appropriate. This can be reasonably well done as the system is in the early phases of limited complexity and of limited size.
- In the **later phases** with a system getting larger and more complex, updates are still manageable when moving from one phase to the next, as one only has to look at those elements of the requirements management system where **progress** has been made and changes have occurred.
- With progress of the disposal programme, things get more detailed: at the stage where some of the 'hardware' (site, facilities, …) is close to getting **fixed** (e.g., licensed) or close to being **implemented**, one has to assure the following issues:
  - The 'real data' from investigations (incl. geology), experiments, etc. that have been used in the design must be **'qualified' for use** to assess compliance with the requirements (verification / validation).
  - If the 'real data' / new **results differ** from the original expectations, one has to check whether there is a need to initiate some changes in the system / system design and/or in the requirements.
  - Then, there is also the need to assess the situation related to the availability of suppliers (planning, construction, production, …) and their capabilities / qualifications. If there are some 'limitations' in the **supply chain market**, this may require some changes in the system and/or the requirements.
- Once issues have been successfully fixed or implemented, they change their status; the requirements for these issues are replaced by **constraints** defined by fixed / implemented issues.

- There may also be the case, that a disposal system has been **developed to a certain extent without using a requirements management system** with now having the intention to implement a requirements management system. This can be done as follows:
  - The decisions taken that **cannot be changed** (e.g. licensing decisions taken / Government decisions taken) and the products developed / objects implemented must be considered as **constraints**.
  - Then, there is the possibility to evaluate whether these constraints are **well justified** by 'backwards engineering'; that means that one has to reconstruct the specifications that did lead to these constraints (the 'level 4 / level 5' - requirements) and what their 'level 0 to level 3' - requirements are.
  - If this leads to positive results, nothing needs to be done – if some deficiencies are detected, it should be checked whether some measures need to be taken.
  - For those issues still to be implemented, the process as described in this document can be followed.

In the stepwise approach, it is important to distinguish between the phases before **site selection** and those after having selected the site:

- **Before site selection**, the 'level 1 to 3' - requirements related to the geological environment (host rock, geological situation) can be used as input to site selection. However, depending upon the site selection process used, their level of ambition differs. If a **'volunteer' - approach** is taken, then for the 'level 1 to 3' - requirements the 'minimum requirements' (*'need to have'*) are applied, whereas in the case that one looks for **'the most suitable site' - approach**, not only the 'minimum requirements' but also 'the 'preferred requirements' apply (*'want to have'*). The 'level 1 to 3' - requirements for site selection are to some extent discussed in section 4.2.2.
- **After the site has been selected**, only requirements related to the allocation of the disposal rooms (and other elements of the repository) are needed; the properties of the host rock and of the geological situation and the situation at the surface have become **constraints for the design** of the system.

  Thus, after having selected the site, the main emphasis in requirements management is on the design of the repository with the engineered barriers being tailored to properties of the geology, taking the properties of the waste foreseen for disposal into account. Furthermore, also the site-specific implementation-related issues need to be addressed.

6.2 Issues to be considered

With respect to the content of the requirements management system, several issues must be considered when **moving from one phase to the next**:

- For the 'needs' domain:
  - The **level of detail increases** with time as plans, designs, etc. get more detailed. The level of detail in the requirements must be in balance with level of detail in planning. Thus, there may be a need to **decompose overarching requirements** into more detailed requirements, if needed (e.g., decomposition of a function into sub-functions or decomposition of characteristics into sub-characteristics). This should be done in consultation with the corresponding (internal) stakeholders (if the information is not already available from their documents).

  - With progress of the disposal programme, more and more **final (binding) decisions** are made (e.g. selection of the site) and **elements of the disposal system are implemented**, and these issues become **constraints** for the remainder of the program, and this has to be considered in the requirements management system.
- For the 'solution' domain:
  - The level of detail in the 'level 4 and 5' - requirements (specifications) increases when moving from the early phase with only **'conceptual thoughts'** towards later phases where at least some of the system elements move towards '**detailed design** for construction' and get fixed (e.g. binding decisions taken in licensing process) and eventually get constructed (facilities) and become **constraints**.
  - Thus, the disposal system captured with the **'functional architecture'** will also develop and **get more detailed** (one element being split up into several sub-elements), e.g. as follows:
    - initial stage: system with some sub-systems
    - next stage: system with some sub-systems, with (some of) the sub-system(s) consisting of several system elements.
    - next stage: system with some sub-systems, with (some of) the sub-systems consisting of several system elements, with some of the system elements consisting of several components.
    - etc.
- For both domains and the 'functional architecture:
  - In general, with progress of the disposal programme, the level of detail and the amount of flexibility left change in the 'needs domain', the 'solution domain' and the 'functional architecture' as the **stage of the different system-elements** change (initial thoughts, planning, producing, using the system / system element / product, decommission / dismantle / closure of the system / system-elements), with the 'functional architecture' getting more detailed and the requirements becoming **constraints** if binding decisions have been taken and/or products / objects have been produced.
  - The **scientific-technological basis** for the requirements ('needs domain') and for the system ('solution domain' and the corresponding 'functional architecture') gets more mature – the requirements thus move from 'assumptions' in the early days towards 'solid knowledge supported by a sound scientific-technological basis', e.g., due to RDD and/or design work.
  - In this process, it is important to systematically **check / assure the quality** of the 'scientific-technological basis' before moving from one phase / stage to the next to be sure that the planned path forward is still adequate.

To remember: Besides the update when moving from one phase to the next, also the **iterative nature within each phase** has to be considered, see description in section 8 on using the requirements management system.

6.3 Summary

The following issues are of importance:

- Disposal solutions are developed and implemented in a **stepwise approach** that delineates the implementation into a number of different phases that have different characteristics with respect to the information available and the (irreversibility) of the decisions taken.
- The evolution of the requirements management system goes in parallel to the stepwise approach as the level of detail in the requirements management system increases with progress of the disposal programme.
- The milestones at the end of each phase are **valuable 'check points'** to assess the quality of the available 'scientific-technological basis' and the adequacy of the path forward. As part of this assessment, it may be worthwhile to assess the importance of remaining uncertainties and risks (see also section 9).

7. Developing the requirements management system for implementing a disposal system

7.1 Introduction and overview

Below, a possible way to develop or update the requirements (the 'needs domain') and to define the way how the requirements are fulfilled (defining the 'functional architecture' and specifications of the system elements in the 'solution domain') and their documentation and management in the requirements management system is described – this is one possibility, but there are also other possibilities.

Before starting the development (or the update) of the requirements, there is a need to summarise the **current status of the disposal programme** and to compile the available **information about the disposal programme**. This includes e.g. (an update of) the description of the following elements:

- The **constraints / boundary conditions** including the waste foreseen for disposal (existing waste / expected future waste), siting options available / site selected, existing facilities, (irreversible) decisions taken in the implementation process of relevance to disposal, etc.
- **Legal and regulatory requirements** as well as national (and international) **agreements** and **guidance** related to the closed repository and its implementation that also define the responsibilities for defining, reviewing / approving, deciding on and implementing requirements, etc. (e.g. high-level decision-makers, regulator, implementer, contractors / supply chain (e.g. for worker's safety during construction according to their professional standards)).
- International / national **standards and codes** of importance, e.g. for design or implementation.
- The key characteristics of the **waste streams (**and their properties) foreseen for disposal in the disposal system investigated (including the corresponding WAC, if available).
- The **disposal concept** – the parts of the system that are relevant for **post-closure safety**: the host rock selected / under consideration, the siting region selected / under consideration, the safety concept (informed by a preliminary safety case), more detailed **design information** of the system of engineered barriers) with a broad description of the key **properties** of the **waste** and of the **barrier system** (geology, engineered barriers) and of the broad features, events and processes acting on the disposal system that are of potential relevance for post-closure safety.
- If such information is not yet available in a programme, an **adequate 'analogue'** from an advanced programme may be used to develop first ideas.
- The **disposal concept** – the parts of the system that are relevant for **implementation** of the closed repository (underground investigations, construction, encapsulation, emplacement of encapsulated waste and of the engineered barriers, closure), including a broad assessment of technical implementation feasibility.
- The **implementation plan** for the disposal system – current status, future milestones / decision-points, documentation / material needed at each of the future decision-/licensing-points (documents and underlying RDD), resulting goals for the different future phases, rough timeline, etc.) based on a **roadmap** and on a **work breakdown structure** as discussed in chapter 5.2.
- Finally, all **requirements available** from both the 'needs domain' ('level 0 to 3' - requirements) and the 'solution domain' ('level 4 and 5' - requirements) already defined / considered in the disposal programme as well as any information about the **'functional architecture'** not yet captured by the points mentioned above.
- etc.

The development and refinement / update of **requirements** has to consider the information compiled as mentioned above.

- The development and refinement / update of requirements starts with those elements of the closed repository system that are important for **post-closure safety**.
- As a next step, the requirements for **implementation process** and for the **objects / products** to be implemented (characterisation of the site chosen and implementation of the needed monitoring devices, construction, operation / emplacement of encapsulated waste and engineered barriers and closure of the repository) are defined / updated. They have to ensure that the final product – the closed repository – fulfils all post-closure safety requirements as defined above.
- Then, the requirements for **planning**, for the **licensing process** and for developing the **detailed design** need to be defined / updated to ensure that the implementation process (all steps up to the closed repository) will be achieved as planned.
- Finally, it is important to define / update the requirements for the **interaction with society**.

Implementing the **requirements management system** and **populating it with information** requires a range of activities. A brief summary of these activities is given below:

- The implementation requires good **preparation** to ensure that:
  - the **disposal system** looked at is **defined correctly** and in **sufficient detail** for the current phase of the project,
  - the information is available to perform a **preliminary configuration** of your requirements management **database** and to map dependencies (e.g., implementation of the hierarchically organised functional architecture),
  - all **essential stakeholders** that need to be involved in the early phase of starting the project are identified and/or **their documents** relevant for requirements management are known and available, e.g., based on a 'map' of the relevant stakeholders with their documents that also captures dependencies.
- The following issues can be performed in parallel:
  - analyse the documentation available related to **requirements**,
  - start the compilation of requirements of the 'needs domain', including the **elicitation process** with the 'external' stakeholders to collect their input related to defining the requirements.
  - analyse the documentation available related to the **'functional architecture',**
  - start analysing your needs for **attributes** for the different applications (workflows, evaluations, ensuring traceability, etc.).
  - getting a **suitable tool** for the requirements management system:
    - evaluate the **database options** and acquire a suitable database software,
    - start with the **configuration** of the database software,

- **Populating** / filling the database with information can start as soon as the information mentioned above is available.
- During the population of the database, **tests** should be performed to continuously check consistency, completeness, etc.

Section 7.2 below provides some **more information** on the issues mentioned above.

7.2 Steps when starting with the requirements management system

The different steps to be made when starting with implementing a requirements management system are discussed below.

- Project initiation – compilation of the **information needed**:
  - Define the **system to be captured** and investigate the **boundaries of the system** – advantages / disadvantages when making the system larger – advantages / disadvantages when making the system smaller (e.g., waste encapsulation facility within the system or external),
  - Give some thoughts on how to manage the **interfaces** to external systems (e.g. by defining corresponding constraints, such as WAC's),
  - Start with a list of **sources of requirements** (legislation, guidance, strategies used, 'good practices', ….),
  - Start with the list of **stakeholders** to be involved when defining the 'needs'-related requirements:
    - external to the organisation,
    - internal within the organisation.
  - Based on the preliminary understanding, document **what is available** in the disposal programme in relation to:
    - the **system concept** (functional architecture of the system in the **different stages** of its **life cycle** / in the **different phases** of system implementation),
    - the **implementation concept** (the different broad types of **'means' needed** to arrive at the system in its final stage – the closed repository with all foreseen waste emplaced). The 'means' (the four themes / life cycle stages, and for each theme / life cycle stage the **objects**, **activities** with their deliverables, **other measures** with their achievements) needed in the different phases for implementation, as discussed in section 5.
- Project initiation – definition of a **rough roadmap** and **work breakdown structure** and evaluation of **resources** needed:
  - Develop rough roadmap (including a timeline) with the **major milestones**, the **approximate time** when the milestones should be achieved and a broad overview on the **work to be done** to reach these milestones (see also discussion in chapter 5.2).

   - Be clear about the needed resources (**personnel, budget**)[34]
- Project initiation – evaluation of **capabilities** needed / available within the disposal programme
   - Be clear about the **scientific-technological capabilities** (competence / knowledge / experience, tools, …) available within the organisation responsible for implementation to define the following issues:
      - the **disposal programme** with the **closed repository** and the elements needed for its implementation that has to be developed with the spectrum of goals and functions / characteristics it has to fulfil,
      - the **interfaces** at the boundaries of the disposal programme with the repository,
      - the **environment** the repository is proposed to operate in (resulting in the loads and conditions e.g. from geology to be considered in the design),
      - etc.

     Compensate significant weaknesses in capabilities with support (additional internal workforce, external support by service providers).
   - Be clear about the **methodological capabilities** (competence / knowledge / experience, tools, …) available within the organisation responsible for implementation to perform the following activities:
      - system analysis,
      - system engineering,
      - requirements management methodology,
      - risk analyses,
      - design,
      - etc.

     Again, **compensate significant weaknesses in capabilities** with support (additional internal workforce, external support by service providers).
- Project initiation – define the process to **develop the requirement management system**
   - Define the **different workflows** needed to implement and use the requirements management system, e.g.:
      - overall reviews,
      - checking completeness / consistency,
      - implementing refinements and change management,
      - verification,
      - validation (e.g., supported by system modelling / performance assessment).
   - Define the approach to **visualise dependencies** (e.g. to find mistakes, to achieve traceability. etc.).

[34] In a broader sense also related to requirements management

  - Based on size, complexity and resources available, decide on the **software to be used** (if needed, with external support) and acquire it.

- Starting the work – **configuration of the system**:
  - Define the **structure** of the requirements management system (‘needs domain’ / ‘solution domain’, ‘functional architecture’, hierarchical levels, attributes, links) and implement it,
  - Define approach to ensure bi-directional **traceability**, and traceability of **dependencies** between requirements and implement it,
  - etc.
- Starting the work – work on the **‘needs domain’**:
  - identify **sources** for requirements,
  - get the **documents** available that are of relevance for defining the requirements needed,
  - if needed, get in touch with the ‘external’ **stakeholders** to develop the high-level requirements, taking the already available requirements into account,
  - elicit, assess / discuss / negotiate, and document the **requirements** – one level after the other (‘level 0 to level 3’) with **decomposing** the higher-level requirements (goals) to derive the corresponding lower-level requirements (functions / characteristics with their targets),
  - manage the **interfaces** with the (external) environment to derive the corresponding constraints,
  - ensure that **each of the requirements** fulfils the following **criteria**, see e.g. INCOSE (2023). They have to be:
    - necessary and define an essential function, characteristic or constraint,
    - appropriate in the level of detail in comparison to the element they refer to,
    - unambiguous, ensuring that only one interpretation is possible,
    - complete and describe a function, characteristic or a constraint without needing any additional information to understand the requirement,
    - singular and only describe one function, characteristic or constraint,
    - feasible and allow the implementation within the existing constraints with acceptable risks,
    - verifiable and allowing demonstration of compliance in a satisfactory manner,
    - correct and – together with other requirements – be an adequate representation of its parent requirement,
    - conforms to an approved standard style for writing requirements, when applicable.
  - ensure that also the **set of all requirements together** will fulfil the following **criteria,** see e.g., INCOSE (2023). They have to be:
    - complete and describe the functions, characteristics and constraints that the system has to fulfil without needing any other information,

  - consistent and ensure that the individual requirements are unique, do not contradict each other and do not overlap,
  - feasible and allow the implementation of all requirements together with acceptable risk,
  - comprehensive and ensure that the set of requirements is written such that it is clear what is expected from the system,
  - can be validated to ensure that the requirements from the external stakeholders are met,
  - correct, with all requirements together being an accurate representation of the needs and higher-level requirements from which they were derived.

- Starting the work – work on the **'functional architecture':**
  - develop a draft of the hierarchically organised **'functional architecture'** based on your system understanding of the disposal system and its implementation, using a reasonable level of detail; start with a limited level of details.
  - identify **dependencies** and implement them in the 'functional architecture' (hierarchies, other dependencies).
  - **allocate** the requirements developed in the 'needs domain' to the elements of the disposal system (including the elements needed for its planning and implementation as part of the disposal programme) in the 'functional architecture'.
- Starting the work – work on the **'solution domain'**:
  - start the **design process** that develops the functional architecture into the physical (real) architecture and identify / define the environmental conditions / constraints for the elements of the physical architecture and develop the 'level 4a/b and level 5' - requirements (**product specifications** and **production specifications**).
- Starting the work – perform **tests:**
  - **check the functionality** of the requirements management system as implemented in the software tool,
  - continuously assess **correctness** and **keep track of completeness,**
  - etc.

After having gone through this initial phase of work, **routine will develop** and soon requirement management and using the requirements management system will become part of the 'daily work' of the organisation in charge and supports the organisation in bringing the disposal programme forward.

7.3 Iterations to check the feasibility of meeting the requirements with a reasonable design

Once the system has been initialised, first **'dry runs'** are needed to assess the 'functioning' of the closed repository in the **post-closure phase** and the **feasibility of implementing** the closed repository. Such a dry run may show some problems / weaknesses that then need to be resolved. This is related to risk management as briefly discussed in chapter 8.

7.4 Summary

The following issues are of importance:

- When implementing a requirements management system, in a first step the **information available about the disposal programme** needs to be collected and documented. This is important, as this is the basis for requirements management.
- Next, the **capabilities within the disposal programme** need to be evaluated to see whether there are some weaknesses that need attention.
- Then, the **workflows** for implementing and using the requirements management system need to be defined, at least the ones for integrating new information and for some key tests.
- Then, work can start. This includes:
  - **Transforming the information** compiled into a format suitable for the requirements management system (elicitation of requirements, decomposition of requirements, defining the functional architecture (considering the hierarchy and dependencies)),
  - Evaluate the type of **tool** to be used, acquire the corresponding software and implement the configuration ('structure') to get ready for putting the information into the system,
  - When **putting information into the system**, perform **periodically tests** to check the functionality of the requirements management system, the functionality of the disposal programme and of the closed repository and the correctness of the data.
- After the initial phase, routine will develop, and requirements management will become **part of 'daily life'** of the organisation in charge and will support the organisation in bringing the programme forward.

As part of the summary, the following **working principles** (not discussed before) are considered to provide a good perspective on developing / using a requirements management system:

- The requirements management system provides the combination of stating …
  - the **'problem'** (the goals, needs and expectations of the 'external' stakeholders) and the related **requirements** (the 'needs domain'), and
  - the **resulting solution** that gives the answer to the problem (*'the path towards a solution'*) and the corresponding requirements / specifications (the 'solution domain').
- Requirements management has to ensure that an answer to the 'problem' is given with a proposed system that fulfils the requirements – **requirements without identifying a path towards a solution have no value**.
- Requirements management is about **satisfying the key goals, needs and expectations** of the 'external' stakeholders.
- The requirements management system must be designed and used in a manner that it supports the development of a **common basis of understanding** about the overall disposal programme for implementing the disposal system.
- The requirements management system and the work process have to ensure that the **context is visible** and has been taken into account.

- The requirements management system provides a good **platform for optimisation**.
- The requirements management system provides a good **platform to assess the importance of remaining uncertainties and risks**.
- **Verification and validation** are essential parts of requirements management.
- **Changes and refinements** in the requirements management system are not an accident, they are the normal case and can / will improve the system.
- Planning of implementation of the disposal programme and the implementation of the closed repository and the development of the corresponding information requires **structured, systematic and disciplined work** that is supported by requirements management.

8. Using the requirements management system for implementing a disposal system

8.1 Introduction and overview

Using a **fully implemented requirements management system** includes the following issues:

- **Extracting the information** to be used by a project / person as input for the development / design work of some specific elements of the disposal programme.
- **Following up the work done**, the **progress made** and the **quality achieved** with using the requirements in the development / design work and evaluate the progress with developing of the products and the quality of the work done ('verification' and 'validation') when the design work is finished.
- Using the requirements management system for **optimising the overall disposal programme** (planning, implementation, post-closure safety).
- Using the requirements management system for assessing **the importance and the impact of uncertainties and risks** (also to be used to identify mitigating actions if considered useful – e.g., through changes in the design of the disposal system and/or through focused RDD).
- **Changing information** in the requirements management system, because ongoing work shows that some changes are needed. The changes can involve:
  - **deleting** specific requirements because their use has become obsolete (e.g., a change has made in the requirements management system (in the 'needs domain' and/or the 'solution domain') that makes a system element superfluous),
  - replacing 'level 0 to 3'- requirements (needs, functions / characteristics, targets) with **constraints** (factual boundary conditions) because binding decisions have been taken and/or products have been produced,
  - **modifying** a specific requirement, e.g., due to changes in its nature,
  - **adding** new requirements. Here, it is important 'not to get lost in all details' – there is a danger that one adds too many not that relevant requirements (**so-called 'requirements creep'**).
- **Change management including management of refinements is an essential part of requirements management as refinements and refinements / changes are expected for several reasons,** e.g.:
  - changes due to **refinements occurring in the stepwise implementation process** of the disposal programme. This affects the 'needs domain', the 'functional architecture' and the 'solution domain'.
  - changed **needs / expectations** of the 'external' stakeholders (e.g. change in legislation, regulation, etc.),
  - changes in the **market** (new material suppliers with alternative materials of similar quality, new production methods, important suppliers disappearing, etc.),
  - changes in the **waste inventory** (changes in treatment / solidification / packaging, waste reduction, new sources of waste, etc.),
  - changes in **technology** (design methods, construction / operational technologies, etc.),

  - **feedback** from system designers, e.g. because of facing some difficulties / non-resolvable conflicts,
  - detection of **errors** in requirements or detection of faulty assumptions.
- There need to be **well-defined workflows** with clearly defined responsibilities in place to be able to perform the different tasks mentioned above in a transparent and reliable manner (e.g. through independence of roles), e.g. for the change-/refinements-management process, where the *'why', 'what', 'when', who' and 'how'*, etc. must be adequately defined and tracked.

8.2 Summary

The following issues are of importance:

- Using a requirements management system requires clearly defined **workflows** that ensure that all requirements are met, including those needed for licensing.
- Such workflows are needed in the design / development work and in the **iterations** taking place in the different phases of system implementation – these workflows can be different from those used when moving from one phase to the next, with these workflows being connected with formal decisions.
- Although assessing the importance of **uncertainties and risks** is a key activity when moving from one phase to the next, it may be worthwhile to do such an assessment on specific topics also in the course of the development work within a phase.

9. Managing the evolution of the requirements management system and of the disposal system and its implementation

9.1 Introduction and overview

The following issues must be considered:

- The development and the implementation of a disposal system is normally performed in a **stepwise manner**, where the different phases are delineated by milestones with clearly defined goals and corresponding deliverables and decisions.
- Thus, when moving from one phase to the next, the **adequacy of the information** available needs to be assessed, and also an assessment of **uncertainties and risks** should be made to ensure that moving to the next phase is justified.
- The final decision to move ahead is often coupled to a **formal decision** by an 'external' stakeholder (e.g. through clearance by the regulator or a licensing decision by the policy maker (e.g., government, parliament)).
- If the decision has been taken to move into the next phase, as a first step the information in the requirements management system has to be **checked and updated** carefully, also to assess and ensure the scientific-technological correctness. For those issues that have **changed their stage** (e.g., going from planning to implementation), the information related to these issues have to be assessed and modified both in the 'needs domain' and in the 'solutions domain'.
- In connection with implementing refinements and changes, it may be worthwhile to review **progress in general** (within the **disposal** programme but also world-wide) and then integrate all the new information as part of a formal change process.
- All the steps mentioned above need to be performed according to **well-defined workflows** with clearly defined responsibilities.

After such an update, the new phase continues in a manner as described in section 8 until the next milestone is reached.

9.2 Summary

The following issues are of importance:

- In the stepwise approach, the different phases of implementation are **delineated by milestones** where progress is discussed, and remaining uncertainties and risks are assessed. Based on this, a **decision** is taken on the next steps, e.g. (i) to move ahead to the next phase, or (ii) to postpone the decision and clarify first the open issues that prevent the decision, or (iii) to revisit the overall plan and take the time to revise the current plan or to develop a new plan.
- If the decision is taken to continue, as a first step when starting the new phase, the **consequences** of having passed the milestone have to be implemented in the requirements management system – for the items changed through the decision, the corresponding changes have to be made in the requirements management system.

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Appendix A. Schemes illustrating the use of a requirements management system for implementing a disposal system

On the following pages some schemes are shown that illustrate the use of a requirements management system for implementing a disposal solution.

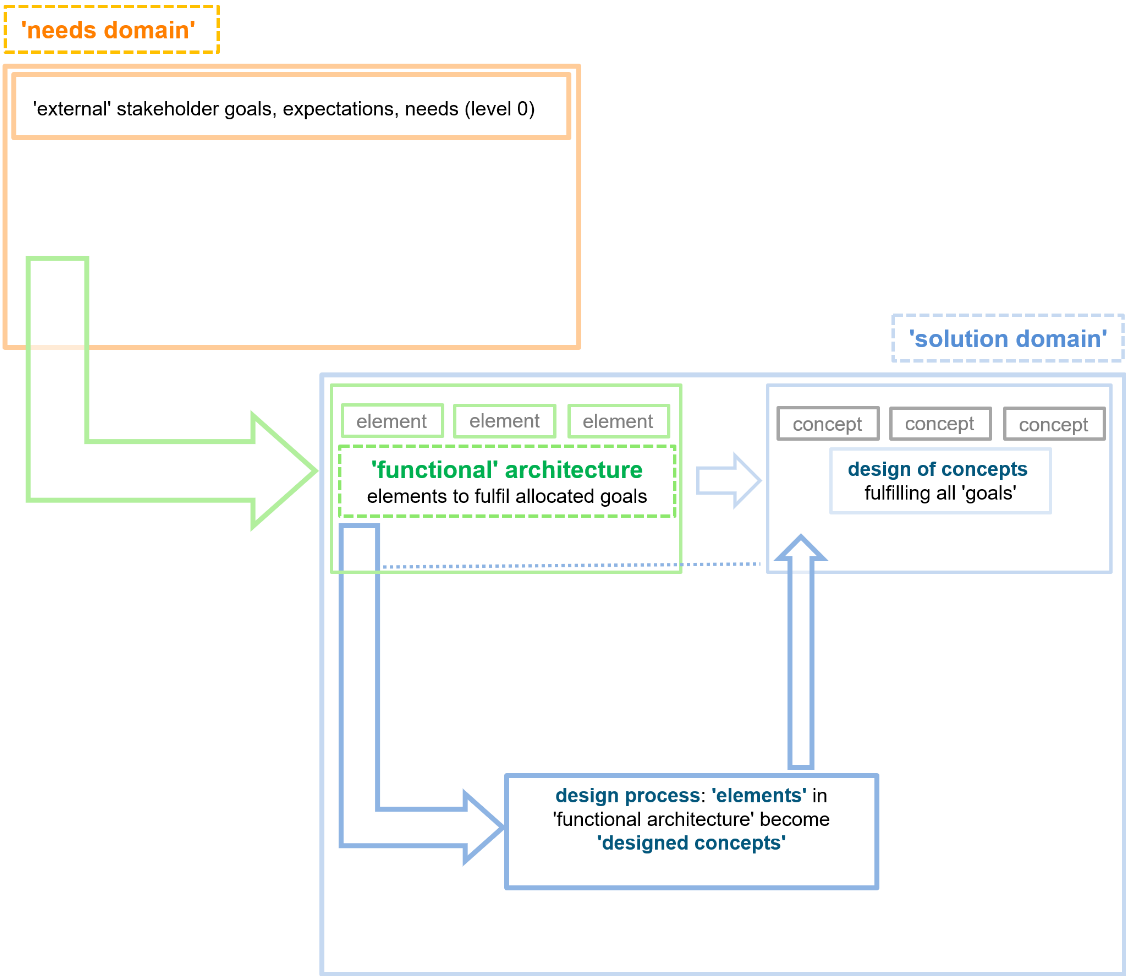

Figure 7 – The elements of the requirements management system: the 'needs domain', the 'functional architecture' with the needs allocated to the elements of the 'functional architecture', the design process and the 'solution domain'

The needs domain describes the *'why? what? when?*', the functional architecture the *'who? with whom? when?'* and the 'solution domain' the *'how?'.*

The elements of the requirements management system are initially only defined at a high level (mainly concepts) and the different elements have only a limited amount of structuring.

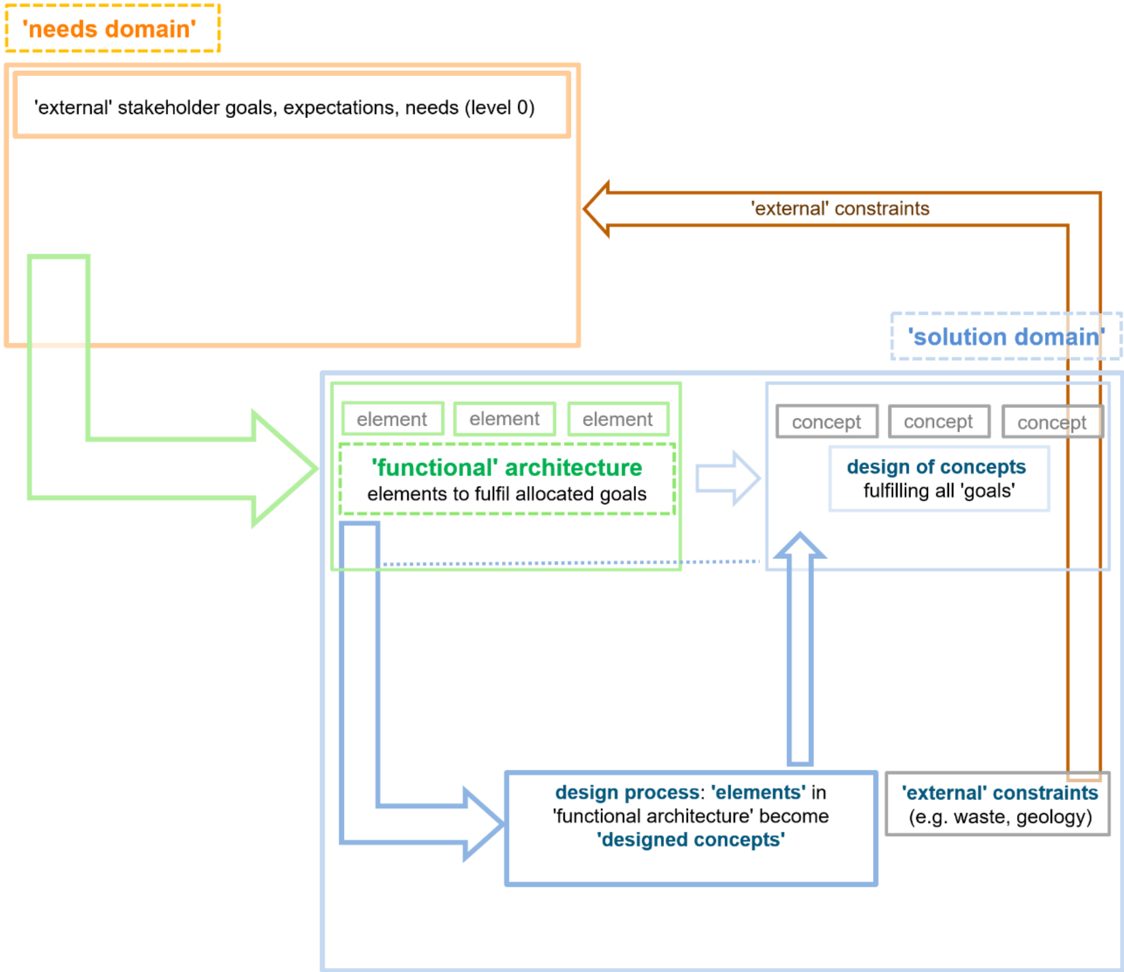

Figure 8 – The stepwise refinement of the requirements management system.

The refinement leads to more information at a more detailed level (incl. constraints) and is followed by the stepwise completion of the different products (documents, decisions, granted licenses, objects being implemented, etc.).

The 'needs domain' gets more details by decomposing the high-level requirements (including the goals and sub-goals for the different themes / life cycle stages defined in chapter 2) into more detailed requirements, the 'functional architecture' becomes more detailed by decomposing the functional architecture into more detailed system elements (sub-elements, components etc.) and the 'solution domain' sees an evolution because of having more elements in the 'functional architecture' and because of the evolution of the specifications from broad concepts into detailed plans. Then, implementation of the needed elements / products starts based on the detailed specifications. This eventually leads to the stage where all elements are implemented with the repository containing all waste and being closed, with the implementation of all elements being properly documented.

In this scheme, an early stage is depicted where the system described by the 'functional architecture' only includes the highest-level system elements and the design only includes concepts, and no decomposition of level 0 (goals) is yet considered. This level of detail is adequate for those system-elements that are still far away from implementation as long as the concepts contain enough information to manage the dependencies and interactions.

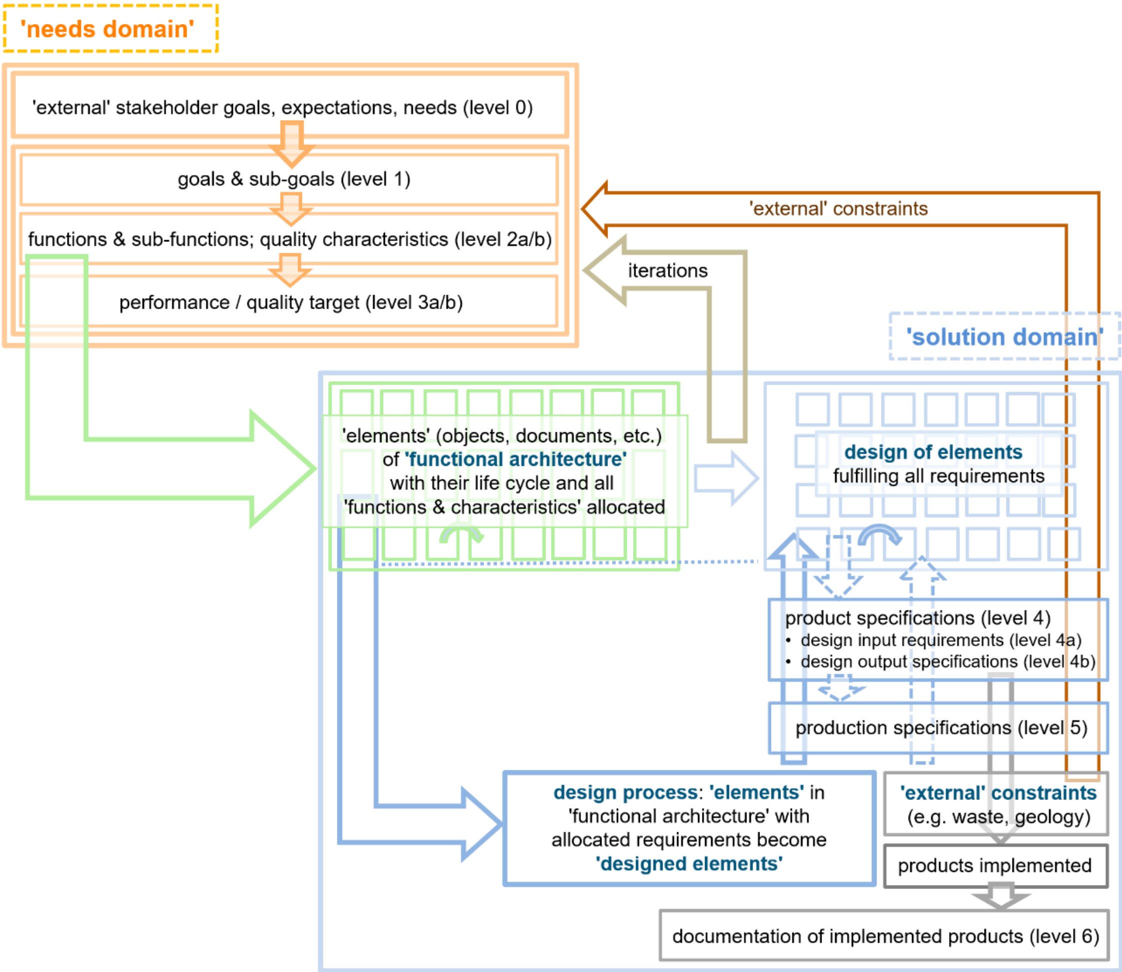

Figure 9 – The end point of the stepwise refinement of the requirements management system is reached when all the products (documents, decisions, granted licenses, objects, etc.) are implemented.

In the schemes that follow, typical steps of the process up to the stage of the closed repository are briefly described. The requirements management system, however, is maintained with all the information of the 'needs domain', the 'solution domain' and the 'functional architecture' to have a transparent and traceable of record of all the important information used and of all the important decisions made, incl. the underlying material.

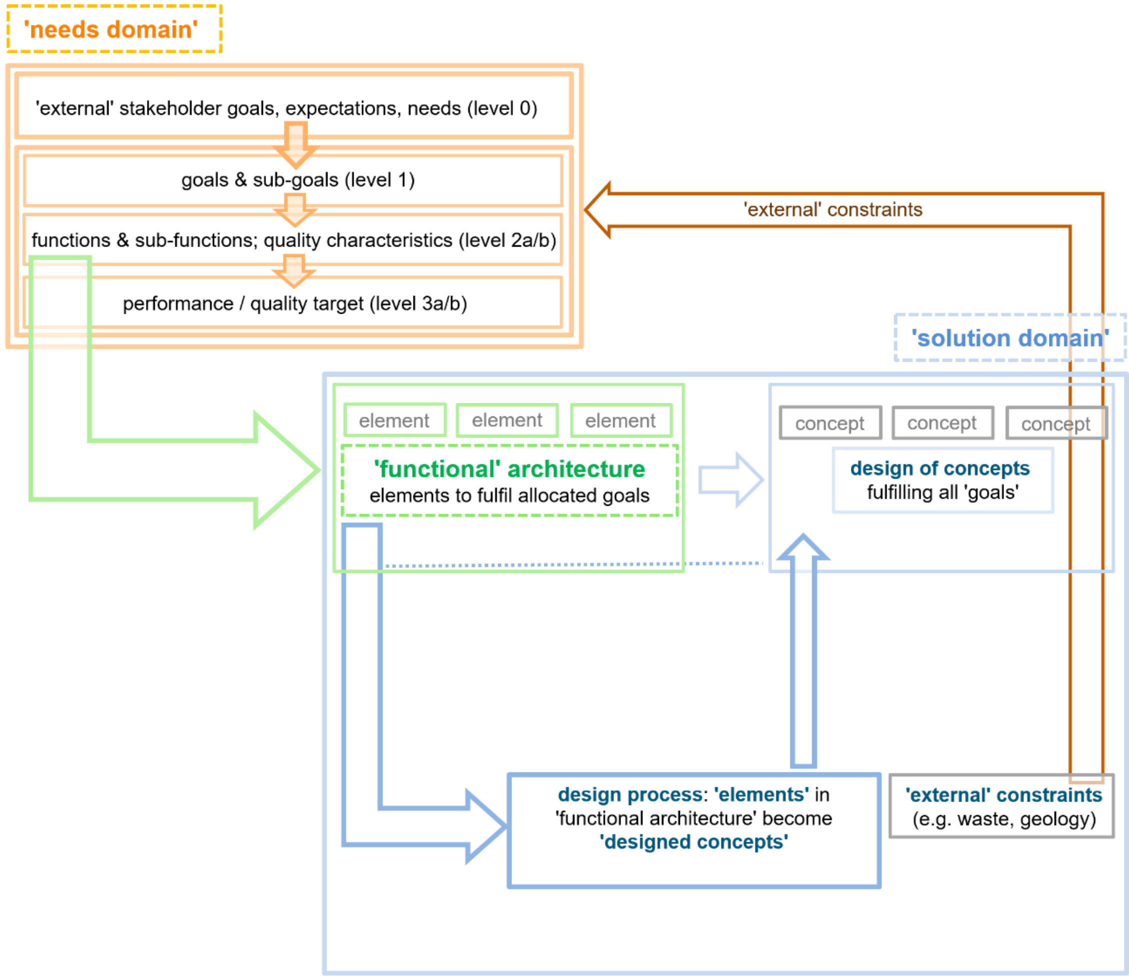

Figure 10 – Already very early in the process, management of (changes of) the external constraints must be started, e.g. the waste foreseen for disposal.

This requires that already the initial requirements for the design of the repository take the properties of the waste into account (in an early phase when not all information on the waste is available, partially based on assumptions).

The requirements have to ensure that the compatibility of the broad concepts for the disposal system with the waste foreseen for disposal is checked – these checks must be repeated when the information on the waste gets more detailed or changed or when new information for the disposal system becomes available and the design becomes more detailed. This can lead to modifications in 'need domain' and to feedback to waste treatment / packaging.

As an example, the case of having new information on solid mixed waste (with actinides) with organic material is discussed in the schemes that follow.

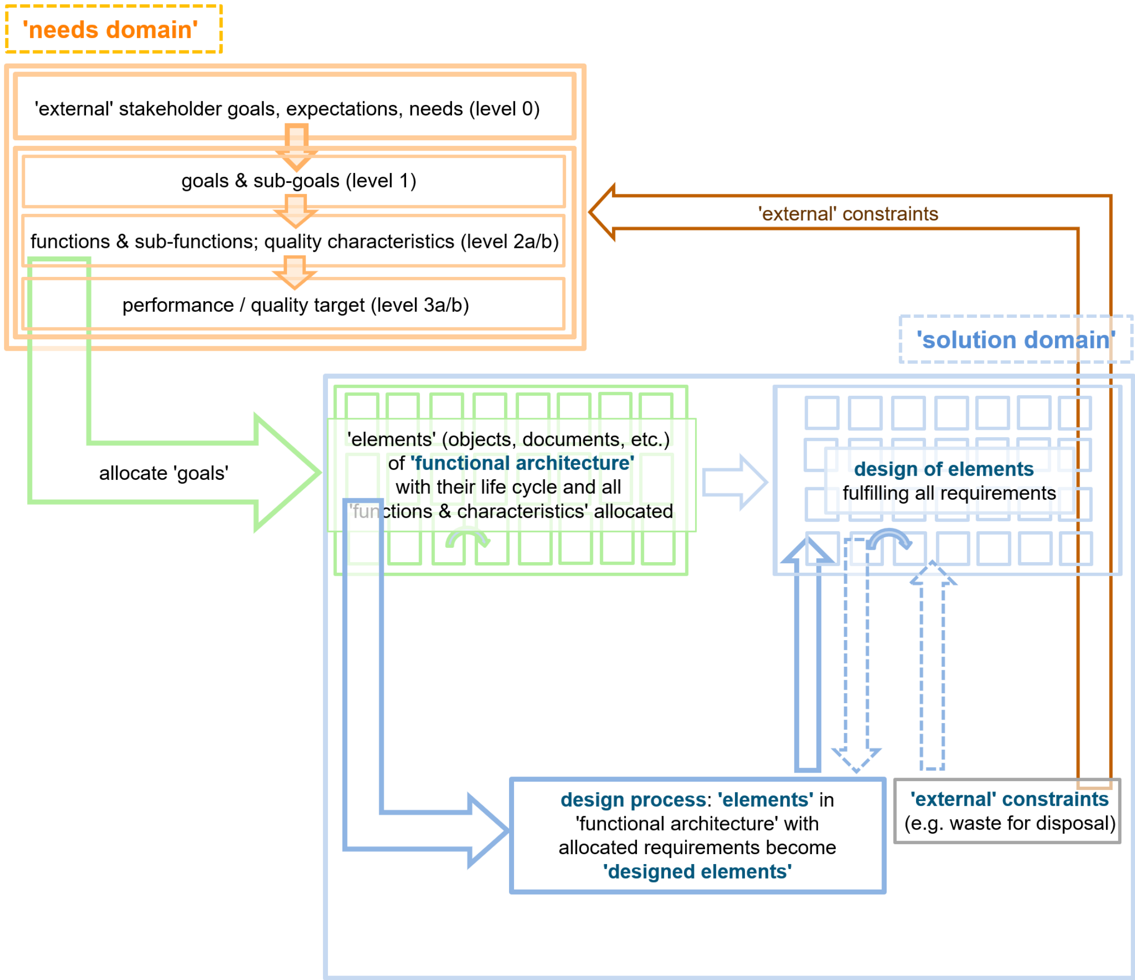

Figure 11 – For assessing the compatibility of the initial requirements for the design with the external constraint, the design of the repository has to be sufficiently advanced; only then the compatibility can be checked.

The existing requirement to keep mobility of radionuclides sufficiently low (a 'goal') asks for an environment that ensures high sorption of radionuclides. The design measure (‘solution domain’) requires a suitable backfill material in the corresponding disposal rooms – a cementitious material. The assessment of compatibility raises some concerns about the degradation of the organics in the waste that could degrade the cementitious backfill (unfavourable environment for steel corrosion leading to gas) and about the impact of the degraded organics (‘complexants’) on actinide mobility.

The concerns trigger some feedback to waste treatment (next scheme).

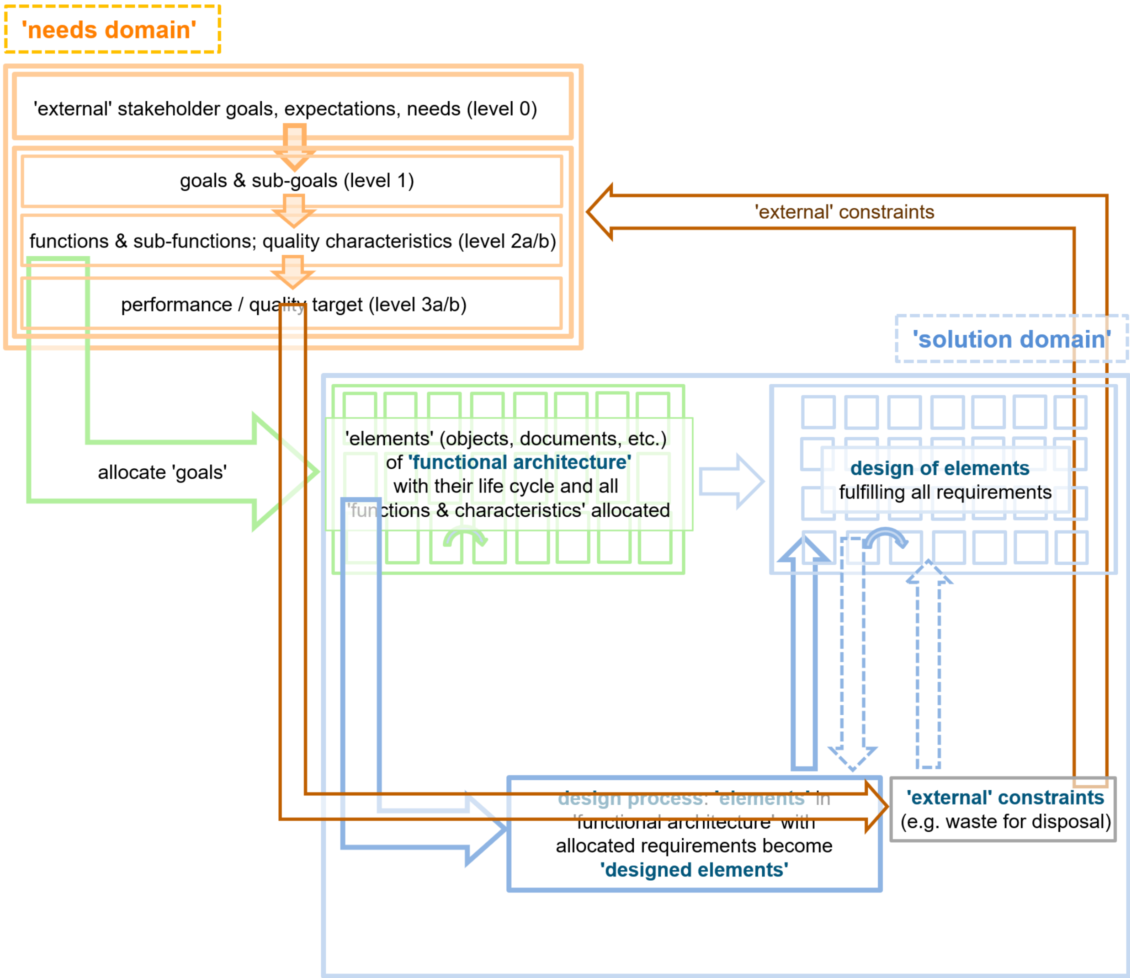

Figure 12 – The assessment of compatibility raises some concern that leads to some feedback – iterations to optimise the requirements and the system (incl. waste treatment) will start.

The example discussed here consists of solid mixed waste (with actinides) with organic material.

The feedback asks for some additional waste treatment measures. This is reflected in modified waste acceptance criteria (WAC) that ask for sorting of the waste to limit the organic content in waste with actinides.

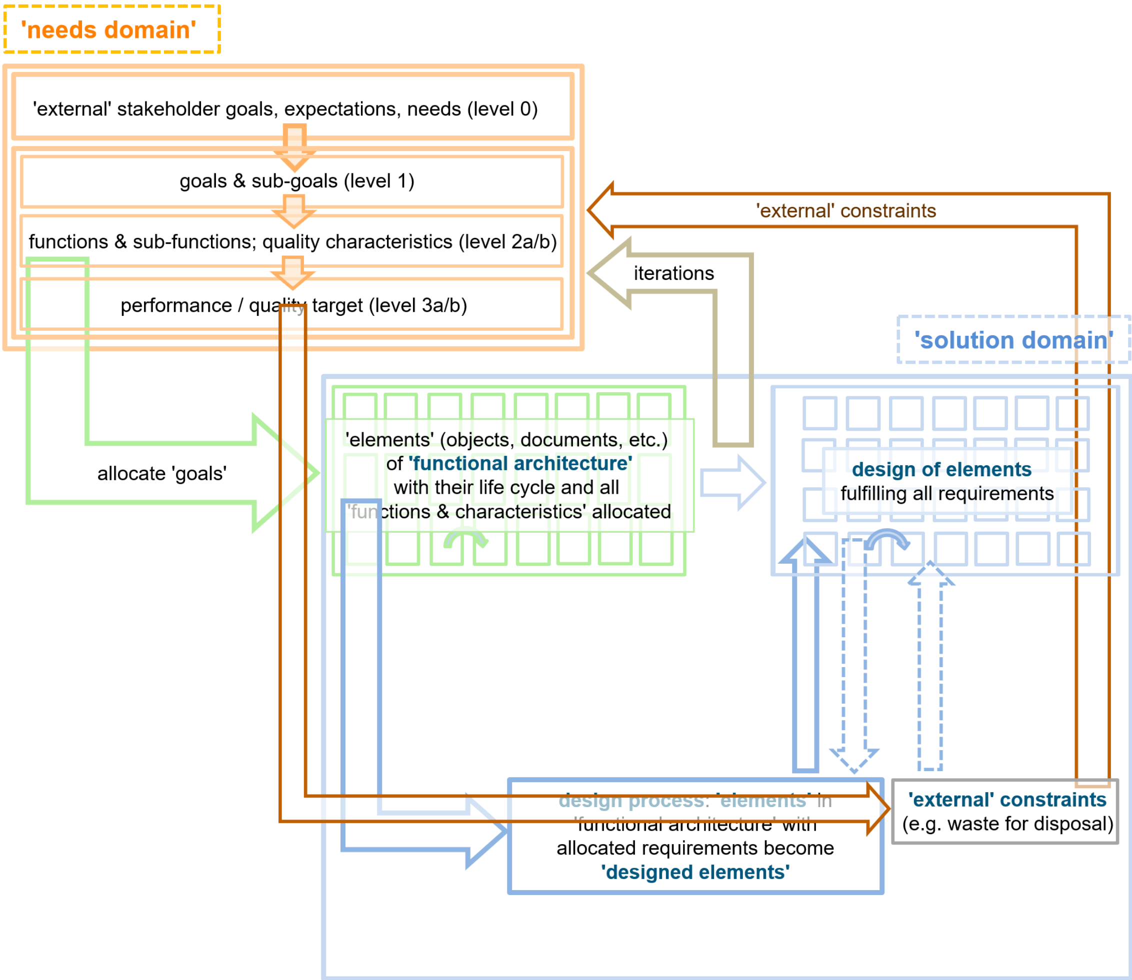

Figure 13 – The feedback with modified waste acceptance criteria leads to a new waste stream that requires a separate disposal room (requirement for change in the design).

The organic waste to be separated (a 'goal') requires a separate (additional) disposal room for organic waste (requirement). This leads to a change in the 'functional architecture' (additional element) and requires the design of an additional element of the disposal system ('solution domain').

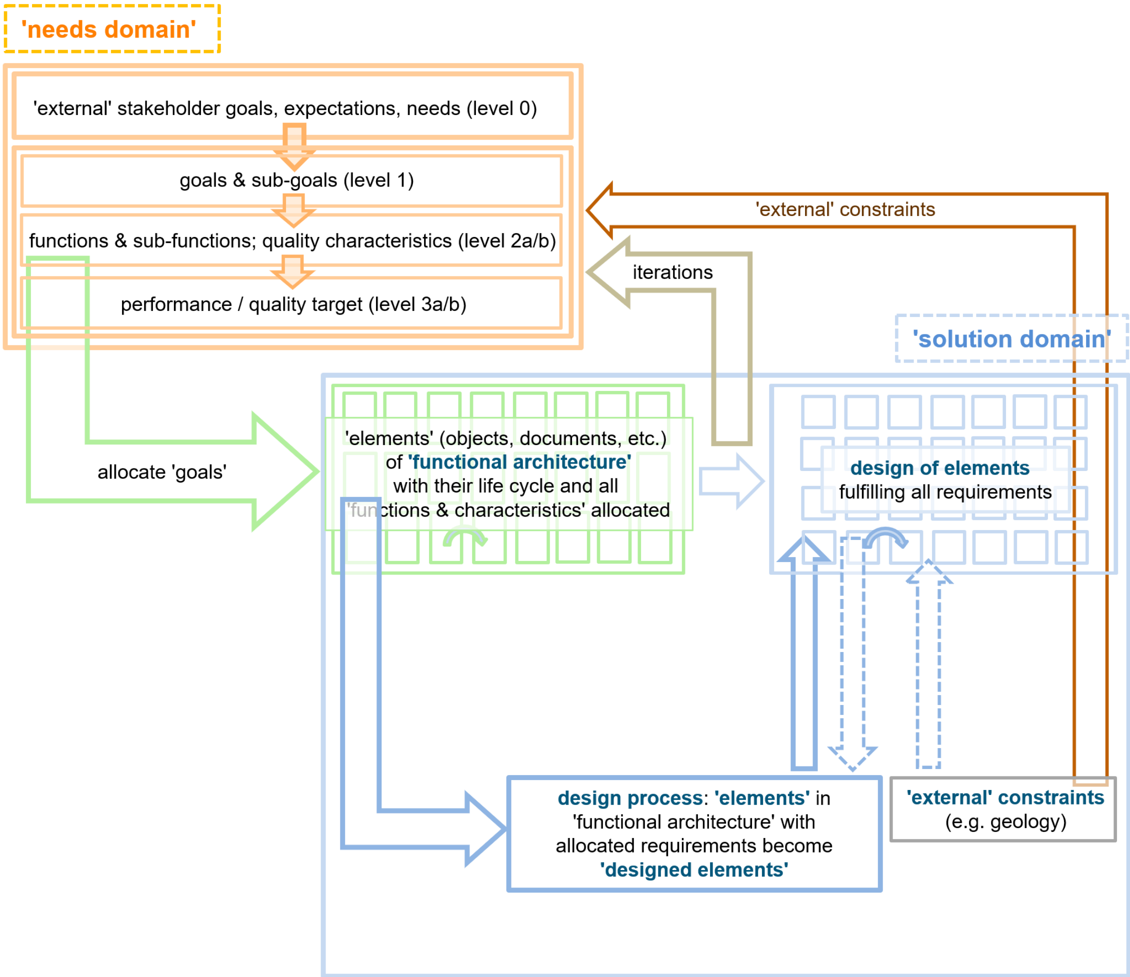

Figure 14 – The site or siting options with the corresponding host rock are also an external constraint that must be explicitly addressed.

The initial concepts of the disposal facility are based on broad concepts of the siting possibilities available. Once more detailed information on the properties of the selected site becomes available, this may lead to a modification of some important design parameters where up to that point only assumptions were available.

Example: The site characterisation work shows that the mechanical strength of the host rock is lower than originally expected (external constraint). To ensure construction feasibility of the disposal rooms a reduction of the cross-sections is needed, and this requires more disposal rooms (change in design).

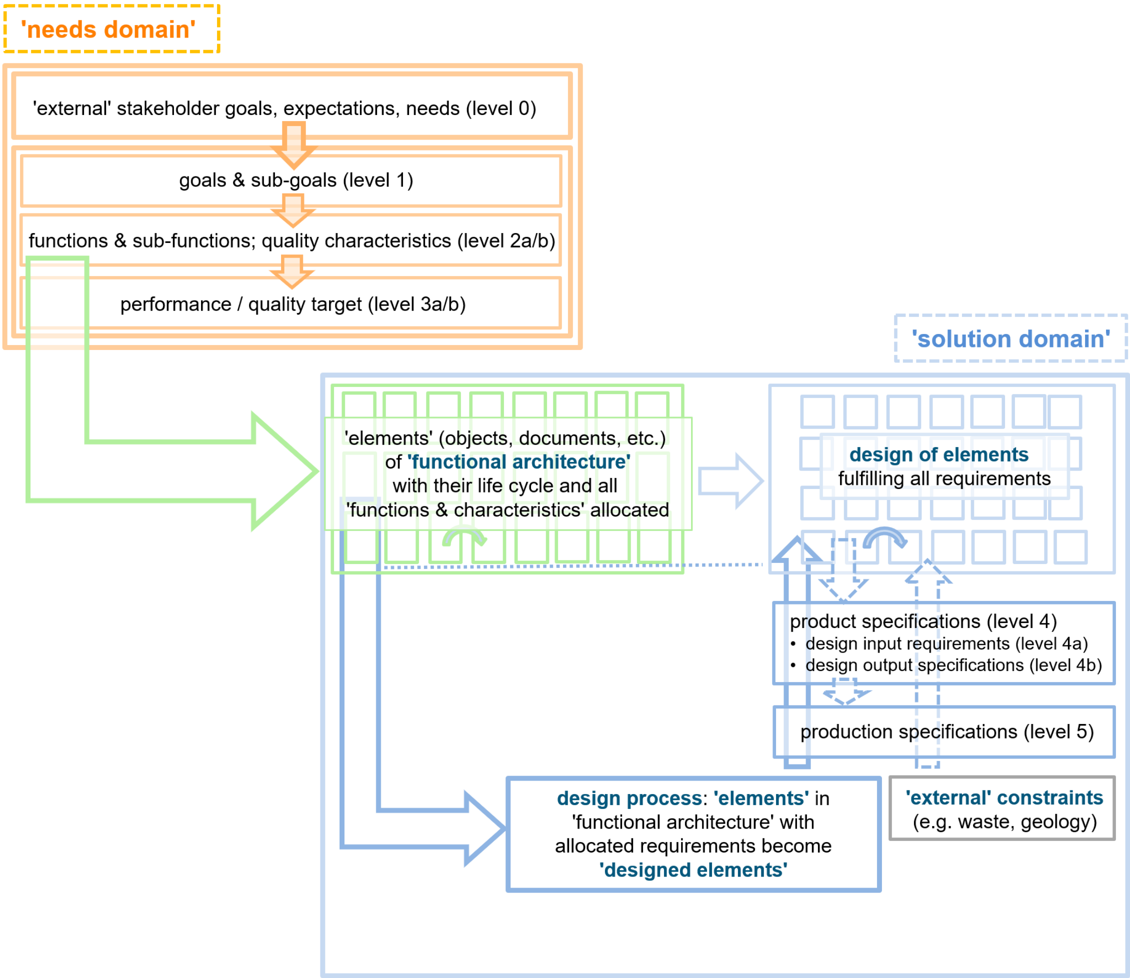

Figure 15 – After some iteration all requirements (for the waste stream discussed and its disposal rooms and for the geological properties) are agreed and 'frozen'.

Then, the specifications for the final products and their production are prepared (as part of the 'solution domain' based on a proper design process that takes the loads and conditions into account and follows the relevant standards and codes).

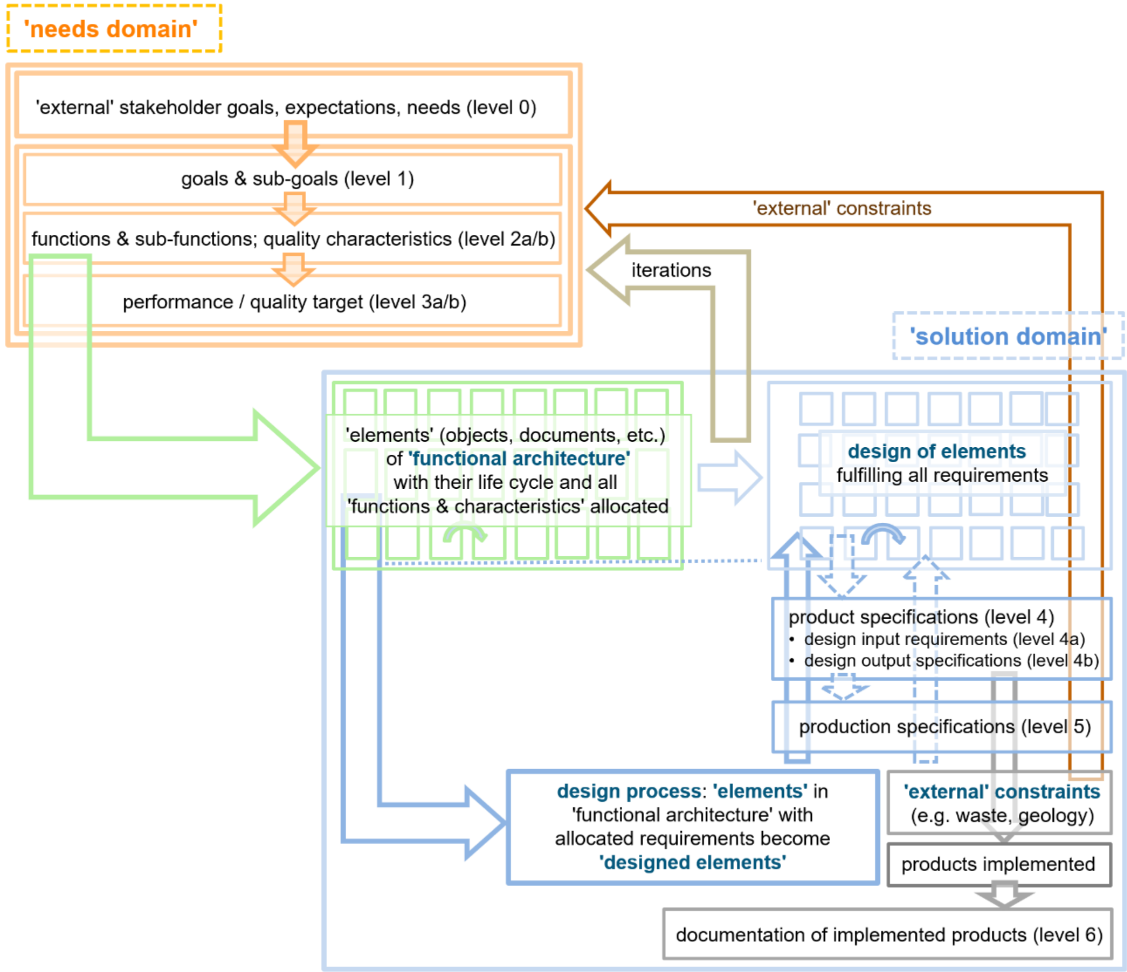

Figure 16 – The construction of the disposal rooms is completed, and the waste is emplaced.

The specifications are replaced by real elements with the corresponding final documentation being available that contains the demonstration of compliance with all requirements. The implemented products have become constraints (replacing the corresponding 'needs').

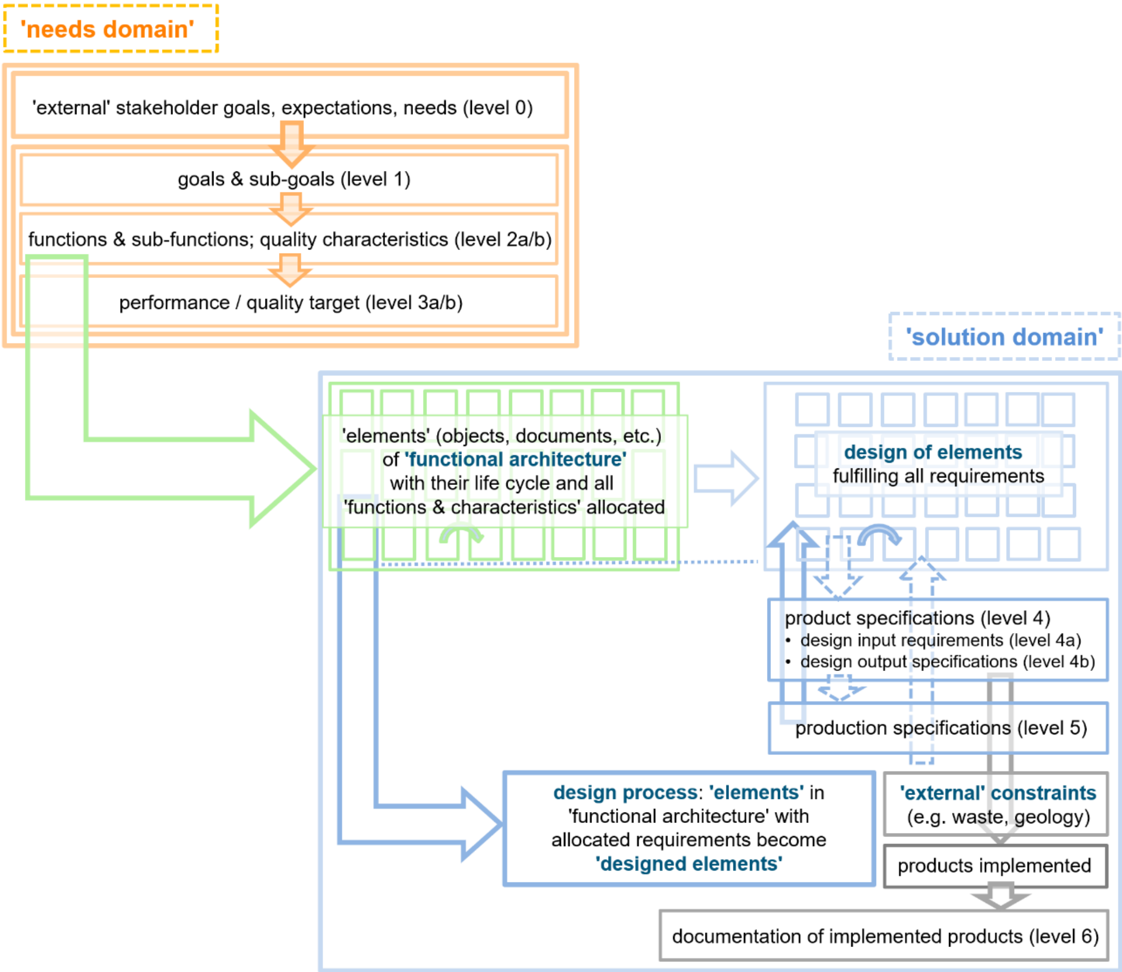

Figure 17 – The implementation of the closed repository is completed; all specifications are replaced by real products.

The corresponding final documentation also contains the demonstration of compliance with all requirements. The 'needs' (level 0 to level 3) and the 'solution', the specifications (level 4 and level 5) and the documentation of successful implementation (level 6) are archived to provide traceability for a long as this is considered useful (as part of institutional control).

Appendix B. Glossary

architecture	the (functional) architecture identifies all elements of the system of interest that are needed to perform the functions and show the (quality) characteristics of the system of interest as specified by the requirements of the 'needs domain'. The (functional) architecture defines the interfaces between these elements and their hierarchical structure. The functional architecture is used to document the allocation of the requirements of the 'needs domain' to these elements. The elements act as black boxes (no design defined yet).
as built	for disposal / waste management systems. This reflects the fact that not everything is built as planned – deviations (detected / non-detected) occur and are accepted.
(quality) characteristic	is related to a requirement ((quality) characteristic requirement); it includes characteristics such as reliability, availability, repairability, etc.
constraint	a requirement that limits the solution space beyond what is necessary for meeting the given functional requirements and (quality) characteristic requirements; constraints are often externally imposed.
element	element (of the disposal system) applies to all issues used to implement the closed repository. The elements provide the 'means' to implement the disposal system.
end-of-life	last stage of the life cycle after the stage of using a product has come to an end. The 'end-of-life' of a repository is reached at the end of the period of concern.
external entity	is outside of the system of interest but interacts with the system of interest.
FEPs	features, events and processes; FEP-catalogues are used to ensure that in analysing post-closure safety all important issues are considered.
function	a task, action, activity or behaviour that must be performed to achieve a desired outcome.
goal	instead of goal (for a high-level requirement) also the terms 'objective' or 'principle' are sometimes used.
level 0	needs, expectation and goals (high-level requirements) expressed by the external stakeholders to be fulfilled by the system of interest.
level 1	goals for the different phases / different stages of the life cycle derived by the internal stakeholders to fulfil the 'level 0' requirements.
level 2a	functional requirements derived from decomposing the 'level 1' requirements.
level 2b	(quality) characteristic requirements derived from decomposing the 'level 1' requirements.
level 3a	performance target related to specific functional requirement.
level 3b	(quality) target related to specific (quality) characteristic requirement.
level 4a	design input requirements.
level 4b	design output specifications.

level 5	production specifications.
level 6	documentation of implemented product.
loads and conditions	acting on a system element; is considered in the development of both the design input requirements and design output specifications.
means	objects, activities with their deliverables / products / decisions, and other measures with their achievements / situations (e.g. stability) that form the elements of the functional architecture.
needs domain	defines the 'why', 'what', 'when'. It contains all the 'level 0 to level 3' – requirements.
outside world	elements outside of the system of interest but potentially relevant for the system of interest.
problem	needs, expectations and goals of the 'external' stakeholders.
product	can be an object (building, equipment, etc.), a document, a contract, a decision, etc.
requirements creep	danger of adding too many not that relevant (not needed) requirements.
service provider	supports the 'internal stakeholder' with implementing the system of interest. The (external) service provider is available on the market.
solution domain	contains all the system elements that make up the (total) system; the system elements make up the 'means' (with the objects, activities with their deliverables and other measures with their achievements) to achieve the 'level 0'-goals of the 'needs domain' The 'solutions domain' defines the 'who, 'with whom' (dependencies), 'when, and 'how'.
stakeholder	external stakeholder: is not involved in the development of the system of interest but has a strong interest in its implementation and has the corresponding needs, expectations and goals (sometimes summarised as the 'problem' statement). internal stakeholder: has the task to implement the system of interest.
stage	(or status) defines where in the life cycle an element of the disposal system is; the stage / status can be: 'initial thoughts / planning', 'production / construction / building',' using the system / system element / product', 'decommission / dismantle / close'.
supply chain	supports the 'internal stakeholder' with implementing the system of interest by providing components for the system. The supply chain is available on the market.
system	items fulfilling the defined requirements, consists normally out of several elements.
the way of thinking	described by the methodology to be applied.
V-model	verification of 'having done the things right' and validation of 'having done the right things' are in the literature sometimes represented as the 'V-model', where each verification-step and each validation-step is linked to the corresponding requirement as defined at the outset of the implementation process.

validation	validation includes the evaluation whether 'the right things have been done'; thus, it is evaluated whether the needs, expectations and goals of the (external) stakeholders are met; validation applies to the whole system of interest or to its sub-systems.
verification	verification includes the evaluation whether 'the things have been done right'; thus, it is evaluated whether all requirements are fulfilled; verification applies to sub-systems, components, etc (only part of the system of interest); however, all sub-systems, components must undergo verification.
voluntarism	describes an approach of site selection where municipalities must volunteer to be considered as a municipality that potentially will host a facility. The approach by providing a 'veto-right' to municipalities falls in the same category
why, what, when, who and how:	the cornerstones of the requirements management process – the 'why' captures the 'needs', 'expectations' and goals of the 'external stakeholders', the 'what' defines the functional requirements and the (quality) characteristic requirements and their targets, the 'when' defines the phase when then 'what' needs to be achieved, the 'who' defines the element (as part of the functional architecture) that has to fulfil the allocated requirements and the 'how' is defined by the 'design input requirements' and the 'design output specification' (together: the 'product specification') and the 'production specification'.

Appendix C. Abbreviations used

EURAD	European Joint Programme on Radioactive Waste Management
FEP	Features, Events and Processes
DGR	Deep Geological Repository. Normally used for the disposal of SF, HLW and LL-ILW
DS-RMS	Document 'Developing, Using and Modifying a Requirements Management System for Implementing a Disposal System' (this document)
GEOSAF	IAEA international intercomparison and harmonisation project on the demonstration of the operational and long-term safety of geological disposal facilities for radioactive waste
G-RMS	Guidance document 'Guidance on Developing, Using and Modifying a Generic Requirements Management System' (EURAD document)
HLW	High-level radioactive waste
INCOSE	International Council for System Engineering
LL-L/ILW	Long-Lived Low-/Intermediate-Level Waste disposed in mined repositories at greater depth,
L/ILW	Low-/Intermediate-Level Waste disposed in near surface disposal facilities or in mined repositories at limited or greater depth,
LLW	Low-Level Waste disposed in (near) surface disposal facilities or in mined repositories at limited depth
NEA/IGSC	OECD's Nuclear Energy Agency's (NEA) Integration Group for the Safety Case (IGSC)
OAM	Object (O), activity (A), other measure (M)
QA	Quality assurance
RDD	Research, development, demonstration
RMS	Requirements management system
SF	Spent Fuel
TSO	Technical support organisation (for the regulator)
VLLW	Very Low-Level Waste often disposed in surface disposal facilities
WAC	Waste acceptance criteria
WMO	Waste management organisation (the implementer)
WMP-RMS	Guidance document 'Guidance on Developing, Using and Modifying a Requirements Management System for Waste Management Programmes with their Different Systems' (EURAD document)

Appendix D. References related to requirements management used for specific applications (selection)

Andra (2016a): Safety Options Report – Operating Part (DOS-Expl), CG-TE-D-NTE-AMOA-SR1-0000-15-0060

Andra (2016b): Safety Options Report – Post-Closure Part (DOS-AF), CG-TE-D-NTE-AMOA-SR2-0000-15-0062

COVRA (2017): OPERA Safety Case, COVRA NV

IAEA (2020): Design Principles and Approaches for Radioactive Waste Repositories, IAEA Nuclear Energy Series, No. NW-T-1.27

IAEA (2020): Approaches to Management of Requirement Specifications for Nuclear Facilities throughout Their Life Cycle, IAEA-TECDOC-1933

ONDRAF/NIRAS (2012): Research, Development and Demonstration (RD&D) Plan for the geological disposal of high-level and/or long-lived radioactive waste including irradiated fuel if considered as waste - State-of-the-art report as of December 2012

Posiva / SKB (2017): Safety functions, performance targets and technical design requirements for a KBS-3V repository - Conclusions and recommendations from a joint SKB and Posiva working group, 2017

Posiva (2012) Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto - Design Basis 2012, POSIVA 2012-03 report, 2012

Radioactive Waste Management (2016): Geological Disposal - Generic Disposal System Specification - Part A: High Level Requirements, NDA Report no. DSSC/401/01

Radioactive Waste Management (2016): Geological Disposal - Generic Disposal System Specification - Part B: Technical Specification, NDA Report no. DSSC/402/01

Radioactive Waste Management (2016): Geological Disposal - Generic Disposal Facility Design, NDA Report no. DSSC/412/01

SKB (2009): Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses, SKB TR-09-22

SKB (2011) Long-term safety for the final repository for spent nuclear fuel at Forsmark - Main report of the SR-Site project - Volume I, SKB TR-11-01

Appendix E. References related to 'needs'-related requirements (selection)

IAEA (2006): Safety Fundamentals – Fundamental Safety Principles – IAEA Safety Standards Series No. SF-1

IAEA (2011): IAEA Safety Standards – Disposal of Radioactive Waste – Specific Safety Requirements No. SSR-5

IAEA (2014): IAEA Safety Standards – Near Surface Disposal Facilities for Radioactive Waste – Specific Safety Guide No. SSG-29.

IAEA (2016): IAEA Safety Standards – Safety Assessment for Facilities and Activities – General Safety Requirements No. GSR Part 4 (Rev. 1)

IAEA (2017): IAEA Safety Standards – Safety of Nuclear Fuel Cycle Facilities – Specific Safety Requirements No. SSR-4

IAEA (2022): IAEA Safety Standards – Leadership, Management and Culture for Safety in Radioactive Waste Management – General Safety Guide No. GSG-16