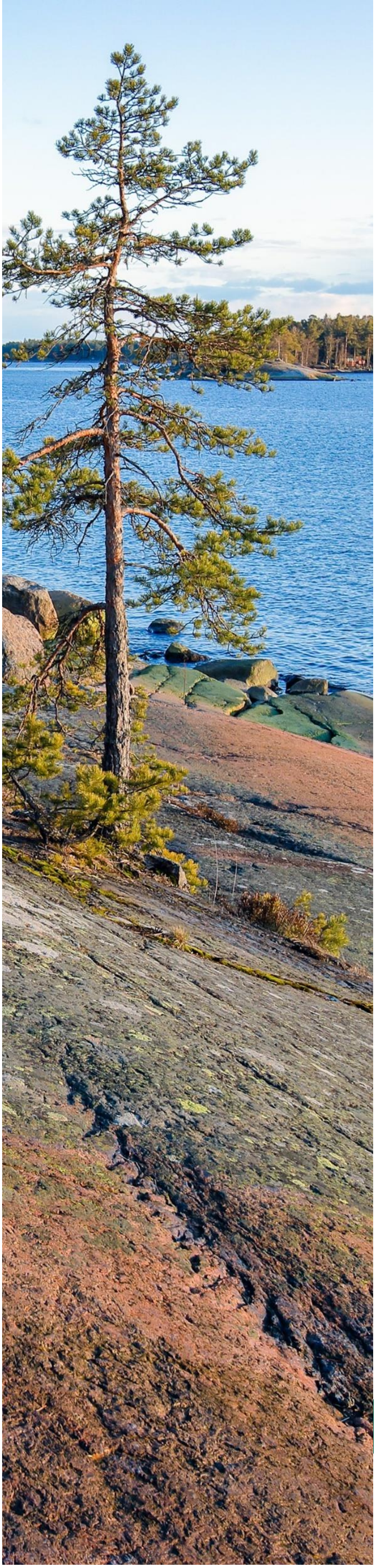

Technical Memorandum

Technical Readiness Level Assessment

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ABSTRACT

Norwegian Nuclear Decommissioning (NND) is developing disposal concepts for the Norwegian radioactive waste inventory. Current such concepts include the following facilities:

- Intermediate depth repository for low and intermediate level waste (LILW),
- Deep geological repository (HLW-DGR) OR deep borehole repository (HLW-DBD) for high-level waste,
- Landfill-type repository for non-radioactive decommissioning waste.

This memorandum describes a technical readiness level (TRL) assessment that was conducted as part of the technical assistance to NND. TRL assessment was conducted for two HLW repository types (DGR and DBD), and for LILW repository.

TRL can be used to help to identify low TRLs to determine where to focus potential future needed research and development work. TRL assessment can provide input to the overall comparison of the different concepts and indicates how advanced the required technology is. TRL assessment can also form a basis for communication helping to clarify that a large proportion of the concepts and solutions are sufficiently developed to be implemented.

This TRL assessment groups nine technology readiness levels (TRL 1 to TRL 9) into three broader technology development stages:

1. Fundamental Research
2. Research and Development
3. Pilot and Demonstration

Higher TRL scoring means more mature technology.

The repository lifecycle was divided into five distinctive phases that follow each other: Site Investigation, Site characterisation, Construction, Operations and Closure. For the TRL assessment the phases were subdivided into main technology related processes or component. This was done for each repository type separately.

The assessment found out that most technologies and components are fairly mature. There are some development areas that were highlighted in the work. Especially HLW-DBD needs some development work before it is feasible to make the final decision on which concept will be chosen in Norway.

TRL assesses the maturity of technologies. Whether the technology is applied correctly and appropriately in practice is not part of the assessment. These fall under experience, expertise, know-how and the capacity of an organization. TRL is a tool that can be used as part of a bigger picture to evaluate if a concept is mature enough to be implemented in practice.

Keywords: Technical Readiness Level assessment, high level waste disposal, DGR, deep borehole disposal, development needs

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List of terms and abbreviations (adapted from Saanio et al. 2021).

Barrier	Refers to an engineered or natural barrier used for achieving long-term 'safety functions'.
Containment	Methods or physical structures designed to prevent or control the release and the dispersion of radioactive substances.
DBD	Deep Borehole Disposal, which is the method used in a 'deep borehole repository'.
Decision on site	Decision to perform comparison and recommend one site for the development of the National Facility (decision on the site).
Deep borehole repository	A repository for disposing of high-level radioactive waste (spent nuclear fuel) in a deep borehole drilled from the Norwegian National Facility, where the deep borehole repository is an alternative to the 'deep geological repository'.
Deep geological repository	A repository for disposing of high-level radioactive waste (spent nuclear fuel) in a mined repository within the Norwegian National Facility. Alternatively, a 'deep borehole repository' can be used (Ikonen et al. 2020). In a generic sense, a deep geological repository is a facility where radioactive waste is placed in a deep, stable geological formation (usually several hundred metres or more below the surface). The facility is engineered to isolate and contain radioactive waste to provide the long-term isolation of nuclear substances from the biosphere.
Deposition hole	The in-floor shallow borehole in a 'KBS-3V repository' where the waste canister is placed. In some countries term "emplacement borehole" has similar meaning.
DGR	Acronym for 'deep geological repository'.
Disposal	Emplacement of waste in an appropriate facility without the intention of retrieval.
Disposal facility	An entirety comprising the rooms for the disposal of the waste packages (emplacement rooms; see 'repository') and the adjoining underground and above-ground auxiliary facilities. A disposal facility may include different types of radioactive wastes and engineered barriers, and these may be separated into several repositories.
Disposal system	An entirety comprising the 'disposal facility' and the bedrock and ground surface environment of the disposal site.
DSA	Norwegian Radiation and Nuclear Safety Authority
EBS	Engineered barrier system
EIA	Environmental Impact Assessment
FEP	Features, Events and Processes. Identification and documentation of all the features, events and processes (FEPs) that may be relevant to the long-term safety or performance assessment studies of radioactive waste disposal facilities.
GIS	Geographic information system
GR, geological repository	Geological Repository; GR is the acronym used in this report for the requirements that may apply to any of the geological-type repositories: 'intermediate depth repository', 'deep geological repository' or 'deep borehole repository'.
GTK	Geological Survey of Finland
HLW	High-level radioactive waste
Host rock	Host rock is the rock surrounding an underground 'repository' that shall, together with the engineered barrier system, provide containment and isolation and ensure that the transport of radionuclides is limited in the case of release. Host rock can either be considered synonymous to the natural barrier or refer to a part of it closest to the repository (up to a distance of, e.g., some tens of metres).
IAEA	International Atomic Energy Agency
IDR	Acronym for 'intermediate depth repository'.
ILW	Intermediate-level radioactive waste
Intermediate depth repository	Repository for very low, low and intermediate level radioactive waste within the Norwegian National Facility at intermediate depth.
Isolation	The physical separation and retention of radioactive waste away from people and from the environment.

KBS-3	An abbreviation of kärnbränslesäkerhet (nuclear fuel safety) version 3. The KBS-3 method for implementing the spent nuclear fuel disposal concept based on multiple barriers.
KBS-3V	(Kärnbränslesäkerhet 3-Vertikal). The reference design of the KBS-3 method, in which the spent nuclear fuel canisters are emplaced in individual vertical deposition holes.
KBS-3V repository	Mined geological repository for the disposal of high-level waste developed by SKB. In this report, the KBS-3V repository design is relevant for the ‘deep geological repository’, which may be included in the National Facility.
KLDRA	Kombinert lager og deponi for radioaktivt avfall
Landfill repository	Landfill type near surface repository planned for the Norwegian National Facility as an option for disposing of non-radioactive decommissioning waste, mainly soil and concrete, and in some cases also VLLW.
LILW	Low and intermediate-level radioactive waste
LLW	Low-level radioactive waste
Long-term safety	The safety of disposal after the closure of the disposal facility, taking account of radiation exposure on humans and the environment. The evaluation of long-term safety is typically extended to one million years after closure (see also ‘safety case’).
LR	Landfill repository
Management system	A set of interrelated or interacting elements (system) for establishing policies and objectives and enabling the objectives to be achieved in an efficient and effective manner.
NND	Norwegian Nuclear Decommissioning
NPP	Nuclear power plant
Post-closure	Refers to the time period starting from the closure of a ‘repository’ or a ‘disposal facility’.
Quality management	Quality management or quality assurance refers to the function of a ‘management system’ that provides confidence that specified requirements will be fulfilled.
Repository	Emplacement rooms for a certain type of waste. The Norwegian National Facility (‘disposal facility’) may include several repositories: ‘landfill repository’, ‘intermediate depth repository’ and either ’DGR’ or ‘deep borehole repository’ (in addition to other openings, such as shafts).
Safe disposal	‘Disposal’ that results in protection of workers, the public and the environment from undue radiation risks, during the operational phase and in ‘post-closure’ conditions; see also ‘long-term safety’.
Safety assessment	Safety assessment entails evaluating the performance of a disposal system and quantifying its potential radiological impact on human health and the environment. Safety assessment is a major component of the ‘safety case’ for a ‘disposal facility’ and should take account of the potential radiological impacts of the facility, both in operation and after closure. Safety assessment should demonstrate whether the disposal facility complies with applicable regulatory requirements.
Safety case	A collection of arguments and evidence in support of the ‘safety’ of a facility or activity. A safety case includes a quantitative assessment (‘safety assessment’) and a qualitative assessment.
Safety function	Safety functions are functions achieved by the characteristics or processes of engineered and natural ‘barriers’ that are intended to isolate the nuclear waste from the bedrock and the biosphere or to impede the migration of radionuclides. In this report, only the safety functions of the natural barrier (host rock) are discussed, not those of the engineered barriers.
Site characterisation	Site-specific studies at the selected disposal site. In other nuclear waste programmes, the term “site characterisation” is often used interchangeably with ‘site investigations’.
Site investigation plan	A plan for ‘site investigations’, which goes beyond the ‘site selection criteria’ and ‘target properties’.

Site investigations	Site investigations done in 'Phase C' of the siting process at the sites selected in 'Phase B'. They consist of a broad range of geoscientific activities to acquire geoscientific information relevant to the safety case and engineering. Site investigations provide information for conceptual models of the natural systems, engineered system and for coupled processes, and for the biosphere.
Site selection Phase A	The site screening phase, where the goal is to exclude regions that are not suited for hosting the National Facility; carried out as a desktop study.
Site selection Phase B	The phase of evaluation of siting areas, where the goal is to narrow down to a subset of sites that are potentially suitable for hosting the National Facility; carried out as a desktop study and as limited field visits. Volunteer municipalities enter this stage.
Site selection Phase C	The phase of 'site investigations' and evaluations, where the goal is to gather and analyse enough site-specific data so that the sites can be evaluated and compared.
Site selection process	The process to narrow down from several regions, siting areas and sites to a single site.
Siting areas	Areas potentially suitable for locating a (disposal) site. The surface areas of the siting areas are approximately tens to hundreds of square kilometres.
Siting process	Used with a similar meaning to "site selection process"
SKB	Svensk Kärnbränslehantering Ab (Swedish Nuclear Fuel and Waste Management Company)
SNF	Spent nuclear fuel
Stakeholder	An interested party, i.e. a person, company, etc., with a concern or interest in the activities and performance of an organization, business, system, etc.
Technical site selection process	The part of the 'site selection process' that considers specifically the 'technical site selection criteria', not logistical or socio-economic-political factors.
TRL	Technical readiness level assessment
VLLW	Very low-level radioactive waste
VSLW	Very short-lived radioactive waste
VTT	Technical Research Centre of Finland

1 INTRODUCTION

1.1 Background

Norwegian Nuclear Decommissioning (NND) is working with the Finnish AINS Group together with subconsultants VTT Technical Research Centre of Finland and BGE Technology GmbH of Germany. The group assists NND with the concept development and technical design for their disposal solutions for radioactive waste in Norway.

Norway's inventory of radioactive waste is characterised by high-level waste (HLW) from the research reactors in Halden and Kjeller, taken out of operation. In addition, there will be low and intermediate level waste from the planned decommissioning of the research reactors and other nuclear facilities. Norway has also other low- and intermediate-level waste generated, e.g., by the medical sector. NND is developing a comprehensive strategy for management of all classes of radioactive waste. Such a strategy could include the following facilities:

- Intermediate depth repository for low and intermediate level waste,
- Deep geological repository OR deep borehole repository for high-level waste,
- Landfill-type repository for non-radioactive decommissioning waste.

Repository types are presented in the report "Concept Description for Norwegian National Disposal Facility for Radioactive waste" (Ikonen et al. 2020). The report includes concise concept descriptions of the possible disposal options. The borehole disposal concept was further developed in Fischer et al. (2020), Wunderlich et al. (2021), and Engelhardt et al. (2021). Encapsulation processes for HLW, both for DGR and DBD concepts, were described in Saanio et al. (2022).

This technical memorandum describes a high-level technical readiness level (TRL) assessment that was conducted as part of the technical assistance to NND. The TRL assessment has several goals. TRL assessment is the basis for the communication and should help to clarify that a large proportion of the concepts and solutions are sufficiently developed to be implemented. It helps the identification of low TRLs to determine where to focus on for potential research and development work. Finally, the TRL assessment provides input to the overall comparison of the different concepts and solutions and indicates how advanced the required technology is.

Technology readiness level assessment was conducted for deep geological repository (HLW-DGR), deep borehole disposal (HLW-DBD) and intermediate depth repository (LILW) concepts.

The assessment looked into the following main technical phases.

- Site investigations
- Encapsulation
- Repository (construction, operation and closure)

The deliverable is in two parts: This Technical Memorandum is complemented with adjoining PowerPoint file.

1.2 Technical Readiness Level assessment

In this section the used TRL assessment is described and the common terms are defined.

The TRL Assessment Tool groups nine technology readiness levels (TRL 1 to TRL 9) into three broader technology development stages (see Science Media Center Germany GmbH (2022) for example):

1. Fundamental Research
2. Research and Development
3. Pilot and Demonstration

Followed by these three stages, a fourth stage can be named, which describes the stage in which the technology is commercially available. This stage is not part of the TRL assessment, but describes any technology that is regularly used in different operations and can therefore be ranked after the TRL 9.

DOE (2011) uses TRL tool to distinguish between various design phases of a project. They state that project can commence Concept Design phase when the TRL score is 4. Preliminary Design phase is from TRL score 6, which is when licensing process can also start.

The tool provides a description of each TRL along with a checklist to determine if the technology is at that specific TRL. Therefore, this tool can be used as an add-on to understand the TRL assessment. Another aspect that needs to be mentioned is the fact that the described technologies are looked at by themselves. The overall application and combination of the different technologies need to be assessed additionally. Another important point is that only the availability and technical readiness is looked at. In detail, this means that the technologies considered are used as such, but may not yet be used in the field of final disposal of high-level radioactive waste or in final disposal in general. Some technologies might be used in different industries and due to this, they have a high TRL.

The following principles are applied when determining the TRL of a technology:

- **Start with the broader technology development stage:** When determining a TRL, it is best to start with the development stage of the technology. This helps to get a first classification, which can then be finalized by specific assignment to a TRL.
- **Proceed rather conservatively:** If there are uncertainties regarding the final assignment of a technology to a TRL, the lower TRL should be chosen.
- **Ensure the operating environment is well understood:** A key aspect of the various TRLs is the testing environment of a technology. It is important to be clear about what real-world conditions are expected and whether or how the test environment (e.g., laboratory, simulated or operational) represents those conditions.
- **A TRL is only valid for the specific operational environment for which it was tested:** If a developed technology is to be used in a different operational environment than the one for which it was tested, the technology is no longer considered fully developed. In this case, a new test of the technology in the respective environment must be carried out so that it can be classified the same TRL.

Important distinction: A technology is said to have achieved a specific TRL if it has met the requirements for that level and all prior levels. A technology is said to be at a certain TRL if the research team is currently working on achieving the requirements specific to that level. Figure 1-1 depicts the nine TRLs in the three technology development stages.

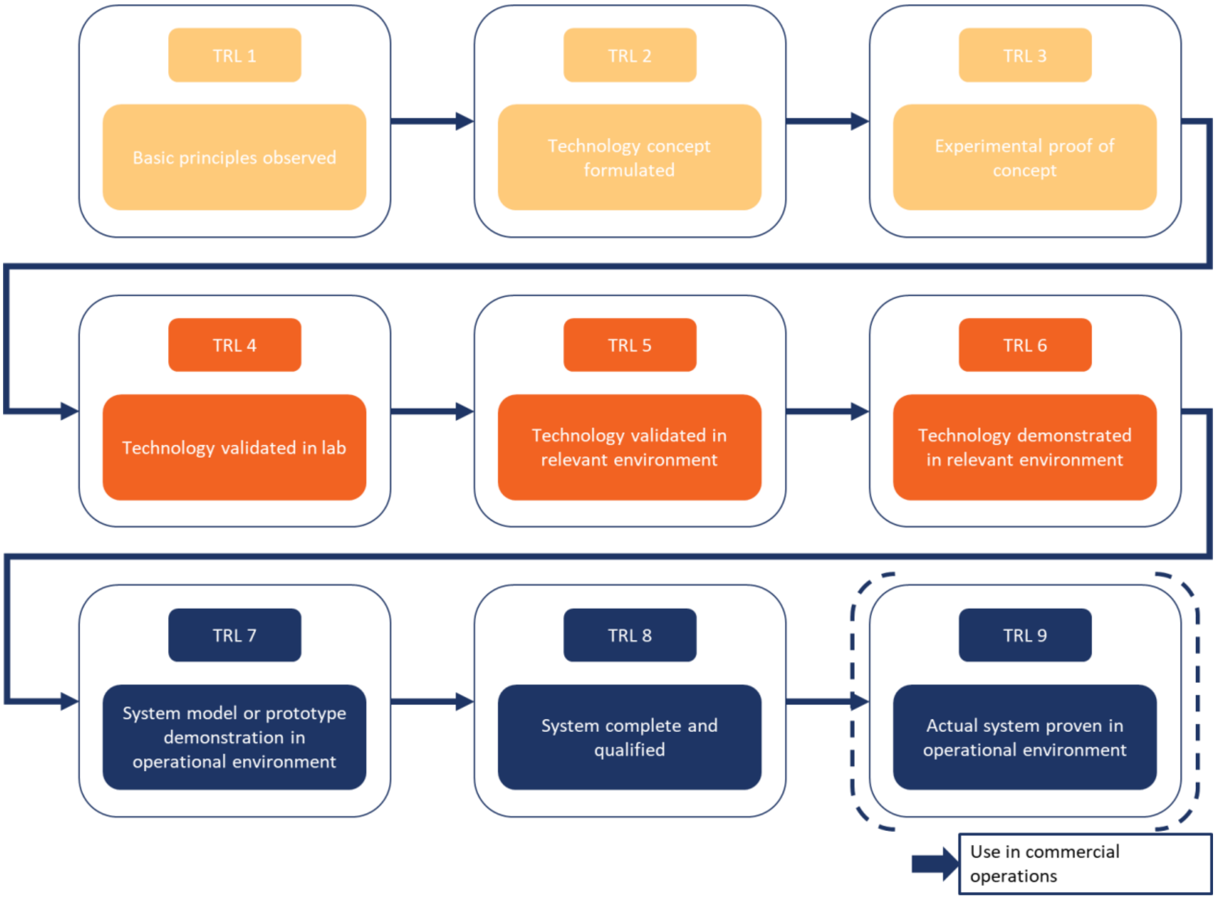

Figure 1-1. Nine Technology Readiness Levels in three broader technology development stages. See the full graphic as chart "Section 1.2 TRL scale" in the adjoining file (adapted from TWI Ltd, 2022).

Technology Development Stage	TRL	Definition	Description	Checklist of activities to achieve this level
Fundamental Research	1	Basic principles observed and reported	Scientific research begins with properties of a potential technology observed in the physical world. These basic properties are being reported in the literature.	Basic research activities have been conducted and basic principles have been defined. Principles and findings have been published in the literature (e.g., research articles, peer-reviewed papers, white papers)

	2	Technology and/or application concept formulated	Applied research begins with identification of practical applications of basic scientific principles. There is an emphasis on understanding the science better and corroborating the basic scientific observations made during TRL 1 work. Analysis of the feasibility of speculative applications is being conducted and reported in scientific studies.	Applications of basic principles have been identified. Applications and supporting analysis have been published in the literature (e.g., analytical studies, small code units for software, papers comparing technologies)
	3	Experimental proof of concept	Active research and development begins. The applications are being moved beyond the paper stage to experimental work. Feasibility of separate technology components are being validated through analytical and laboratory studies. There is not yet an attempt to integrate components into a complete system.	Proof of concept and/or analytical and experimental critical function has been developed. Separate components have been validated in a laboratory environment
Research and Development	4	Validation of component(s) in a laboratory environment	Basic technological components are integrated “ad-hoc” to establish that they will work together in a laboratory environment. The “ad-hoc” system would likely be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment in order to function.	“Ad-hoc” integrated components, sub systems and/or processes have been validated in a laboratory environment. How “ad-hoc” integration and test results differ from the expected system goals is understood
	5	Validation of semi-integrated component(s) in a simulated environment	The integrated basic technological components are performing for the intended applications in a simulated environment. Configurations are being developed but can undergo fundamental changes. The technology and environment at TRL 5 is more similar to the final application than TRL 4.	Semi-integrated component(s)/ subsystems or processes have been validated in a simulated environment. How the simulated environment differs from the expected operational environment and how the test results compare with expectations is understood
	6	System and/or process prototype demonstrated in a simulated environment	A model or prototype, that represents a near desired configuration, is being developed at a pilot scale, generally smaller than full scale. Testing of the model or prototype is being conducted in a simulated environment.	Pilot scale model or prototype developed. Pilot scale model or prototype system is near the desired configuration in performance, and volume but generally smaller than full scale. Pilot scale prototype or model system has been demonstrated in a simulated environment. How the simulated environment differs from the operational environment, and how results differed from expectations is understood

Pilot and Demonstration	7	Prototype system ready (form, fit and function) demonstrated in an appropriate operational environment	A full scale prototype is being demonstrated in an operational environment but under limited conditions (i.e., field tests). At this stage, the final design is very close to completion.	Full scale prototype with ready form, fit and function developed. Full scale prototype demonstrated in an operational environment but under limited conditions
	8	Actual technology completed and qualified through tests and demonstrations	Technology is being proven to work in its final form and under expected conditions. This stage commonly represents the end of technology development. At this stage, operations are well understood, operational procedures are being developed, and final adjustments are being made.	Final configuration of the technology developed. Final configuration successfully tested in an operational environment. Technology's ability to meet its operational requirements has been assessed and problems documented; plans, options, or actions to resolve problems have been determined
	9	Actual technology proven through successful deployment in an operational environment	Actual application of the technology in its final form is being conducted under a full range of operational conditions. Sometimes referred to as "system operations", this stage is where technology is further refined and adopted.	The technology has been successfully deployed and proven under a full range of operational conditions. Operational, test and evaluation reports have been completed

1.2.1 **Key terms**

Scientific research: research aimed at expanding the base of theoretical scientific knowledge and predictions that have universal applicability

Applied research: the application of scientific knowledge to solve specific practical problems or answer certain questions

Research and development: systemic work designed to produce new products, techniques or processes or improve existing products, techniques or processes

Proof of concept: analytical and experimental demonstration of hardware/software concepts.

Model: a reduced scale, functional form of a system, near or at operational specification

Prototype: the first early representation of the system which offers the expected functionality and performance expected of the final implementation

Laboratory environment: a fully controlled test environment where a limited number of functions and variables are tested. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment

Simulated environment: a relevant working environment with controlled realistic conditions, generally outside of the lab. If the technology will be used in various environments (e.g., the Artic and Southern Canada), the technology must be developed and tested in a simulated environment for all conditions.

Operational environment: "real-world" environment with conditions associated with typical use of the product and or process. If the technology will be used in various environments (e.g., the Artic and Southern Canada), the technology must be developed and tested in each operational environment.

1.3 Scope, structure and limitations

The TRL assessment breaks down the repository concepts into two levels of processes phases, or technologies. These are presented in Chapter 2.

The TRL assessment looks into technologies involved and excludes human resources and expertise. The assessment for each repository type is presented in Chapter 3. The adjoining PowerPoint file includes the related graphics. These are referenced "*See the full chart in the adjoining file titled "Section 1.2 TRL scale"*, or similar".

The TRL assessment of LILW repository (Section 3.3) will be very high-level and concentrates only on construction, disposal and closure phases. The assessment excludes the encapsulation of waste (that is, packaging of LLW and ILW).

Long-term safety assessment is not part of TRL assessment. However this is discussed separately in Chapter 4.

Chapter 5 presents the discussion and points out the important differences between the repositories and their TRL assessment scoring.

TRL assesses the maturity of technologies. Whether the technology is applied correctly and appropriately in practice is not part of the assessment.

The TRL assessment is based on the expert judgement of the project team. It is also emphasized that TRL scoring is not strictly scientific or analytic but based on subjective assessment of the technologies. The project team spent considerable time brainstorming and discussing the assessment so that each TRL score would be consistent with the other TRL scores in this work. The TRL scoring was not compared or benchmarked against other similar studies.

2 PHASES AND TECHNICAL PROCESSES

2.1 Introduction

Charts referenced in this chapter are part of the adjoining PowerPoint file.

The disposal programme and repository lifecycle are divided into five distinctive phases that follow each other. These are Site Investigation, Site characterisation, Construction, Operations and Closure. (This is illustrated in chart Section 2.1: Main phases for TRL assessment in the adjoining PowerPoint). For the TRL assessment the phases were subdivided into main technology related processes. The division was done for each repository type separately. (This is illustrated in chart “Section 2.1 Main components by phase”). The main components of the disposal systems are referenced as “WBS” in the context of this work.

Long-term safety assessment (safety case) is an important part of the licensing of a nuclear waste repository, but not relating to development of the technology of the concept. Therefore, it is not included in the technical processes, but will be discussed separately from the assessment feasibility point of view between the different disposal concepts.

2.2 WBS for HLW-DGR

There are two repository types considered in Norway for disposing the high-level radioactive waste. One of the repository types is based on the Finnish and Swedish KBS-3 concept. In this work the repository concept is referenced as “HLW-DGR”.

The repository lifecycle for the purpose of TRL assessment comprises of five main phases where the applied technology within site investigation and site characterization are alike. All sub-phases of construction involve excavation, building technology and systems. Disposal operations include buffer, canister and pellet emplacement, and tunnel operations include installation of backfill materials and construction of tunnel plugs.

This is illustrated in chart “Section 2.2 Main components of HLW-DGR”.

2.3 WBS for LILW

The main phases of LILW disposal are the same as in HLW-DGR concept but the packing of the waste has been left out from the TRL assessment.

This is illustrated in chart “Section 2.3 Main components of LILW repository”.

2.4 WBS for HLW-DBD

The other repository type for disposing of HLW in Norway is deep borehole disposal concept. This is referenced as HLW-DBD in the work.

The main components of the concept as it relates to TRL is presented in chart “Section 2.4 Main components of HLW-DBD”.

3 TECHNICAL READINESS LEVEL ASSESSMENT

3.1 Introduction

This chapter presents the Technology Readiness Level assessment for the three disposal concepts with justification for each TRL score.

The TRL assessments are presented visually in separate charts in the adjoining PowerPoint.

Regarding HLW-DGR disposal, similar repository programmes have been advanced in Finland and Sweden. The assessment of the technologies planned to be used, or already tested, in the existing programmes have been used as basis for the HLW-DGR TRL assessment.

Regarding LILW disposal, repositories for LILW have been operational in Finland and Sweden for several decades, so these countries and their repository programs have been the principal references for TRL assessment. References of operating repositories and their technologies can also be found in other countries but from the TRL assessment point of view they were used minimally.

Regarding the HLW-DBD concept, no underground research facilities of HLW disposal like Äspö in Sweden or ONKALO for the HLW-DGR in Finland exist. The TRL assessment for HLW-DBD is based on the industries that use technology that can be applied also in deep borehole disposal of radioactive waste.

3.2 TRL for HLW-DGR

3.2.1 Overview of the assessment

The entire TRL assessment for HLW-DGR is elaborated in Table 3-1, and as chart "Section 3.2 TRL for HLW-DGR" in the attached PowerPoint. The same chart is also presented in small scale in Figure 3-1. More detailed justification for the TRL scores is presented in the following sections.

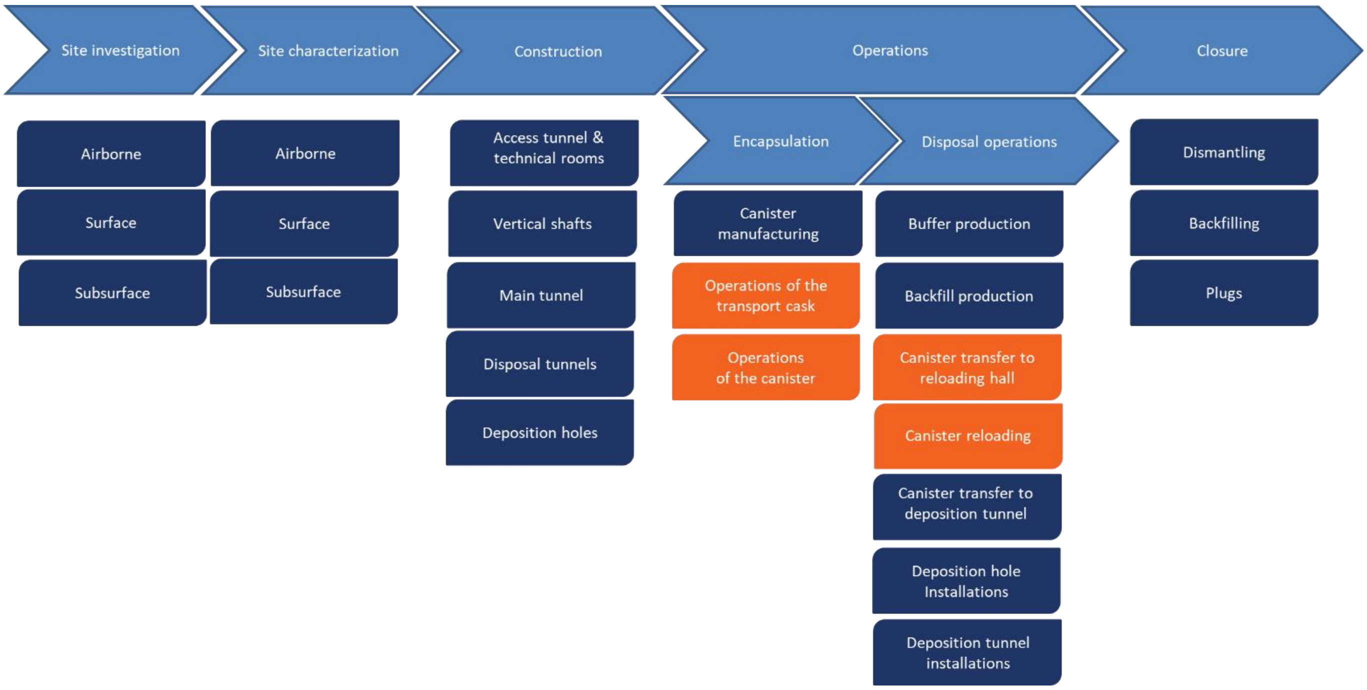

Figure 3-1. Summary of HLW-DGR TRL assessment. Please refer to the attached PowerPoint file for the full resolution chart.

Table 3-1. TRL assessment of HLW-DGR concept.

PHASE OF THE DGR	TRL	TRL DEFINITION	JUSTIFICATION
Site investigation			
Airborne	9	*"Actual technology proven through successful deployment in an operational environment"*	Airborne technology (geophysical surveys) has been applied in site investigations since late 1970s/1980s (e.g. SKB, Posiva)
Surface	9	–II–	Technology of surface geophysical investigations have been applied similarly as airborne investigations
Subsurface	9	–II–	Deep borehole drillings and related technology to characterise host rock have been applied in repository siting since late 1970's
Site characterization			
Airborne	9	–II–	–II–
Surface	9	–II–	–II–

Subsurface	9	–II–	–II–
Construction		–II–	
Access tunnel & technical rooms	9	–II–	ONKALO
Vertical shafts	9	–II–	Ventilation, personnel and canister shafts have been constructed in ONKALO
Main tunnel	9	–II–	Construction of a main tunnel started in ONKALO in 2020
Disposal tunnels	9	–II–	Start of the excavation of first disposal tunnels in 2021
Deposition holes	9	–II–	Test deposition holes have been bored in ONKALO since 2011

PHASE OF THE DGR	TRL	TRL DEFINITION	JUSTIFICATION
Encapsulation			
Canister manufacturing	7	*"A full-scale prototype is being demonstrated in an operational environment but under limited conditions (i.e., field tests). At this stage, the final design is very close to completion"*.	Full-size canisters have been manufactured by Posiva since 1999, but they represent prototypes and not the final design
Operations of the transport cask	6	*"A model or prototype, that represents a near desired configuration, is being developed at a pilot scale, generally smaller than full scale. Testing of the model or prototype is being conducted in a simulated environment"*.	Equipment and systems for the operations of the transport cask in the encapsulation plant are being manufactured and partly delivered (e.g. docking station of a transport cask), but not assembled or tested in the operational environment (encapsulation plant)
Operations of the canister	6	–II–	Equipment and systems for the operations of the canister are being manufactured but not yet assembled or tested in the operational environment. The prototype for canister transport cask is not yet manufactured
Disposal operations			
Buffer production	7	*"A full-scale prototype is being demonstrated in an operational environment but under limited conditions (i.e., field tests). At this stage, the final design is very close to completion"*.	Bentonite buffer rings and disc blocks were manufactured for Posiva's FISST (Full Scale In Situ System Test, 2018 =>), but the design of the buffer is still under development
Backfill production	7	–II–	Pre-compacted bentonite blocks were manufactured for Posiva's FISST (Full Scale In Situ System Test,), but the design of the backfill is still under development
Canister transfer to reloading hall	6	*"A model or prototype, that represents a near desired configuration, is being developed at a pilot scale, generally smaller than full scale. Testing of the model or prototype is being conducted in a simulated environment."*	Prototype for canister transfer vehicle (MODE) has been manufactured by SKB, but it has not been tested in an access tunnel with the canister transport cask which is under development.
Canister reloading	6	–II–	SKB has manufactured a full-size prototype of canister installation vehicle, but the reloading process has not been demonstrated yet

PHASE OF THE DGR	TRL	TRL DEFINITION	JUSTIFICATION
Canister transfer to deposition tunnel	7	*“A full-scale prototype is being demonstrated in an operational environment but under limited conditions (i.e., field tests). At this stage, the final design is very close to completion”.*	Posiva has demonstrated canister transfer in FISST 2018-2019
Deposition hole installations	7	–II–	Posiva has demonstrated installation of bentonite buffer &pellets and canister within FISST
Deposition tunnel installations	7	–II–	Posiva has demonstrated installation of tunnel backfill and plug within FISST
Closure			
Dismantling	9	*““Actual technology proven through successful deployment in an operational environment””*	Dismantling of a deposition tunnel has been demonstrated by Posiva within FISST, and in the context of decommissioning of ore mines.
Backfilling	9	–II–	Backfilling of a deposition tunnel has been demonstrated by Posiva within FISST, and in the context of decommissioning of ore mines.
Plugs	9	–II–	Plug construction of a deposition tunnel has been demonstrated by Posiva within FISST.

3.2.2 Site Investigations

Site investigations comprise airborne, surface and subsurface investigations where technologies for obtaining data for assessing site suitability for nuclear waste repository have been used in Sweden and Finland since late 1970’s. Technology is well proven and the TRL score 9.

3.2.3 Site characterization

In principle the same technology is used in site characterization as with site investigations, but the emphasis is on the subsurface research where information is gathered from deep drillings and measurements conducted in boreholes. The TRL score is 9 as with the site investigations.

3.2.4 Construction

For the TRL assessment the underground construction of the final disposal facility is covered. The surface facilities, such as office buildings (apart from encapsulation, Section 3.2.5) are considered typical civil engineering operations and are no interest for the overall TRL scoring of a disposal facility.

In Finland, the underground rock characterization facility ONKALO has been under construction at the final disposal site in Olkiluoto since 2004. The access tunnel, shafts and technical facilities have been implemented down to final disposal depth (420 meters below surface) where the construction of main tunnel and first disposal tunnels are underway. In addition, first test disposal tunnels and deposition holes have been implemented already in the 2010's. The technology for construction is well proven in operating environment. The TRL score is 9. This is illustrated in chart "Section 3.2.4 HLW-DGR Construction".

3.2.5 **Encapsulation**

Encapsulation of spent nuclear fuel for HLW-DGR has not been realised anywhere yet. The first prototypes of the current dual structure KBS-3 canister with copper overpack and cast-iron insert have been manufactured in Sweden and in Finland in the 1990's. The current manufacturing technology for the copper overpack is extrusion but Posiva has also used pierce and draw method for manufacturing of the copper tube. Canisters to be used in final disposal have not been manufactured yet, so the TRL score 7 corresponds to the readiness level of full type prototype.

Spent nuclear fuel is packed into the disposal canisters in the encapsulation plant. The first of a kind is under construction in Olkiluoto by Posiva and is expected to be operational approximately in 2025 (Posiva 2021, operating license application). The operations of the encapsulation plant comprise basically process of the spent fuel transport cask and the disposal canister. Some equipment and systems for removing spent fuel bundles from transport cask to disposal canister are already in place and some at the manufacturing state. Overall, encapsulation technology is not tested in operational environment. Integrated system test (trial run) comprising the entire encapsulation and disposal process with dummy fuel bundles is expected to take place in 2023 (www.posiva.fi). Contrary to underground operations, full size testing of encapsulation has not taken place yet and therefore the TRL score for the encapsulation comprising transport cask and disposal canister operations is 6. However, it should be noted that the encapsulation process that has been described as a part of the Norwegian national facility concept is not fully identical with the one of Posiva. In the national facility process, a disposal canister is placed inside a special transport cask (KTB, Kapsel Transport Behållare) after encapsulation, adopted from the SKB's conceptual plan. The canister transport cask is planned to be manufactured by 2029 (SKB 2019, FUD). Consequently, TRL score for NND's encapsulation will be also 6.

3.2.6 **Disposal operations**

Disposal operations comprise buffer and backfill production for deposition holes and disposal tunnels, canister transfer from the encapsulation plant down to reloading hall at the repository level, canister reloading on the transfer and installation vehicle, canister transfer to the disposal tunnel, deposition hole and disposal tunnel installations.

Intensive research and development work on the buffer and backfill have been ongoing for decades. Both SKB and Posiva have tested this material in repository conditions (Prototype repository in Äspö, since 2003, Full Scale in Situ System test in ONKALO since 2017). Due to the full-scale experiments in operational environment, the TRL score is 7.

TRL score for the canister transfer to the reloading hall at the repository level is assessed 6, because the canister transport cask is not yet manufactured nor the transport of the cask via the access tunnel has been tested. The same applies with the canister reloading where no full-scale testing has taken place because the canister transfer cask is not available.

Canister transfer to the disposal tunnel and the subsequent installations in the deposition hole and the disposal tunnel are estimated to correspond to the TRL 7. These operations have been tested in SKB's prototype repository and in Posiva's FISST. Deposition hole installations involve placement of bentonite buffer rings, discs, pellets and canister into the deposition hole. Disposal tunnel installations involve tunnel backfill, pellets and the tunnel plug.

The operations above are illustrated in chart "Section 3.2.5 and 3.2.6 HLW-DGR Encapsulation and disposal operations".

3.2.7 **Closure**

Closure comprises dismantling of man-made structures (e.g. shotcrete, steel meshes, drainage pipes, etc.), systems and building technology in the main tunnel, technical rooms, shafts and the access tunnel followed by backfilling and plug constructions in the tunnelways and shafts. With the deposition holes and tunnels, closure will take place along with the disposal progression.

In regard to deposition holes and tunnels, closure has been tested in the prototype repository in Äspö and in the FISST procedure in ONKALO. For the main tunnel and the access tunnel and shafts, the corresponding tests have not taken place yet. However, similar technologies with the deposition tunnel operations will be applied with rest of repository as well. Closure technology used in ore mines are also applicable suggesting the TRL value 9 for closure of a repository. Note that the closing of deposition holes and tunnels are part of disposal operations (Section 3.2.6).

3.3 TRL for LILW repository

3.3.1 **Overview of the assessment**

The entire TRL assessment for LILW disposal is elaborated in Table 3-2, and in chart "Section 3.3 TRL for LILW disposal" in the attached PowerPoint. The same chart is also presented in small scale in Figure 3-2. More detailed justification for the TRL scores is presented in the following sections.

It is noted that the TRL assessment is based on the operating LILW repositories in crystalline rock, representing corresponding geological conditions as in Norway. Thus, the technologies used for instance in Finland and Sweden are applicable to the planned repository in Norway. More detailed justification for the scores is presented in the following chapters.

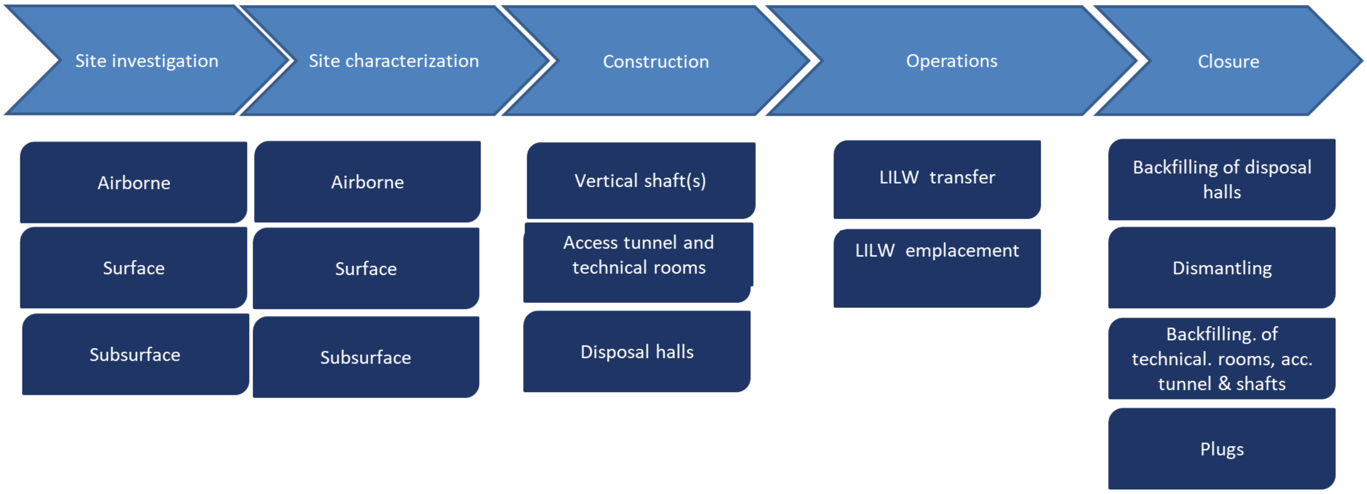

Figure 3-2. Summary of LILW TRL assessment. Please refer to the attached PowerPoint file for the full resolution chart.

Table 3-2. TRL assessment for the LILW disposal.

PHASE OF THE LILW	TRL	TRL DEFINITION	JUSTIFICATION
Site investigation			
Airborne	9	"Actual technology proven through successful deployment in an operational environment"	Airborne technology (geophysical surveys) has been applied in site investigations since late 1970s/1980s (e.g. SKB, Posiva)
Surface	9	–II–	Technology of surface geophysical investigations have been applied similarly as airborne investigations
Subsurface	9	–II–	Deep borehole drillings and related technology to characterise host rock have been applied in repository siting since late 1970's
Site characterization			
Airborne	9	–II–	–II–
Surface	9	–II–	–II–
Subsurface	9	–II–	–II–
Construction			
Access tunnel & technical rooms	9	–II–	Olkiluoto VLJ 1992, Loviisa 1997
Vertical shafts	9	–II–	Ventilation and personnel shafts have been completed in Olkiluoto VLJ in 1992, in Loviisa in 1997
Disposal halls (silos)	9	–II–	Completed at Olkiluoto in 1992, at Loviisa 1997
Operations		–II–	
LILW transfer	9	–II–	Started at Olkiluoto in 1992, at Loviisa at 1997
LILW emplacement	9	–II–	Started at Olkiluoto in 1992, at Loviisa at 1997, SFR 1988
Closure			
Backfilling of disposal halls (silos)	9	"Actual technology proven through successful deployment in an operational environment"	Backfilling materials and technology have been tested in the FISST and in Prototype repository.

Dismantling	9	–II–	Reference can be made to the prototype repository and FISST
Backfilling of technical rooms, access tunnel & shafts	9	–II–	Backfilling materials and technology in disposal tunnel have been tested in the FISST and in Prototype repository. Examples can be found from decommissioning of mines?

3.3.2 Site investigations

Airborne, surface and subsurface investigations for LILW repository siting have been applied in Sweden and Finland since 1970's when investigations started to locate sites for repositories close to nuclear power plants in Forsmark and in Olkiluoto. Corresponding technology in investigations has been applied as with the siting of a KBS-3 type repository. TRL score is 9.

3.3.3 Site characterization

For site characterization, the same technology has been applied as with the site investigations. TRL score is 9.

3.3.4 Construction

Construction comprises access tunnel, technical rooms, vertical shaft and disposal halls (or silos). In Sweden and Finland LILW repositories have been constructed in the 1980's and the technology applied is well proven in the operational environment. TRL score is 9.

3.3.5 Operations

Operations comprise LILW transfer to and emplacement in the repository. SFR in Sweden was taken into operation in 1988 and VLJ repository in Olkiluoto in 1992. Technology for LILW transfer and emplacement is well proven with several decades of experience of these operations. The TRL score is set to 9.

3.3.6 Closure

Underground LILW repositories that meet today's safety standards have not been fully closed (completely decommissioned) anywhere. LILW repositories constructed in crystalline rock are operational worldwide, like in Sweden and Finland where not even partial closure of disposal halls or silos have taken place. Although practical experience of full closure is lacking in the repository context, materials and technology are well proven in connection with closure of test deposition tunnels in Äspö hard rock laboratory and in the ONKALO facility. In addition, well proven technology for closure have been applied in decommissioning of ore mines, justifying the TRL score 9 for closure.

3.4 TRL for HLW-DBD

3.4.1 Overview of the assessment

The entire TRL assessment for the HLW-DBD concept presented in Table 3-3, and in chart “Section 3.4 Overview of TRL for HLW-DBD” in the attached PowerPoint. Same chart is also presented in small scale in Figure 3-3. More detailed justification for the scores is presented in the sections below.

Several of the technical components that are required for the implementation of the deep borehole disposal have already been used for years in other industries (such as drilling). The technological components have proven their usability and efficiency within this time. There are a couple of recent deep borehole projects that can be mentioned, such as KTB in Germany and ST1 project in Finland. In Finland, a depth of 6.4 km has been reached with a diameter of 0.31 meters. To a depth of 2.9 km, the borehole diameter was 0.448 meters. The knowledge and technical understanding from these can be applied to the deep borehole disposal concept. Still, the experience is limited and the required drill bit sizes are probably not directly commercially available but would need to be custom-made. This results in generally relatively high TRL score.

The TRL assessment for HLW-DBD is visually presented in charts “Section 3.4.3 HLW-DBD construction”, “Section 3.4.4 HLW-DBD Operation” and “Section 3.4.5 HLW-DBD Closure”. The following tables provide the details for the TRL assessment with justification for each TRL score. At the end of the Section additional information for selected components are also provided.

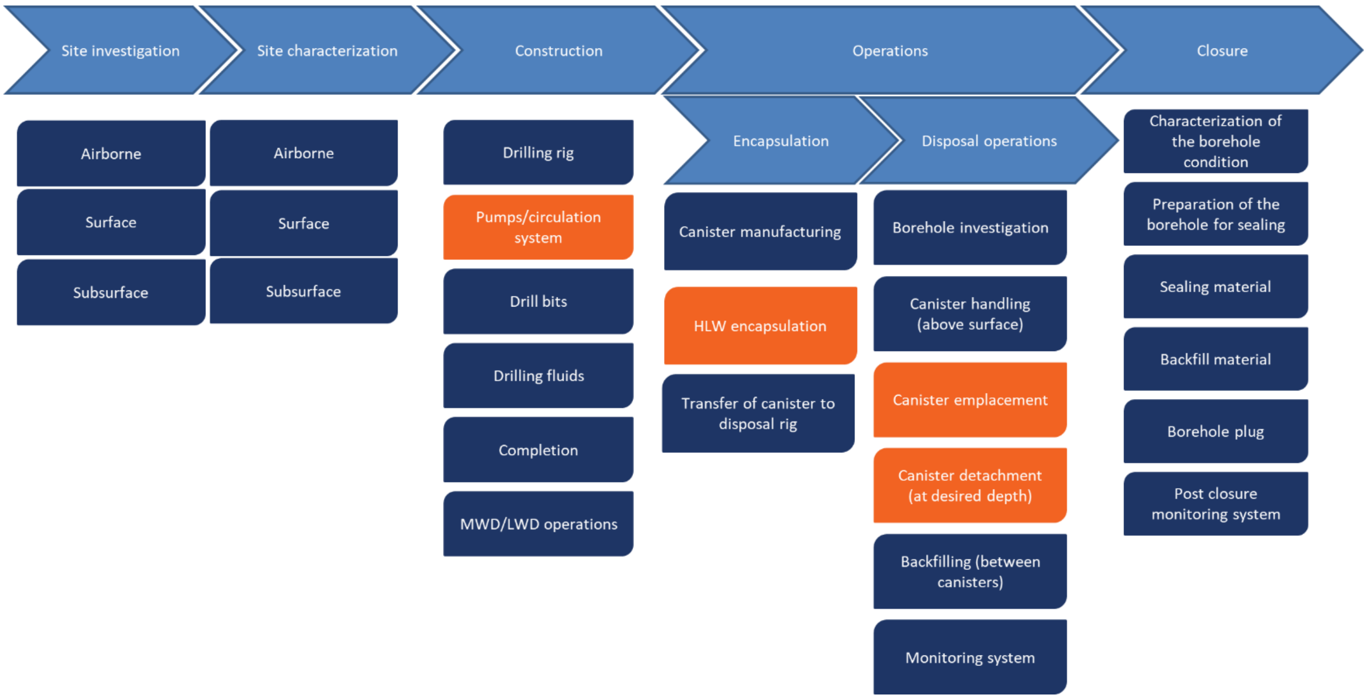

Figure 3-3. Summary of HLW-DGR TRL assessment. Please refer to the attached PowerPoint file for the full resolution chart.

Table 3-3. TRL assessment of HLW-DBD.

PHASE OF THE HLW-DBD	TRL	TRL Definition	JUSTIFICATION
Site investigation			
Airborne	9	”Actual technology proven through successful deployment in an operational environment”	Airborne technology (geophysical surveys) has been applied in site investigations since late 1970s/1980s (e.g. SKB, Posiva).
Surface	9	–II–	Technology of surface geophysical investigations have been applied similarly as airborne investigations.
Subsurface	9	–II–	Deep borehole drillings and related technology to characterise host rock have been applied in repository siting since late 1970’s.

PHASE OF THE DBD	TRL	TRL Definition	JUSTIFICATION
Site characterization			
Airborne	9	–II–	–II–
Surface	9	–II–	–II–
Subsurface	9	–II–	–II–

PHASE OF THE HLW-DBD	TRL	TRL Definition	JUSTIFICATION
Construction			
Drilling rig	9	–II–	Rigs are available in different sizes and with different equipment. The limiting factor will most likely be the hookload, here commercially 420 ton rigs are available and commonly in use. This should be sufficient to handle the upcoming loads. Other parts like the blowout preventers are commercially available in sizes of at least 30" (76 cm). Larger tools can be manufactured individually, since the basic technology is already available and has proven its usability.
Pumps/circulation system	6	”System and/or process prototype demonstrated in a simulated environment”	Pumps with the required power are available. They are not used currently, since there is no need for that. The pumps and overall circulation system only need to be merged and coordinated with the rigs.
Drill bits	8	”Actual technology completed and qualified through tests and demonstrations”	Hammer drill bits are available and used in the required sizes (ST1 borehole). In case other drilling techniques are planned to be used, sizes need to be checked.
Drilling fluids	9	”Actual technology proven through successful deployment in an operational environment”	Drilling fluids for all kind of different operations, formation types and geochemical environments are available. For every operation, the drilling fluid will be designed individually according to the requirements.

Completion	8	”Actual technology completed and qualified through tests and demonstrations”	Larger diameter casings used commercially (especially in the upmost sections of boreholes), therefore the casings are available. Adaptations (wall thickness and material) might be required in order to withstand the formation pressures.
Hole characterisation	9	“Actual technology proven through successful deployment in an operational environment”	Commercially applied in drilling operations, larger diameter will be beneficial for the tools, since more space is available for the technology.

PHASE OF THE HLW-DBD	TRL	TRL Definition	JUSTIFICATION
Operation			
Packaging			
Canister manufacturing	7	”Prototype system ready (form, fit and function) demonstrated in an appropriate operational environment”	Full-size canisters have been manufactured (fabricated BSK 3 canister dummy; see Filbert et al. 2010), but these are only present prototypes and not the final design which needs to be decided on. The emplacement/detachment concept needs to be considered during the finalization of the design process.
HLW encapsulation	6	”Validation of component(s) in a laboratory environment”	The encapsulation tools exist. Currently Posiva is building an encapsulation plant. An encapsulation plant for DBD could be based on a modified version of Posiva’s encapsulation plant.
Transfer of canister to the disposal rig	7	“Actual technology proven through successful deployment in an operational environment”	Transport of waste canisters is carried out regularly, transport vehicles, preferably remote controlled, might need to be adapted slightly in order to fit to the final canister design.

PHASE OF THE HLW-DBD	TRL	TRL Definition	JUSTIFICATION
Operation			
Disposal operations/emplacement			
Borehole investigation	9	–II–	Investigations of the borehole can be carried out with the help of MWD/LWD tools.
Canister handling (above surface)	7	”System and/or process prototype demonstrated in a simulated environment”	Canisters can be handled with cranes or other vehicles, principle concept can be adapted from the IDR, still more detailed development work required.
Canister emplacement (below surface)	4	”Validation of component(s) in a laboratory environment”	Different concept ideas are available (wireline or drill string) and small scale experimental programs have been carried out (DENKMAL Project, BGE TEC).
Canister detachment (at desired depth)	4	–II–	Deep Isolation has shown that the detachment and retrieval of canisters is possible. This technology needs to be developed further and adapted to larger diameters. Canisters need to be designed accordingly.

Backfilling (between canisters)	9	"Actual technology proven through successful deployment in an operational environment"	Backfilling operations are carried out in conventional drilling (and the related P&A) operations. Different techniques are available and the right option can be selected based on the backfill material.
Monitoring system	7	"Prototype system ready (form, fit and function) demonstrated in an appropriate operational environment"	

PHASE OF THE HLW-DBD	TRL	TRL Definition	JUSTIFICATION
Closure			
Characterization of the borehole condition	9	"Actual technology proven through successful deployment in an operational environment"	Investigations of the borehole can be carried out with the help of MWD/LWD tools.
Preparation of the borehole for sealing	9	–II–	Tools and equipment for the removal of the casing (if necessary) and recutting of the borehole walls are available. Maybe adaptations in regard of the borehole/tool diameter are required.
Sealing material	9	–II–	A wide range of sealing materials are already available, individual adaptations of the mixtures can be easily done, but are most likely not required. The suitable emplacement techniques are available as well and can be selected according to the material.
Backfill material	9	–II–	A wide range of backfilling materials are already available, individual adaptations of the mixtures can be easily done, but are most likely not required. The suitable emplacement techniques are available as well and can be selected according to the material.
Borehole plug	9	–II–	P&A operations in the drilling industry provide a wide range of plugs.
Post closure monitoring system	--	No specification	Here no specification is possible, since the monitoring system bases on the requirements set by the government. Note: the TRL should be relatively high, since a wide range of monitoring systems is available.

3.4.2 Site investigation and site characterization

All three repository concepts require similar site characterization methods. Especially the airborne and surface characterization is the same in all three concepts. Slightly different will be the subsurface characterization, since here the HLW-DBD concept needs to look into significantly deeper regions of the ground. Here, once again the experience and technical expertise from conventional drilling operations in the oil, gas and geothermal drilling can be used. Conventional exploration work from these industries examines and investigates the subsurface down to several thousands of meters, which will be sufficient for the borehole required for the disposal of radioactive waste. Therefore the TRL score is set to 9.

3.4.3 Construction

The construction of the borehole and therefore the disposal facility can be subdivided in order to provide a high-level TRL assessment. In this case six components or techniques which are essential for the creation of the borehole are considered. Each aspect is looked at individually and an overall evaluation will shortly be provided afterwards.

Drilling rig:

Examples for drilling rigs which are commercially available and can handle the required loads, as they are expected in the DBD operation, are the HAS Innova Rig (manufactured by Herrenknecht Vertical and operated by Anger's Söhne) and the Euro Standard Rig (operated by benTEC).

Most tools are manufactured specifically for the operation, adaptations can be made individually and will not pose a problem and a resulting reduction of the TRL.

Examples/references:

- HAS Innova Rig - Anger's Söhne (angers-soehne.com)
- https://www.bentec.com/rigs/euro-rigs/stationary-standard-euro-rig/stationary-standard-euro-rig.html

Pumps/circulation system:

Most rigs are put together modularly, especially parts like the pumps can be exchanged relatively easily, in order to fit the requirements of the operation. Since more powerful pumps are available on the market, the right dimensioned pumps only need to be merged with the drilling rig in order to ensure the circulation of the fluids and maintain a stable borehole. The comparably low TRL can be explained by the fact that rigs have not yet or only rarely been operated with such powerful pumps and thus there is hardly any experience available.

Examples/references:

- https://www.herrenknecht-vertical.com/fileadmin/herrenknecht-vertical/06_Media_Downloads/01_Data_Sheets/02_Components/HK2686_DB_HVG_Mud_pumps_TSP_1804.pdf
- https://www.bentec.com/equipment/mechanical-drilling-rig-equipment/mud-pumps/mud-pumps.html

Drill bits:

The Gas Storage Well Project in Pennsylvania, Eastern United States, contains a large diameter borehole. For this operation, the company Numa Hammers provided the bits. The only downside here is that the hammer drilling method was used. Still, the potential damage from hammer bits is still less than formation damages caused by the drill and blast method, which is used in mined repositories (DGR).

Examples/references:

- https://www.numahammers.com/projects/gas-storage-well-project/

MWD/LWD operations:

Many MWD and LWD tools are produced according to the requirements. The techniques are available, only their diameter need to be increase. In this case, this can be beneficial, since a greater diameter will mean more space for the technical elements.

Examples/references:

- Schlumberger
- Halliburton
- Weatherford

3.4.4 **Operations**

The operations comprise not only from the canister emplacement in the borehole, but also include the placement of backfilling between the canisters. In addition, the transfer of the canisters from the encapsulation plant to the disposal hole are included in the disposal operations.

For the transportation of the packages, research and development work has been carried out for several years. Here the experience and knowledge from SKB and Posiva can be used for example.

The actual disposal, which describes the emplacement process of the canisters down to the final position in the borehole, can be seen as the area where most research and development is needed. Even though first techniques and prototypes, like the DENKMAL Project (DBE Technology, 2009) or the disposal demonstration operation by Deep Isolation (2022), have been tested, the systems still have to be adapted to the final conditions and dimensions described in previous reports (Ikonen et al., 2020).

3.4.5 **Closure**

All the closure aspects have a high TRL. They are commonly used in the oil and gas industry. All techniques, materials and equipment are available (or can be adapted).

- **Note**: The retrieval of the waste is not considered after backfilling material is introduced to the borehole with the first disposed canister. During the disposal operation, the lowering of the canisters to the desired depth, emergency options are available. Here conventional tools and techniques for fishing operations from the drilling industry can be considered.

3.4.6 Summary

Most of the drilling, completion and closure related techniques are based on experience and knowledge gained from conventional deep drilling operations. As discussed and pointed out for example in Ikonen et al. (2020), Fishcer et al. (2020) and Engehardt et al. (2021) here the diameter is usually significantly smaller than the required borehole diameter to fit disposal canisters. Therefore, many techniques and tools, like the drill bits, MWD/LWD tools and any casing related topics need to be adapted and fully tested for the requirements. Since these tools are sufficiently working and have proven their practicability in hundreds of thousands of commercial operations, the general TRL is at a high rate. Still, considering the overall concept, and the TRL score is lower.

4 TRL AND SAFETY ASSESSMENTS

Safety assessment is not a technology per se as it relates to TRL. This is similar to for example repository engineering or the performance of EBS. They rely on technology by providing them input data for design or long-term analysis. This section presents a discussion on the differences between safety assessments of the studied repository types. It does not provide TRL type rating of their maturity level.

A radioactive waste disposal facility is aimed (see e.g. IAEA 2011, p.3)

- (a) To contain the waste;
- (b) To isolate the waste from the accessible biosphere and to reduce substantially the likelihood of, and all possible consequences of, inadvertent human intrusion into the waste;
- (c) To inhibit, reduce and delay the migration of radionuclides at any time from the waste to the accessible biosphere;
- (d) To ensure that the amounts of radionuclides reaching the accessible biosphere due to any migration from the disposal facility are such that possible radiological consequences are acceptably low at all times

The importance of each of the above mentioned aims and the extent to which and the way in which they are accomplished varies significantly between disposal concepts and repository types: HLW-DGR, HLW-DBD and LILW.

There are several operational LILW facilities in numerous countries. For the purpose of licencing of such facilities related safety assessments and safety cases have been conducted. Each facility has different waste inventories, however the process and expertise in conducting safety assessments exist. These can be adapted and used in the Norwegian situation as well. The safety assessment related to LILW is not discussed further in this section.

Several assessments of the long-term safety of HLW-DGR (KBS-3) repositories have been conducted by Posiva (TILA-99, TURVA-2012) and SKB (SR-CAN, SR-Site 2011) over the years. The most recent one (TURVA-2020) is the safety case prepared for the operation licence application of ONKALO repository in Olkiluoto in late 2021. In these safety cases the disposal depth is around 400-500 meters.

Regarding deep borehole disposal (HLW-DBD), a site-specific safety case is still lacking but generic studies on the safety of the concept has been prepared (Brady et al. 2009, Freeze et al. 2013, 2019). Currently, NND is carrying out a generic safety assessment for DBD in crystalline rock. The suggested disposal depth for DBD is about 2 to 3 km.

In the HLW-DGR method, the safety depends primarily on the containment of the spent fuel in the copper-iron canisters and its long-term isolation in the bedrock. The longevity of the canister is supported by favourable near-field conditions and the well-characterised material properties and proven technical quality of the engineered barriers including the buffer that protects the canister against both chemical and mechanical impacts. The location of the repository at sufficient depth in the rock and the favourable and predictable conditions in the host rock contribute to the favourable near-field conditions for the canister. However, should the canister lose its containment function and radionuclides released, the secondary safety features supporting the retention and retardation of radionuclides become important. Such safety features are slow release from the spent fuel matrix, slow diffusive transport in the buffer and slow transport in the geosphere. That is, the role of the buffer is very important in protecting the canister, and in case of canister failure in retarding the transport of radionuclides to the geosphere.

Within the HLW-DBD concept, the role of retardation due to depth is much more pronounced than in the HLW-DGR concept. According to current design, the canister lifetime is expected to be significantly shorter than with the KBS-3 canister. Because of the material (e.g. austenitic or duplex steel) and structural (thinner canister wall) reasons, it is expected that HLW-DBD canister may lose its integrity by corrosion in 1000 – 10 000 years (Wunderlich et al. 2021). The corrosion rate can even be more accelerated in brines with high chloride that may be present at the planned disposal depths. Neither the buffer surrounding the canisters is planned to be as tight as in the HLW-DBD concept partly due to installation reasons and partly because the concept relies heavily on the depth of burial. However, the buffer can still retard radionuclides and other engineered barriers like plugs can be used to prevent or limit the deep borehole itself to become a significant transport route or part of such. Further on, the host rock should provide stable conditions and be able to retard the released radionuclides. The groundwater at disposal depth is substantially stagnant due to the density stratification that the salinity of the groundwater provides in combination with the low permeability of the rock. On the other hand, saline conditions will also impair flow and diffusion resistance of bentonite buffer surrounding canisters in deep borehole.

In order to bring the understanding of the expected evolution of deep borehole repository closer to the level of the HLW-DBD concept, more geoscientific data from great depths in crystalline rock and specifically at the disposal site, are needed. The assumption that the strength of the host rock is higher and the permeability lower at the disposal depth of 2-3 km than compared with the rock at disposal depth of HLW-DGR (400-500 meters), may require less characterisation holes. On the other hand, the large depth as such is a challenge, not for the characterisation of the host rock itself, but for the characterisation of any fracture that may intersect it. Attention should also be paid to not disturbing the site, and for the near field rock, the deep borehole itself is the primary source of information. As a result, the knowledge of the host rock will remain more limited with the HLW-DBD concept, and it seems likely that the safety case will include more uncertainties and assumptions compared to HLW-DGR disposal. In addition, studies on the performance of the engineered barriers in the conditions relevant for HLW-DBD are needed. For example, Brady et al. (2009), in their safety assessment for a single disposal borehole indicated that radiological dose to a human receptor via the groundwater pathway would be limited to a single radionuclide (I-129) and would be negligibly small, approximately 10 orders of magnitude below the current regulatory criteria for Yucca Mountain. In that analysis, the mechanism considered for upward movement of fluid was thermal expansion of formation fluids but scenarios such as errors in emplacement or borehole seal(s) failure were not considered.

From the HLW-DBD post-closure safety point of view, a central issue is the definition of the initial state of the disposal system. Disposal system is an entity composed of the repository, the seals and plugs and the surface environment. A detailed description of the initial state of the HLW-DBD disposal system is the basis for the safety case. The initial state refers to the last controllable and documentable properties of disposal system. The time when a part of a repository can be considered be in its initial state is not self-evident but must be defined in the safety analysis.

The initial state of the sealing system in the HLW-DGR concept is easier to attain because compliance with requirements of seal installations can be more easily inspected than in the HLW-DBD concept. Within the HLW-DGR concept, deposition of each canister will be followed and documented by cameras, allowing to detect possible failures in the process. Corresponding procedures can be developed for HLW-DBD as well, but inspection may be more challenging because of the depth and overlapping placement of the canisters and the surrounding buffer. Undetected failures in the EBS installation within the HLW-DBD concept can lead to deviations from the required initial state.

From the operational safety point of view, a canister getting stuck in the borehole during disposal cannot be ruled out. With the HLW-DGR concept, retrieval of disposed of canisters have been described and taken into account in the repository design. Corresponding preparedness is also needed for the DBD, including a scenario quantifying the possible radiological consequences of the failure already during the operational phase in the underground part.

5 DISCUSSION AND RECOMMENDATIONS

The TRL assessment is based on the expert judgement of the project team (authors of the report). TRL scoring is not strictly scientific or analytic but based on subjective assessment of the technologies. It was aimed that each TRL score would be consistent with the other TRL scores in this work.

The TRL assessment for HLW-DGR was mainly based on the technologies planned to be used in the KBS-3 concept in Finland and in Sweden. The Norwegian HLW inventory is small and technical solutions for encapsulation (canister, fuel handling cell, welding) can be simplified compared to the KBS-3 concept, which is highly automated and industrialised. Therefore in some instances the score for NND's concept is lower compared to the same technical component in Finland, as some development may be needed to adapt the components to the Norwegian disposal concept.

The HLW-DBD concept and its technology are fairly simple compared to the HLW-DGR. There are several technical components that are used daily in the industry, such as drilling of deep holes, and borehole sealing and plugging. Those techniques can directly be used, or with some modifications, in the HLW-DBD concept. The greater depth required in HLW-DBD compared to HLW-DGR, poses some challenges in the site investigation. However, it is not foreseen that new techniques need to be developed. Site investigation shall rely more on techniques that have deeper penetration. Various geophysical investigation methods exist that can be used.

<u>HLW-DGR main development needs</u>

- The current concept for HLW-DGR differs partly from the KBS-3 disposal that is highly developed. The main differences, and hence development areas are related to the canister handling during the encapsulation process and during the disposal operations.
- Emphasis on these two topics should be placed if the concept is decided to be used in Norway. However at this stage there is no urgency for the development.

<u>For HLW-DBD main development needs</u>

- Purpose designed HLW-DBD canister (when there is decision on the HLW waste form)
- Refinement to the encapsulation process (for example the design of the cask, which should be done after the concept for the canister design has been decided)
- Main development need is related to the disposal operation: tools and methods how to take the canister from the surface to the desired disposal depth, and how to place buffer between canisters. This development work should take place, in some capacity at least, prior to the decision on which HLW disposal concept will be chosen in Norway.

Any development work should ideally use and adapt as much as possible the tools and techniques available in the mechanical heavy industry or similar. This will make the licensing easier, and would have positive effect on the timelines and budgets.

Several of the process components have high TRL score. The components were assessed individually and hence scored individually. Sometimes TRL score is presented as single score to the entire system (for example for the entire disposal operation or for the lifetime of the facility). However this presentation does not provide additional information on the system and the potential needs for example for R&D of the components. Though it can be used as a basis for communication. However how one deduces a single higher-level TRL score from the lower-level components is not defined. One can use weighted average, or conservatively, the high-level TRL of the entire system is the same as the lowest TRL score of all the sub-components.

DOE (2011) uses TRL to distinguish between various design phases of a development project. They state that a project can commence Concept Design phase when the TRL score is 4. Preliminary Design is from TRL score 6. Using their approach, all of the analysed disposal concepts are mature enough for the Concept Design phase (IAEA: Generic Design phase). And in most parts the disposal concepts are ready for the Preliminary Design phase (IAEA: Conceptual Design phase).

Sevougian & MacKinnon (2017) discussed thoroughly if and how TRL assessment could be applied to geological repositories. They strongly emphasised that TRL is only an indicative tool for identifying technologies or processes in pre-closure phase that may need further development. Their advice was to rely more on FEPs (Features, Events and Processes) in the assessment of the performance and maturity of a repository system. They summarised: "*TRLs provide a measure of the maturity of particular technology, they cannot be used as the sole basis for comparing competing technologies, since, by itself, TRL does not assess the risks, schedule, or costs of advancing a particular technology to its needed maturity.*"

TRL is only one tool that can be used as part of a bigger picture to evaluate if a concept is mature enough to be implemented in practice. It is advised against to use TRL scoring in direct comparison of concepts. The scoring does not indicate the amount of effort (time and money) to raise the score from lower to higher value. It does not show whether the required effort is 1000 NOK and a week of work or a 10-year long massive R&D programme.

TRL can be used to identify the differences in the development needs between different concepts and then further to analyse the R&D needs to raise the TRL scoring. This can be then used in the concept choice study to guide the decisions.

TRL assesses the maturity of technologies. Whether the technology is applied correctly and appropriately in practice is not part of the assessment. These fall under experience, expertise, know-how and the capacity of an organization.

Nuclear waste management is unique industry, especially the disposal of spent nuclear fuel in small scale, such as in Norway. Therefore it is worth considering whether "test" or "demonstration" activities/operations are already good and mature enough for the purpose of disposing the waste. The goal of the waste management programme is not to commercialise/industrialise the process/service as such. Therefore lower TRL scores might be acceptable in the small scale disposal programme.

6 CONCLUSION

In the work a Technical Readiness Level (TRL) assessment was conducted for three repository concepts that are currently considered in Norway. These are two types of HLW repositories: HLW-DGR (mined repository) and HLW-DBD (deep borehole disposal), and LILW repository. The assessment looked into the main phases of the repository lifetime: site investigations and characterisation, construction, operation and closure.

The assessment found out that most technologies and components are fairly mature. There are some development areas that were highlighted in the work. Especially HLW-DBD needs some development work before it is feasible to make the final decision on which concept will be chosen in Norway.

The TRL assessment can be used in communication to clarify which portions of the concepts are sufficiently developed to be implemented and which might need some additional work. This can be used to focus the potential research and development work. Partly, and cautiously, the TRL assessment can be used as an input to the overall comparison of the different disposal concepts.

7 REFERENCES

"Technology Readiness Assessment Guide," U.S. Department of Energy, DOE G 413.3-4A, 9-15-2011, 2011.

Anderson, Carly (2020) Tools for Technology Evaluation – An Introduction to Technology Readiness Levels. Published in Prime Movers Lab. April 21, 2020. Accessed March 9, 2022. https://medium.com/prime-movers-lab/tools-for-technology-evaluation-trls-11daec23689

BCIP (2017) Build in Canada Innovation Program Definitions.

Blanc et al. (2017) First-time Implementation of Innovative In situ Biotechnology on an Offshore Platform in Arabian Gulf for Continuous Water Quality Monitoring and Early Leak Detection. SPE-188821-MS.

Brady P. V., Arnold B W, Freeze G A, Swift P N, Bauer S J, Kanney J L, Rechard R P, Stein J S, (2009) Deep borehole disposal of high-level radioactive waste. Sandia report SAND2009-4401, Sandia National Laboratories, Albuquerque, New Mexico.

CloudwatchHUB (2016) A brief refresher on Technology Readiness Levels (TRL).

DBE Technology GmbH (2009) Optimization of SF Direct Disposal by Canister Emplacement in Boreholes – Final Report. DENKMAL Project. TEC-10-2009-AB. FKZ 02E9854.

Deep Isolation (2022) Technology Demonstration. https://www.deepisolation.com/... /technology-demonstration/ last accessed on 20.04.2022.

Engelhardt, H-J, Fischer, T. & Wanne, T. 2021. Sealing of Deep Boreholes in Crystalline Rock. Norwegian National Facility. AINS Group Technical Report. BGE TEC Germany. September 2021.

Ensipire. science (2020) TRL Scale in Horizon 2020 and ERC – Explained. Accessed February 17, 2020.

European Commission (2017) Technology Readiness Level: Guidance Principles for Renewable Energy Technologies.

European Commission (2017a) Technology Readiness Level: Guidance Principles for Renewable Energy Technologies. Annexes.

Filbert, W., Bollingerfehr, W., Heda, M., Lerch, C., Niehues, N., Pöhler, N., Wehrmann, J. (2010). Optimization of the Direct Disposal Concept by Emplacing SF Canister in Boreholes. Peine, German. DBE Technology GmbH.

Freeze, G., Stein, E., Brady, P., Lopez, C.,Sassani, D.,Travis, K. , Gibb, F., Beswick, J. (2019). Deep Borehole Disposal Safety Case. Energies. 12. 2141. 10.3390/en12112141.

Freeze, G.; Voegele, M.; Vaughn, P.; Prouty, J.; Nutt, W.; Hardin, E.; Sevougian, S. (2013) Generic Deep Geologic Disposal Safety Case, SAND2013-0974P, REV 1; Sandia National Laboratories: Albuquerque, NM, USA.

Government of Canada (2022) Clean Technology Data Strategy. Accessed March 9, 2022. Clean Technology Data Strategy - Clean Growth Hub (ic.gc.ca)

IEA (2020) Technology Perspectives 2020: Special Report on Clean Energy Innovation Accelerating technology progress for a sustainable future. International Energy Agency.

Ikonen, A.; Engelhardt, J.; Fischer, T.; Gardemeister, A.; Karvonen, S.; Keto, P.; Rasilainen, K.; Saanio, T.; Wanne, T. (2020) Concept Description for Norwegian National Disposal Facility for Radioactive Waste. Technical Report. Technical Assistance "National Facility". Espoo, June, 2020.

Fischer, T.; Engelhardt, J.; Wanne T. (2020) Deep Borehole Disposal Concept. Technical Report. Technical Assistance "National Facility". Germany. September 2020.

International Atomic Energy Agency (2011) Disposal of Radioactive Waste. Specific Safety Requirements No. SSR-5. IAEA, VIENNA, 2011.

Mankins, J.C. (2007) Technology Readiness Assessments: A Retrospective. 58th International Astronautical Congress – 2007. IAC-07-Session D3.4.04.

Natural Resources Canada (2019) Applicant's Guide for the Clean Growth Program. Appendix D – Technology Readiness Level.

NYSERDA (2018) Technology and Commercialization Readiness Level Calculator Tool. New York State Energy Research and Development Authority.

S. D. Sevougian and R. J. MacKinnon, "Technology Readiness Assessment Process Adapted to Geologic Disposal of HLW/SNF.," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2017.

Saanio, T.; Seppälä, T; Gardemeister, A; Wunderlich, A.; Herold, P, & Wanne, T. (2022) Encapsulation of HLW Canisters – Norwegian National Disposal Facility for Radioactive Waste. Technical Report. Technical Assistance "National Facility". Finland Germany, January, 2022.

Saanio, T; Hagros, A. & Wanne, T. 2021. Site Selection Criteria and Site Selection Process for Norwegian National Facility. Technical Memorandum. Technical Assistance "National Facility". Finland Germany, July, 2021.

Science Media Center Germany gGmbH (2022) Technology Readiness Level – fact sheet. 17.02.2022.

Sermeus, K.; Piperni, P.; Yang, H. (2015) CAE-specific Criteria for Technology Readiness Levels (TRL) in the Industrial R&D Environment. Proc. of 23rd Annual Conference of the CFD Society of Canada Waterloo, ON, June 7-10, 2015.

Svensk Kärnbränslehantering (2019) Fud-program 2019. Program för forskning, utveckling och demonstration av metoder för hantering och slutförvaring av kärnavfall. ISSN 1104-8395, ID 1873202. Stockholm.

TWI Ltd (2022) Was sind Technology Readiness Levels (TRLs)?. Accessed March 9, 2022. https://www.twi-global.com/locations/deutschland/was-wir-tun/haeufig-gestellte-fragen/was-sind-technology-readiness-levels-trls

U.S. Department of Defense (2010) Technology Readiness Levels in the Department of Defense.

U.S. Department of Energy (2010) Standard Review Plan Technology Readiness Assessment Report. 2nd Edition.

U.S. Department of Energy (2015) Technology Readiness Assessment Guide.

U.S. Department of Transportation (2015) Technology Readiness Level.

U.S. GAO (2020) Technology Readiness Assessment Guide. United States – Government Accountability Office. Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects.

U.S. National Science Foundation (2018) Definitions of Research and Development: An Annotated Compilation of Official Sources.

U.S. SBIR (2014) Select Appendices: Appendix A – Technology Readiness Level (TRL) Descriptions. United States - Small Business Innovation Research program.

Wunderlich, A., Seidel, D., Herold, P., Wanne, T. 2021. Deep Borehole Disposal Canister. Germany. AINS Group.

Technical Readiness Level Assessment – Norwegian National Facility

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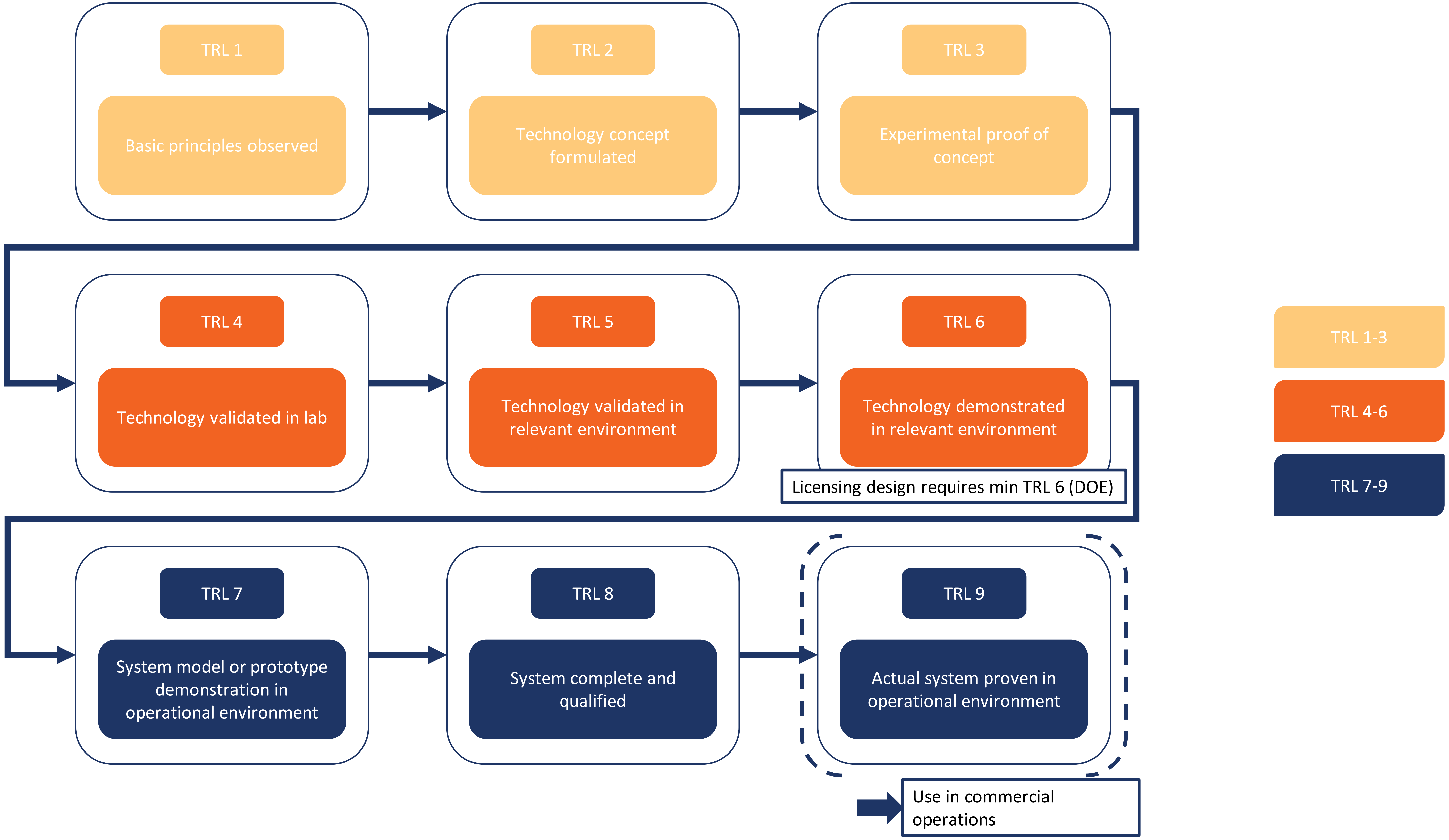
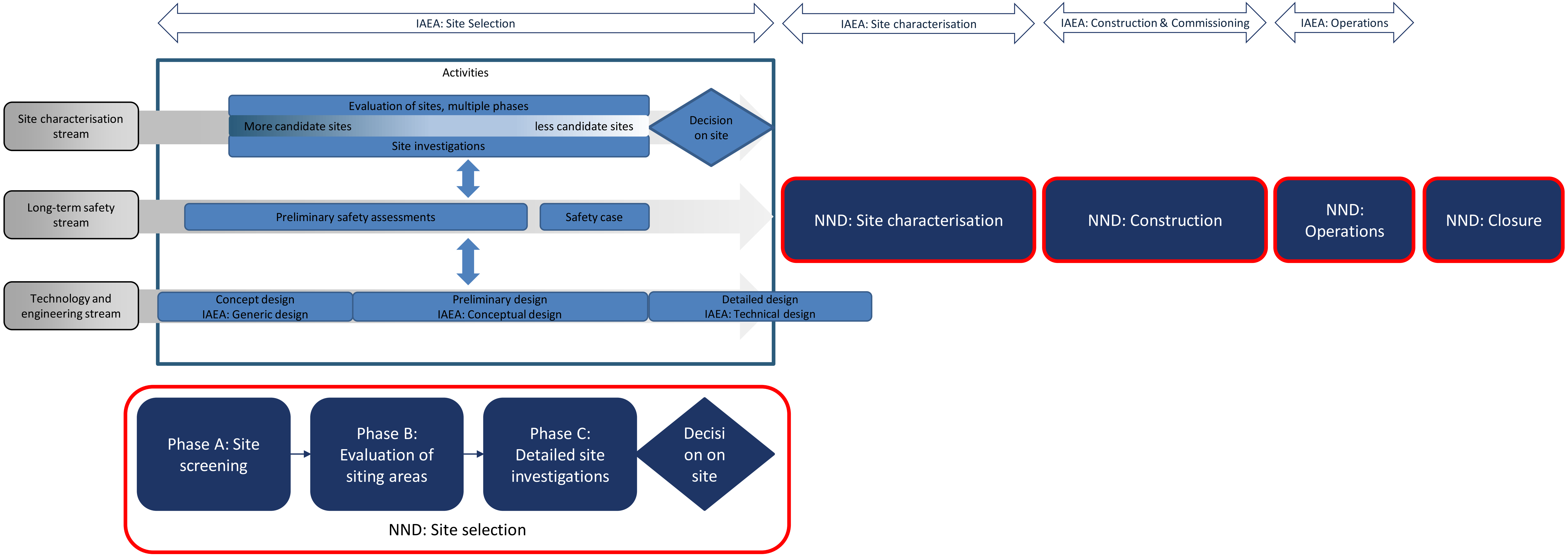
The deliverable is in two parts: This PowerPoint file is complemented with adjoining Technical Memorandum.

Section 1.2 TRL scale



Section 2.1: Main phases for TRL assessment (marked in red)

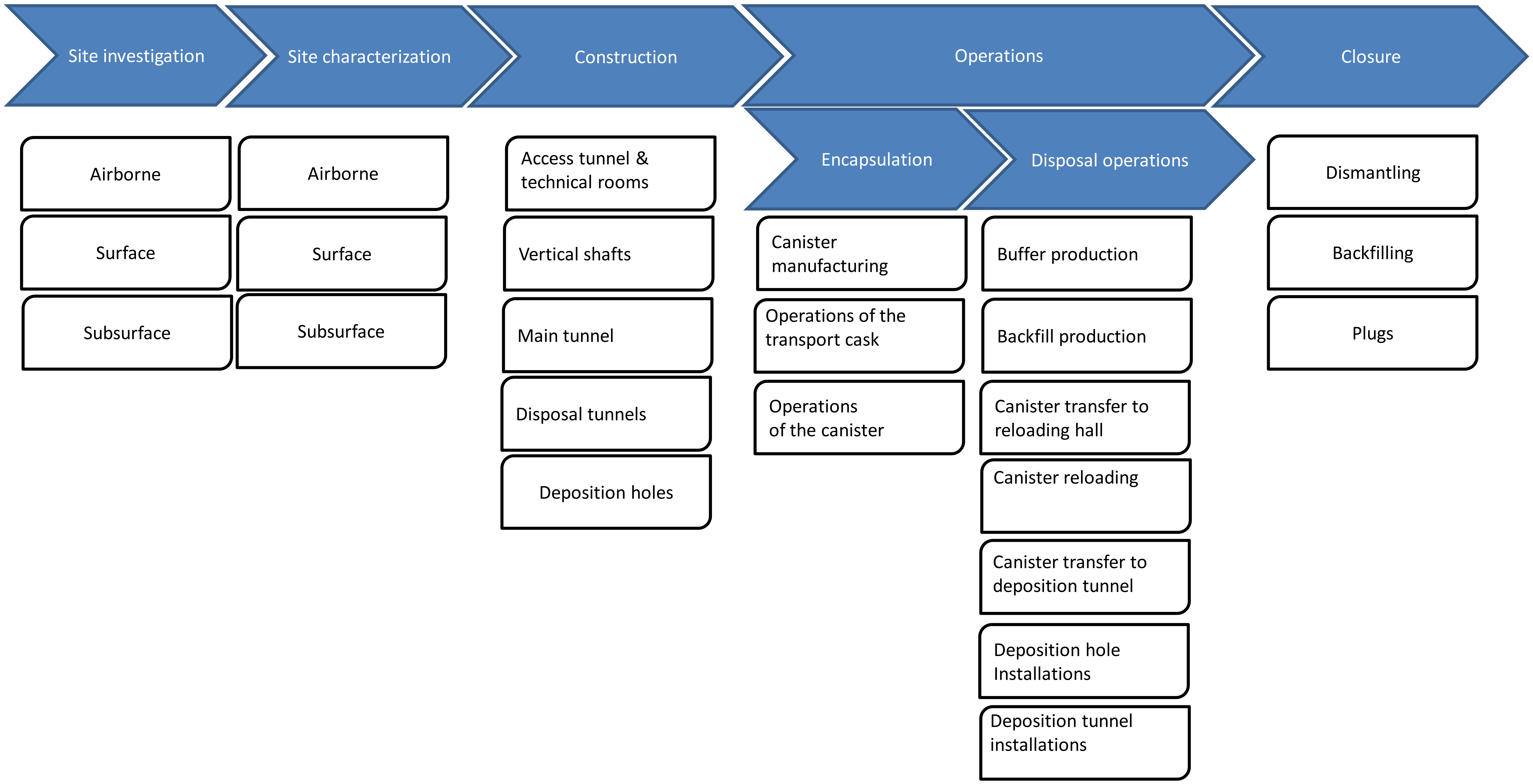


Section 2.1: Main components by phase

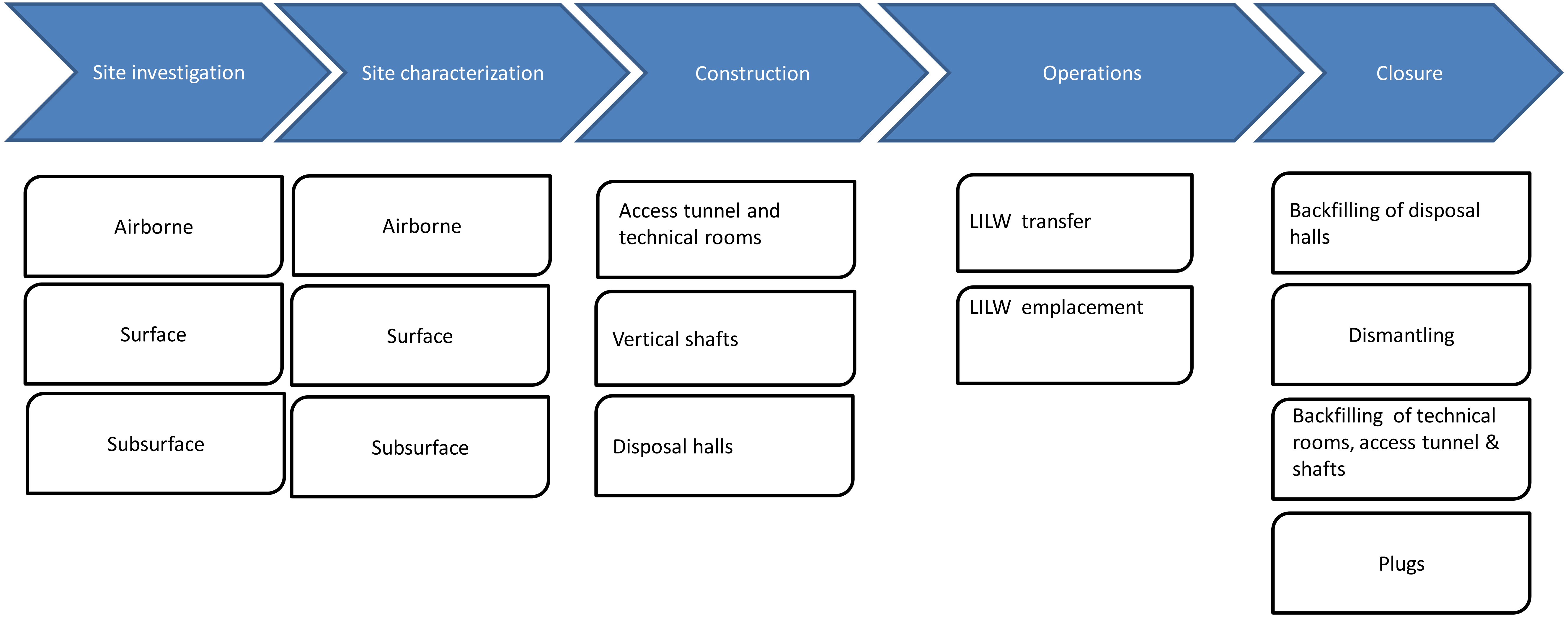
	Site investigations	Site characterisation	Construction	Operations		Closure
HLW-DGR	*Airborne* *Surface* *Subsurface* *(investigation depth ~1000 m)*	Similar to previous phase	Investigations during construction, installation of monitoring systems, shaft and tunnel excavation, systems, etc.	Packaging: Canister manufacturing and HLW encapsulation	Disposal operations: Canister emplacement, buffer installation, and disposal tunnel backfill, etc.	Backfill of tunnels and shafts, plugs and seals, monitoring, etc. (Excluded: dismantling, decommissioning of surface infrastucture
LILW	*Airborne* *Surface* *Subsurface* *(investigation depth ~300 m)*	Similar to previous phase	Investigations during construction, Installation of monitoring systems, shaft and tunnel excavation, systems, etc.	Excluded	Disposal operations: Waste package emplacement, backfill, etc.	Backfill of tunnels and shafts, plugs and seals, monitoring, etc. (Excluded: dismantling, decommissioning of surface infrastructure)
HLW-DBD	*Airborne* *Surface* *Subsurface* *(investigation depth ~4000 m)*	Similar to previous phase	Investigations during drilling, installation of monitoring systems, drilling, casing installation, etc.	Packaging: Canister manufacturing and HLW encapsulation	Disposal operations: Canister emplacement techniques and buffer installation, (casing removal?) , etc.	Casing removal (?), sealing and backfilling of the borehole and final plug. (Excluded: dismantling, decommissioning of surface infrastructure)

Operational and post-closure safety assessments

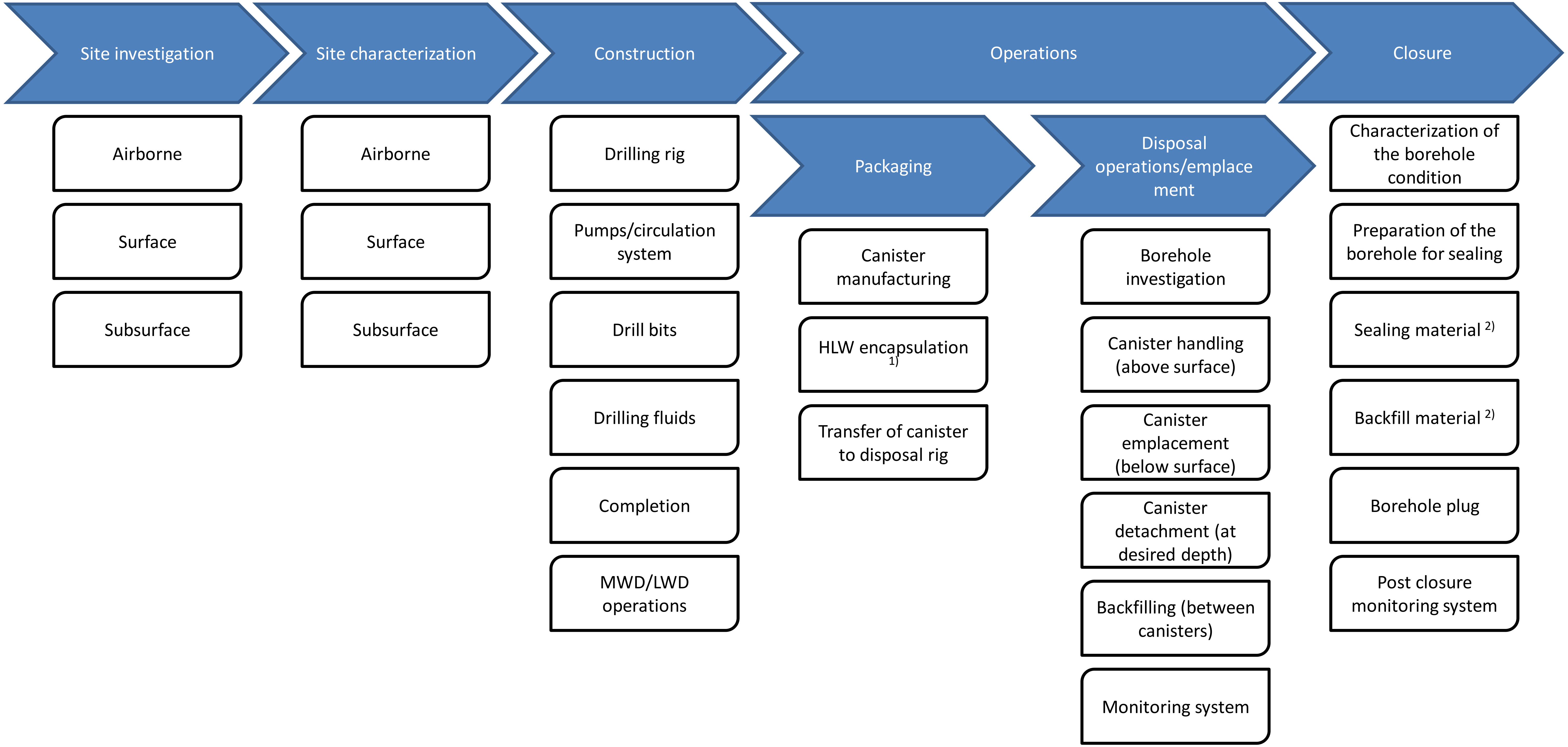
Section 2.2: Main components of HLW-DGR



Section 2.3: Main components of LILW repository

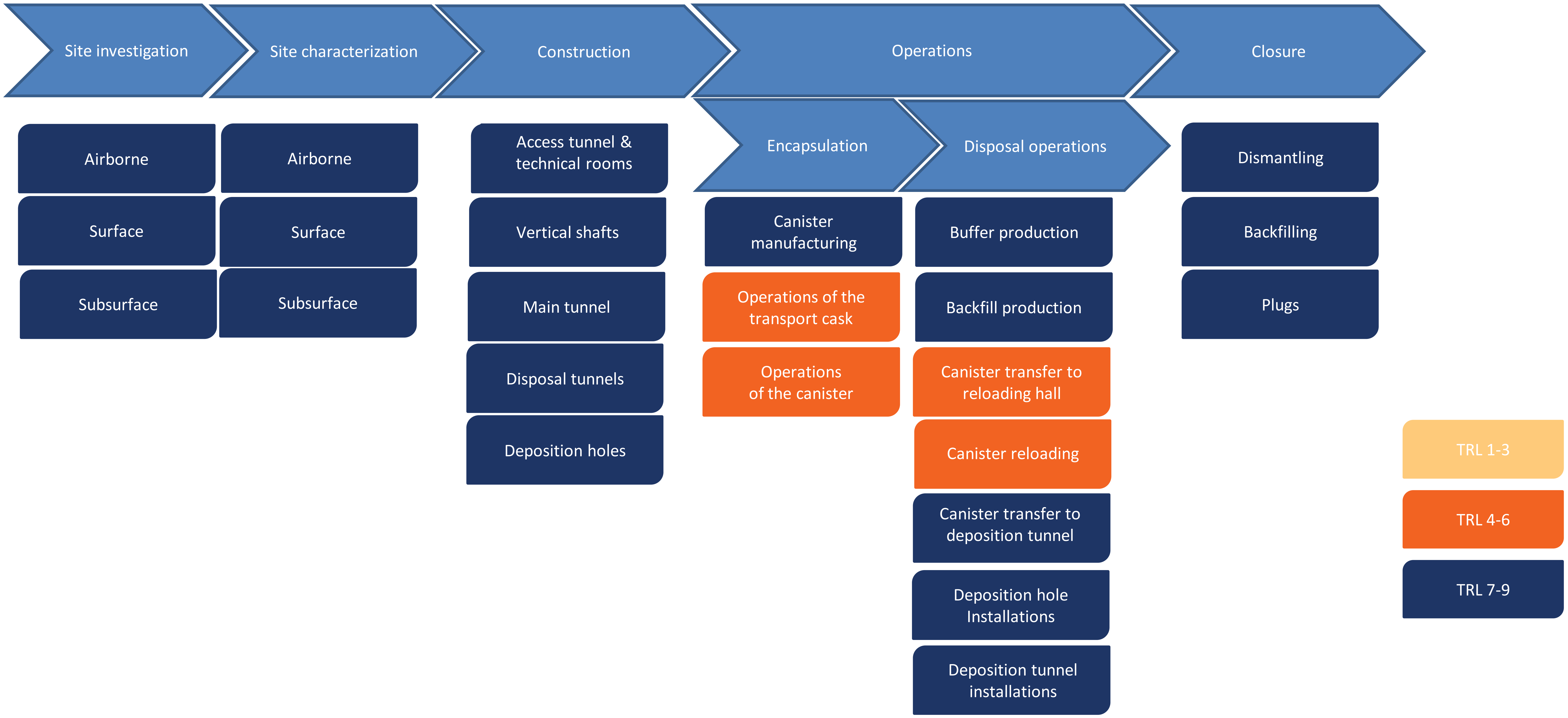


Section 2.4: Main components of HLW-DBD



[1] this includes the fuel handling cell operations, the welding of the canister lid, the non-destructive testing of filled canisters
[2] this includes the material selection as well as the emplacement method

Section 3.2: Overview of TRL for HLW-DGR



Section 3.2.4 HLW-DGR Construction

Construction

- Access tunnel & technical rooms
- Vertical shafts
- Main tunnel
- Disposal tunnels
- Deposition holes

- Excavation
- Building technology
- Systems

TRL 1-3

TRL 4-6

TRL 7-9

Sections 3.25 and 3.26 HLW-DGR Encapsulation and disposal operations

Encapsulation

Canister manufacturing

Operations of the transport cask →

- Cask transfer trolley
- Predocking station
- Fuel handling cell

Operations of the canister →

- Canister transfer trolley
- Fuel handling cell
- Welding of the lid
- Machining
- NDT inspection
- Placement into the canister transport cask

Disposal operations

Buffer production

Backfill production

Canister transfer to reloading hall →

- Canister transport cask
- Canister transport vehicle

Canister reloading →

- Removal of canister from transport cask and reloading to canister transfer and installation vehicle

Canister transfer to deposition tunnel

Deposition hole Installations

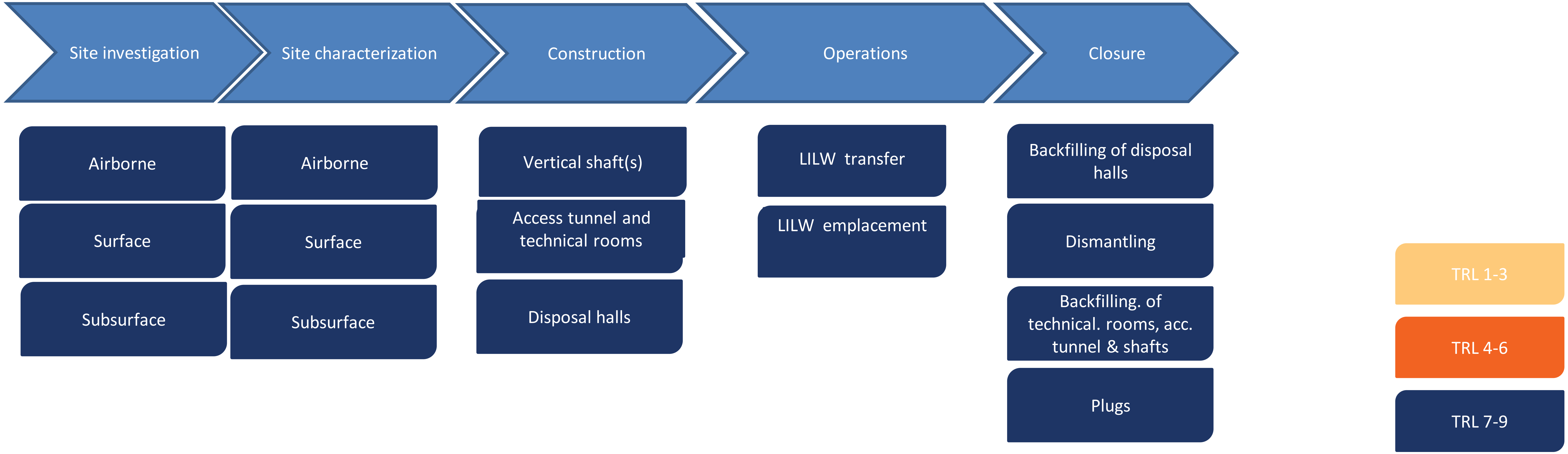
Deposition tunnel installations

TRL 1-3

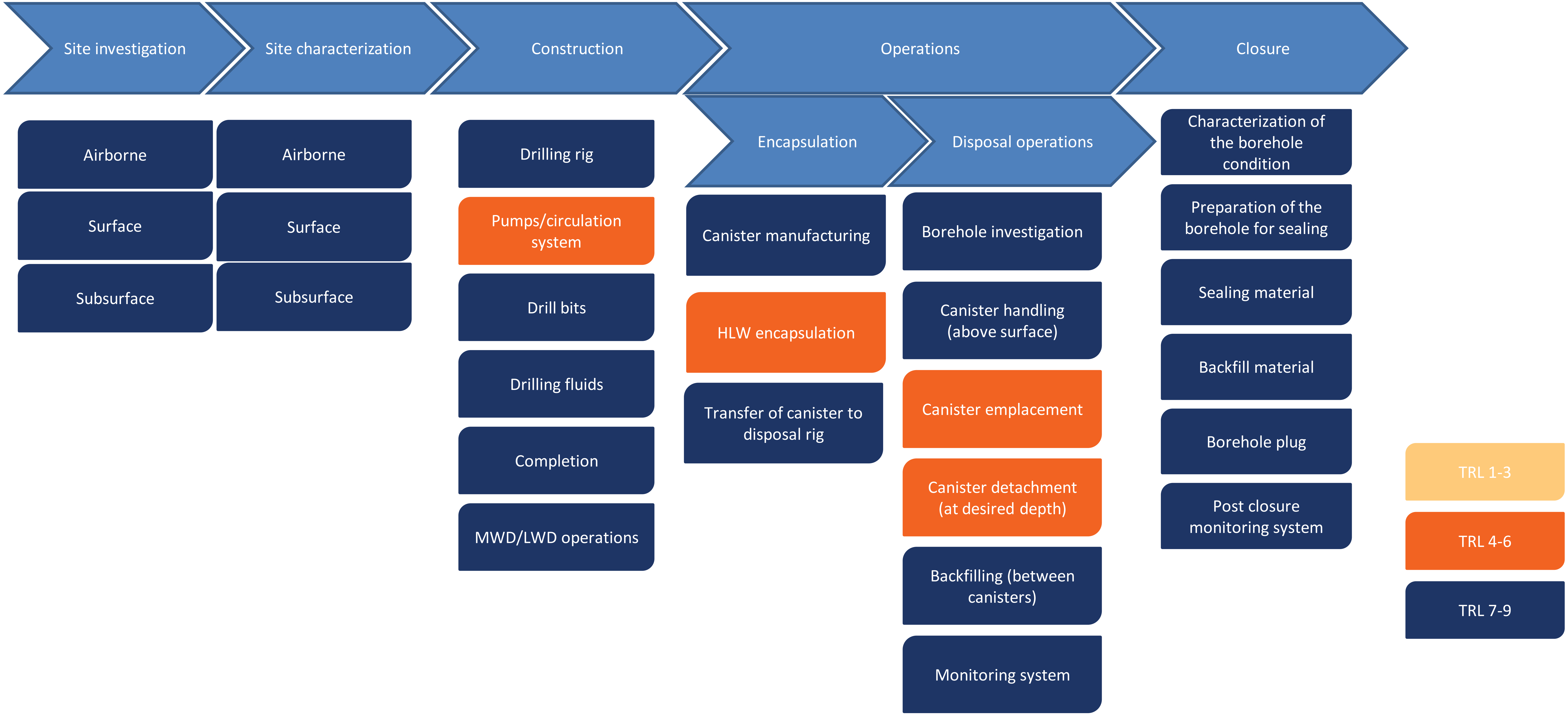
TRL 4-6

TRL 7-9

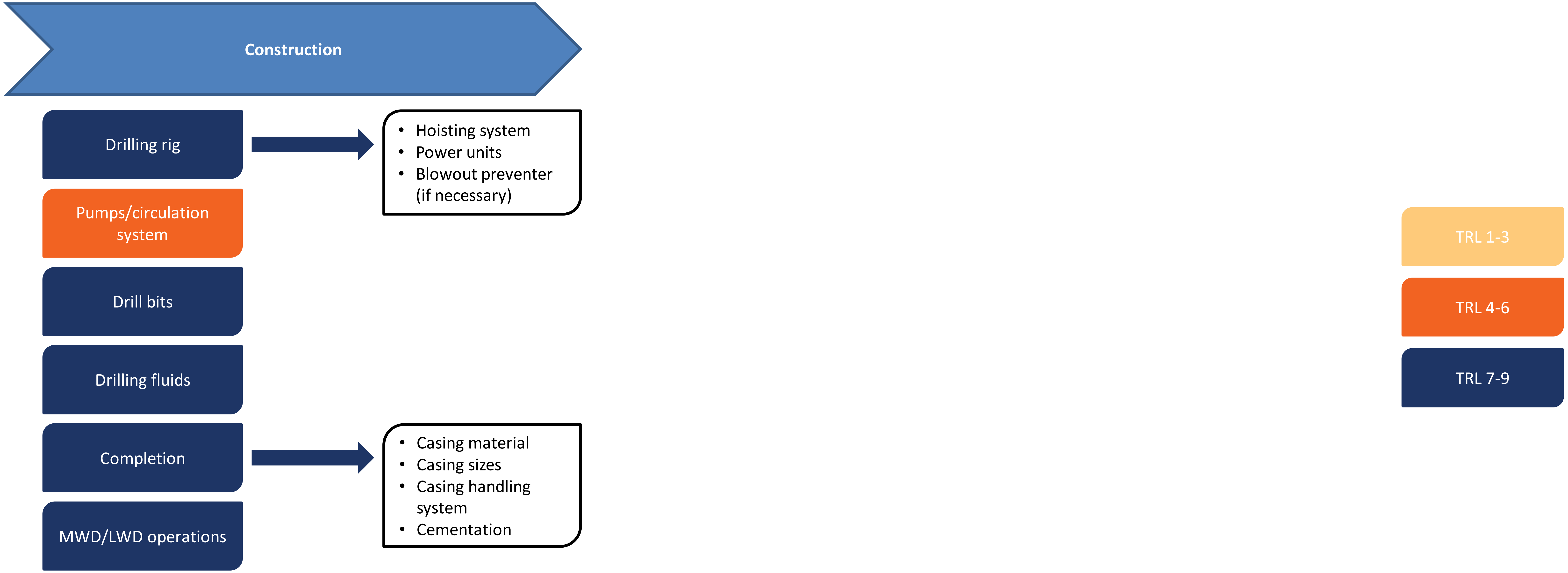
Section 3.3 TRL for LILW disposal



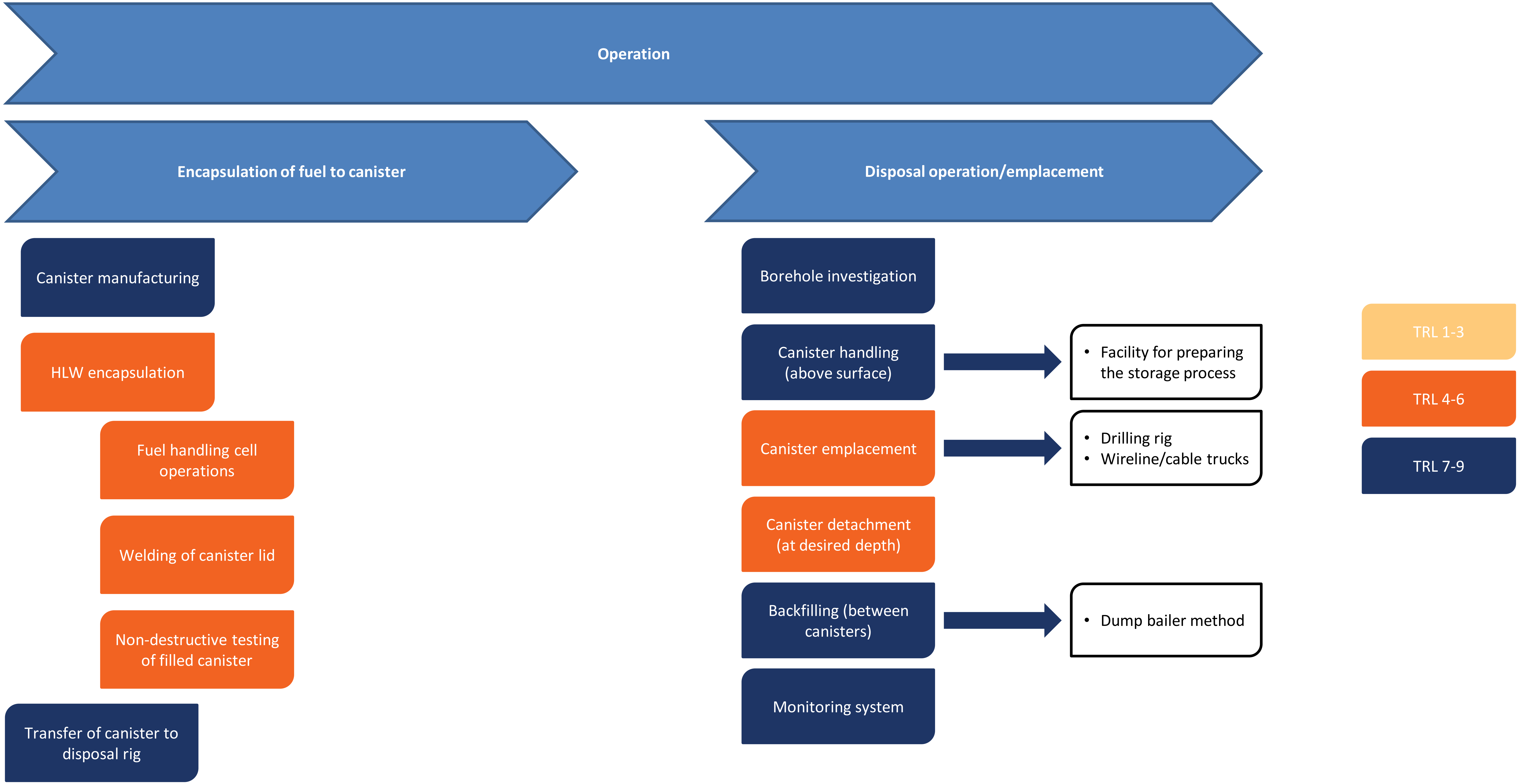
Section 3.4: Overview of TRL for HLW-DBD



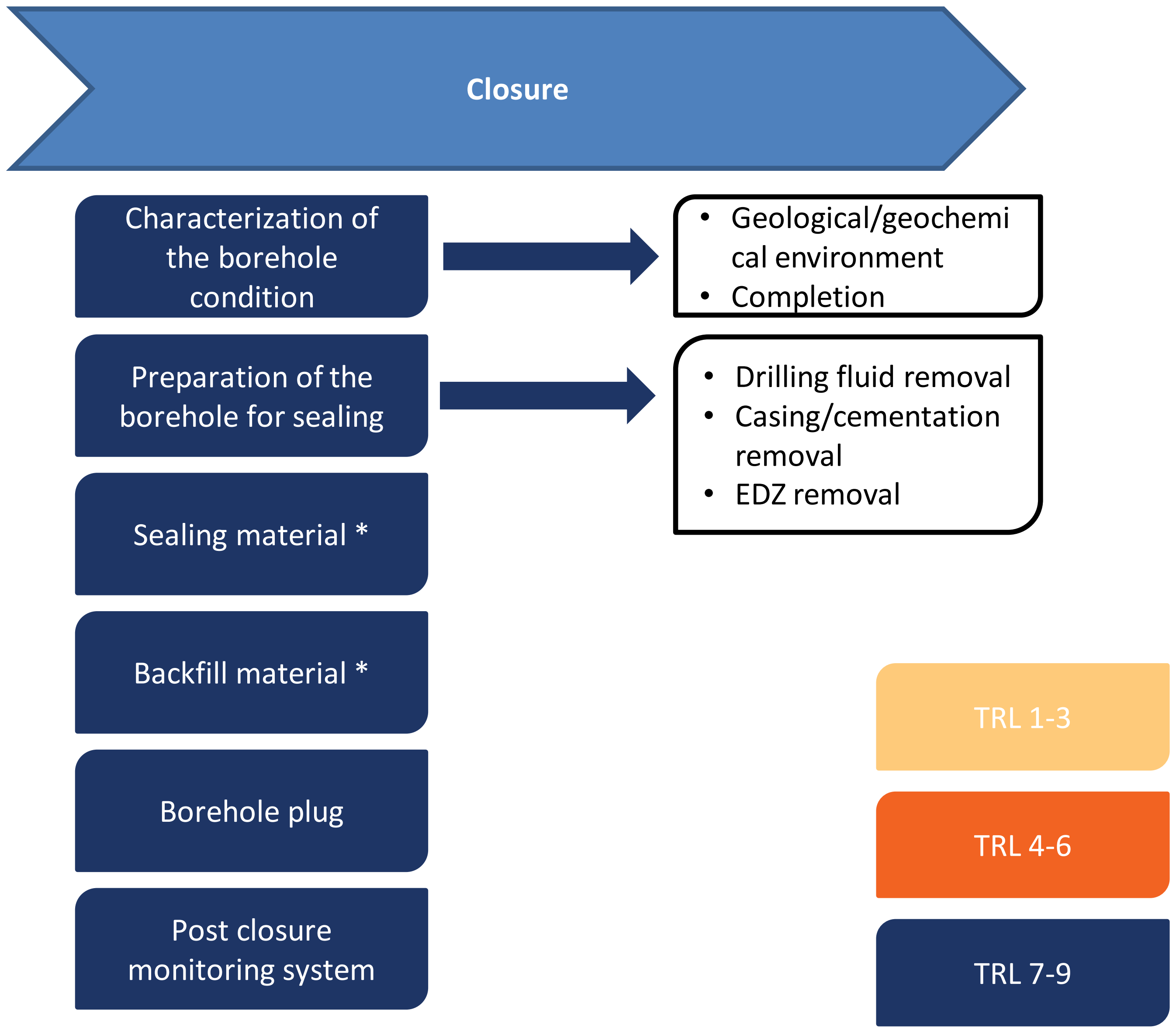
Section 3.4.3 HLW-DBD Construction



Section 3.4.4: HLW-DBD Operation



Section 3.4.5 HLW-DBD Closure



* This includes the material selection as well as the emplacement method