DEVELOPMENT OF SOLUTIONS FOR DISPOSAL OF SPENT FUEL AND OTHER RADIOACTIVE WASTE IN ONE OR MORE DEEP BOREHOLES

SUBCONTRACT 2

TASK C002 – ROADMAPPING – ACTIVITY 2.3.1

April 2025

Roadmap

Schedule of activities for implementation of DBD in Norway

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The report outlines a roadmap for activities to be undertaken in order to implement deep borehole disposal (DBD) of high-level radioactive waste in Norway. The work has been undertaken as part of Activity 2.3, to inform planning by NND of possible future work on DBD.

EXECUTIVE SUMMARY

Norwegian Nuclear Decommissioning (NND) has initiated a process to develop disposal solutions for all classes of radioactive waste in Norway. A considerable amount of work has been undertaken on generic design and technical appraisal and two concepts have been explored to manage spent fuel / high-level radioactive waste (HLW): a mined geological disposal facility and disposal in one or more boreholes (Deep Borehole Disposal, DBD).

This report summarises the development of a generic (not site specific) roadmap for future work relating to possible implementation of DBD in Norway. The report reviews several approaches to develop such a roadmap, and the roadmap is then structured consistent with International Atomic Energy Agency guidance:

- The roadmap is arranged into activity sets using a Work Breakdown Structure with top-tier headings - disposal programme management, stakeholder involvement, disposal system development, deep borehole field test, and disposal implementation.

- Changes in activities as the project progresses are discussed by key programme development stage - project initiation and site identification, site selection, site characterisation, construction and commissioning, operations, closure and decommissioning, and post-closure.

CONTENTS

APPENDIXES

ABBREVIATIONS

ACE	–	Assumption, Constraint, Exclusion
ASTRA	–	Alternative RWM Strategies
CDE	–	Common Data Environment
CRP	–	Coordinated Research Project
DBD	–	Deep Borehole Disposal
DBFT	–	Deep Borehole Field Test
DGR	–	Deep Geological Repository
ERDO	–	European Repository Development Organisation
FEPs	–	Features, Events and Processes
HLW	–	High-Level Waste
IAEA	–	International Atomic Energy Agency
ILW	–	Intermediate-Level Waste
KVU	–	Concept Evaluation Study
LILW	–	Low-level and Short-lived Intermediate-level Waste
MCA	–	Multi-Criteria Analysis
Nagra	–	Swiss National Cooperative for the Disposal of Radioactive Waste
NND	–	Norwegian Nuclear Decommissioning
NGO	–	Non-Governmental Organisation
PLM	–	Project Lifecycle Management
QMS	–	quality management system
RD&D	–	Research, Development and Demonstration
RWM	–	Radioactive Waste Management
RMS	–	Requirements Management System
SMART	–	Specific, Measurable, Achievable, Relevant and Time-bound
SNF	–	Spent Nuclear Fuel
SB2	–	Technical Assistance to NND on Deep Borehole Disposal
TRL	–	Technology Readiness Level
WBS	–	Work Breakdown Structure
WAC	–	Waste Acceptance Criteria

GLOSSARY

Selection of terms from the SB2 Glossary [1].

Borehole	Any cylindrical ground excavation made by a drilling device for purposes such as site investigation, testing, monitoring, resource exploitation, or disposal.
Borehole Disposal	A disposal concept that entails the emplacement of waste in a borehole directly from the land surface.
Canister	Spent nuclear fuel or high-level waste is put in canisters, which are the primary container.
Closure	Administrative and technical actions directed at a disposal facility at the end of its operating lifetime.
Co-location	Co-location is: • Separate disposal modules at the same location with common infrastructure. • Separate disposal facilities for different types of waste at the same location.
CRP	Coordinated Research Programme
Deep Borehole Disposal	The concept of disposing of waste at a depth of one or more kilometers in boreholes with waste emplaced directly from the land surface.
Engineered barrier system	The combination of the engineered components of a disposal facility, including the waste packages / disposal containers, any buffer, backfills and seals, collectively designed to isolate radioactive waste in, and to prevent or to inhibit migration of radionuclides from, a disposal facility.
Geological / natural barrier	In the context of geological disposal this comprises the host rock in which a disposal facility is constructed, and the surrounding rocks.
Geological disposal facility / Deep Geological Repository	A facility for radioactive waste disposal located underground (usually several hundred metres or more below the surface) in a stable geological formation to provide long-term isolation of radionuclides from the biosphere. Includes both mined disposal and deep borehole disposal.
Groundwater	All water which is below the surface of the earth in the saturated zone and in direct contact with the ground or subsoil.
High level waste (HLW)	The radioactive liquid containing most of the fission products and actinides present in spent fuel — which forms the residue from the first solvent extraction cycle in reprocessing — and some of the associated waste streams; HLW also comprises the same material following solidification, usually by vitrification.
Host rock	The rock in which a disposal facility is located.
Intermediate level waste (ILW)	Radioactive waste that, because of its content, in particular its content of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal.
Inventory for disposal	The total amount of radioactive material, radioactive sources or radioactive waste within a certain specified area or intended to be managed in a certain specified way (or a breakdown of the characteristics of the material or waste within that total amount, for example the total activity of each radionuclide present).
Low level waste (LLW)	Radioactive waste that is above clearance levels, but with limited amounts of long-lived radionuclides.
Mined Repository	Used in this study in place of Geological Disposal Facility / Deep Geological Repository as DBD is also a Geological Disposal Facility. A disposal facility / repository where waste is disposed of in openings that are excavated at depth, and the disposal area is accessed via a shaft or an inclined tunnel.

Multi-barrier system	Two or more natural or engineered barriers used to isolate radioactive waste in, and to prevent or to inhibit migration of radionuclides from, a disposal facility.
Multi-criteria analysis (MCA)	MCA is a systematic method for making complex decisions by using criteria, objectives, and other tools to rank and compare options.
Optioneering	A structured evaluation of options in support of decision-making. Such an evaluation may take the form of an option study that collates information on the options and the different attributes that will influence the decision to be made and may also consider how the decision is influenced by different value judgements.
Overpack	A secondary or additional outer container for one or more waste packages, used for their handling, transport, storage or disposal.
Retrievability	Retrievability is a special case of reversibility, being the ability to reverse the action of waste emplacement in a repository; retrieval is the action of removal of the waste or waste packages. Retrievability implies making provisions in order to allow retrieval should it be required.
Reversibility	Reversibility is the ability to reverse one or a series of steps in repository development (including predisposal waste management) at any stage of the programme.
Safety Case	A collection of arguments and evidence in support of the safety of a facility or activity. This will normally include the findings of a safety assessment and a statement of confidence in these findings. For a GDF, there will be a number of safety cases required covering nuclear safety, environmental safety, and transport. A safety case may also relate to a given stage of development (e.g. site investigations, commissioning, operations, closure, post-closure, etc.). The safety case should acknowledge the existence of any unresolved issues and should provide guidance for work to resolve these issues in future development stages.
Screening	Screening is a way to filter options before more detailed analysis or to compare options that are difficult to quantify.
Spent Nuclear Fuel (SNF)	Nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage.
Waste container	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, molten high level waste glass would be poured into a specially designed container (canister), where it would cool and solidify.
Waste form	Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid) prior to packaging.
Waste package	The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal.

ASSUMPTION, CONSTRAINT, EXCLUSION

ACE 1	It is considered that a full-scale demonstration of the chosen concept in the field, will be a necessary before any actual implementation of DBD could be actioned or sanctioned in Norway.
ACE 2	A DBD facility in Norway will be designed, delivered, operated and closed by 2050. This date is open to ongoing review and stakeholder challenge.
ACE 3	NND will undertake review of regulatory and planning milestones in parallel – therefore, these are outside the current scope of the roadmap.
ACE 4	DBD in Norway will not include ILW.
ACE 5	The DBD for HLW is developed (i.e. sited and constructed) separately to any other facility for radioactive waste management in Norway.
ACE 6	Norway will pursue an option for its own wastes independently of any initiatives established by the ERDO Association.
ACE 7	The DBD infrastructure considered in the roadmap starts from the encapsulation process and extends until the post-closure period. It includes transportation from a centralised storage facility to an encapsulation plant, and/or from an encapsulation plant to a repository depending on encapsulation plant location.

FIGURES

TABLES

I. INTRODUCTION

1. Background to Norway's radioactive waste management issues

In Norway, KLDRA-Himdalen, the combined disposal and storage facility for low-level and short-lived intermediate-level waste (LILW), has been operating since 1999. The facility manages waste from the Halden and Kjeller nuclear research reactor facilities and low-level radioactive waste generated by other industries such as the medical sector. However, the capacity of the facility is not sufficient to accommodate projected waste volumes arising from the decommissioning of the research reactors. Further, high-level waste (HLW) and/or spent nuclear fuel (SNF) from the decommissioned research reactors will also need to be managed.

Norwegian Nuclear Decommissioning (NND) has therefore initiated a process to develop disposal solutions for all classes of radioactive waste. A considerable amount of work has been undertaken on generic design and technical appraisal and two concepts have been explored to manage SNF / HLW: a mined geological disposal facility and disposal in one or more deep boreholes (Deep Borehole Disposal, DBD). Initial consideration has been given to the disposal overpack[1] design, spent fuel processing options and co-location with other waste disposal facilities issues for both disposal concepts [1].

In 2023, a framework contract was awarded to a consortium to continue the work on developing DBD solutions. Subcontract 2 (SB2) concerns the development of disposal solutions for SNF or other HLW in one or more boreholes. This framework contract currently consists of four tasks:

- **Task C001: Framework management**
  General project management including progress reporting, preparation of task form proposals quality control procedures, and management of interfaces.

- **Task C002: Roadmapping of activities**
  Establish in close collaboration with NND an achievable, prioritised, and costed programme of work to address existing knowledge gaps, and further the development of DBD options and disposal concepts in Norway.

- **Task C003: Ad hoc technical support and capacity building to NND**
  Mobilising experts from our Project Technical Committee to provide support to NND as needed. (This task is tentative and is still being scoped with NND.)

- **Task C004: Optioneering of DBD options**
  Undertake multi-criteria analysis (MCA) to inform selection of preferred DBD option(s).

This report is the final output under Task C002.

[1] The term overpack is used here for the outer container that will be used for the handling, transport, storage or disposal of waste packages. The DBD concept is that waste is put into canisters, which are emplaced in an overpack, and the item as a whole is referred to as the disposal package. This terminology is consistent with the Glossary developed for NND as part of Task C001 [1].

2. Objective

This report presents a high-level roadmap of activities that will need to be undertaken to implement DBD of SNF and/or other HLW in Norway. The development of the roadmap has been informed primarily by:

- A review of the NND generic DBD studies conducted previously [2].
- A review of work on DBD being undertaken by waste management organisations outside Norway [3].
- Consideration of the Technology Readiness Levels (TRLs) for implementation of the various components of the DBD solution [4].

The detail of the roadmap is greatest for the near-term, where the focus of activities is primarily to address knowledge gaps identified in the reviews and raise the TRLs to the necessary state for the programme to proceed with confidence. It is considered that a full-scale demonstration of the chosen concept in the field, perhaps in Norway, will be a necessary part of these activities, before any actual implementation of DBD could be actioned or sanctioned in Norway (ACE 1).

3. Scope

3.1. Scope

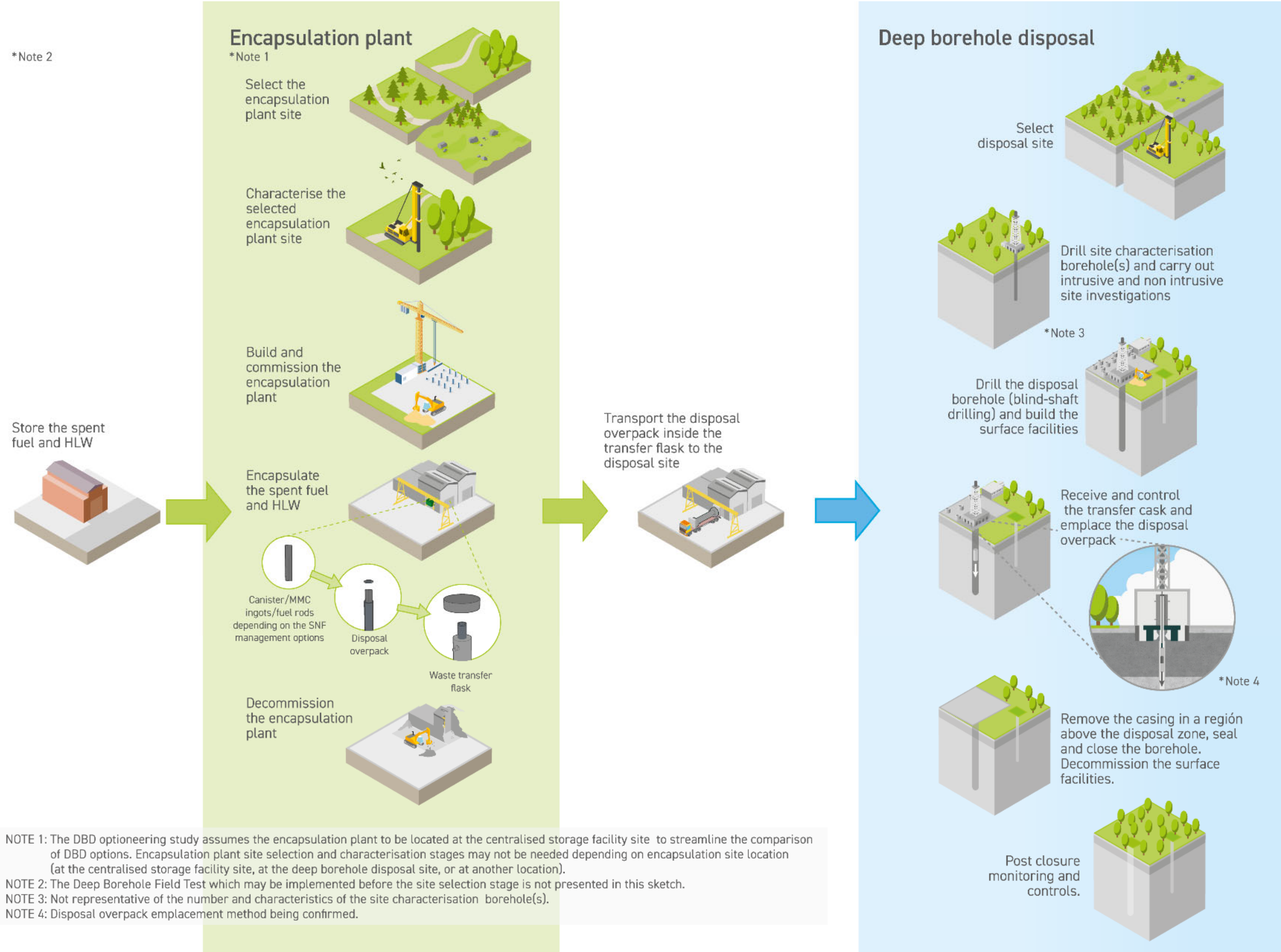
The scope of the roadmap is to encompass milestones to design, deliver, operate and close a DBD facility in Norway (the tentative closure date for spent fuel disposal in Norway suggested for this work is 2050, but this date is open to ongoing review and stakeholder challenge) (ACE 2). The roadmap should outline a R&D programme including a deep borehole drilling and operational demonstration activity. The work is informed by a preceding study conducted for NND presented in [5]. NND is reviewing in parallel the planning and regulatory framework, and these aspects of the work programme are included but not expanded in this issue of the roadmap (ACE 3).

The DBD programme does not include management of wastes other than HLW and spent fuel (ACE 4).

The scope of the roadmap is limited to implementation of DBD and does not include activities associated with pursuing other options for management of HLW, such as a mined repository (ACEs 5, 6).

The DBD infrastructure considered in the roadmap starts from the encapsulation process and extends into the disposal borehole post-closure period (Figure 1). It includes transportation from a centralised storage facility to an encapsulation plant, and/or from an encapsulation plant to the borehole, depending on encapsulation plant location (ACE 7).

Figure 1: Scope of the DBD Roadmap



3.2. Team

Table 3 lists the expert team involved in the drafting of the roadmap with a precis of their experience and the main roles they brought to the task.

Table 1: Roadmap contributors

Name	Experience	Contribution focus
Mark Crawford Galson Sciences Ltd, part of Egis group	More than 25 years' technical and management experience of safety and risk assessments for geological and near-surface radioactive and hazardous waste disposal and 35 years' experience in geochemical modelling and software development.	Review and roadmap development lead. Environmental safety and geological disposal requirements management.
Karl Patrick Travis University of Sheffield	Over 20 years' experience in computational modelling most of which involves research related to nuclear waste disposal. He is an internationally recognised authority on DBD, leading a DBD research group. Ongoing research activities focus on cementitious grouts for DBD applications, rock welding, sealing and support matrices for waste packages, and the safety case for DBD.	Deep borehole research understanding.
John Beswick Marriott Drilling	More than 45 years' experience in studies of radioactive waste repositories and 35 years' involvement in developing and evaluating the concept of deep borehole disposal. He has led deep drilling operations in over 50 countries, including Scandinavia, with depths up to almost 7000 m.	Deep borehole disposal and drilling.
José Luis Cormenzana Empresarios Agrupados	More than 35 years' experience in the nuclear industry including radioactive waste disposal site selection, repository design, alternative concept review, performance assessment and disposability (waste acceptance criteria) for geological and near-surface disposal facilities.	Geological disposal safety assessment and International Atomic Energy Agency (IAEA) standards.
Paul Shaughnessy Orano	Over 20 years' engineering and management experience specialising in machine design and materials handling, 12 years of which have been in the nuclear industry.	Mechanical and waste packaging and encapsulation methods.
Rune Skarstein COWI	Over 30 years' planning and managing large and complex infrastructure development in Norway. He is supporting NND as a Project Manager for the public plan for decommissioning of the nuclear facilities at Halden and Kjeller.	Norwegian regulatory and planning framework.
Merete Grøtt Grinde COWI	Over 5 years' experience supporting a wide array of infrastructure projects across Norway, carrying out and reviewing impact assessments, cost-benefit analyses and socio-economic analysis.	Norwegian regulatory and planning framework, socio economics and environment.
Daniel Galson Galson Sciences Ltd, part of Egis group	30 years' technical and management experience of safety and risk assessments for geological and near-surface radioactive waste disposal.	Technical review and oversight.
Laure Prévot Egis	Over 10 years' experience in coordinating multi-disciplinary consultancy framework contracts and engineering projects across their lifecycle worldwide. She is supporting site evaluation for the UK geological disposal programme, is participating in the IAEA CRP on DBD Implementation, and is leading a Task on DBD within the EURAD-2 European collaborative research project.	Compliance with the Task C002 roadmapping and Task 004 optioneering scope and Task C002 objectives and consistency of delivery. Chair the roadmapping workshop.

Name	Experience	Contribution focus
Shivangi Prasad Galson Sciences Ltd, part of Egis group	Over 2 years' experience in consultancy for radioactive waste predisposal and disposal programme, supporting the UK Deep Geological Disposal programme site evaluation, inventory analysis and PREDIS European collaborative research programme to compare and assess the value of pre-disposal treatment options.	Roadmap workshops secretariat and inputs coordination.

4. Structure of this report

Section II discusses the overall structure of the roadmap and describes the activities set out in the roadmap in terms of the main programme stages. Considerations for some activities at the detailed level are provided for the early programme stages. A number of these considerations are made to address comments made during the review of existing material ([2],[3],[4]).

- Section II.1 reviews several approaches to develop such a roadmap.
- Section II.2 applies the chosen approach, considering the current status of NND's overall work.
- Section III.3 presents the roadmap in the form of a plan on a page (high-level Gantt chart).

This report contains one Appendix:

- Appendix 1 contains the DBD implementation Roadmap of activities over the project lifecycle.

II. ROADMAP OF ACTIVITIES OVER THE PROJECT LIFETIME

1. Roadmap structure

The purpose of the roadmap is to define the major products (the "what") that must be developed in each phase of the disposal programme (the "when") to deliver (design, construct, operate and close) a DBD facility for SNF and/or HLW in Norway. The roadmap should cover the period from now (2025) to completion, cessation of post-closure monitoring and relinquishing of any control of the site. However, the primary focus of the roadmap is the period from now to the beginning of waste emplacement, during which most of the activities will take place, including the vast majority of the underpinning Research, Development and Demonstration (RD&D) activities.

The development of roadmaps to visualise and structure multi-disciplinary, multi-decade disposal programmes aligns with best practice across the radioactive waste management sector. In recent years, several European geological disposal programmes and international initiatives have adopted the use of roadmaps to improve strategic planning. Three examples are described below [6, 7, 8].

1.1. International Atomic Energy Agency (IAEA)

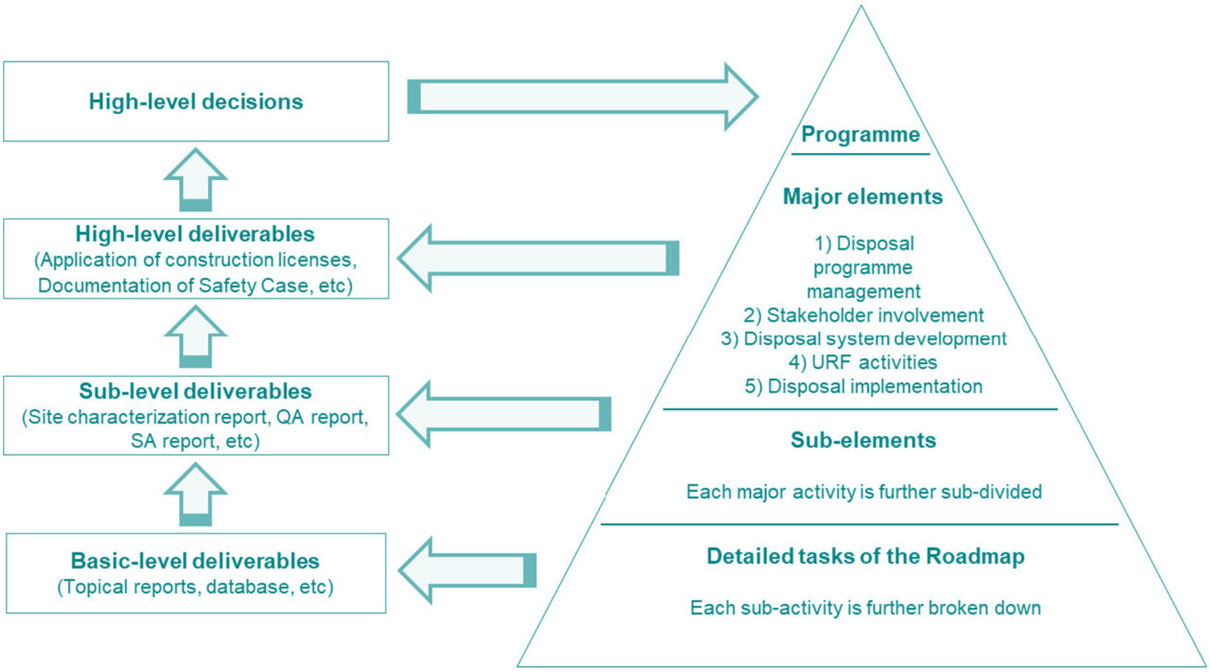
The IAEA has developed a roadmap for the development and implementation of a deep geological repository (DGR) [6]. The roadmap describes key management and technical activities and deliverables for each major phase of a geological repository programme (and their interdependencies) in a Work Breakdown Structure (WBS) format (Figure 2). The emphasis is on how the activities support decision making within each phase for proceeding to the subsequent phase. Four main development and implementation phases are defined, consistent with other IAEA guidance [9]:

- **Initiation phase**.
- **Siting phase**: site(s) survey and selection, site(s) investigation.
- **Disposal phase**: construction (including commissioning), operation, closure.
- **Post-closure phase**.

Within each phase, the WBS is used to group the associated levels of activities and deliverables (Figure 2). At the top-level tier is high-level decision-making. At the next tier directly below, the high-level deliverables and activities are grouped according to five major work elements: disposal programme management, stakeholder involvement, disposal system development, underground research facilities (note that the roadmap is for the development of a mined DGR), and disposal implementation. At the next tier, the major elements are broken down into sub-elements. At the lowest level, the basic-level deliverables and associated detailed tasks are described.

Figure 2: Work breakdown structure for the IAEA roadmap and associated levels of deliverables to support a geological disposal programme

([6], Figure 2)



The IAEA roadmap is generic, describing the activities common to each phase but not specifying the method to complete the activity or time allotment.

1.2. European Joint Programme on Radioactive Waste Management (EURAD)

As with the IAEA, the intended purpose of the European EURAD roadmap is to provide a high-level checklist of generic and typical activities needed to implement a radioactive waste management (RWM) programme, leading to geological disposal [7]. The roadmap also provides signposts to existing knowledge in the RWM arena. As with the IAEA roadmap, the EURAD roadmap is organised around the phases of implementing a geological repository programme but these have been adapted slightly from the IAEA structure, primarily splitting site selection and site characterisation into two distinct phases:

- **Initiation**: Policy, framework and programme establishment.
- **Site selection**: Site(s) identification and selection.
- **Site characterisation**: Underground investigations and site confirmation.
- **Construction**: Facility construction.
- **Operations and closure**: Facility operation and closure.

Within each phase, the EURAD roadmap organises the programme goals, activities and capabilities needed around seven themes, which are each further broken down into sub-themes and domains in a Goals Breakdown Structure (GBS).

1.3. Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra)

The "Nagra Roadmap" (Figure 3) supports planning, coordination and visualisation of the expected programme over the following broad phases: site selection, construction and operation of a facility for underground investigations at the chosen site(s); construction of the repository; operation of the repository; and closure. The roadmap is built over three integrated tiers, each with a different focus:

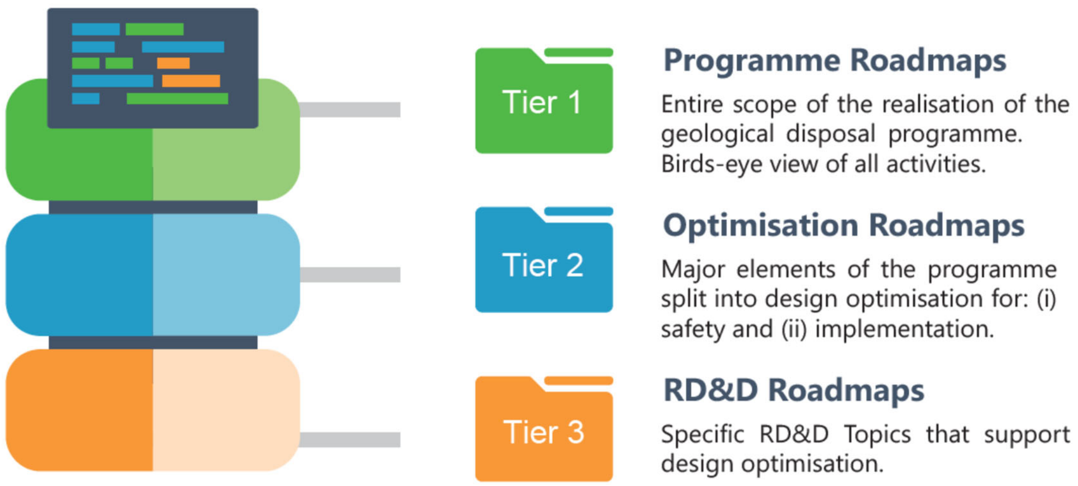
- **Tier 1: Programme**, captures a high-level description of the disposal programme all the way to the return of the site(s) to a greenfield state. Tier 1 covers the iterative repository design and safety assessment process and the legally binding repository licensing process. It sets out the overarching framework against which programme activities are mapped at Tier 2 and Tier 3.
- **Tier 2: Optimisation**, captures the activities at the core of the programme, up to the return to greenfield. Specifically, Tier 2 covers the development and optimisation of the repository design from the perspective of safety during construction, operation and post-closure; it also covers implementation to ensure technical feasibility and practicability.
- **Tier 3: RD&D**, captures the underpinning RD&D activities necessary to optimise and realise a Swiss repository up until first HLW emplacement. Tier 3 covers all RD&D activities required to support specific optimisation work at Tier 2, communicating the necessity and sufficiency of the Nagra RD&D programme.

At each tier in the overall Nagra Roadmap, the activities are grouped into a number of constituent roadmaps according to:

- **Tier 1**: One roadmap, structured in time against "Programme Elements".
- **Tier 2**: Two roadmaps, structured in time against workstreams which cover design development and optimisation from the perspectives of post-closure safety and repository implementation. Implementation covers the construction, operation and closure of the repository and includes operational safety.
- **Tier 3**: Ten roadmaps, structured in time against aspects of the Nagra disposal programme with a significant RD&D component, defined as RD&D topics.

Figure 3: The tiered structure of the Nagra Roadmap

([8], Figure 3.1)



1.4. Summary

The three examples of roadmaps from the IAEA, EURAD and Nagra illustrate the variation and the flexibility that exist in the organisation and presentation of activities around a RWM programme. A further degree of variation for consideration by NND is that these three examples concern development of a mined geological disposal facility (GDF) rather than DBD. There is also the question of the level of detail appropriate for specifying the activities for NND at the current point of the Norwegian programme. This flexibility in detail is illustrated in Table 2 by comparing the activities from the three examples for the specific issue of developing the disposal concept.

Table 2: Comparison of activities specified in different roadmaps for developing the disposal concept

Roadmap Level	Activity		
	IAEA	EURAD	Nagra
Level 1	Disposal system development	Theme 3. Develop an engineered barrier system (EBS), tailored to the characteristics of the waste and compatible with the natural (geological) barrier, which performs its desired functions for the long-term disposal of radioactive waste	Repository conceptual design
Level 2	Safety strategy	3.1 Confirm waste form compositions, properties and behaviour 3.2 Identify container materials and designs for each waste form 3.3 Identify appropriate buffer, backfill and seal/plug materials and design 3.4 Confirm integrated EBS system understanding	Develop conceptual UTA [underground facilities] design Develop closure concept Develop post-closure safety concept and adapt to site Develop operational safety concept and adapt to site
Level 3	Develop generic safety strategy	3.1.1 SNF 3.1.2 Vitrified HLW 3.2.1 HLW and SNF containers 3.3.1 Buffer components 3.3.2 Backfill components 3.3.3 Plugging and sealing components 3.4.1 Confirm complete and integrated EBS system understanding 3.4.2 Confirm interactions between EBS materials do not compromise performance (e.g. in the case of co-disposal of different waste types)	Numerous activities, e.g. overpack testing, corrosion rates, gas permeability

The use of three tiers or levels to categorise activities is common to the examples and is useful for the purposes of the drafting of the NND roadmap. The roadmap set out here has been based primarily on the IAEA WBS, but drawing from the EURAD and Nagra roadmaps to help identify and audit the scope of the activities at each level of the structure. However, to try to capture all the details of the activities given at the lowest level of the roadmaps is too ambitious for the current state of the NND programme. The current draft of the roadmap presented here generally only extends to Level 2 of the IAEA roadmap with examples of the activities expected being drawn from Level 3. The definition of the programme at the lower level will evolve as early activities are completed. Further, the roadmap will be used as a live planning document, and it will develop and change as the programme proceeds. The tracking of the status of activities using the roadmap is discussed below.

2. Programme development stages

As demonstrated by the examples of the roadmaps in the preceding section, all radioactive waste management programmes develop as a series of staged decisions and corresponding hold points, from early generic studies, to more specific concept studies, to various site-specific stages. The stages can be categorised and titled in different ways but each of the examples above are essentially the same.

In the Stage 1 studies conducted for NND, the development process described by Saanio et al. [5] for a national Norwegian facility for management of radioactive waste was structured according to Figure 4. This figure reflects the main stages for the generic repository programme life cycle (green boxes) set out in IAEA guidance that provide a more detailed breakdown of the IAEA phases (blue boxes) [9]:

- Site identification.
- Site selection.
- Site characterisation.
- Construction and commissioning.
- Operations.
- Closure and decommissioning.
- Post-closure.

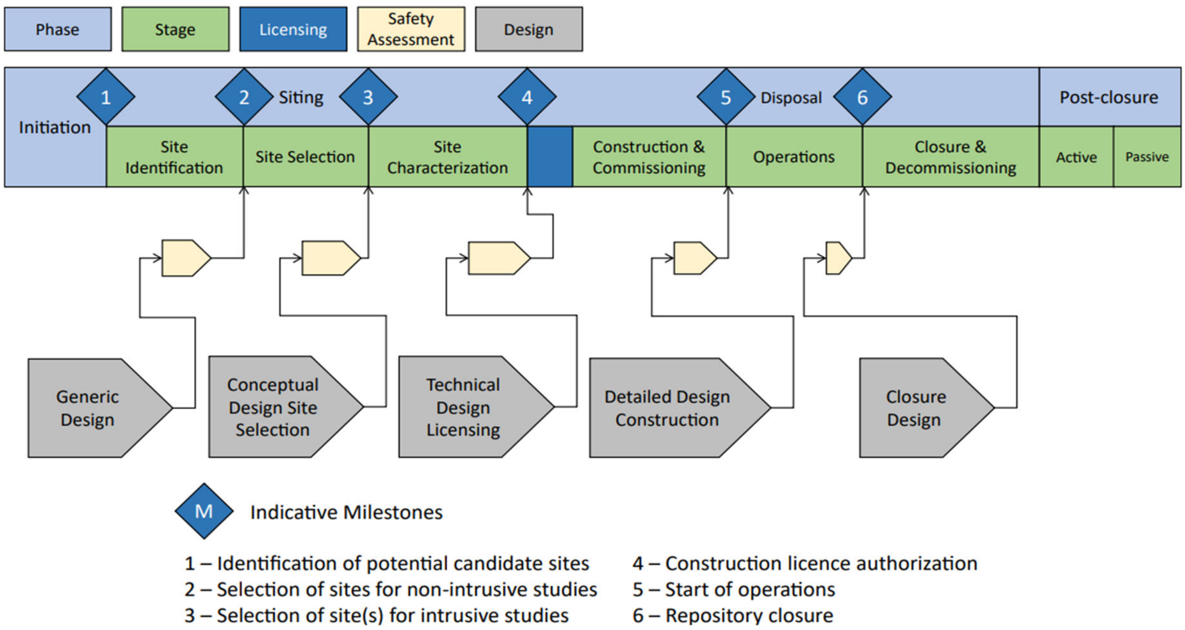
Mapped to these stages in Figure 4 are five design stages and six milestones:

- Generic design.
- Conceptual design for site selection.
- Technical design for construction licensing.
- Detailed design for construction and operation.
- Design for closure.

The generic design stage covers the first two milestones of site identification and screening. For certain disposal concepts, the volume of wastes and the rate at which they are delivered will allow for a staged, modular approach to repository design. This means that detailed design for repository construction could be extended in time into design for operation and expansion. However, this is not relevant to the implementation of DBD in Norway involving the drilling of only one disposal borehole. Consequently, a single point for completion of the detailed design before construction is adopted in the roadmap here.

Figure 4: Generic repository programme lifecycle and associated design stages aligned with indicative milestones

([9] Figure 4)



The application of Figure 4 to the current position in Norway is complicated by the situation that an options assessment is still ongoing to decide on the preferred management option for SNF. The main drivers to consider DBD in Norway are its lower cost compared with a mined repository, and potentially a better public perception. The main blocker is its maturity compared with a mined repository and the associated upfront investment costs needed to reach the maturity needed to enable the selection of this disposal concept.

Over the next few years, NND will set out its proposals in the form of a concept evaluation study (Konseptvalgutredning or KVU). This decision point can be added to the initiation phase of Figure 4 as Milestone 0. Beyond this milestone, the roadmap is set out assuming that DBD is chosen as the preferred option for disposal of SNF/HLW.

A preliminary general schedule for construction and commissioning by NND of a National Facility for radioactive waste management in Norway is presented in [5, Figure 3-3]. The base case scenario for this schedule assumed that separate disposal systems for the different Norwegian wastes were developed and operated at a single site. However, a DBD for HLW or SNF could also be developed separately, and at a separate site to a repository for other less radioactive wastes including longer-lived intermediate-level waste (LL-ILW) (Scenario S3 in [5]). This separation of the sets of activities for different facilities and waste types has been assumed here and the development of activities for other facilities has not been considered in the roadmap (ACEs 5, 4). However, activities such as requirements management focused in the roadmap on DBD might instead be conducted more broadly as part of a collective approach for several or all components of NND's programme. Such possibilities are noted where appropriate.

The schedule for NND presented in [5] considers preliminary content for the first three stages of the development process titled to be consistent with the first three stages in Figure 4, but with additional phasing terminology for Phases A to D of the "siting process":

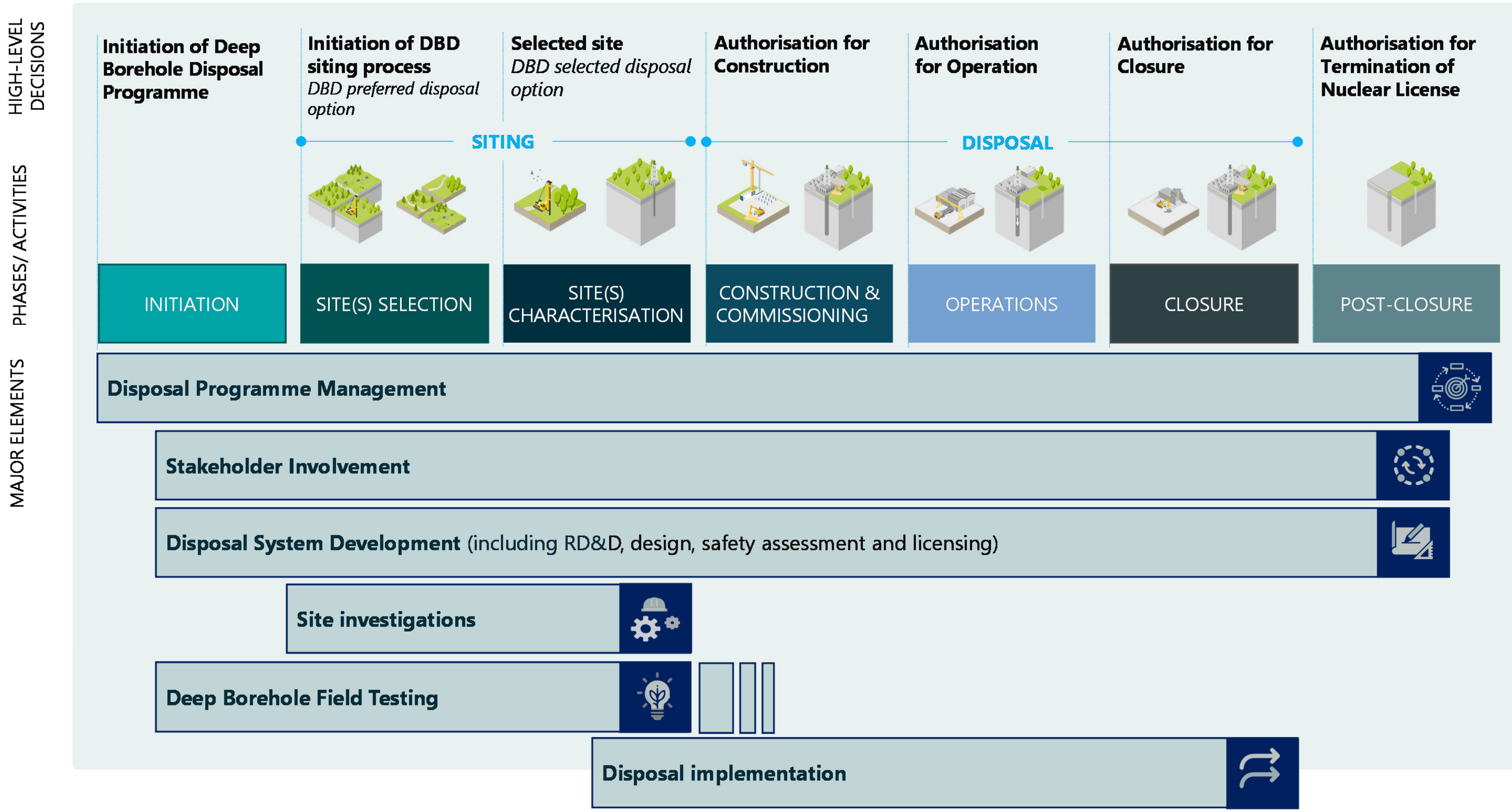
- Project[2] initiation and site identification stage.
- Site selection stage, Siting process Phases A-C.
- Site characterisation, Siting process Phase D.

For consistency with [5], the same programme headings are used for the first three stages in the roadmap developed here with the later stages titled according to Figure 4. One caveat noted in the review of [5] presented in [2] is that it is not clear if the early schedule in [5] includes the time that will be necessary to manage the planning process, which involves dialogue with Municipality, Regional and Governmental Bodies. The planning process will take place partly in parallel to work on developing the safety case, and the two activities are considered alongside each other in the schedule presented here.

Within the programme stages for the NND roadmap, the five major work elements used in the IAEA roadmap are adopted generally as headings for group activities (Figure 5). The headings used by the IAEA are disposal programme management, stakeholder involvement, disposal system development, underground research facilities, and disposal implementation [9]. However, because the NND roadmap is for DBD rather than a mined DGR, the phase for underground research facilities is instead retitled as two phases concerned with (1) field testing and (2) site investigations. The Deep Borehole Field Test (DBFT) is started in the early stages of the project so that it can be used to address questions for the options assessment decision supporting the development of the strategy for disposal of Norwegian radioactive waste (Figure 5).

[2] Note that Figure 4 from the IAEA guidance [9] uses the term "project" when referring to the milestones and this term has been adopted in [5] in reference to the overall disposal programme. It is used in the headings here in the same context for transparency with [5].

Figure 5: Norwegian DBD Implementation Roadmap Phases



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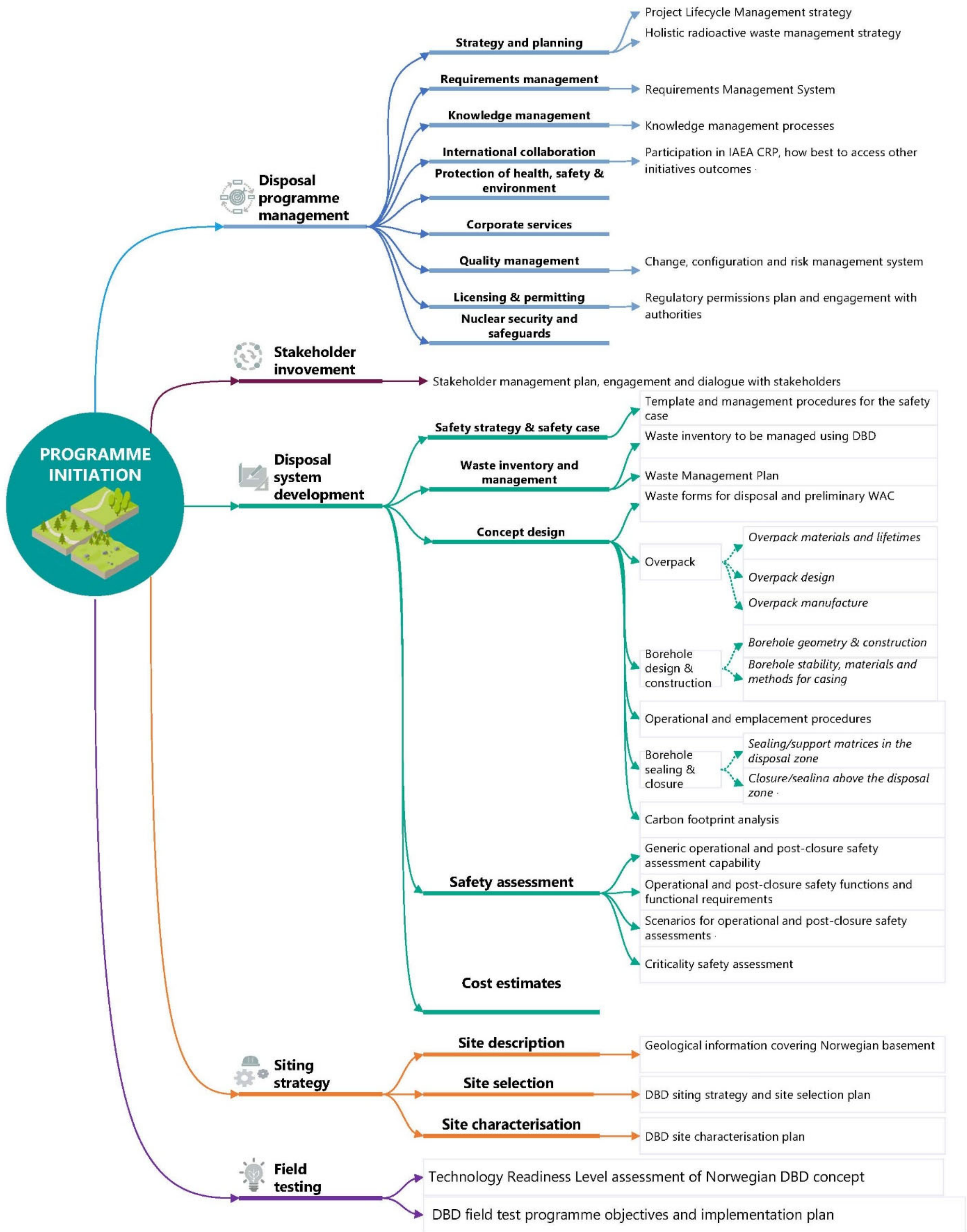
2.1. Project initiation

2.1.1. Overview

Regarding the IAEA and EURAD roadmaps, several activities in the project initiation phase are concerned with establishing capabilities, resources and management structures for the programme. Another key aspect is setting up stakeholder involvement. Such activities have already been started by/for NND, and some of them such as knowledge management and requirements management are underway for DBD under the current framework. These activities are shown on the roadmap and are key, but NND is reviewing in parallel the planning and regulatory framework and these aspects of the work programme are therefore not described in this issue of the roadmap. The focus of this current draft of the roadmap is on the technical RD&D activities needed to address knowledge gaps and design issues with regard to the concept and physical implementation of DBD.

The IAEA roadmap WBS groups activities in the project initiation phase largely under the three high-level headings of disposal programme management, stakeholder involvement, and disposal system development. The roadmap for NND proposed here adopts these headings and adds the heading for the DBFT, recognising that the early testing will support decision-making on the preferred option (Figure 6). This can be considered as an extension of the underground testing phase for a mined facility set out in the IAEA roadmap. Beneath the high-level headings, at Level 2, a series of activities are defined to capture the IAEA WBS tasks collectively where they can be currently considered together by NND for planning purposes, perhaps on the basis of a common theme or a common responsibility. While tasks under the top-level headings – disposal programme management and stakeholder involvement in particular – will continue to be developed and undertaken throughout the entire lifecycle of the programme, early establishment of the tasks is essential for successful time and resource management.

Figure 6: Mind map of the programme initiation stage



High-level critical path review. A prerequisite to DBD project initiation in Norway is demonstration that DBD has a sufficiently high TRL. However, Norway will not be the host for a DBFT, as in the short term NND's priorities prevent the investment required. Therefore, to advance DBD to the same TRL as a mined repository, another country would have to host a DBFT to build sufficient confidence in the concept. There is a high risk that it could be many years before another country is able to undertake a DBFT or otherwise sufficiently demonstrate DBD.

A development that could drive the implementation of DBD in Norway would be its adoption by another country for SNF or HLW disposal.

One driver for the selection of a disposal option is stakeholder input, licensing and permitting. There have been technical issues encountered at one of the Norwegian fuel storage facilities, increasing the need for improved storage conditions and/or early implementation of disposal. There is a need for stakeholder involvement throughout the waste management and decommissioning programme and for demonstration that any proposed concept is feasible.

Management options for LL-ILW are being considered in parallel by NND. A decision to dispose of LL-ILW at the same facility as HLW/SNF would require co-disposal issues (thermal, hydrological, mechanical, chemical) to be explored.

NND is also considering development of a new centralised store for SNF in parallel with decision making on disposal concept, and there are schedule and disposability interfaces between the two decisions. For example, consideration could need to be given to disposability interfaces if the fuel is further degraded in the current storage conditions, and to schedule interfaces if several storage facilities are developed.

High-level interdependencies review. The implementation of a concept is contingent on identifying a site with the desired conditions for a mined DGR or DBD facility. The project initiation phase will depend on the NND programmes listed in Table 3.

Table 3: Interdependencies with other NND programmes at the project initiation stage

NND Programme	Interdependency
SNF management programme	The treatment method for SNF or the fuel condition may impact borehole design and/or safety and delay project initiation.
NND safety assessment process	The requirements of the safety assessment, for example retrievability requirements, may lead to difficulties making a safety case.
GeoReN disposal concept study	The GeoReN assessment outcomes may underpin NND decision that a mined DGR is the preferred option. Potential impact in case of co-location of repositories.
NND decommissioning programme	LL-ILW will arise from decommissioning activities and may need to be disposed of with the HLW/SNF. The decision about whether LL-ILW will be disposed of with HLW/SNF may affect project initiation.
NND SNF/LL-ILW storage programme	Waste condition could impact the DBD programme in terms of disposability or in terms of schedule.
NND siting strategy and stakeholder engagement process	NND overall siting strategy applicability to DBD needs review. The DBD stakeholder engagement plan and its implementation will be agreed across NND, to understand all stakeholder requirements (regulator, planning authorities, civil society, potential siting communities, politicians, etc.) with the aim of ensuring ongoing stakeholder buy-in to the process.

High-level risk review. The NND DBD Programme Risk and Opportunity Register [10] maps risks to NND programme during project initiation. The top risks and showstoppers at this stage are summarised in Table 4.

Table 4: Top risks and showstoppers during project initiation

Risk Description	Comments (Impact Insight)	Mitigation Strategy
There is a risk that DBD is not the selected option. - **SHOWSTOPPER**	If the risk materialises, DBD will not be the option implemented in Norway and another disposal option will be implemented.	Mined disposal is considered in parallel with DBD. Regular engagement with regulators and authorities to anticipate any programmatic change.
There is a risk that the DBD TRL is not sufficiently high to enable a decision to proceed.	If the risk materialises and the TRL cannot be shown to be sufficiently high to move forward with DBD, then another option must be considered or further DBD RD&D must be carried out.	Mined disposal is considered in parallel with DBD. Early development and possible implementation of a RD&D programme for DBD to increase TRLs. Leverage DBD RD&D programmes in other countries and those of international organisations.
There is a risk around changes or lack of applicability of Norwegian or international regulatory guidance, and safety standards and safeguards for DBD. For instance there is a risk of the regulator requiring retrievability of disposed packages pre-closure, or of an evolution of permitting and planning requirements.	If the risk materialises, this could result in the DBD system needing to be redesigned, leading to programme delays, and surface storage may be prolonged. This could also lead to an increase in cost (storage costs, additional disposal RD&D).	A potential requirement for retrievability was considered under the Flexibility criterion in the DBD MCA in Task C004 [11]. Regular stakeholder engagement. Involvement in planned IAEA activity to review application of mined GDF safety standards to DBD.
There is a risk that Norway's ILW or LLW and any potential waste associated with future new build activities will need to be disposed of by DBD.	If the risk materialises, additional design, safety and optioneering assessment work will be needed to take account of a revised inventory. For instance, an additional borehole or a deeper and/or wider borehole may be needed.	Evolution of inventory was considered under the Flexibility criterion at the DBD MCA in Task C004. NND can take a holistic radioactive waste management approach to ensure consideration of all wastes arising.
There is a risk of delay to production of a robust safety case for permitting of disposal operations.	If the risk materialises, this may result in borehole site operations needing to stop, leading to programme delays and surface storage may be prolonged. This could also lead to an increase in cost (storage costs, additional disposal RD&D).	Development of a RD&D programme to address low TRLs and a sound, iterative safety assessment programme. Ensure development of a safety case methodology applicable to DBD and approved by regulators.
There is a risk that NND priorities evolve (for instance prioritisation of NND storage programme), leading to delays in implementation of the disposal programme.	If the risk materialises, the disposal programme may slow down, impacting the start date of disposal operations.	Holistic review and implementation of radioactive waste and decommissioning management programme and strategy, with a full lifecycle perspective. Any delays in the implementation of SNF disposal would provide additional time for the development of a DBFT.

2.1.2. Disposal programme management

Strategy and planning

As a starting point in the project initiation phase, the roadmap takes as its basis that, in accordance with Requirement #1 of the IAEA guidance for disposal of radioactive waste [12], the Norwegian Government has established the responsibilities of the principal stakeholders in the waste management programme. NND has been tasked with the responsibilities of the Waste Management Organisation. Within NND, the roadmap assumes that a team tasked with the specific objective of developing the disposal facilities has already been established.

The decision on the preferred options for disposal of different wastes is included in the roadmap as part of the overall strategy and planning. This work is currently being undertaken by NND and the activities are referred to collectively here as the options assessment.

[3]Activity - Clearly set out the Project Lifecycle Management (PLM) strategy
The strategy sets out the entire project lifecycle from concept through end of life, showing the different functions and the multiple supply chain partners. Setting up the PLM strategy as early as possible facilitates establishing a robust and capacity-building system across all the teams within NND, supporting programme performance and knowledge management. The progress of the project and commissioned activities could be tracked using the roadmap entered in an application such as MS Project©.

Activity - Develop a holistic radioactive waste management strategy

Programme requirements management

NND will need to demonstrate to all stakeholders that the final repository will meet the defined and agreed set of performance requirements. This requires a complete understanding of these requirements and of the way that NND is intending to ensure they are met during the planned development stages (e.g. via engineering studies, RD&D on waste conditioning or site conditions, construction methodologies, etc.).

Activity - Develop the Requirements Management System (RMS)
NND has already undertaken work on requirements for radioactive waste management ([13], [14]). In the context of DBD, this work could be further developed and this is likely to be linked to international collaboration (see section 'International cooperation' below). The work could develop a hierarchical structure to the requirements and help to establish a RMS that will set out the activities and the associated performance measures (SMART – Specific, Measurable, Achievable, Relevant and Time-bound) that will be used to meet the requirements as the programme proceeds.

Knowledge management

Work has been started under SB2 to provide NND with a technical library of information regarding DBD and to establish a Common Data Environment (CDE) that will provide a controlled route to approved and consistent data for the underpinning of safety assessment and design (as part of Task C001).

[3] Activities are provided here as considerations for work needed at the detailed level in the early project stages based on comments made when reviewing existing reports on DBD.

Activity - Formalise knowledge management processes
Building on the work already started under SB2 such as setting up a technical library and considering a CDE, knowledge management processes can continue to be established across the NND team to help build robustness and to support innovation, safety case development, siting and design stages, compliance demonstration, and planning for future developments.

International cooperation

The IAEA is currently managing a Coordinated Research Project (CRP) with the objective to enhance the international knowledge basis available on DBD. Organisations from many countries interested in DBD are participating. The IAEA Waste Safety Section has reviewed in 2024 the applicability of existing IAEA safety standards to DBD. A preliminary review outcome is to recommend the issue of a specific safety document on DBD for HLW and LL-ILW [15]. The impact of potential future evolution of the IAEA safety standards applicable to DBD will be assessed in subsequent development stages of the DBD programme.

EURAD-2 is currently launching a work programme called ASTRA (Alternative RWM STRAtegies) within which a task is concerned with development of a state-of-the art report on TRLs for DBD, and identification of key stakeholder concerns and additional R&D needed to build confidence in the implementation of DBD.

Both of these initiatives offer NND the opportunity to collaborate internationally, to share experience, and to access RD&D and information from other programmes.

Activity - Continue to participate in the IAEA CRP and to consider how best to access the work being undertaken by the EURAD-2 ASTRA programme

Protection of health, safety and environment

Plan and initiate health and safety and environmental monitoring programmes. Clearly, such programmes cannot be specified in full until siting and design have proceeded further, but the generic tenets of such programmes such as following best practice and how to establish baselines can be set out at the project initiation stage. Health and safety and environmental aspects are an essential part of an Environmental Impact Assessment process. The main structure and aspects of such programmes may be defined and addressed irrespective of final site selection. This is left as a broad generic task in the roadmap.

Corporate services

Under the IAEA roadmap, this activity includes capability management, training and recruitment, procurement procedures, and facility management. All of these are important to the smooth, efficient and effective running of the programme. However, it is assumed here that they are covered by NND's quality management system (QMS) and so they are not defined as part of the NND roadmap separately to quality management below.

Quality management

This covers the high-level procedures prescribed by the NND certified QMS including procedures for contracting activities, training, and auditing. It is assumed that these are already established and no explicit activity for further work is specified here. General development of the QMS is left as a generic task in the roadmap. The need for more specific procedures in the future to manage activities such as site investigations are covered in the relevant later programme stages. However, a specific early activity to establish change management procedures is included here to ensure that the procedures are in place to manage the development of the concept design. These procedures concern the responsibilities and tools for capturing what assumptions may need to be re-examined or work potentially redone if something changes in the programme (e.g. changes to inventory, pre-disposal waste management, assumed disposal environment, etc.).

Activity - Develop the change, configuration and risk management approach
How to manage risks and to capture and review what assumptions need to be re-examined or work potentially redone if there is a change in the programme or in the concept design, and their potential impact on requirements.

Licensing and permitting

As noted earlier, NND is reviewing the planning and regulatory framework in Norway in parallel to this work, and so these aspects of the work programme are largely included here as a generic task but not expanded in this issue of the roadmap. However, although it is not NND's role to develop the regulatory framework, it would be helpful to have a task to allow NND to consider the kinds of regulatory criteria that could make sense for DBD, and to provide a technical basis for interacting with the regulator as they work to define any such criteria. For instance, there is currently no requirement regarding waste retrievability in Norway. This is included here as a specific activity although the work might also be covered by other NND work.

Activity - Consider regulatory requirements for DBD, develop a regulatory permissions plan and engage with regulatory activities
Safety and design criteria for DBD may differ in important ways from criteria developed for a mined GDF. A key activity in parallel to the development and implementation of the stakeholder management plan is planning for all of the regulatory interactions that will be needed for the project, including construction of the storage and encapsulation facilities, field tests, site investigations, surface infrastructure, etc. NND is currently reviewing the planning and regulatory framework in Norway, and so this aspect of the work programme is simply included here as a single task.

Nuclear security and nuclear safeguards

Nuclear security principles and obligations related to radioactive materials must be maintained throughout the programme. Physical activities involving radioactive material are not likely to occur before the testing and operational phases, but design and planning must take future security needs into account. Similarly, regarding safeguards, the requirement for independent verification that nuclear material has not been diverted to a non-peaceful activity must be considered throughout the programme. The approach to verification should be established with the relevant stakeholders and this might be agreed as part of the concept termed safeguards-by-design. Both nuclear security and establishing nuclear safeguards are left as generic tasks in the roadmap.

2.1.3. Stakeholder involvement

The project will only progress successfully if stakeholders buy into it throughout. It is important that regulators and potential siting communities are happy with the DBD concept at the outset, recognising shortcomings and the R&D being undertaken to address these. It is of utmost importance to manage and safeguard the interests of third-parties such as the local community including the general public, local administration, infrastructure and business. NND will ensure that issues related to the DBD programme are articulated in a clear and easily understandable way to assist NND to promote efficient communication and assist NND to efficiently communicate with all stakeholders. As the programme and associated RD&D deliver, the stakeholders can indicate their satisfaction or otherwise. Only when stakeholders are generally satisfied will the programme succeed.

Activity – Establish a detailed and comprehensive stakeholder management plan and engage in dialogue with stakeholders
This activity has been started as part of the options assessment studies [10]. The plan should include all planning and information activities throughout the programme, and involve all relevant authorities including:

- NND.
- Institute for Energy Technology and other waste producers.
- National public.
- Local community / municipalities.
- Local / regional government.
- Governmental Officials, Norwegian Radiation and Nuclear Safety Authority, Norwegian Directorate for Civil Protection, Norwegian Environment Agency.
- Media, Non-Governmental Organizations (NGOs), scientific and academic community.

2.1.4. Disposal system development

Safety strategy and safety case development

The safety strategy identifies key principles and objectives such as defence in depth, containment and isolation of the waste. It also covers how these principles are met including identification and evaluation of safety-related features, events and processes, optimisation, and interdependences with predisposal management of wastes. A safety strategy is an important driver for any radioactive waste disposal programme. The strategy should link to Norwegian and international standards and guidance via the RMS. A strategy has started to be developed as part of the options assessment for DBD, and this should be periodically reviewed and updated considering the emerging conceptual design(s) for DBD of Norwegian wastes. The establishment of the strategy and keeping it under review supports staged decision-making while recognising that different design decisions could be taken to meet the same strategy.

As an output of the review of regulatory and planning milestones and from the key design stages in Figure 4, it will be apparent when the main iterations of the safety case will be needed. The safety case will be informed by the outcomes of the safety assessment described in paragraph 4.

Activity – Develop safety case template and management procedures
Based on the safety strategy, international guidance and good practice, and Norwegian regulatory requirements, NND should develop a template for the safety case and procedures for managing its development and update. This template and the associated management procedures should be discussed with the regulators.

Waste inventory and waste management

Activity - Monitor the waste type/characteristics and volume to be managed using DBD
The characteristics of the HLW and SNF to be disposed of in a DBD was compiled as part of the DBD concept options assessment [16]. However, an options assessment for SNF treatment is ongoing in parallel. Therefore, the DBD radiological and non-radiological inventory will need to be confirmed against the fuel treatment decisions taken. The available data will need to be reviewed periodically to

ensure reliable estimations of the waste inventory and characteristics for DBD. Some of the SNF has degraded and this will affect its future management requirements – the extent of fuel degradation must also be characterised. All of this information is necessary as inputs to the DBD concept design (e.g. overpack internals, number of overpacks) and modelling (thermal evolution, radiological performance). In tandem with the safety assessment, waste acceptance criteria (WAC) will be defined and compared to the developing waste inventory information.

It should be noted here that current Norwegian regulatory guidance [17] seems to anticipate that long-lived ILW and SNF/HLW will be disposed of in the same facility. This aspect should be discussed by NND and the regulators. If confirmed, it may be necessary to build on existing work to evaluate ILW waste forms that could be disposed of by DBD, including evaluation of treatment options to optimise such disposals.

Activity – Develop a waste management plan covering all DBD activities
There will be wastes associated with constructing, operating and decommissioning ancillary facilities related to DBD. Further, the excavated material from constructing deep boreholes will most likely be characterised as waste (spoil) and its management, therefore, will also likely need to be considered as part of the overall waste management strategy for DBD. At the very least, the management approach for these wastes will need to be set out in the Environmental Impact Assessment process for DBD. The main characteristics of all potential wastes and their management may be defined and considered at an early point in the programme, in advance of any site selection.

Concept design

The IAEA guidance [9] proposes that a "generic design" is developed during the project initiation phase. Outputs from the generic design are:

- Generic layout.
- Generic Product Breakdown Structure.
- Preliminary budget.
- Preliminary programme development plan.
- Identification of main design risks and opportunities.

As noted above, there is currently no single conceptual design for DBD of Norwegian wastes [2]. While this is acceptable and keeps options open during the early stages of a programme, the ongoing design optimisation process should in due course lead to a preferred design in conjunction with the development and refinement of the overall safety strategy for DBD in Norway.

A preferred DBD concept consistent with the technology available and anticipated technology development capability will be specified at the outset of the development programme based on the outcome of options assessment studies. Some decisions will already have been taken in the options assessment [11] on the basis of firm advantages of one choice over others with regard to DBD options – for example, use of a vertical borehole. These decisions can then provide the basis for proceeding on to the next set of choices and requirement setting. Other decisions might be made subject to the outcome of the options assessment on fuel treatment/reprocessing, e.g. decisions on the minimum external diameter of the waste canister and overpack[4], which in turn controls the minimum diameter of

[4] The SB2 glossary [1] adopts the terminology that waste is put in "canisters", which are emplaced in an "overpack" and the item as a whole is referred to as the "disposal package".

the borehole. In this way, a decision tree can be set up and used as an ongoing and evolving basis for managing the project roadmap.

The conceptual design output from options assessments will cover waste forms, disposal overpacks and lifetimes, the geological environment, the borehole diameter and depth, any use of a sealing and support matrix to fill the voids in the disposal zone, use of casing, and the design of borehole seals above the disposal horizon. Activities to develop the concept will build on the activities developing the option descriptions for the options assessment [11] and include:

Activities

Identify waste concerned (type and volume) and waste forms for disposal

This activity will be linked to the options assessment for SNF treatment and overlap with the activity on waste characterisation above. The concept design, safety assessment and waste inventory will be used to establish preliminary WAC, considering the diversity of the research reactor fuel types and waste forms under consideration against characteristics that could be unacceptable for DBD.

Overpack design activities

Overpack design

As part of the DBD options assessment work, two broad categories or designs of disposal overpack have been discussed, a narrower option for SNF that is not reprocessed or otherwise treated, and a wider option for vitrified HLW (or other reprocessed waste). The disposal overpacks need to be leakproof after welding, be sufficiently strong to ensure mechanical integrity during emplacement and for a given period after closure and provide substantially complete containment (not be breached for a given period after closure, nominally taken to be greater than 1000 years in the options assessment, until the main thermal pulse from the waste has passed). These functional requirements mean that safety factors and tolerances for properties such as yield strength and gas pressure resistance should be formulated in terms of properties, and instructions for determination of these properties, both during transport (if encapsulation is undertaken before transport to the disposal site) and disposal. The design can then be tested against these requirements. One key issue is the specification of an appropriate filling material to minimise voids inside the disposal overpack. The overpacks may also require internal furniture to hold the contents securely in place. This work can build on the work undertaken for the DBD options assessment ([18] and [19]) and will be informed by further decisions on the waste forms to be managed.

Overpack materials and lifetimes

Overpack materials can be specified and associated overpack lifetimes estimated based on construction methods and anticipated disposal conditions [18]. This activity is closely associated with the above activity on overpack design, and the two will most likely be undertaken in parallel. Processes such as generalised or uniform corrosion and pitting corrosion should be considered. It will be necessary to model the chemical evolution of the near-field taking into account the natural groundwater composition [20], the evolving temperature [21], the host rock properties, and reactions with the materials making up the engineered barrier system [18].

Overpack manufacture

Studies of corrosion of different types of lid welds should be reviewed to help decide the optimum welding method [18]. Assuming that the waste canisters inside the disposal overpack have little structural strength, the disposal overpack itself should have sufficient strength to protect the waste canisters during emplacement operations and for the desired overpack lifetime thereafter.

Borehole design and construction activities

Borehole geometry and drilling

Schematic layouts of borehole geometry and drilling approach have been presented as part of the options assessment work ([22], [23]). Supplementary information can be added and adjustments made

to address questions and uncertainties (e.g. [24]), and to accommodate refinements in design for other components such as overpacks and cement.
This task will consolidate material on borehole geometry and drilling option for the chosen option(s) and address remaining uncertainties to resolve issues ahead of field testing. Timescales for construction will also be constrained further based on the chosen design(s) and the costing of boreholes undertaken for the options assessment [25].

Borehole stability, materials and methods for borehole casing
Once the construction of the borehole is complete, it is essential that the disposal zone is 100% secure with no risk of blockages. This can only be achieved before waste emplacement by using casing (e.g. [18], [23]). This is consistent with the reference design for DBD in the US [26]. The use and emplacement of casing was discussed in the work undertaken on borehole design for the options assessment ([18] and [21]). However, it was noted that the final casing design would be site-specific and should include analysis of rock defects, horizontal stress, hydrogeological conditions and groundwater chemistry. To support the safety case, evidence for the ability to sustain stability of the deep boreholes during operations should be compiled (e.g. from analogous projects and field testing).

Establish operation and emplacement procedures
The transport, handling and emplacement procedures for the overpacks should be outlined. A clear picture of overpack handling and overpack loading is needed for the safety assessment and should be considered as part of the design process (e.g. [21] and [27]). Adding features or changing the design later to deal with identified emplacement or retrieval issues retrospectively can add significant cost. Only one accident situation or event tree is explored for emplacement in [28] – dropping of an overpack – but no broader picture of overpack handling is presented. In particular, a mechanism for overpack release at disposal depth has not been set out in the Norwegian work on DBD to date.

Borehole sealing and closure design activities
Sealing and support matrices to fill the voids in the disposal zone
This task can be developed on the basis of the work undertaken to support the DBD options assessment [29]. Research is needed on issues such as materials, use of cement, setting time, organic components, and emplacement methods under different groundwater conditions and temperatures.

Closure/sealing of the borehole above the disposal zone
Sealing materials and sealing methods can be set out with expected performance envelopes for safety assessment [29]. The ability to seal deep boreholes has already been shown in the oil & gas and geothermal industries. However, regulators are now asking for better sealing practices. Even when well-emplaced, cement is not a very long-term sealing solution by itself, and only sites compatible with emplacement of a more durable seal such as bentonite above the waste can be considered as candidates for DBD. One suggestion is a 'sandwich' of materials to provide both short-term and long-term sealing with layers protecting each other from degradation. This is a subject that needs rigorous discussion as it is key to stakeholder perception of using boreholes for disposal. This task should set out which materials are widely used today to seal boreholes and which are only concepts under development or in the prototype stage. The latter includes the concept of "rock welding", where siliceous material with a granitic composition is emplaced in a section of the borehole and then melted using an external source of heat. When the material solidifies, it completely closes the borehole forming a cap above the waste. This concept also deals with the stress-related relaxation zone around the borehole that has created problems with sealing deep boreholes in Sweden. As part of this activity, the placing of several seals whose working principles are different should be considered, as this may increase confidence via provision of a multi-barrier system.

Develop carbon footprint analysis
International deep repository and deep drilling carbon footprint analyses should be reviewed, to determine their applicability to DBD in the Norwegian context. Following this a Norwegian DBD carbon footprint analysis framework should be developed, which can then be applied to the Norwegian shortlisted DBD options.

Safety assessment

The performance of the design will need to meet set criteria and these will be evaluated as part of the safety assessment. The development of the safety assessment will define a reference case and alternative scenarios that need to be addressed through both siting and design.

Activities
Establish a generic (non-site-specific) safety assessment capability
Develop the assessment methodologies for operational and post-closure safety and security. Consider the need for different approaches for the operational and post-closure periods.

Specify operational and post-closure safety functions and functional requirements for each component of the disposal system, using the concept design and safety assessment modelling
This could link to the requirements management activity in Section 2.1.1 by specifying an overall design basis / design criteria for each component of the disposal concept as part of the RMS. Where design options are available, different detailed requirements might be formulated for each alternative under a common top-level requirement.

Develop scenarios for operational and post-closure safety assessment
Undertake a functional analysis and evaluation of a comprehensive list of features, events and processes (FEPs) to underpin scenario development for operational and post-closure safety assessment, respectively.

Develop a criticality safety assessment methodology for both the operational and post-closure periods
Consideration of criticality safety should feed into the choice of both SNF treatment method and disposal overpacks. Initial work can be done considering the possible masses of fissile material in each disposal overpack. Scenarios should include water entering a stuck overpack during emplacement and slumping of material post-closure. The safety assessment should also consider the tolerability of criticality events under each circumstance. For any overpacks containing enriched spent fuel, a basket with neutron absorbent may be necessary to ensure that criticality is not reached during emplacement, even if the interior of the overpack were to fill with water after an overpack failure. Eliminating void spaces inside the overpacks (that could be filled with water after failure) will be helpful to keep the overpack under subcritical conditions during and after emplacement. Eliminating void space will also reduce the risk of deformation and possible damage under prevailing hydrostatic pressures and axial load stresses. Management of void space has been included in the activity for overpack design, but the means of achieving the filling requirements can be linked to the supporting criticality safety assessment. Various materials have been suggested for filling such as sand, cement, silicon carbide, glass, copper and molten lead. All of these materials have potential advantages and disadvantages that need evaluation.

Cost assessment

Activity - Confirm cost estimates for the generic design concept
Review of existing cost estimates for DBD in [2] found considerable variability, reflecting the considerable uncertainty involved compounded by different assumptions between the different studies.

A deep borehole could be drilled, filled and closed on a much shorter timescale compared to a mined facility and at lower cost. However, the implementation timescale and cost of DBD could be adversely affected by the need for pre-construction RD&D for technology development and stakeholder approval (given that there are no examples of DBD yet anywhere in the world). There will be a lengthy, sequential process of developing regulations, site selection and planning, data acquisition and analysis, licensing, and construction. Operation and decommissioning costs for the encapsulation plant and overpack manufacture (or encapsulation services if performed abroad) should be included in the cost estimates. A basis for costing has been provided as part of the options assessment [25], and this can be used as a starting point to provide a consistent cost estimating tool for the programme.

2.1.5. Siting strategy

In terms of disposal system development, the project initiation and site identification phase can be considered complete when the site selection process is launched. [5] identified the main milestones to prepare for site selection in the project initiation stage as:

- Siting strategy.
- Detailed site selection plan.

The IAEA roadmap defines an activity under "Site investigations" to collect information on national geology and geodynamics. This is reflected by EURAD Theme 4 which aims to assemble geological information for site selection, facility design and demonstration of safety. These activities reflect the knowledge gap in [2] on how to select a site for DBD. Hagros et al. [30] discuss the host rock requirements for various waste management facilities in Norway, but it is not clear how the requirements (e.g. depth, rock type, hydrochemistry, stagnant pore fluid isolated from shallower hydrogeological systems) will be evaluated as part of a siting strategy on the basis of current levels of knowledge.

A key requirement for DBD is that groundwater flow in the rock at the disposal depth must be negligible. Such low flow can be confirmed by high salinity and old age of the groundwaters e.g. [31]. Information about the depth at which the desired conditions are reached in Norway will be useful to make preliminary estimates of the necessary depth of the disposal borehole. Conversely, where information is lacking, there may be flexibility in the setting the design concept to allow for uncertainty in meeting the requirement.

Activities

Site description - compile available geological information covering the basement in Norway to help establish the design concept and constrain the siting strategy

Geological information from crystalline formations in other countries that are similar to those in Norway could also be usefully compiled if the information base in Norway is sparse. A brief search of the open literature for data from analogous environments has already been conducted to inform the DBD options assessment ([20], [21]).However, more detailed work including coverage of technical publications for Norway and potentially other countries that are not easily available should be done. The searches should focus on:

- Rock characteristics.
- Structural geology and the relation of crystalline basement to major fault zones.
- Representative groundwater compositions at depths of the disposal zone (1500 to 5000 m).
- Temperatures at the depths likely for definition of the disposal overpacks.

We note that a similar activity on compiling available data on geochemical measures in crystalline basement rocks is indicated by Sandia National Laboratories (SNL) in [**Error! Bookmark not defined.**] as one of the prioritised research areas for DBD.

Site selection – develop DBD siting strategy and detailed site selection plan
Consolidate the concept design, stakeholder engagement plan, licensing and permitting requirements, safety assessment and programme considerations into a siting strategy and detailed site selection plan. This will be clear on the siting requirements and how they will be tested against the anticipated level of knowledge.

Site characterisation – develop site characterisation strategy
There is a wide range of views on the extent of any characterisation required for DBD and a strategy for resolving differences of opinion is needed. Issues include how the approach could differ from site characterisation for a mined GDF, any special considerations specific to DBD, and whether the required effort might differ for different geological environments and different DBD concepts.

2.1.6. Field testing

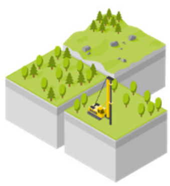
In parallel with collation of information and development of the siting strategy for the actual disposals, there could be a need to conduct field testing of the DBD concept at an early stage of the project in order to support any decision to proceed with DBD as the disposal option. However, the field test need not be carried out in Norway, if there is a suitable test conducted in another country and NND could effectively learn from that experience. Any field testing in Norway might not involve a full site selection and screening procedure such as would be used in order to identify an actual disposal site, but a similar process could be used to test the eventual DBD siting processes.

Activities
Identify and prioritise R&D needs – review TRL of Norwegian shortlisted DBD concept options

Develop a DBD field test programme objectives/implementation plan
As a link back to the RD&D activities described here under concept design, a plan for the field testing to be conducted and the timeline for different aspects of the testing should be prepared. For example, similar planning has been and is being conducted for the US DBD programme ([32], [33], [34]). It is important that the test is planned to supply the information when it is needed in the decision-making and design activities.

Develop a permissioning schedule
A plan should be prepared for obtaining the necessary regulatory permissions throughout any testing exercise, including site selection, site characterisation, operations and eventual sealing and closure. Waste management, discharge permits, permits for temporary installations and preliminaries, and work permits will all be needed at various junctures. This planning will later be repeated for construction of the disposal borehole and associated surface infrastructure.

2.2. Site identification and selection (Siting process Phases A-C)



2.2.1. Overview

The goal of the site selection process is to find a suitable site for DBD. The selection process set out in [5] is divided into phases A to D, and the associated decision points are illustrated in Figure 7 [5]. The figure considers a single site for all of the facilities for radioactive waste management Norway and, in particular, separate facilities for HLW and LILW disposal. However, the chosen site for DBD may or may not be chosen for as the location of other Norwegian waste management facilities. Further, there may be several locations satisfying the technical requirements for DBD, and the final selection of the site will be supported by evaluation of both technical and non-technical factors.

The optimum location for siting the encapsulation plant also has to be considered as part of the disposal project. The most obvious locations are at the planned centralised site for storage of the SNF/HLW, or at the DBD site itself. Encapsulating for disposal at the centralised storage site would simplify transport of the SNF/HLW to the borehole. If encapsulation is done at the borehole site, then wasteforms of varying shapes and sizes and differing amounts of degradation would need to be transported, potentially requiring a larger number of transport flasks having different internal furniture.

Figure 7: Proposed process for the development of a National Facility for radioactive waste disposal in Norway illustrating Phases A to D

([5], Figure 4-1)

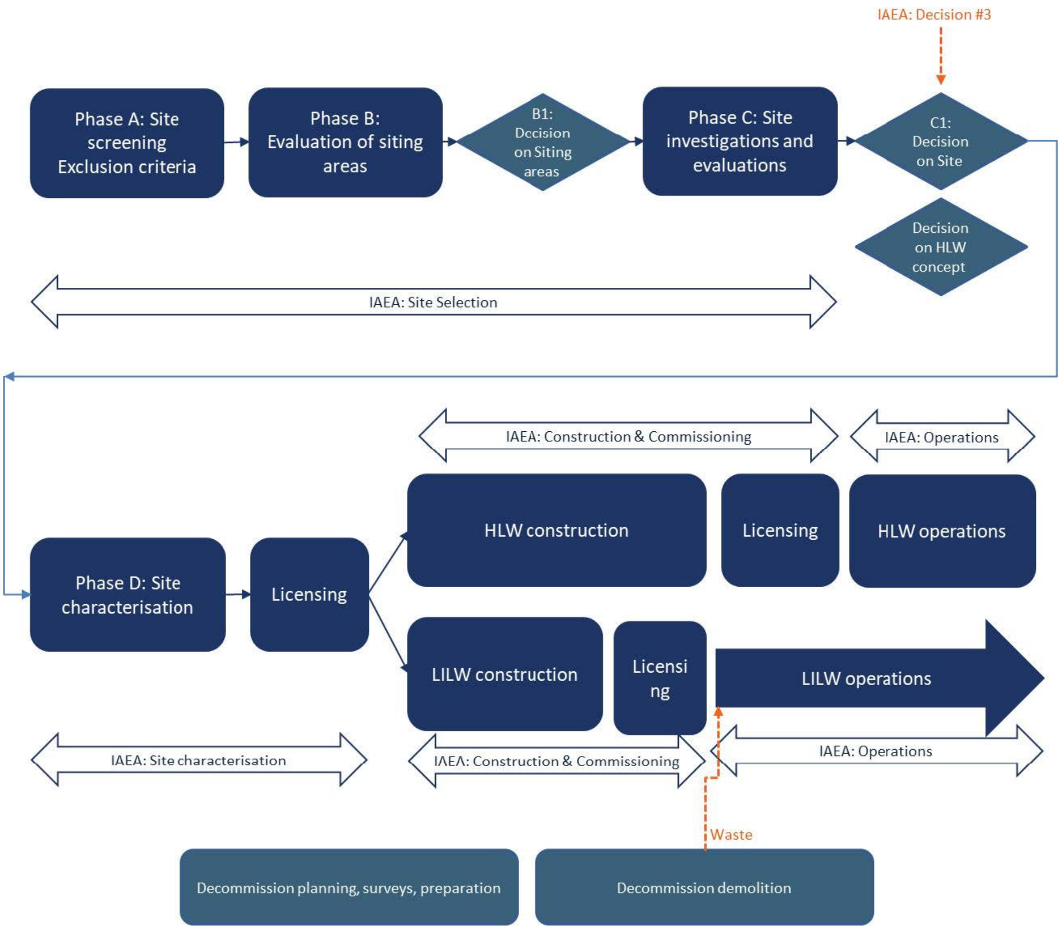
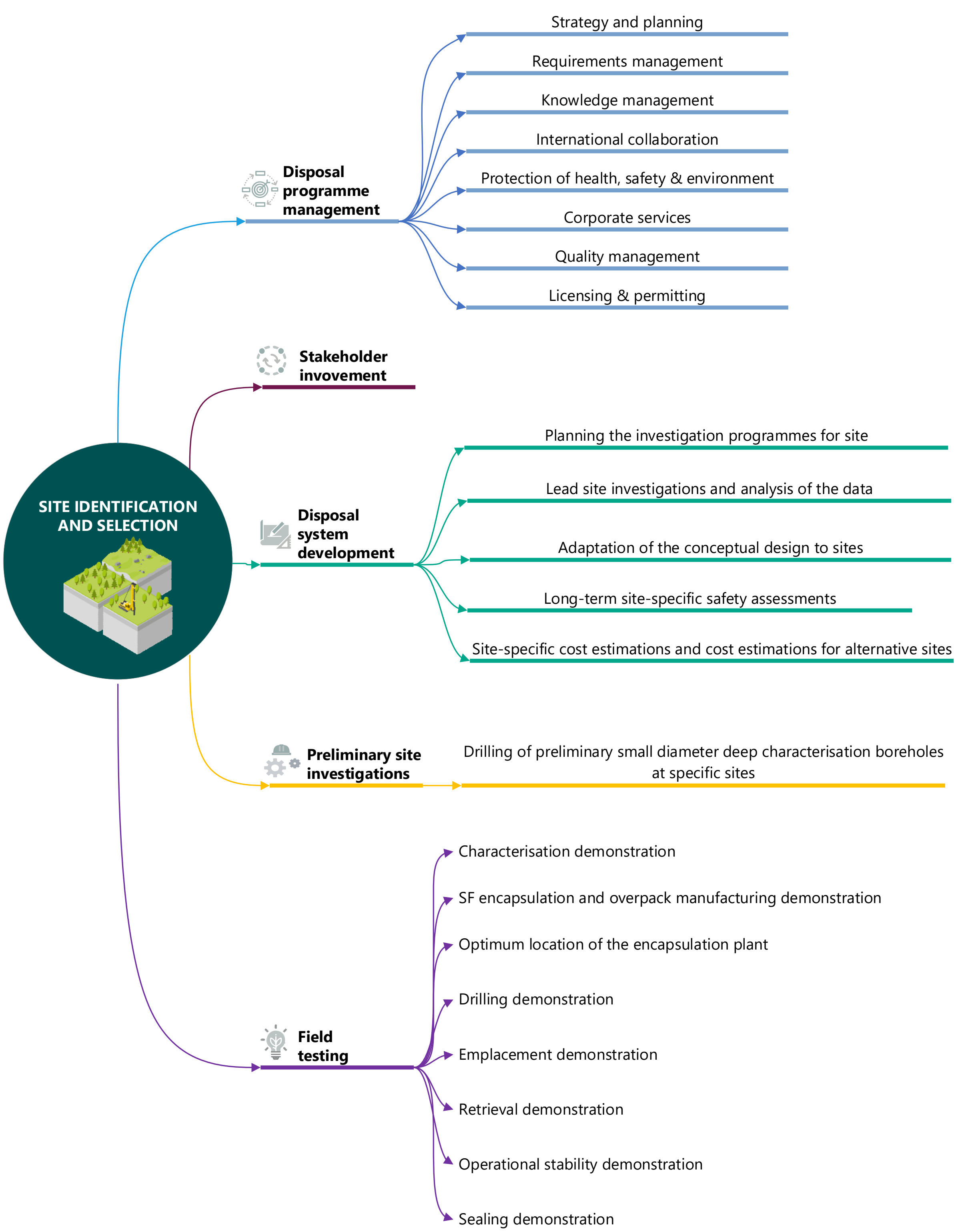


Figure 8: Mind map of the site identification and selection stage



High-level critical path review. The selection of a site is contingent on identifying a site with the desired conditions. Additionally, the siting process requires a community that is willing to host a DBD facility including the required investigation borehole(s).

To develop the technology and prove feasibility of the concept before proceeding to site characterisation and implementation, a DBFT will be required (although not necessarily in Norway). The

DBFT must include demonstration of surface handling and waste/seal emplacement capabilities, drilling tools and techniques, and operational stability (Figure 8).

The start of borehole investigations at any proposed disposal site will require a drilling permit, noting the permit may fall under nuclear permitting regulations, and will depend on the procurement and mobilisation of drilling and drilling supervision services.

High-level interdependencies review. The site selection phase will depend on the NND programmes listed in Table 5.

Table 5: Interdependencies with other NND programmes during site selection

NND Programme	Interdependency
Norwegian Geological Institute (NGI)	Collaboration with NGI to identify site(s) with the desired site conditions.
NND siting strategy and stakeholder engagement processes	A site with the desired site conditions and a willing host community must be identified. The permitting to start preliminary site characterisation must be achieved.
NND SNF/LL-ILW storage programme **GeoReN disposal concept study**	Potential impact in terms of desired co-location of storage, encapsulation and/or disposal facilities for other wastes.
NND safety assessment programme	The potential evolution of the safety assessment requirements across the lifecycle of the disposal programme may increase complexity of the safety case and licensing process.

High-level risks review. NND's DBD Programme Risk and Opportunity Register [10] maps risks to the NND programme and DBD implementation during the site selection stage.

The top risks at the programme identification stage listed in Table 4 (DBD option selection, DBD TRL maturity, regulatory and permitting framework, inventory to be managed using DBD, and delay to the safety case) still apply to the site selection stage. The top additional risks emerging at this stage are summarised in Table 6:

Table 6: Top additional risks emerging at the site selection stage

Risk Description	Comments (Impact Insight)	Mitigation Strategy
There is a risk of the rock being more resistant to drilling than expected during site characterisation	Drilling proceeds more slowly and is more costly, leading to programme delays and extended waste storage. This could also lead to additional RD&D costs.	Ensure robust site characterisation and adopt conservative margin in drilling design to manage uncertainties (e.g. on rock strength, discontinuities and permeability/transmissivity/porosity). Develop an operating procedure should the risk arise on site. Ensure the risk is accounting for in the drilling and supervision contracts.
There is a risk that poor underground rock conditions are encountered	Materialisation of this risk could result in the borehole having to be abandoned and a new location needing to be found, causing programme delays and increased costs.	Development of a staged site characterisation programme, with a combination of desktop studies, and

Risk Description	Comments (Impact Insight)	Mitigation Strategy
		intrusive and non-intrusive techniques. Account for uncertainties in design and safety assessment margins.
There is a risk that the site is more difficult to characterise than expected, or that drilling encounters material requiring specialised management when excavated	Materialisation of this risk would result in additional effort to support site investigations, and a potential for schedule delay.	Develop a robust site characterisation programme, including non-intrusive, intrusive characterisation and desktop studies. Consider RD&D and testing of siting equipment if needed. Account for the risk when defining the siting contract.
There is a risk of there being a poor safety audit	Poor safety audit results or safety incidents could result in temporary project shut down leading to programme delays.	Ensure drilling processes being used have been tested and rehearsed elsewhere. Ensure all safety precautions, measures, requirements, procedures and training are considered and implemented.
There is a risk of there being a failure to achieve community support	Materialisation of this risk could result in a programme delay for additional community engagement or, in the worst case, a new site being needed, increasing the cost for site characterisation activities.	Develop a sound stakeholder management plan and DBD siting strategy. Engage regularly with potential host site communities, and incentivise hosting of the DBD site.
There is a risk of site characterisation activities causing damage to the site	Materialisation of this risk could result in a new site being needed, increasing the cost for site characterisation activities.	Develop a robust site characterisation programme, including non-intrusive and intrusive characterisation, and desktop studies. Provide specific training for scientific drilling, and develop of operating and emergency procedures appropriate to the intended use of the site. Consider RD&D and testing of siting equipment if needed. Account for the risk when defining the drilling contract.
There is a risk that rig and other drilling equipment mobilisation and modifications take longer than expected.	Materialisation of this risk could result in more time being needed for rig mobilisation, which would delay the start of drilling and increase costs.	Early engagement with drilling supply chain. Anticipate rig mobilisation and earlier rig sourcing

2.2.2. Disposal programme management

Disposal programme management includes the following level 3 activities:

- Site(s) recommendation.
- Strategy and planning: updated programme plans, strategies.
- Requirements management: programme requirements for safety and industrial safety.
- Knowledge management: updated database and archive.
- International collaboration: leverage RD&D activities conducted in other national DBD programmes or multinational initiatives.
- Protection of health, safety and environment: occupational health and safety and environment plans.
- Corporate services: updated cost estimate, procurement, and legal service.
- Quality management: updated quality management system for site identification.
- Licensing and permitting: obtain the licensing of preliminary site characterisation boreholes.

2.2.3. Stakeholder involvement

Activity – Define the investigation programme for both the field test and for the site selection for one or more sites with contributions from stakeholders
The validity of investigation techniques at disposal depths will need to be considered. Although there is wide experience in site characterisation for geological disposal, the site characterisation needs for DBD are not yet clear. A methodology for site characterisation for DBD is still needed. An activity for developing the strategy for site characterisation has been proposed for earlier in the programme. The strategy will need to be implemented, and investigations developed with input from different stakeholders (waste management organisation, scientific community, regulators).

2.2.4. Disposal system development

To enable site selection, enough information should be gathered to be able to evaluate and compare alternative sites (assuming more than one site is investigated). Activities are:

- Planning the investigation programmes.
- Lead site investigations and analysis of the data.
- Adaptation of the generic conceptual design to site-specific information.
- Site-specific post-closure safety assessment.
- Refined site-specific cost estimates.
- Consideration of the optimum location for the encapsulation plant.

2.2.5. Preliminary site investigations

Although the review for NND of site characterisation techniques by Halliburton [35] give a generally positive view of the available technology readiness, it is not clear from the information provided for the equipment currently used for oil and gas drilling that it will be sufficient for a deep borehole for SNF/HLW disposal. This applicability must be considered when defining a site investigation plan and, subsequently, undertaking the site characterisation. The characterisation objectives or expectations for

DBD should be made clear. According to [36], a single characterisation borehole could rule out a site, but is unlikely to provide adequate verification of the wider geological conditions to support the post-closure safety case.

It should be noted that geophysical logging is not practicable in large diameter boreholes and so the characterisation needs to be carried out in small diameter holes ideally cored and typically 6-7 inch (150-178 mm) in diameter. It is also important that any site investigations do not unnecessarily perturb the hydrogeological system at the potential disposal depth, and that any drilling and casing be done in such a way to provide confidence that the system will return to its original state within a reasonable period.

It is not considered that preliminary site investigations would be needed at any proposed site for the encapsulation plant.

Activity – Drilling of preliminary small diameter deep characterisation boreholes at specific sites
At the initial site investigation phase, less intensive and costly testing might suffice, e.g. to confirm only that the desired old stagnant brines are present at a given site and obtain a broad idea of the main geological features. For dating of the groundwater, it is essential to sample virgin fluid rather than contaminated fluid. In later stages of investigation, more comprehensive testing might be needed perhaps including extraction of core and monitoring of the boreholes for an extended period. Imagery is far better than attempts to orient core and will show the *in situ* state of the rock. Flow testing should monitor flow in and flow out and determine delta flow. *In situ* stress and horizonal anisotropy are also important data. The drilling, logging and sampling in successive phases of characterisation boreholes will need careful specification and discussion/agreement.

2.2.6. Field testing

To develop the technology and prove the concept before proceeding to detailed site characterisation and implementation, it is proposed that NND needs to undertake a demonstration activity or at least participate in such an activity in another country. Such an exercise was planned in the US (the Deep Borehole Field Test [DBFT]), but funding was withdrawn before it could proceed [**Error! Bookmark not defined.**]. A full-scale DBD demonstration has been considered in Australia [37] and, if confirmed and conducted in time, NND should be able to draw information and experience from this work. It is currently planned to include demonstration of surface handling and waste/seal emplacement capabilities and the full-scale field testing of a large-diameter (0.7 m or 27.5 inch) demonstration borehole (currently the maximum depth has been put at 2000 m). NND might also learn something of value from experience elsewhere of drilling intermediate-depth boreholes for disposal of sealed sources – even if these boreholes are considerably shallower and narrower than the deep boreholes for DBD.

No assumption has been made here about the location for the field test and the location of the disposal borehole itself. Site selection and site characterisation activities will need to be carried out for both, the field test providing an exercise with which to develop and try out proposals and alternatives. Ultimately, there is no reason *a priori* why a full-scale field test could not be used eventually as the location for a disposal borehole – the characterisation investigations undertaken for the former would then be useful for the latter. However, the large diameter borehole for the field test should not be used as a 'characterisation' borehole for the disposal borehole, as it is preferrable to use smaller boreholes. Further, particular effort should be made to reassure stakeholders in advance of the field test that any decision to then use the site for the disposal borehole has not been made in advance. The field test should include a "lessons-learned" exercise to support the development of a good-practice guide for actual DBD implementation later, wherever it might be.

The activities surrounding the field test in which NND could be involved in the future and the knowledge gaps they will address will be:

Activities

Demonstrate characterisation

Drilling, logging, and sampling need careful specification and discussion. The disposal borehole itself could be used for characterisation, but it could be preferrable to use smaller boreholes for this task because they are cheaper, can be drilled faster and a sophisticated range of measurement and logging tools are available. The proposed DBFT in the US planned to drill two boreholes nominally 200 m apart to approximately 5 km depth [**Error! Bookmark not defined.**]. The Characterization Borehole (CB) was the smaller diameter borehole. The majority of the geologic, hydrologic, geochemical, geomechanical and thermal testing would have taken place in the CB. The Field Test Borehole (FTB) would have been the larger diameter borehole. The surface handling and borehole emplacement operations demonstrating engineering feasibility and safety of disposing of expected waste forms would have been tested at the FTB. If this approach is followed, the larger-diameter borehole can be drilled faster, while minimising the damage to the host rock.

Demonstrate SNF encapsulation and overpack manufacture

Overpack manufacture and any proposed use of Electron Beam Welding (EBW) should be demonstrated.

Demonstrate drilling

The process of producing a drilling specification, selecting the preferred drilling contractor, applying the controls and checks, and testing the completed installation will need to be clearly set out.

Demonstrate emplacement

The disposal overpack emplacement/detachment process needs to be established and demonstrated.

Demonstrate retrieval

The demonstration needs to cover retrieval of an intact overpack during the emplacement process (in case of a problem) and dealing with a stuck overpack, irrespective of the stated likelihood of it happening.

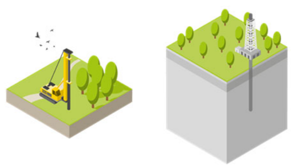
Demonstrate operational stability

Demonstrate the ability to maintain borehole stability over the planned duration of operations for the actual disposal borehole. The likely duration of the operations must be discussed in this context. Assuming that all wastes are already in overpacks in storage, the borehole operation time is largely a function of the emplacement process and the regulatory requests for testing. Any need to keep the borehole open for a long period would impact casing selection.

Demonstrate sealing

Emplace seals according to the design and undertake monitoring to demonstrate performance.

2.3. Site characterisation (Siting process Phase D)



The activities in the site characterisation phase (Phase D of [5]) build on the site investigations in the previous phase to gather sufficient information for the detailed design and safety assessment needed to build the safety case to support the licensing process. Design and safety assessment together confirm the site suitability. In this phase, one or several characterisation boreholes will be drilled to a depth greater than the bottom of the disposal borehole to obtain the information necessary to plan the construction of the disposal borehole and build the safety case.

For the design, the milestone is to develop a "Technical design for construction licensing" [9]. Outputs from the technical design are:

- Technical design of the facility (layouts, scaled drawings).
- Cost estimation.
- Preliminary construction development plan.
- Preliminary construction and operating rules.
- Risk and opportunity assessment.

Activities are the same as in the previous stage, but with the endpoint being sufficient information for the construction licence application at a single site, rather than an evaluation that a safety case could potentially be made at a site and a comparison between alternative sites (if more than one site is investigated in any detail).

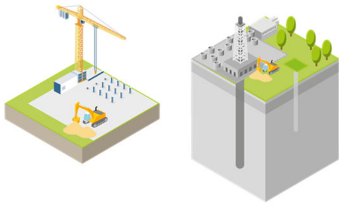
High-level critical path review. To be able to successfully characterise a site, the host site community must be willing to host investigation borehole(s) and an eventual DBD facility following the site selection stage.

There is potential during the site characterisation phase that the further site characterisation demonstrates that a suitable DBD site with the desired conditions cannot be found at the location, which would lead to a need for a new site.

The timely start of deep site investigations during the site characterisation stage will depend on the development of mature drilling and characterisation technologies, supported by the field testing activities described in section II.2.2.6, the obtaining of a drilling permit, which may vary from the previous stage, and the procurement and mobilisation of deep drilling and drilling support services.

High-level interdependencies review. The site characterisation phase will depend on the same NND programmes as during the site selection stage listed in Section 2.2.

High-level risk review. NND's DBD Programme Risks and Opportunities Register [10] maps risks to the NND programme and DBD implementation during site characterisation. The same top risks during the site selection stage identified in section II.2.2.1 apply to the site characterisation.



2.4. Construction and commissioning

The techniques to be used for drilling the deep borehole should be reviewed and confirmed. Considering the diameter and depth of the disposal borehole, the basis of design for drilling in the concept options assessment [23] uses the reverse circulation drilling method. While hammer drilling with air flush might lead to less disturbance of the host rock, it is not really practical in the large diameter boreholes and it would be very expensive.

Data gathering activities should be accounted for in planning drilling operations. Although most of the characterisation work will be carried out in the characterisation borehole(s) in the preceding phase, data gathered during drilling of the disposal borehole could be useful to confirm the results obtained in the characterisation borehole(s). During construction of the disposal borehole, information about the water-conducting features intersected should be gathered, which could delay drilling.

The construction of the encapsulation plant at its chosen location (the location of SNF storage, or the borehole site) should also be covered in the roadmap for this stage of the project. Transport infrastructure for delivering waste or overpacks to the DBD site should be considered.

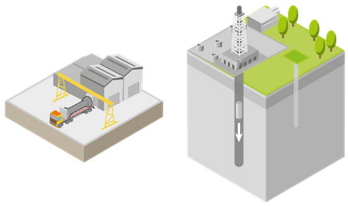
High-level critical path review. Two critical precursors for this stage are the authorisation for construction and the demonstration of sufficient TRL of the proposed disposal borehole drilling and emplacement methods, and approval of the encapsulation method. The planning is then led by mobilisation and drilling operations at the DBD site and encapsulation plant construction, with the timely procurement of equipment.

High-level interdependencies review. The construction and commissioning phase will depend on the same NND programmes as during the site selection stage listed in Section II.2.2.

High-level risk analysis. NND's DBD Programme Risk and Opportunity Register [10] maps risks to the NND programme and DBD implementation during construction and commissioning. The top risks at the programme identification stage listed in Section 2.2 also apply to the construction and commissioning stage. An additional risk emerging at this stage is summarised in Table 7:

Table 7: Additional risk emerging during construction and commissioning

Risk Description	Comments (Impact Insight)	Mitigation Strategy
There is a risk of equipment design not meeting performance expectations	Materialisation of this risk would result in equipment needing to be replaced and some of the construction and waste emplacement work may need to be redone, leading to programme delays and increased cost.	Develop a robust RD&D and equipment testing programme. Ensure back-up equipment is readily available, and conduct risk studies. Take this risk into account when developing design and equipment procurement contracts.



2.5. Operations

Given the relatively small amount of HLW/SNF to be disposed of in Norway, emplacement of the overpacks in the disposal zone could be completed within 1-2 years. Emplacement speed will be controlled by the production rate of the encapsulation plant. An alternative would be having a buffer facility to store the filled overpacks until all have been produced and then all the overpacks could be emplaced at the speed they can be accepted for disposal operations. To avoid a transport bottleneck, the buffer storage facility could be placed at the borehole site. The buffer storage facility will need to provide shielding and heat removal for the disposal overpacks.

A transfer flask will be needed to transport filled disposal overpacks from the encapsulation plant to the disposal facility. The transfer flask must provide shielding during transport and handling at the surface.

High-level critical path review. Three critical precursors for this stage are the authorisation for the start of emplacement operations, the demonstration of sufficient TRL of the proposed disposal borehole emplacement method, the availability of waste forms and the encapsulation plant, and the readiness of any associated transportation infrastructure. The planning is then led by operations at the DBD site.

High-level interdependencies review. The operations phase will depend on the NND programmes listed in Table 8.

Table 8: Interdependencies with other NND programmes during operations

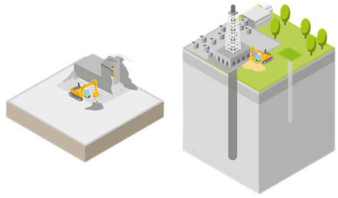
NND Programme	Interdependency
NND stakeholder engagement process	Interactions with a willing host community must be managed during operations. Licenses to start operations must be granted.
NND SNF/LL-ILW storage programme **GeoReN disposal concept study**	Potential impact in terms of desired co-location of storage, encapsulation and disposal facilities for other wastes.
NND safety assessment process	The potential evolution of the safety assessment requirements across the lifecycle of the disposal programme may increase operational complexity.
SNF management programme	The late availability of disposable waste forms ready for encapsulation with a sufficient cooling time may delay the start of operations.

High-level risk analysis. NND's DBD Programme Risk and Opportunity Register [10] maps risks to NND programme and DBD implementation during operations.

The following top risks identified in the previous programme stages still apply to the Operations stage: regulatory and permitting framework and delay to the safety case (Table 4), poor safety audit, and community support (Table 6), and non-compliant equipment (Table 7). Additional risks emerging at this stage are summarised in Table 9.

Table 9: Additional risks emerging during operations

Risk Description	Comments (Impact Insight)	Mitigation Strategy
There is a risk of SSM emplacement difficulties	SSM emplacement difficulties could result in waste emplacement being interrupted or slower than expected, leading to a delay in disposal operations, leading to programme delays, extended storage, and greater cost.	Develop a RD&D programme to address SSM emplacement TRL needs, and adapt the design accordingly. Test the technologies in a DBFT. Develop emergency operating procedures, train operators, and ensure availability of spare parts and recovery equipment.
There is a risk of stuck waste packages	A stuck waste package could result in waste emplacement being interrupted or slower than expected, leading to a delay to disposal operations, leading to programme delay, extended storage and greater cost.	Develop a RD&D programme to address waste emplacement TRL needs, and adapt the design accordingly. Test the technologies in a DBFT. Develop emergency operating procedures, train operators, and ensure availability of spare parts and recovery equipment.
There is a risk that the DBD system does not evolve as planned (e.g. heat source induces hydrothermal flow, or post closure monitoring indicates facilities not performing as expected.).	If the risk materialises, for instance hydrothermal flow is induced by the heat output of the HLW, this will potentially increase the duration of surface storage needed so that the thermal perturbation of deep borehole disposal is reduced. This could also lead to programme delays and also to an increase in costs (costs of a new store & additional RD&D).	Keep engaging in international collaborative research programmes on DBD such as the IAEA CRP to keep abreast of DBD initiatives worldwide to enable anticipation of the risk impact on the programme.



2.6. Closure and decommissioning

Removing a casing when fixed is difficult - the concept assumes cemented casing is left *in situ* on closure, except in the region above the disposal zone where seals will be emplaced. The uncemented casing in that region will be cut and retrieved so that the seals, when emplaced, are in contact with the host rock. The concept for sealing the borehole is considered by Engelhardt et al. [38]. There are several details regarding the information in [38] that could merit further attention as part of future work on sealing. These include:

- The efficacy of methods to reduce the potential detrimental impact on long-term safety of the borehole excavation disturbed zone.
- The possible use of a tremie emplacement option (a material reservoir above a pipe down the borehole with its foot in the cement) as an alternative to normal cementing where the stress regime is anisotropic.
- Material emplacement using a dump bailer.
- The potential use of Cement Bond Logging tools, which are not applicable as yet in large-diameter boreholes.
- A Downhole Placement System for delivery of dry pre-compacted bentonite.
- Specifying time limits for emplacement and setting, use of alternative chemical additives to delay setting, and use of organic additives in emplacement materials close to waste.
- Using different cements in intervals might allow the use of organic-free cement in part.
- Use of an anti-intrusion plate to reduce the chances of human intrusion into the disposal zone of the deep borehole.
- Use of bitumen (another potential source of organic material) in the abutment in the upper zone sealing design.
- Cement emplacement using a squeezing technique.

Issues such as high suction of water of hydration from cements in certain rock types will be addressed during construction and operation.

As discussed earlier, the design of the sealing system will also consider alternative sealing methods such as "rock welding". Use of several sealing methods could be proposed to provide a multi-barrier approach.

High-level critical path review. Two critical precursors for this stage are the authorisation for closure and the demonstration of sufficient TRL of the proposed disposal borehole sealing and closure emplacement. The planning is then led by closure activities at the DBD site.

High-level interdependencies review. The closure and decommissioning phase will depend on the same NND programmes as during the operations stage listed in Table 8.

High-level risk analysis. NND's DBD Programme Risk and Opportunity Register [10] maps risks to the NND programme and DBD implementation during closure and decommissioning.

The following top risks identified in the previous programme stages still apply to the borehole closure and decommissioning stage: regulatory and permitting framework and delay to the safety case (Table 4), poor safety audit and community support (Table 6), non-compliant equipment (Table 7), risk of casing removal difficulties and unplanned evolution of the system (Table 9). An additional risk emerging at this stage is summarised in Table 10.

Table 10: Additional risk emerging during closure and decommissioning

Risk Description	Comments (Impact Insight)	Mitigation Strategy
There is a risk that borehole sealing/closure activities run into difficulties	Materialisation of this risk could result in borehole closure operations taking longer and being more costly than anticipated.	Increase TRL of site closure activities, with a robust RD&D, design and testing programme. Anticipate the risks building on lessons learned from siting, construction and operating phases.

2.7. Post-closure

The long-term use of a fit-for-purpose monitoring system for any type of geological disposal system has not yet been demonstrated – but nor is such a system necessarily needed (depending on national requirements and stakeholder wishes). It is an accepted principle that any closed disposal facility should be passively safe, i.e. safety should not depend on any ongoing active human controls or monitoring after closure.

Confidence in long-term monitoring of DBD, if required, is only likely to improve once a real system has been in use in for decades. To inform the delicensing safety case, evidence for the long-term stability of boreholes in different media and different casing strategies should be compiled and evaluated.

High-level critical path review. Two critical precursors for this stage are the authorisation for termination of nuclear license, and a decision on the need for any post-closure monitoring system for DBD – and what kind of monitoring that might be. Nuclear security and safeguards requirements could impact borehole design and the potential need for long-term monitoring of any SNF disposal, but requirements in this area are subject to ongoing international discussion.

Interdependencies with other NND programmes. The post-closure phase will depend on the NND programmes listed in Table 11.

Table 11: Interdependencies with other NND programmes during post-closure phase

NND Programme	Interdependency
NND safety assessment process	The potential evolution of the safety and security of the DBD site after closure may impact this stage.
NND stakeholder engagement process	Engagement with stakeholders (regulators, planning and permitting authorities, civil society, IAEA) will frame requirements applicable to the post-closure stage.

High-level risk analysis. After the site has been delicenced, the only real risk at this stage is the new risk identified in Table 12.

Table 12: Additional risk emerging during post-closure period

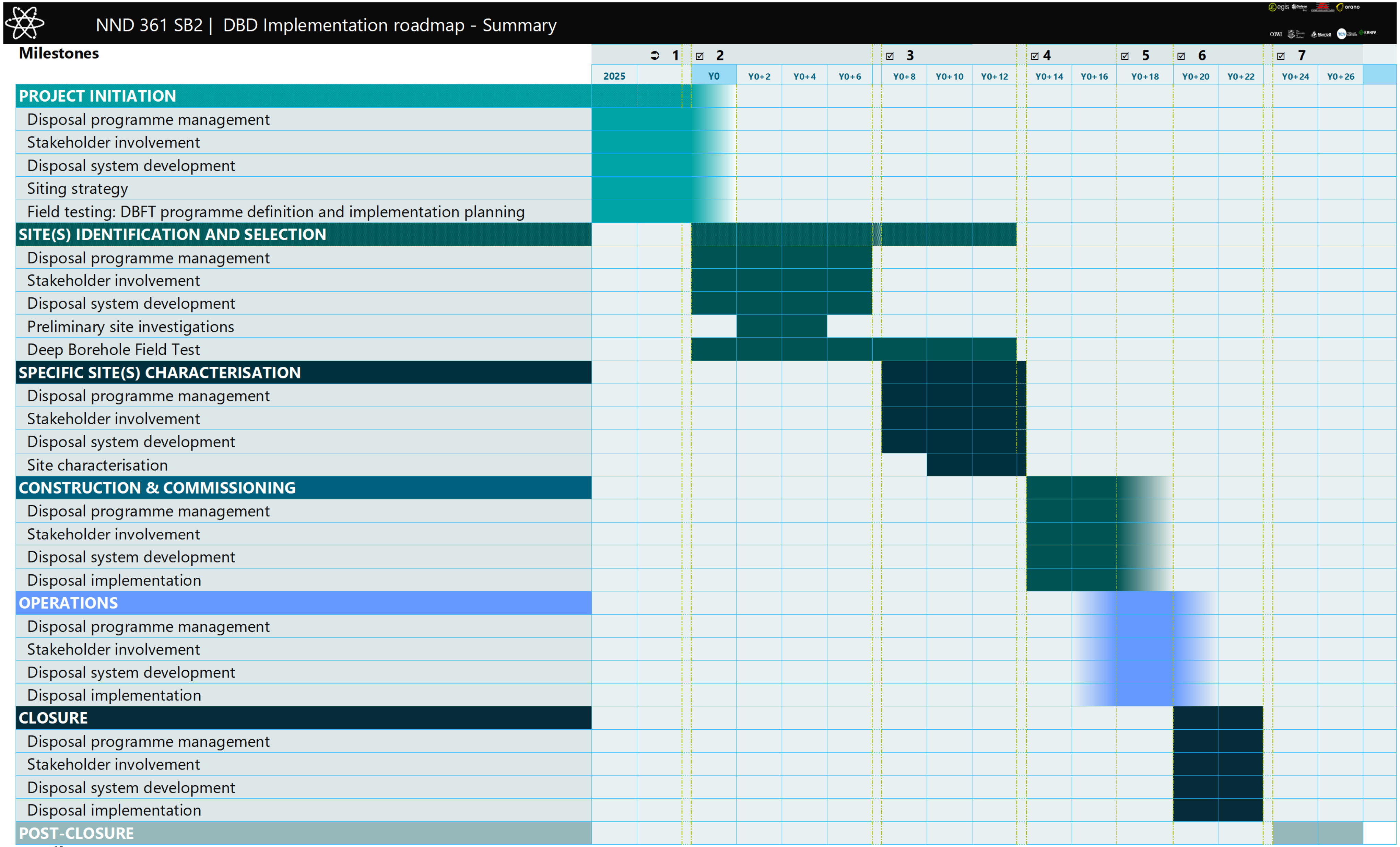
Risk Description	Comments (Impact Insight)	Mitigation Strategy
There is a risk that the DBD system does not evolve as planned (e.g. heat source induces hydrothermal flow, or post-closure monitoring indicates facilities not performing as expected.).	Materialisation of this risk would lead to additional monitoring to review the evolution of any perturbation, additional studies to assess whether the perturbation could impact safety, additional site investigations to better understand/manage the risk, or potentially even re-excavation and retrieval of wastes - in order of increasing programme impact and cost.	Keep engaging in international collaborative research programmes on DBD to keep abreast of DBD initiatives worldwide to enable anticipation of the risk impact on the programme.

3. Roadmap for DBD implementation in Norway

A proposed DBD implementation roadmap for Norway is summarised in Figure 9, and further detailed in Appendix 1.

This roadmap corresponds to DBD closure in 2050, if Year 0 is taken to be 2028 – depending on evolution of NND disposal programme priorities, and considering a two-year permitting and licensing period before each milestone.

Figure 9: Summarised DBD Implementation Roadmap Phases (next page)



Milestones

- ➲ **1** Holistic Radioactive waste management study - KVU and DSA review - Norwegian decision of DBD as preferred option
- ☑ **2** Initiation of a DBD Siting process and launch of a Deep Borehole Field Test
- ☑ **3** Site selection for future investigations and confirmation of DBD as Norwegian
- ☑ **4** Authorisation for construction
- ☑ **5** Authorisation for operation
- ☑ **6** Authorisation for closure
- ☑ **7** Authorisation for termination of nuclar license

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APPENDIX 1

DBD IMPLEMENTATION ROADMAP

Rev	Written by	Reviewed by	Approved by	Date	Description
B	M. Crawford L.Prévot	S. Wickham	L. Prévot	04/02/2025	Second revision following answers to NND comments on the Final Report Revision B and included as Appendix 1 to Roadmap report.
A	L.Prévot	M. Crawford C. Herbert	L. Prévot	26/11/2024	Transmitted as brief material following Roadmap workshop #1.

DEVELOPMENT OF SOLUTIONS FOR DISPOSAL OF SPENT FUEL AND OTHER RADIOACTIVE WASTE INCLUDING BOREHOLE DISPOSAL SUBCONTRACT 2

NND 361 - DBD IMPLEMENTATION ROADMAP

TASK C002 - ROADMAP DEVELOPMENT

Reference 361-SB2-C002-REP-004-B-Appendix 1

REVISION	PREPARED BY	REVIEWED BY	APPROVED BY	ISSUE DATE	COMMENT
A	L. Prévot	M. Crawford C. Herbert	L. Prévot	26/11/2024	Transmitted as brief material following Roadmap workshop #1.
B	M. Crawford L.Prévot	S. Wickham	L. Prévot	04/02/2025	Second revision following answers to NND comments on the Final Report Revision B and included as Appendix 1 to Roadmap report.

NND 361 SB2 | DBD Implementation roadmap

Milestones	➲ 1	☑ 2				☑ 3			☑ 4		☑ 5	☑ 6		☑ 7	
	2025	Y0	Y0+2	Y0+4	Y0+6	Y0+8	Y0+10	Y0+12	Y0+14	Y0+16	Y0+18	Y0+20	Y0+22	Y0+24	Y0+26
PROJECT INITIATION															
Disposal programme management															
Strategy & planning : Project Lifecycle Management and holistic radioactive waste management strategy															
Requirements management															
Knowledge management															
International collaboration: e.g. IAEA CRPs															
Protection of health, safety & environment															
Corporate services															
Quality management, including risk, change and configuration															
Licensing & permitting															
Stakeholder involvement															
Comprehensive stakeholder management plan and stakeholder dialogue															
Disposal system development															
Safety strategy & template for the safety case															
Waste inventory															
DBD concept design															
Safety assessment															
Cost estimates for the generic concept															
Siting strategy															
Staged siting strategy, confirm availability of suitable host rock															
Field testing: DBFT programme definition and implementation planning															
DBFT programme definition															
DBFT implementation plan (permitting, costing, planning)															
SITE(S) IDENTIFICATION AND SELECTION															
Disposal programme management															
Stakeholder involvement															
Disposal system development															
Plan the investigation programmes for sites															
Launch and interpret site investigations & site selection process															
Adaptation of the conceptual design to sites															
Long-term safety assessment for site characterisation licensing															
Site specific cost estimations															
Preliminary site investigations															
Carry out preliminary site investigations															
Deep Borehole Field Test															
Characterisation demonstration															
Encapsulation and overpack manufacturing demonstration															
Drilling (several phases) demonstration															
Emplacement demonstration															
Retrieval demonstration															
Operational stability demonstration															
Sealing demonstration															
SPECIFIC SITE(S) CHARACTERISATION															
Disposal programme management															
Stakeholder involvement															
Disposal system development															
Siting for the borehole and surface facilities															
Plan, launch and lead site characterisation programme and interpret data															
Site specific detailed design and safety assessment for construction licensing															
Site characterisation															
Drilling characterisation hole(s) and sealing															
CONSTRUCTION & COMMISSIONING															
Disposal programme management															
Stakeholder involvement															
Disposal system development															
Detailed design and safety assessment for operation licensing															
Disposal implementation															
Drilling of the disposal borehole (right first time) and completion															
Construction of the surface facilities															
Development of overpack and transfer flask manufacturing/procurement route															
OPERATIONS															
Disposal programme management															
Stakeholder involvement															
Disposal system development															
As-built design and safety assessment for closure licensing															
Disposal implementation															
Spent fuel and HLW encapsulation and transportation															
Disposal operations and waste emplacement															
CLOSURE															
Disposal programme management															
Stakeholder involvement															
Disposal system development															
Safety assessment for application of Termination of Nuclear License															
Disposal implementation															
Sealing and backfilling the disposal borehole															
Dismantling the surface facilities															
Interim monitoring															
POST-CLOSURE															
Disposal programme management															
Stakeholder involvement															
Institutional control															

Milestones

- ➲ **1** Holistic Radioactive waste management study - KVU and DSA review - Norwegian decision of DBD as preferred option
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