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The Use of Underground Research Laboratories to Support Repository Development Programs: A Roadmap for the Underground Research Facilities Network

by

The Underground Research Facilities Network

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Abstract

Under the auspices of the International Atomic Energy Agency (IAEA), nationally developed underground research laboratories (URLs) and associated research institutions are being offered for use by other nations. These facilities form an Underground Research Facilities (URF) Network for training in and demonstration of waste disposal technologies and the sharing of knowledge and experience related to geologic repository development, research, and engineering. In order to achieve its objectives, the URF Network regularly sponsors workshops and training events related to the knowledge base that is transferable between existing URL programs and to nations with an interest in developing a new URL. This report describes the role of URLs in the context of a general timeline for repository development. This description includes identification of key phases and activities that contribute to repository development as a repository program evolves from an early research and development phase to later phases such as construction, operations, and closure. This information is cast in the form of a matrix with the entries in this matrix forming the basis of the URF Network roadmap that will be used to identify and plan future workshops and training events.

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1 INTRODUCTION

Under the sponsorship of the International Atomic Energy Agency (IAEA), the Underground Research Facility (URF) Network was formally initiated in 2001 to address the needs of all IAEA Member States involved in the development of civilian nuclear technologies. It is specifically intended to share between Network members an understanding of the requirements (safety, security and safeguards) and methodologies (technologies) for radioactive waste disposal, with particular emphasis on the underground disposal of high-level waste and spent fuel declared as waste. The URF Network goal is to encourage the development of safe, sustainable and effective geological disposal programs around the world through demonstrations of technology, improved training, enhanced communications, and sharing of knowledge between participating organizations. Specific objectives are (1) to encourage the preservation, sharing and transfer of knowledge and technologies, (2) to work on solutions for Member States currently without URFs, (3) to supplement national efforts and promote public confidence in waste disposal schemes, and (4) to contribute to the resolution of key technical issues.

A goal of this report is to identify the key phases and activities that contribute to repository development as a repository program evolves from an early research and development phase to later phases such as construction, operations, and closure. This information is arranged in the form of a matrix comprising rows and columns, where the rows are key activities and the columns are the phases in the repository development timeline. This construction provides the URF Network a high-level view of those activities that need to be accomplished to complete a repository program and a vehicle to readily identify which of these activities are of specific interest to participating organizations and their programs. Future URF Network workshops and training exercises can then be planned to target these activities.

This goal is supported by the three lines of discussion in this report:

- Describe the different phases and activities in a repository development program for the disposal of HLW/SNF.
- Identify the links between research and development (R&D) conducted in URLs and the overall repository development program
- Describe the role of URLs in the development of new repository technologies and provide examples of these technologies.

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2 BACKGROUND

URLs are underground research facilities wherein characterization, testing, and demonstration activities can be carried out in realistic geologic environments. There are two main types of URLs, generic and site-specific [1, 2]. Generic URLs are facilities that are located at sites that will not be used for waste disposal, but can provide relevant information and support a broad range of R&D activities to recommend disposal elsewhere in a similar geologic environment. They are used to investigate processes and to develop, test, and demonstrate expertise, methods and technologies needed to site, construct, operate, and close a safe repository. They may also provide opportunities for training of technical staff, as well as for stakeholder engagements relevant to enhancing the general understanding of, and improving confidence in, the viability of geologic disposal. Site-specific URLs have a role similar to that of generic URLs but are located at sites where there is potential for future waste disposal and have the important additional function of providing site-specific characterization data needed for repository design, construction, safety assessment, and confirmation that the site is suitable. Arguably, the applicability or transferability of data and experiences from either a generic or site-specific URL to the safety case for the final disposal facility may require a similar justification. For example, some features, events, and processes (FEPs) may not be strongly dependent on variability in host rock properties, while others may be greatly influence by local heterogeneities. Thus, depending on the potential influence of each FEP on safety confidence, the transfer of data and knowledge from either a generic or site-specific URL must be correspondingly justified [3].

Over the last 40 years numerous underground research laboratories (URLs) (see Figure 2.1) have played a significant role in the development of methods, technologies, and technical bases necessary for safely isolating nuclear wastes in deep geologic repositories for extended periods of time. This knowledge base supports and facilitates all of the major elements of a phased repository development program and associated safety case, including site selection and site characterization, repository design, safety assessment, licensing, construction, operation, and closure (Figure 2.2). URLs have also played a key role in supporting less technical, but equally important, elements of a safety case, such as stakeholder interactions, public confidence, international collaboration, and training.

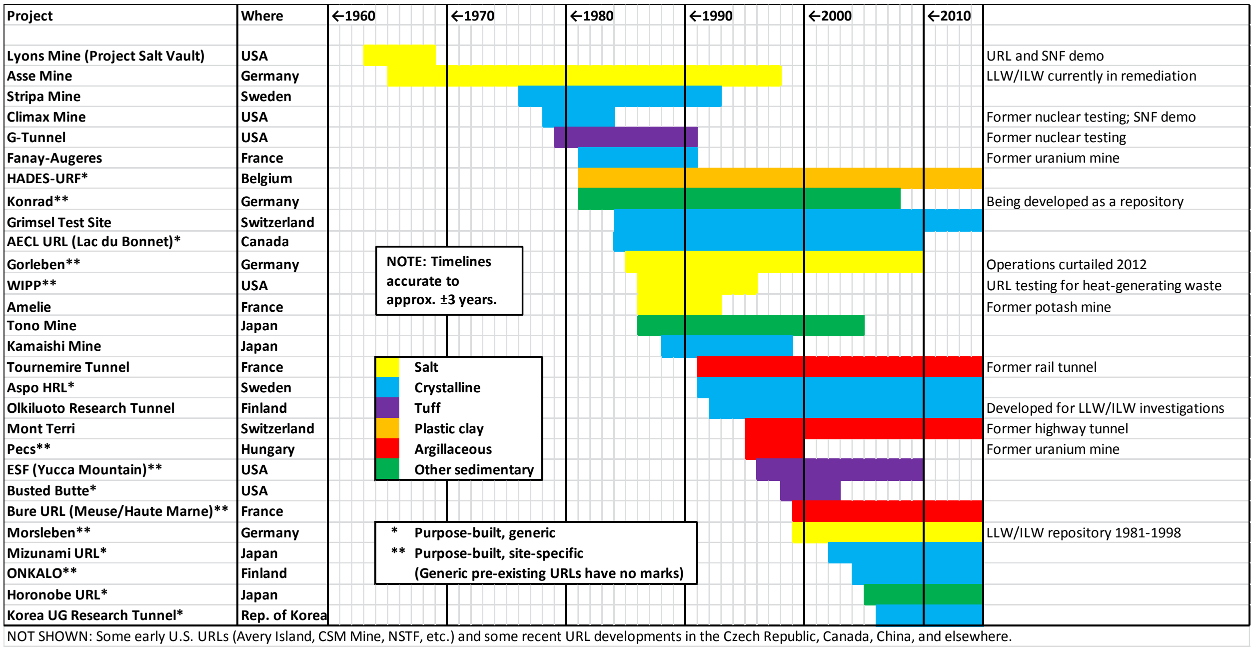


Figure 2.1. Worldwide URL Summary – Timelines [4].

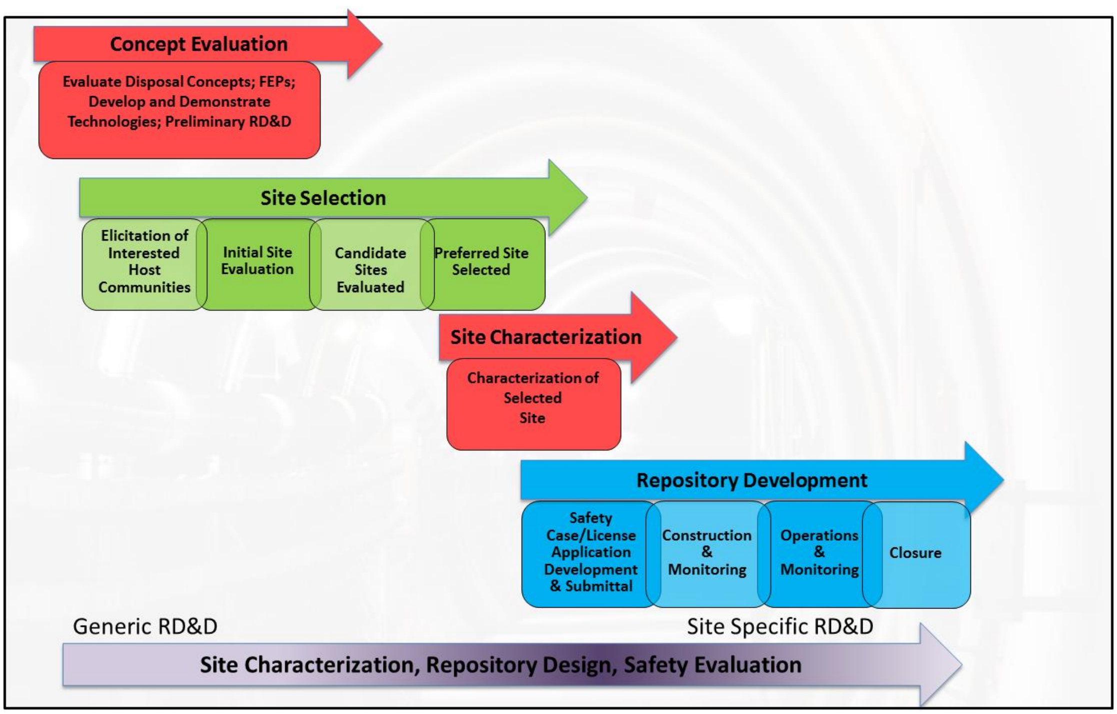


Figure 2.2. Timeline for a repository development program and associated RD&D.

3 GEOLOGIC REPOSITORY DEVELOPMENT PROGRAM AND THE ROLE OF URLS

Geologic repository programs take place over a period of decades (often with a planned timeline of over a century from initiation to final closure) and, as a result, they must be adaptive and flexible, since the route to success will be influenced not only by technical advances, but also by dynamic societal and political challenges. Figure 2 presents a general timeline for a repository program that is divided into four typical stages: Concept Evaluation, Site Selection, Site Characterization, and Repository Development. Representative phases in each of these stages are also illustrated; however, it should be emphasized that both these stages and phases themselves are not necessarily discrete but often overlap, as indicated in the figure. Also, while typical of most repository programs, the exact phases and steps shown in Figure 2.2 can differ from country to country since approaches to disposal driven by each nation's policy goals and context. In addition, experience to date indicates that phases leading up to repository construction can last decades. Repository construction can take up to a decade while the duration of repository operations is highly dependent on waste volume and throughput constraints, and can last significantly longer than a decade. The purpose here is to provide a framework for discussing the evolving role of URLs in typical phases of a repository development process.

Also shown in Figure 2.2 is a representation of the two major types of RD&D that generally take place as the development program progresses: generic RD&D at the beginning, transitioning to site-specific RD&D. Consistent with the definitions of generic and site-specific URLs given above, generic RD&D refers to science and engineering investigations that are intended to have broad applicability and have the goal of providing information and understanding to make informed assessments of alternative technologies and concepts as a program progresses. By definition, site-specific RD&D is focused on a specific location and, in this particular context, is focused on a site that is being evaluated in the Site Selection phase or a site being characterized in the Repository Development phase. Concurrent with all the repository phases indicated in Figure 2.2 are the three primary processes that support and inform RD&D prioritization: site characterization, repository design, and safety evaluation. These three processes form an iterative framework (not strictly linear, as implied in Figure 2.2) that guides the RD&D program from phase to phase.

3.1 Concept Evaluation

In the Concept Evaluation phase most of the work is generic in nature and is conducted to further the understanding of disposal concepts and associated FEPs, and to develop, evaluate and demonstrate technologies and methods. The preliminary RD&D conducted during this phase lays the groundwork for making informed decisions and assessments of alternative technologies and concepts that will be required as the development program progresses into the Site Selection and Repository Development phases. RD&D during the Concept Evaluation phase also supports stakeholder interactions during the Site Selection phase and helps build confidence in the safety of potential disposal concepts and technologies.

During the Concept Evaluation phase, several types of media and host rocks may be under consideration as viable alternatives for the final deep geologic repository. To support general conceptual developments and fundamental understanding of relevant FEPs, generic URLs may be constructed in each of these media. For example, in the Japanese repository program, generic URLs have been constructed and currently have an active RD&D program in both crystalline rock (Mizunami) and sedimentary (mudstone) rock (Horonobe) [5]. These two "purpose-built" URLs serve several purposes [5], including (1) confirming the applicability of disposal technologies, site investigation methods, and safety assessment methods, (2) developing a deeper understanding of each host rock disposal environment, (3) providing training to staff, and (4) promoting the public's understanding of deep underground disposal.

Other disposal concepts, besides mined repositories, may be under consideration during the Concept Evaluation phase. An example comes from the US program, which is considering deep borehole disposal in crystalline basement rock. For this concept the equivalent *in situ* demonstration project is not a mined URL but, rather, a deep "field test" borehole [6]. Many typical URL objectives may be addressed by this deep borehole field test, such as site-characterization, assessment and demonstration of constructability, and demonstration of operational feasibility, in principle (i.e., without actual radioactive waste). Others, such as conducting a progressive RD&D program, as is commonly accomplished over a period of decades in a URL, may not be possible during such a deep borehole test.

3.1.1 Role of URLs during Concept Evaluation

During the Concept Evaluation phase and early part of the Site Selection phase, any URL would be classified as generic. Because generic URLs are expensive undertakings, many nations cannot afford, or would not choose, to fund a URL for the purpose of supporting early-phase disposal program activities such as siting, design, and safety assessment. Moreover, a program may not need to develop its own generic URL because of the abundance of information available from existing URLs in other nations. In fact, all URLs, whether considered to be generic or site-specific by the particular repository program that operates them, can be considered to be generic URLs from the perspective of other nations. The results obtained therein are useful to the extent that they can be transferred to the generic safety case for a nation's specific geologic disposal concept. Thus, a careful assessment of the extensive, existing URL knowledge base should first be conducted before a nation decides whether to construct its own generic URL. Even if there appear to be knowledge gaps, it may be considerably more cost effective for countries to collaborate on future specific studies in existing URLs to meet their information needs.

On the other hand, as discussed at the IAEA URF workshop (2014), discussions also emphasized that a nation's own generic URL can offer benefits that are not directly available from collaboration with international URLs, including a number of key technical, economic, societal, and political benefits. Examples include (1) developing the national, technical expertise and capability to implement a geologic repository and (2) developing a vehicle to facilitate stakeholder interactions and open public participation in the repository development process.

Generic URLs have played important roles in the evaluation and demonstration of design concepts, investigation of features, events, and processes (FEPs), and measurement of large-scale coupled processes for the purpose of developing and validating models. An example for all three of these roles is the full-scale engineered barriers (EB) heater test conducted at Mont Terri for investigating the behavior of a bentonite buffer and clay host rock during the heating phase that follows waste emplacement [7]. This test includes large-scale heat and mass transfer processes, thermal alteration and drying of the buffer and host rock, evolution of pore-water pressures in the near field, and resaturation processes in the buffer and near-field host rock. Another example is the Long-Term Diffusion (LTD) Experiment at the Grimsel Test Site (GTS) located in a sparsely fractured granite host rock [8]. This experiment has the goal of quantifying *in situ* matrix diffusion processes in sparsely fractured granite host rock over long-time scales. Although some aspects of these, and similar, tests in clay and granite may be site-specific,[1] the dominant processes should be representative, respectively, of those that occur in similar clay and fractured granite host rocks. Data from such tests can be used to quantify FEPs, evaluate design concepts, and develop, test, and validate models. This *technical basis* can be used to inform and support R&D related to other similar host rocks, and provide an advanced starting point for informing the Site Selection phase and site-specific R&D for developing programs. The technical basis developed from generic URLs can also position a program to have a sufficient knowledge base to allow the use of a site-specific URL to focus more on site characterization and confirmatory and demonstration activities related to a chosen site.

In addition to evaluating FEPs relevant to processes in the engineered barrier system (EBS) and surrounding near-field host rock, generic URLs are also useful for evaluating and improving the utility and accuracy of characterization and monitoring methods and technologies. Detailed subsurface information on the properties of overlying formations can be gathered from the access tunnels and shafts, in addition to properties of the host rock itself. These measurements can be compared to measurements obtained using conventional surface characterization methods and aid in the development of new methods, both prior to and after excavation [5]. Generic URLs are also useful for evaluating construction and emplacement techniques, assessing their impact on the geosphere and host rock, and developing techniques to mitigate significant impacts [7, 9].

3.2 Site Selection

The site selection process begins with development of fundamental siting criteria for safe geologic disposal and preliminary identification and assessment of host formations likely to meet most of these criteria. Based on this, the process continues with eliciting expressions of interest in possibly hosting a deep geologic repository. Proposed sites associated with interested communities are evaluated ("down-selected") against technical screening guidelines to identify those sites that are obviously not suitable and those that show potential. If communities with suitable sites want to go forward in the process, the next phase involves preliminary but more detailed site investigations using available characterization and geological data. This process continues in a iterative approach based on increasingly detailed site investigations and interactions, as well as information exchanges with the corresponding community decision makers, interested or affected parties, the general public, and governmental institutions—all referred to herein as stakeholders. The goals of increasingly detailed site investigations and associated stakeholder interactions are to assess the suitability of a site to safely host a deep geologic repository and to convey gathered information to stakeholders in a transparent and ethical fashion, openly addressing any issues or concerns. This iterative process continues until one or more sites are selected as a preferred repository site. This last step generally requires both surface and subsurface investigations, a conceptual

[1] Numerous other relevant tests have been conducted in clays and fractured granite at Mont Terri [6] and Grimsel [7], respectively; and the reader is also referred to http://www.mont-terri.ch/internet/mont-terri/en/homepage.html and http://www.grimsel.com/ .

repository design, and a preliminary safety assessment before the preferred site(s) can be selected and acceptance by stakeholders granted. This selection will be made by the responsible implementer with the consent of local decision-making stakeholders. At this stage the majority of the RD&D becomes site specific at the host site (see Figure 2.2); however, large-scale demonstrations at generic URLs may still be valuable for a number of aspects of the safety case, including demonstrations related to model validation, emplacement, construction, and operations.

3.2.1 Role of URLs in Site Selection

During the Site Selection phase, RD&D is transitioning from generic to site-specific (Figure 2.2), with a key goal being to quantify important attributes of each candidate site, in order to be able to confidently evaluate each one against the site-selection criteria. Generic RD&D conducted in generic URLs still remains as a valuable activity to support the Site Selection phase, via evaluation of design, construction, and operating methods, FEPs understanding and model testing/validation activities, and development and proof of *in situ* testing methods. However, by necessity, a greater emphasis is placed on site-specific RD&D.

URLs constructed during the Site Selection phase would almost certainly be site-specific URLs with the specific purpose of gaining more information about the feasibility of disposal at a given site/medium. Depending on the country and its applicable laws, these site-specific URLs may have the possibility of becoming part of the repository after a final disposal site is chosen, such as in the Finnish [9] and Swiss concepts [8]. As mentioned above, regarding the construction of more than one URL during the Concept Evaluation phase, a similar strategy may be initiated during the Site Selection phase to gain sufficient confidence to choose the final site. This strategy would more likely be initiated after the "down-selection" step in Figure 2.2, i.e., after an initial narrowing of candidate sites. Such a stepwise site-selection process is currently being utilized in most national programs, such as Switzerland [8], Canada [10], Finland [9], and Japan [5].

During the Site Selection phase some of the key uses of URLs comprise (1) in-depth characterization and reduction of uncertainties for the candidate sites and media, including an appropriate quantification of data, model, and scenario uncertainties at the end of each stage, step, or milestone, (2) refinement or optimization of testing, excavation, and operations methodologies for a specific medium and geologic environment, (3) evaluation of EBS design concepts most suitable for the candidate sites/media, (4) development, refinement, and testing of safety assessment and process-level models for each candidate medium, (5) continuity of the training base and knowledge base for underground disposal, and (6) building of confidence with stakeholders (public, local communities, regulators, scientific community, other interested parties) in the safety of geologic disposal in general and for particular site, as well as confidence in the implementer to manage a large project (i.e., the URL as a prelude to the actual repository) in a safe, ethical, and transparent fashion.

3.3 Repository Development

The Repository Development phase includes four major steps: (1) development and submittal of the safety case/license application for repository construction, (2) construction and monitoring, (3) operations (including the application for an operating license) and monitoring, and (4) closure of the repository. As indicated in Figure 2.2, the major categories of RD&D activities (site characterization, design, and safety assessment) continue in varying degrees throughout the first three of these phases.

Safety Case/License Application

The repository implementer submits a license application for repository construction when the safety case demonstrates the safety of the geologic repository with a level of confidence that is acceptable by stakeholders. The safety case will be comprised of a very large body of documentation [11] containing the entire collection of evidence, analyses, and other qualitative and quantitative arguments developed up to this point in the repository development program, starting with site selection. The license application draws from the safety case to specifically present focused arguments for why the repository complies with regulatory criteria, requirements, and standards. The safety case and license application is submitted to the regulators and evaluated during this licensing phase.

Some of the more important elements of the safety case to be documented are shown in Figure 2.3. *In situ* research in URLs will play a key role in almost all of these elements of the safety case. The few elements where URL research will have less of an impact are those that are "grayed-out" in Figure 2.3; however, even for many of those grayed-out elements, such as the technical basis for aquifers and other geologic units, URL research can provide valuable information. Much of the technical aspect of URL research (i.e., data gathering and process testing) is related to the behavior of post-closure FEPs, of which there are three main categories, as indicated in Figure 2.3: those related to the waste and engineered barriers, those related to the natural system barrier, and those related to the biosphere [12].

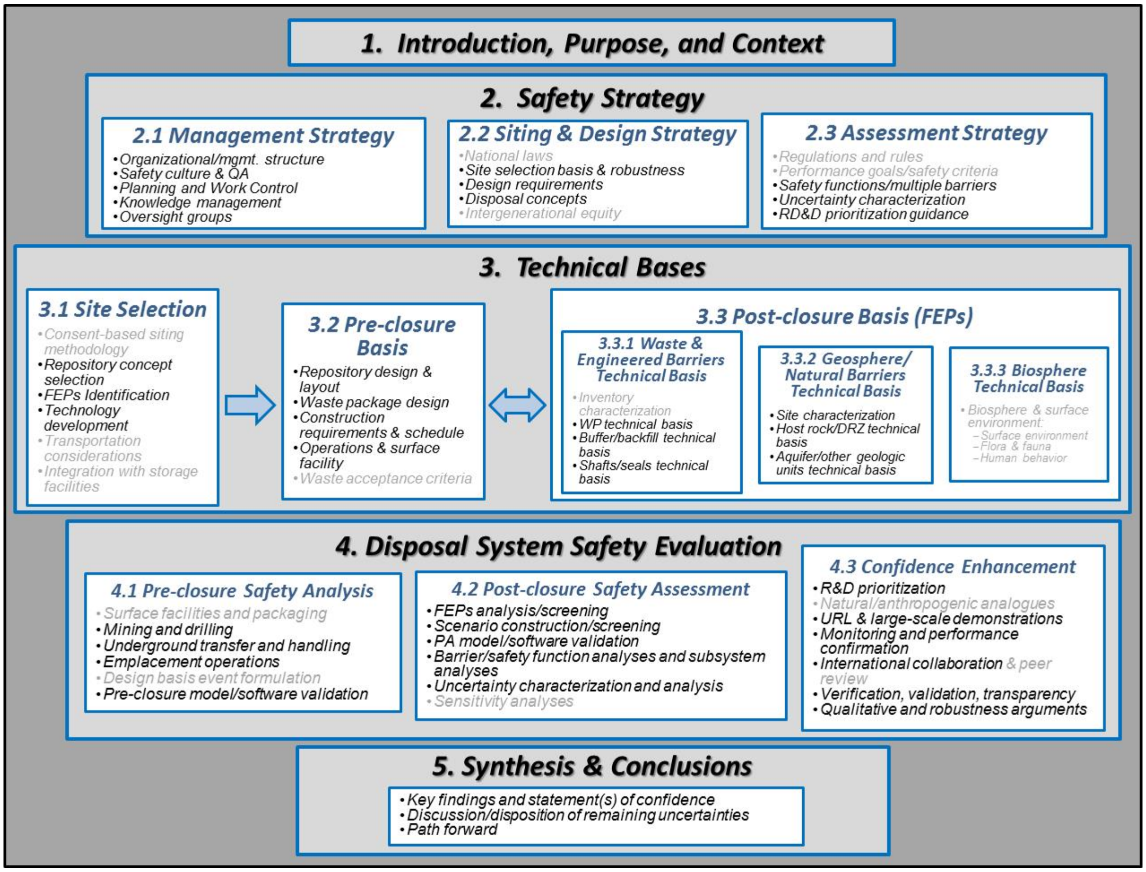


Figure 2.3. Key elements of a repository safety case (grayed-out elements are those not as strongly supported by *in situ* RD&D in URLs).

The licensing phase involves significant iteration and feedback between site characterization, repository design, and safety evaluation until high confidence in safety is achieved by the implementer and stakeholders. These three major processes (Figure 2.2), which are the basis of R&D prioritization for both surface and subsurface investigations, encompass and support most of the elements of the safety case shown in Figure 2.3. The major goals of site characterization are to collect sufficient site-specific data to support: (1) integrated and confident descriptions of the site geology, hydrogeology, geochemistry, and geomechanical conditions, (2) design of the repository, (3) modeling and analysis of FEPs, (4) characterization and reduction of uncertainties in important data and FEPs, and (5) safety assessments. The primary goal of repository design is to design a repository system that when coupled with the geologic system meets containment, isolation, and other requirements. The primary goal of safety evaluation, which includes both pre-closure safety analysis and post-closure safety assessment, is to develop quantitative estimates of potential radiological impacts, as well as an evaluation of the system's robustness and its ability to meet safety requirements. Other goals of safety evaluations are to inform the site-characterization program of data necessary to reduce uncertainties in system performance estimates and to provide feedback to the design program on potential improvements to reduce safety risks during both the pre- and post-closure operating periods.

The iterative nature of this license-application phase results from the requirement that the engineered system and the geosphere together must meet system performance requirements. The mutual effect and combined behavior of the engineered repository system the and natural barrier system is quantified by the safety assessment and associated sensitivity analyses, which indicate the key parameters, processes, and features (and associated uncertainties) that have the most effect on the combined behavior. This quantified sensitivity then leads to the next phase of RD&D targeted to reduce the most important uncertainties related to repository design behavior and those related to natural system processes.

3.3.1 The Role of URLs in Safety Case/License Application Development and Submittal

Once a site has been selected and work on the detailed license application for construction has begun, a decision should be made as to the value of a site-specific URL located either near the actual repository site or as part of the repository itself (e.g., [8] and [9]). If a site-specific URL had not already been constructed on the chosen repository site, either for fiscal reasons and/or because surface data at the site and surrogate data from other URLs was deemed sufficient for siting, then a new decision regarding the value of URL for the site-specific safety case should be undertaken. Of course, such a site-specific URL may be mandated by national regulation or stakeholder considerations, but in lieu of these factors, a set of technical decision criteria should be developed based on enhanced confidence for key elements of the safety case (Figure 2.3), as well as other criteria such as overall URL development and operating costs and needed technical maturity (technology readiness levels—see discussion below) of various disposal technologies [11]. Part of the consideration in whether to develop a site-specific URL or not must involve a discussion on degree of transferability of knowledge, data, and methods [3] from other nonlocal URLs to the safety case for the local site.

The benefits of a site-specific URL are many but the degree to which it is necessary must be decided upon based on criteria similar to those discussed above. However, based on workshop presentations and current international work [1], it is clear that most programs will develop a site-specific URL. Some of the tangible benefits during the construction licensing phase include (1) development and refinement of site- and media-specific excavation, construction, monitoring, and waste and EBS component emplacement techniques/methodologies, (2) development of a QA program transferable to the repository construction phase, (3) testing and validation of FEPs and PA models, (4) confidence-building with stakeholders, and (5) education and training of technical staff. One of the benefits of a site-specific URL located as part of or very near a chosen site is the opportunity to confirm or refine specific model parameterization data obtained from laboratory and/or surface measurements and to reduce uncertainties in such data. Another important benefit from the in situ site-specific URL research, which is generally not available from laboratory measurements, is to develop detailed knowledge of the disturbed rock zone (DRZ) surrounding the excavations. This knowledge should include both excavation and thermal perturbation effects, with the latter obtained from *in situ* heater tests. Because the DRZ can affect some of the safety functions of the natural barrier system, such as "containment" and "limited or delayed releases" [13, 14], this is an important function of the site-specific URL [15].

<u>Construction and Monitoring</u>

If a construction authorization license is granted, work on repository surface and subsurface facilities begins. This work may be implemented in stages or entire facilities may be constructed prior to waste receipt and emplacement. Details of surface and subsurface facilities construction and the pros and cons associated with phased or complete construction are beyond the scope of this paper and will not be discussed further. Furthermore, the discussion here focuses on the subsurface facility. The goals of subsurface facility construction are to excavate the access tunnels, access shafts, and ventilation shafts; mine the required waste handling areas, access and disposal drifts in the host rock; and install electrical, safety, and ventilation systems. Prior to repository construction, the initial baseline conditions (hydrogeological, geochemical, thermal, mechanical, and biological) of the host rock and geosphere should have been established by site characterization during the licensing phase. An important difference between conventional underground construction for mineral extraction versus that for geological repositories is that repository construction should be conducted in a manner that minimizes adverse impacts to the baseline conditions and geologic barrier.

3.3.2 The Roles of URLs in Construction and Monitoring

During the construction phase, the role of site-specific URL is likely to become more confirmatory than investigative. In other words, the regulator and stakeholders have already been convinced that enough knowledge has been assembled to feel confident that the site will be safe disposal location. However, all programs require monitoring to confirm the original conclusion of safe disposal. Furthermore, the URL can serve as a laboratory or testing facility for refinement of excavation, construction, operation, handling, and emplacement methods and machinery prior to their use on a large-scale or production-scale in the actual repository. For example, testing of excavation techniques has proven to be quite important in ONKALO URL in Finland [9]. The URL may also continue to serve as an education and public-relations facility over the potentially very long period of waste emplacement. Another important use during this period (but which may have been required by regulations during the licensing phase) is the development and testing of retrieval methods and machines, since some type of retrievability or reversibility is usually required by national regulations [16]. Indeed, if specific time periods for retrieval capability are required, the availability of a URL that can provide facilities for testing equipment and processes and for training may be of great benefit if retrieval becomes needed.

<u>Operations and Monitoring</u>

Prior to beginning repository operations the implementer must be granted a license to receive and emplace waste. Waste and EBS emplacement operations are then carried out consistent with the repository construction plan. The emplacement phase, from the time of initial emplacement to final waste emplacement and repository closure, can last several decades and be a function of several variables including the volume of inventory to be disposed, the rate at which waste is received, the rate of waste and EBS emplacement, and the rate of construction. During the operational phase, construction of the underground facility may be ongoing and backfilling and sealing may begin in those drifts that have been filled with waste to capacity. The operational phase ends when all waste and EBS emplacement has been completed and the monitoring period is completed.

3.3.3 The Roles of URLs in Operations and Monitoring

The role of URLs during the operations (waste-emplacement) phase is again mostly confirmatory, as with the construction phase, and will involve additional long-term monitoring of in situ conditions, and could involve long-term experimentation (decades-long) of the effect of in situ conditions and heating on EBS components. Some sort of adverse result could potentially require retrieval of already emplaced waste. It could also involve improvement or refinement of emplacement techniques if unexpected underground conditions are encountered during excavation of repository emplacement drifts.

Closure

Prior to closure the implementer must be granted a license to close and decommission the facility. This license could require an updated safety case and a Closure Implementation Plan. Closure of the subsurface repository involves backfilling and sealing of disposal drifts, handling areas, access tunnels and shafts. The updated safety case would include new information and understanding of the repository and geosphere system gained during construction and operation periods.

3.3.4 The Roles of URLs in Closure

Site-specific RD&D in URLs could be very important for the closure phase through investigations related to effective sealing of the repository. Such investigations would have to be initiated during the construction and/or operations phases, which would allow them to be concluded in time for the commencement of repository closure. The closure step as shown in Figure 2.2 may not be a specific event (i.e., permanent closure of the underground and dismantling of all surface facilities) but may also encompass the period of waste emplacement is concluded but during which the waste must remain retrievable, for example, as mandated in the French program for 100 years [17]. During this long "reversibility" period, the URL may be used to refine existing monitoring techniques.

4 ROLE OF URLS IN TECHNOLOGY DEVELOPMENT

The role of URLs in technology development has been touched upon incidentally in outlining the contributions made in each of the repository phases discussed above. The contribution of URLs to maturing repository technologies and developing new repository technologies should be emphasized as an important international benefit from URLs. In addition to providing equipment and solutions necessary for repository programs, some of these technologies find derivative commercial applications.

4.1 Examples of repository technologies developed by URLs include (see Figures 3.1 and 3.2):

- Excavation equipment, developed for boring deposition tunnels and canister holes for vertical emplacement at the ONKALO URL (Finland)
- Machines for horizontal deposition (emplacement), developed and tested at the Äspö HRL (Sweden) and Mont Terri URL (Switzerland) and a vertical emplacement machine developed and tested at ONKALO
- Equipment for manufacturing and emplacing buffer materials. developed at the granite-based Äspö HRL (in coordination with the bentonite laboratory at the site) and at ONKALO
- A low pH (<11) shotcrete plug, developed at the Grimsel (Switzerland) URL
- Micro-fine grouts and grouting techniques, developed at the Lac du Bonnet URL (Canada) to seal sparsely fractured granite; these grouts and techniques were subsequently applied by a variety of mining and geotechnical projects. [1]
- A system for gas-permeable backfill & sealing that can allow increased gas transport capacity of the backfilled underground structures without compromising radionuclide retention, developed at the granite Grimsel URL.
- A range of repository monitoring technologies, developed by the European Commission's MoDeRn Project in plastic clay at the HADES URL (Belgium), indurated clay at Bure URL (France), and granite at Grimsel Test Site (Switzerland); the technologies investigated include
  - High frequency wireless sensor networks embedded within the barrier system that could provide energy remotely to isolated sensors with data processing techniques that ease battery power limitations and increase effective operating time by a factor of 5 to 10.
  - Wireless through-the-earth transmission a limited amount of data from the repository to the surface over a period of potentially several decades.
  - A variety of seismic, fiber-optic, laser, and other sensing and monitoring techniques.

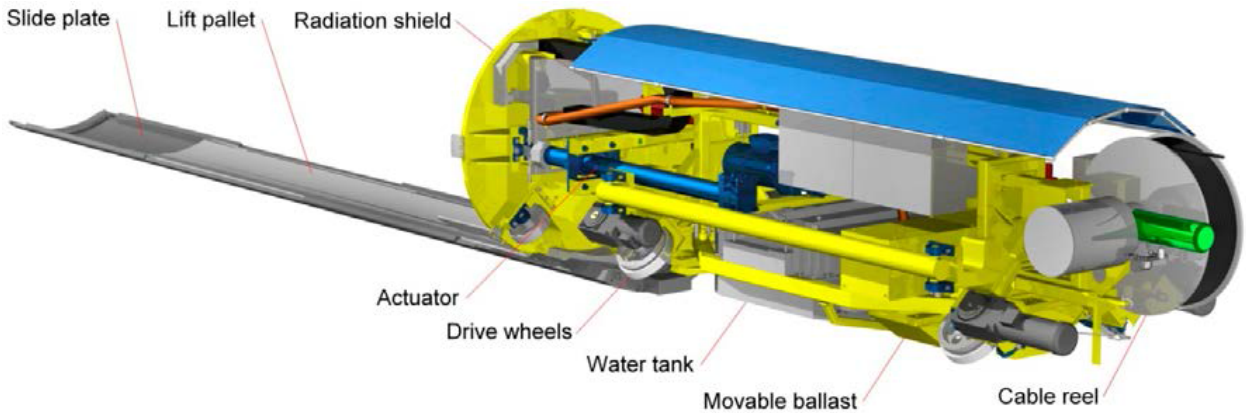


Figure 3.3. Äspö KBS-3H deposition (emplacement) machine (source: Ojala, Markku and Thomas von Numers 2015. Upgrading the deposition machine for the multi purpose test. SKB P-14-08).

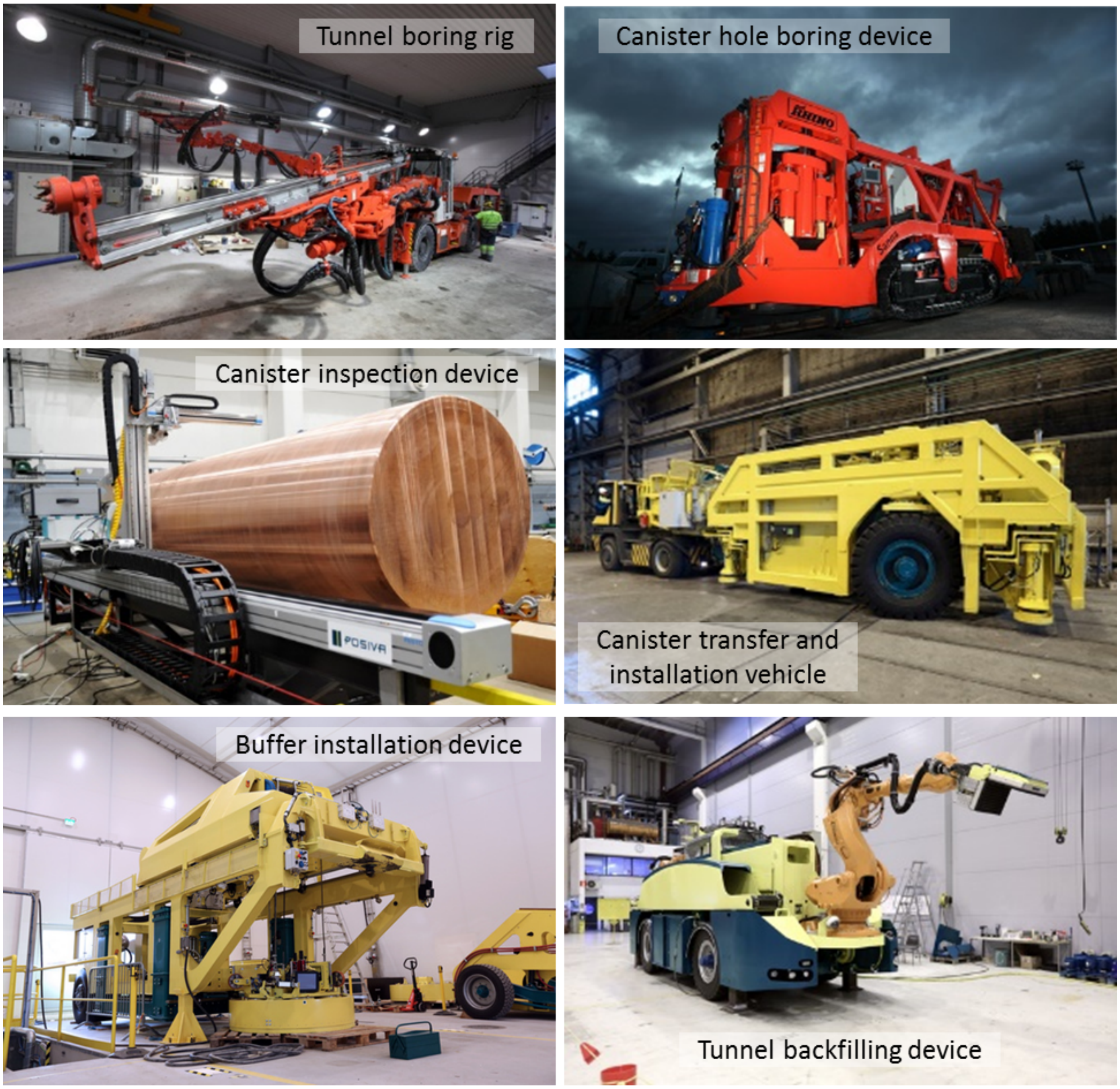


Figure 3.4. Repository equipment developed at the ONKALO URL (source: http://www.posiva.fi/en/final_disposal/basics_of_the_final_disposal/machinery#.VgH6wfQYNdc)

URLs provide testbed capabilities for technology development activities, and they serve as technology development resources for other programs. In some cases, equipment developed at one URL has been subsequently tested at another facility both for confirmation of its functionality and to extend its applicability. The result of such technology development at URLs can be an international resource of repository technologies that are increasingly standardized or increasingly specialized for use in different repository environments.

4.1.1 Use of systematic technology readiness assessment in adapting repository technologies

Based on past experiences, a long-term maturation process is necessary for any new technology in a large one-of-a-kind project, such as high-level nuclear waste disposal. Completion of key milestones in a repository development program will be associated with a certain degree of technical maturity for important characterization, design, operations, modeling, and measurement technologies. To provide a quantitative assessment for the maturity of a given system, component, or methodology relative to its full-scale deployment, the program can employ a technology readiness assessment (TRA) process, like those based on a method developed the National Aeronautics and Space Administration (NASA) and adapted for use by the U.S. Department of Energy (DOE) and Department of Defense (DoD) [18, 19, 20] to determine the technology readiness levels (TRLs) of new systems and technologies. The underlying basis of any TRA is the breakdown of the overall system into critical technical elements (CTEs), that is, technology elements that the system depends upon to meet operational requirements and that are new or applied in new or novel application or in an area that poses major technological risk during detailed design or demonstration. TRLs provide an assessment of the maturity of a particular technology and a consistent comparison of maturity between different types of technologies, but TRLs should not be used to compare competing technologies, since, by itself, a TRL does not assess the risks, schedule, or costs of advancing a technology to its needed maturity. Table 1 provides example definitions of typical TRLs [21]. The levels and descriptions given in Table 1 are readily adaptable to nuclear waste disposal technologies. By associating TRL values with given repository development milestones, the readiness of a program to enter its next phase can be quantified.

Table 1. General Definitions of Technology Readiness Levels [21]

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Abbreviated Description
System Operations	**TRL 9**	Actual system operated over the full range of expected conditions.	The technology is in its final form and operated under the full range of operating conditions.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment.
Technology Demonstration / **Technology Development**	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects.
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated.
Research to Prove Feasibility / **Basic Technology Research**	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
Basic Technology Research	**TRL 1**	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D.

As mentioned by Price et al. [21], TRLs are typically assigned to individual components and technologies, however, a TRA may also be used to assess to overall readiness of the entire system or activity composed of various technologies, such as the entire waste disposal system or portions thereof. A key observation from the URF workshop is the important role played by both generic and site-specific RD&D conducted in past and current URLs for maturing various waste disposal technologies such as EBS design and operation, waste package buffer design, waste emplacement technologies, and underground excavation and construction techniques. This has served to advance the technology readiness for waste disposal systems to a level high enough to warrant submittal of a license application for construction to the regulatory authorities in several countries, e.g., Finland [22], Sweden [23], and the United States [24].

In the context of repository technology maturation, much of the research currently conducted at many URLs can be viewed as basic technology and feasibility research (TRLs 1 to 3), preliminary technology development (TRLs 4 to 5), and laboratory-scale demonstration (TRLs 5 to 6). The examples of technologies listed above, being demonstrated at URLs at full scale in the applicable environment and expected condition, represent TRLs in the range of 6 through 8 (for their intended repository environment). TRL 9 would be accomplished during operations and startup testing in the actual repository environment. However, it should be emphasized that TRLs in this range are tied specifically on the applicable environment and conditions, so these technologies can't be assumed to transfer to other repository projects at the same TRL.

Each repository project, because of the unique geological environments and because of the fundamental importance of that geological environment, would need an independent technology readiness assessment. However, a generic but systematic assessment of repository technologies could be developed that could identify technologies that can be adapted or applied in developing repository projects.

Such a generic TRA or technology list would compile a list of all technologies required (i.e., CTEs) y category (e.g., excavation and construction, containers and waste enclosure technologies, emplacement technologies, backfill and seals, monitoring technologies) and detailed items (e.g., backfill manufacturing equipment for KBS-3H system), and alternatives (e.g., sensor alternatives for a monitoring system). For each technology in the list, the following information could be identified:

- Potential application (i.e., geologic environment and configuration)
- Technology source/technology developer
- Generic TRL level (limited to TRL 6, since TRLs at 7 and above require specific consideration of the local environment)
- Notes on TRL assessment

Such in information should be updated periodically to reflect the maturation of the technology and report the extension of the technology to new environments or applications. Furthermore, since CTEs are, by definition, new or novel, some items could conceivably be retired from the list once their application is determined to provide standard "off-the-shelf" application in broadly defined environments.

5 FRAMEWORK FOR PLANNING: THE REPOSITORY DEVELOPMENT MATRIX

An important goal of this roadmap report is to identify key phases and activities that contribute to repository development as a repository program evolves from an early research and development phase to later phases such as construction, operations, and closure. This information is arranged in the form of a matrix comprising rows and columns, where the rows are key activities and the columns are the phases in the repository development timeline (see Appendix A). This construction provides the URF Network a high-level view of those activities that need to be accomplished to complete a repository program and a vehicle to readily identify which of these activities are of specific interest to participating organizations and their programs. Future URF Network workshops and training exercises can then be planned to target these activities.

6 REFERENCES

1. NEA (Nuclear Energy Agency) 2013. *Underground Research Laboratories (URLs)*, NEA Report No. 78122, Radioactive Waste Management, NEA/RWM/R(2013)2, February 2013, www.oecd-nea.org, Paris, France: OECD 2013.

2. IAEA (International Atomic Energy Agency) 2001. The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste, IAEA-TECDOC-1243, International Atomic Energy Agency, Vienna, September 2001.

3. Mazurek, M., A. Gautschi, P. Marschall, G. Vigneron, P. Lebon, and J. Delay 2008. "Transferability of geoscientific information from various sources (study sites, underground rock laboratories, natural analogues) to support safety cases for radioactive waste repositories in argillaceous formations," *Physics and Chemistry of the Earth*, **33** (2008) S95-S105.

4. Hardin, E. 2014. *URL Cost and Design Considerations*. SAND2014-17981PE. Sandia National Laboratories, Albuquerque, NM.

5. Shigeta, N. 2014. "Case Studies: Currently Operating Generic URLs in Crystalline and Sedimentary Host Rocks (Mizunami and Horonobe)," in *Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments*, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

6. DOE (U.S. Department of Energy). 2013. Deep Borehole Disposal Research: Demonstration Site Selection Guidelines, Borehole Seals Design, and RD&D Needs, FCRD-USED-2013-000409, U.S. Department of Energy, Washington, DC.

7. Bossart P. 2014. "Case Study: The Mont Terri Rock Laboratory," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

8. Vomvoris, S. 2014. "Case Study: The Grimsel Test Site," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

9. Kemppainen K. 2014. "Case Study: ONKALO Underground Rock Characterization Facility," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

10. Lange K. 2014. "Importance of URLs in safety assessment with focus on licensing processes in Canada," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

11. Sevougian, S. D. 2014. *The Role of URLs in Support of the Safety Case*. SAND2014-18391PE. Sandia National Laboratories, Albuquerque, NM.

12. Freeze, G., S. D. Sevougian, C. Leigh, M. Gross, J. Wolf, J. Mönig, and D. Buhmann 2014. "A New Approach for Feature, Event, and Process (FEP) Analysis of UNF/HLW Disposal – 14314," in *Proceedings of the WM2014 Conference*, March 2 – 6, 2014, Phoenix, Arizona USA.

13. Bailey, L., D. Becker, T. Beuth, M. Capouet, J. L. Cormenzana, M. Cuñado, D. A. Galson, L. Griffault, J. Marivoet, and C. Serres. 2011. *PAMINA (Performance Assessment Methodologies in Application to Guide the Development of the Safety Case)*: *European Handbook of the state-of-the-art of safety assessments of geological repositories—Part 1.* European Commission. January 31, 2011. http://www.ip-pamina.eu/

14. Sevougian, S. D. and R. J. MacKinnon 2014. "A Decision Methodology for Prioritizing R&D Supporting Geologic Disposal of SNF/HLW in Salt – 14030," in *Proceedings of the WM2014 Conference*, March 2 – 6, 2014, Phoenix, Arizona USA.

15. Thompson, P. 2014. "Lessons Learned from Canada's Underground Research Laboratory," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

16. Mayer S. 2014. "Overview of International URLs," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

17. Ouzounian, G., A. Harman, T. Labalette, and M. Dupuis 2014. "Cigeo, the Project for Geological Disposal Project of Radioactive Waste in France – 14014," in *Proceedings of the WM2014 Conference*, March 2 – 6, 2014, Phoenix, Arizona USA.

18. DOD (U.S. Department of Defense) 2009. *Technology Readiness Assessment (TRA) Deskbook*, July 2009, prepared by the Director, Research Directorate (DRD), Office of the Director, Defense Research and Engineering (DDR&E).

19. GNEP 2007. "Global Nuclear Energy Partnership Technology Development Plan," Global Nuclear Energy Partnership Technical Integration Office, GNEP-TECH-TR-PP-2007-00020, Rev 0, July 25, 2007, http://www.inl.gov/technicalpublications/documents/3738885.pdf .

20. DOE (U.S. Department of Energy) 2011. *Technology Readiness Assessment Guide*, DOE G 413.3-4A, 9-15-2011, U.S. Department of Energy, Washington, D.C. 20585, www.directives.doe.gov

21. Price R. R., B. Singh, R. J. MacKinnon, and S. D. Sevougian. 2013. "The Application of Systems Engineering Principles to the Prioritization of Sustainable Nuclear Fuel Cycle Options," *J. of Energy Policy*, 53(2013), 205-217.

22. Heinonen J., R. Paltemaa, and K. Hämäläinen 2014. "Regulatory Review and Assessment of the 2012 Construction License Application for an SNF Disposal Facility at Olkiluoto, Finland – 14243," in *Proceedings of the WM2014 Conference*, March 2 – 6, 2014, Phoenix, Arizona USA.

23. Anderberg J. 2014. "Regulatory Challenges in the Licensing of a Spent Nuclear Fuel Repository in Sweden – 14483," in *Proceedings of the WM2014 Conference*, March 2 – 6, 2014, Phoenix, Arizona USA.

24. DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application Safety Analysis Report,* DOE/RW-0573, Revision 1. U.S. Department of Energy, Washington, DC. (http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/yucca-lic-app-safety-report.html#1).

25. Kuhlman, K. 2013. "Historic Testing Relevant to Disposal of Heat-Generating Waste in Salt," *Radwaste Solutions* **20**(4), September–October, 2013, pp. 22-28, American Nuclear Society (www.ans.org), La Grange Park, Illinois 60526.

26. Kuhlman K. 2014. "State of RD&D, Design & Site Characterization in Salt Host Rock," in Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

27. DOE (U.S. Department of Energy). 2009. *Waste Isolation pilot Plant Compliance Recertification Application.* DOE 2009-24-34. March 2009.

28. Bracke G., K. Fischer-Appelt, and B. Baltes 2013. "Preliminary Safety Analysis of the Gorleben Site: Overview – 13298," in *Proceedings of the WM2013 Conference*, February 24 – 28, 2013, Phoenix, Arizona USA.

29. Wieczorek K. and J. Mönig 2014. "Results from the Preliminary Safety Analysis of Gorleben," in *Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments*, Oct. 7-9, 2014, Albuquerque, NM, http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx

APPENDIX A. REPOSITORY DEVELOPMENT MATRIX

This appendix presents a repository development matrix consistent with the timeline presented in Figure 2.1.

Repository Development Program and its Major Activities

Major Development Phases / Major Activities	Planning, R&D, and Concept Evaluation	Site Selection: A consent-based process				Site Characterization	Repository Development			
	Evaluate Disposal Concepts, FEPs, Develop and Demonstrate Technologies, Preliminary RD&D	**Elicitation of Interested Host Communities**	**Initial Site Evaluation**	**Candidate Sites Evaluated**	**Preferred Site Selected**	**Characterization of Selected Site**	**License Application**	**Construction and Monitoring**	**Operations and Monitoring**	**Closure**
Management, Planning, and Project Implementation	Develop waste management policy Establish institutional and legal framework Develop waste management strategy and plan for achieving regulatory requirements including: • High-level transportation and storage plan • High-level repository construction schedule • Safety Strategy Develop consent-based siting process	Establish working relationships with stakeholders and public Enhance scientific and institutional credibility Build awareness among communities of siting process, waste management plan, Safety Case, and opportunities/benefits Identify communities interested in participating and learning more	Engage and Establish working relationships with interested communities and stakeholders Communicate Waste Management Plan, Siting Process, and opportunities/benefits to Stakeholders and communities Respond to stakeholder and community concerns and inquiries Engage and communicate Initial Site Evaluations Identify communities with potentially suitable sites that offer to continue	Engage communities with potentially suitable sites and communicate site evaluation plan and schedule Collaborate and communicate with communities on site evaluations Collaborate with communities to conduct and understand environmental assessments Collaborate with communities on the assessment of potential cultural, social, and economic impacts Collaborate with communities on evaluation of potentially	Communicate Updated Waste Management Plan and schedule, Site Selection Process, and opportunities/benefits to Stakeholders and communities Communicate potential repository design and preliminary safety assessment Communicate Site Characterization Plan and schedule Establish terms and conditions with communities offering to participate in the site characterization process	Communicate Updated Waste Management Plan and schedule, Site Characterization Process and Plan Communicate and collaborate with communities on characterization of site(s) Engage and inform stakeholders and communities on progress of site characterization, repository design, transportation plan, preclosure safety, postclosure safety assessment, environmental impact assessment, and Safety Case	Communicate and collaborate with stakeholders on final plans and schedules for detailed • Site characterization • Repository design • Construction • Transportation • Storage • Preclosure Safety Assessment • Postclosure Safety Assessment • Safety Case • License Application • Monitoring Endorsement of the License Application by the Government and	Communicate Updated Waste Management Plan and schedule Finalize Construction Plan Finalize Operations Plan Finalize Monitoring Plan Develop License for Waste Emplacement Operations	Update Management Plan, Schedule, and Construction, Operations, and Monitoring Plans as needed Finalize Closure Plan	Communicate Closure Activities

	Establish baseline program schedule and costs Establish quality assurance program Establish plan, structure, and schedule for Safety Case and License Application for Construction		in the process	suitable sites Identify communities with suitable sites that offer to continue to the next step	Site Selected and endorsed by Government, stakeholders, and host and affected communities Assess the need and use of a site specific underground research laboratory	Endorsement by the Government, stakeholders, and host and affected communities to proceed with the license application	stakeholders Submittal of the License Application			
Site Characterization	Survey of national and regional geological characteristics of potential host formations, volcanic activity, tectonic and seismic activity, and fault systems Develop software/databases to manage national and regional geological information Develop siting guidelines Develop site characterization methodology and tools Collaborate with international URL activities Develop preliminary conceptual models of generic reference cases for typical natural systems and media: geology, hydrogeology, hydrogeochemistry, and geotechnology Develop preliminary thermal, hydrologic, transport, chemical, mechanical process models for generic	Establish geological guidelines for suitable sites and host media Develop Generic Site Characterization Plan and Budget: Phased approach with Initial Site Investigations based on regional surveys and available information, followed by Detailed Site Investigations Develop Data and Records Management System Develop site characterization methodology and tools Collaborate with international URL activities Develop preliminary conceptual models of generic reference cases for typical natural systems and media: geology, hydrogeology, hydrogeochemistry, and geotechnology	Using existing information and siting guidelines, conduct initial site evaluations using existing information and identify any potential issues that may obviate suitability of proposed sites Develop site characterization methodology and tools Collaborate with international URL activities Develop preliminary conceptual models of generic reference cases for typical natural systems and media: geology, hydrogeology, hydrogeochemistry, and geotechnology Develop preliminary thermal, hydrologic, transport, chemical, mechanical process models for generic reference cases: Engineered Barrier System (EBS) Near–Field Geosphere Biosphere	Develop Site Specific Draft Characterization Plans Conduct assessments of the effects on public health and safety and the environment of the site-characterization activities described in the draft site characterization plan Collect existing site specific information, conduct surface based and subsurface based investigations as needed: exploratory boreholes, geologic mapping, airborne and surface geophysical surveys, aerial photographs, satellite imagery Develop data for preliminary site-specific models of geology, hydrogeology, geochemistry, and geotechnology of candidate host sites Develop host rock and geosphere parameter values for site-specific coupled-process models and performance assessment	Extensive field work begins to collect site specific data to develop geological, hydrogeological, geochemical, and thermal mechanical/geotechnical models of the host rock and natural barrier system Identify location and extent of proposed repository Develop detailed site characterization plan, schedule, and budget Conduct regional hydrogeological and hydrological investigations and monitoring Conduct surface and subsurface investigations and geophysical surveys, including drilling and coring, field and lab testing Develop host rock and geosphere parameter values for site-specific coupled-process models and	Extensive field work continues to reduce uncertainty in site specific data and understanding of the following areas: geological, hydrogeological, geochemical, geotechnical; climatology, meteorology, and reference biosphere Update site characterization plan Continue regional hydrogeological and hydrological investigations and monitoring Continue surface and subsurface investigations and geophysical surveys, including drilling and coring, field and lab testing Continue development of host rock and geosphere parameter values for site-specific coupled-	Geological models and geoscientific understanding of site has been confirmed, with acceptable residual uncertainty in host rock and geosphere parameter values and features, events, and processes (FEPs)	Establish criteria and investigations for evaluation and confirmation/selection of emplacement areas Site investigations to collect data important to PA/Post-Closure Safety Compare data collected to data used in LA PA	Monitor and confirm data and processes important to Post-Closure Safety	

	reference cases: Engineered Barrier System (EBS) Near–Field Geosphere Biosphere	Develop preliminary thermal, hydrologic, transport, chemical, mechanical process models for generic reference cases: Engineered Barrier System (EBS) Near–Field Geosphere Biosphere		models	performance assessment models Characterize uncertainty in host rock and geosphere parameter values Construction of site-specific URL to characterize host formation and confirm subsurface properties and geology Conduct surveys to collect data on flora, fauna, surface water, biota, topography, soils, human communities and land use (data to support Environmental Impact Assessments and Biosphere Modeling)	process models and performance assessment models Reduce uncertainty in host rock and geosphere parameter values to acceptable levels Continue to collect data on flora, fauna, surface water, biota, topography, soils, human communities and land use (data to support Environmental Impact Assessments and Biosphere Modeling)				
Repository Design, including Waste Package Design and Waste Characterization	Literature survey, international collaborations (e.g., at URLs) on typical repository design concepts for potential media, and analysis of repository design concepts and repository layouts in representative generic geologic media Preliminary characterization of inventory and waste forms – quantities, characteristics (e.g., initial enrichment, burnup, age, thermal load, physical characteristics) and chemical and radiological composition of different wastes to be disposed, including HLW, SNF, and intermediate wastes for generic studies Develop waste package solutions for different waste	Develop Waste Characterization Plan Characterize inventory and waste forms for preliminary waste package and repository design Preliminary repository design concept(s), including high-level conceptualization of major subsurface and EBS facilities including waste packages, surface facilities and infrastructure facilities, available elicitation of interested host communities	Waste characterization continues and provides essential input to waste package and repository design, required disposal volume, repository layout and disposal concepts, These factors in turn influence site selection and may set preliminary suitability requirements such as extent of host rock to accommodate waste volume. Progress to more detail in the design concept, tailored to the potential sites Assess constructability at potential sites	Update waste characterization as needed Locations identified and potential repository design concepts adapted to specific rock type and geosphere for preliminary assessments Preliminary repository layout and design concepts in this phase include: major subsurface facility structures and EBS, waste packages, access design, and seals necessary to evaluate constructability and post-closure performance Preliminary consideration of surface and infrastructure facilities in relation to site evaluation and constructability	Update waste characterization as needed Establish preliminary design and functional requirements for waste packages and repository design for site selection Repository conceptual design completed for evaluations and communication to stakeholders Repository conceptual design includes layout and major subsurface facilities and EBS, waste packages, access openings, and seals; surface facilities, systems and components; infrastructure structures, systems, and components	Finalize Waste Characterization Plan Establish design and functional requirements for waste packages and repository LA design Iterate with PA and Site Characterization to finalize EBS design including ventilation system, waste package, backfill, and EBS conceptual design Finalize repository conceptual design and progress to more detail in final design detail as necessary for the License Application	Confirmation of waste characteristics at time of disposition and uncertainties conformance with regulatory waste acceptance criteria. Confirm waste receipt rate. Establish conformance with repository design and functional requirements Sufficient technology readiness levels (TRLs) for the necessary technologies have been demonstrated Demonstrate that “as built” repository	In collaboration with PA, establish constraints on the impacts to the host formation and hydrogeology due to repository construction Flexibility in design maintained to accommodate variability in variability host formation Assess potential impacts to repository’s intended functions due to construction procedures	Full scale operations Waste inventory for disposition received and emplaced Characterization and documentation of waste characteristics and acceptance criteria met	Backfill and seals emplaced

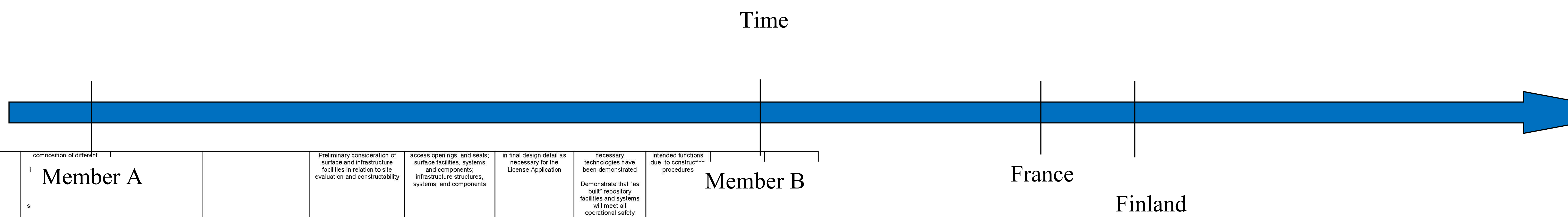
	streams Develop preliminary waste package designs Develop repository system specifications for generic reference geological systems and candidate media						facilities and systems will meet all operational safety requirements Establish proposed schedules for construction, receipt of waste, and emplacements of wastes In collaboration with PA, establish constraints on the impacts to the host formation and hydrogeology due to repository construction			
Post-Closure Safety Assessment	Develop total system performance assessment (TSPA) repository and geosphere conceptual models of generic reference cases Conduct Features, Events, and Processes (FEPs) analysis of generic reference cases and identify scenarios and excluded FEPs Develop database and input parameters for generic reference cases and TSPA Develop TSPA mathematical and computational methodology for probabilistic TSPA simulations, uncertainty quantification, and sensitivity analysis Develop generic post-closure computational safety assessment models for implementation in TSPA	Continue development of safety assessment tools and analyses initiated in preceding phase as necessary to support site selection, site characterization, safety assessment, and License Application Continue development of Post Processing and Presentation Methods for Stakeholder Interactions	If necessary, use data collected in site characterization and understanding of FEPs, generic reference cases, radionuclide screening, and simplified tools to conduct Site evaluations to support identification of candidate sites Continue development of safety assessment tools and analyses conducted in preceding phases as necessary to support site selection, site characterization, safety assessment, and License Application	Using site-specific data develop input parameters for simplified safety assessments and site evaluations Update radionuclide screening assessment as needed. Develop simplified representations of repository designs Conduct site evaluations to support selection of preferred site(s) Continue development of safety assessment tools and analyses conducted in preceding phases as needed to support site selection, site characterization, safety assessment, and License Application Develop site evaluation presentations for communication to	Using site-specific data develop input parameters for simplified safety assessments and site evaluations Revisit generic FEPs analyses and reassess for site specific conditions Develop appropriately detailed representations of conceptual repository designs Update radionuclide screening assessment as needed Revise and tailor conceptual and computational TSPA models for site-specific conditions Conduct Site Selection Analyses incorporating site-specific conceptual repository design and	Continue development of safety assessment tools and analyses conducted in preceding phases as needed to support site selection, site characterization, safety assessment, and License Application TSPA analyses conducted to guide site characterization activities, laboratory testing programs, URL activities, and to support repository LA design studies Conduct Post-Closure Safety Assessments Develop site evaluation presentations for communication to decision makers and stakeholders to support site characterization	Complete total system performance assessment (TSPA) repository and geosphere conceptual models for LA Complete Features, Events, and Processes (FEPs) analysis, define evolution of system and scenarios and excluded FEPs Complete database and input parameters for LA Finalize TSPA mathematical and computational methodology for probabilistic TSPA simulations, uncertainty quantification, and sensitivity analysis Complete	Perform final PA prior to waste emplacement including data and knowledge gathered during construction (including any design changes and construction impacts) and URL Use PA and UA/SA as basis for finalizing monitoring program during operational phase	Final PA for Closure; updates to Safety Case, as necessary including data and knowledge gathered during operations and monitoring	

	Develop TSPA System Model for Safety Assessments and Site Evaluations Conduct radionuclide screening assessment of radionuclide inventory to determine radionuclides important to dose and determine representative inventory for site evaluations to support site evaluation Develop Post Processing and Presentation Methods for Stakeholder Interactions			stakeholders	important site specific FEPs Preliminary uncertainty quantification, sensitivity analyses to inform site characterization planning Continue development of safety assessment tools and analyses conducted in preceding phases as needed to support site selection, site characterization, safety assessment, and License Application Develop site evaluation presentations for communication to decision makers and stakeholders to support site selection		development of post-closure computational safety assessment models for implementation in TSPA Complete TSPA System Model for LA Safety Assessment Finalize radionuclide screening assessment of radionuclide inventory to determine radionuclides important to dose and determine representative inventory for LA Safety Assessment Complete Final Post-Closure Safety Assessment for LA Develop LA presentations for communication to decision makers and stakeholders to support LA submittal			
Generic Underground Research Facilities	Assessment of existing information at existing URLs in other nations Collaborate on specific studies in existing URLs to meet information needs Site URL Develop technologies and methodologies for URL	Assessment of existing information at existing URLs in other nations Collaborate on specific studies in existing URLs to meet information needs Continue to gather generic data, investigate coupled processes and FEPs,, and conduct International collaborations	Engage Stakeholders and interested communities and use URFs as vehicle for information exchange, demonstration of expertise, and confidence building Demonstrate expertise and capability to provide information on site suitability and safe disposal Continue to gather generic data, investigate coupled processes and FEPs, and conduct International collaborations	Engage Stakeholders and interested communities and use URFs as vehicle for information exchange, demonstration of expertise, and confidence building Demonstrate expertise and capability to provide information on site suitability and safe disposal Demonstrate utility and accuracy of surface-based and underground characterization and monitoring methods and	Engage Stakeholders and interested communities and use URFs as vehicle for information exchange, demonstration of expertise, and confidence building Demonstrate expertise and capability to provide information on site suitability and safe disposal Demonstrate utility and accuracy of surface-based and underground characterization and monitoring methods and technologies					

	investigations Investigate FEPs and gather generic data relevant to processes in the EBS and near-field host rock Measure to-scale coupled processes for development and validation of models Improve and assess utility and accuracy of surface-based and underground characterization and monitoring methods and technologies Develop methods, equipment and experience in repository construction Train staff for future repository investigations Foster International Collaboration Promote public confidence in geological disposal	Engage Stakeholders and interested communities and use URFs as vehicle for information exchange, demonstration of expertise, and confidence building Develop methods, equipment and experience for surface-based and underground characterization and monitoring techniques, and staff training Evaluate and demonstrate full-scale disposal concepts Evaluate at full-scale performance of EBS concepts Develop technologies needed to emplace components of the EBS Train staff for future repository investigations Develop methods, equipment and experience in repository construction, operation and closure, and in waste retrieval Testing and further development of conceptual and numerical models Provide data for generic performance assessments	Improve methods, equipment and experience for surface-based and underground characterization and monitoring techniques, and staff training Evaluate and demonstrate full-scale disposal concepts Evaluate at full-scale performance of EBS concepts Develop technologies needed to emplace components of the EBS Train staff for future repository investigations Develop methods, equipment and experience in repository construction, operation and closure, and in waste retrieval Testing and further development of conceptual and numerical models Provide data for generic performance assessments	technologies Continue to gather generic data, investigate coupled processes and FEPs, and conduct International collaborations Train staff for future repository investigations	Continue to gather generic data, investigate coupled processes and FEPs, and conduct International collaborations Train staff for future repository investigations					

Site-Specific Underground Research Facilities						Design, permit, and construct URF Gather site-specific data including detailed host rock properties Develop and/or modify technologies and methodologies for site-specific URL investigations Investigate site-specific FEPs and gather site-specific data relevant to processes in the EBS and near-field host rock Measure to-scale coupled processes for development and validation of LA models Verify utility and accuracy of surface-based and underground characterization and monitoring methods and technologies Evaluate and demonstrate disposal concepts to support LA design evaluations Continue Stakeholder Engagements for	Evaluate, optimize, and finalize LA design concept Conduct investigations to address and reduce uncertainty and conservatism in important safety assessment issues Complete testing and development of technologies and methods for construction, waste and EBS emplacement, and safe operations Demonstrate technologies and methods for construction, waste and EBS emplacement, and safe operations Confirm site-specific data, understanding of full-scale coupled processes, and validate models Continue Stakeholder Engagements for confidence building	Demonstrations completed Repository design and planned operations confirmed Continue Stakeholder Engagements for confidence building Refinement of excavation, construction, operation, handling, and emplacement methods and machinery Development and testing of retrieval methods and technologies	Monitoring of in situ conditions and effects of in situ conditions on the EBS components Refinement or modification of emplacement methods if unexpected conditions are encountered while excavating emplacement drifts	Monitoring of in situ conditions and effects of in situ conditions on the EBS components Conduct investigations related to effective sealing of the repository

						confidence building Evaluate and demonstrate suitable construction and emplacement technologies and methods				



	composition of different i s Develop preliminary waste package designs Develop repository system specifications for generic reference geological systems and candidate media			Preliminary consideration of surface and infrastructure facilities in relation to site evaluation and constructability	access openings, and seals; surface facilities, systems and components; infrastructure structures, systems, and components	in final design detail as necessary for the License Application	necessary technologies have been demonstrated Demonstrate that "as built" repository facilities and systems will meet all operational safety requirements Establish proposed schedules for construction, receipt of waste, and emplacements of wastes In collaboration with PA, establish constraints on the impacts to the host formation and hydrogeology due to repository construction	intended functions due to construc… procedures		
Post-Closure Safety Assessment	Develop total system performance assessment (TSPA) repository and geosphere conceptual models of generic reference cases Conduct Features, Events, and Processes (FEPs) analysis of generic reference cases and identify scenarios and excluded FEPs Develop database and input parameters for generic reference cases and TSPA Develop TSPA mathematical and computational methodology for probabilistic TSPA simulations, uncertainty quantification, and sensitivity analysis Develop generic post-closure computational safety assessment models for implementation in TSPA Develop TSPA System Model for Safety Assessments and Site Evaluations Conduct radionuclide screening assessment of	Continue development of safety assessment tools and analyses initiated in preceding phase as necessary to support site selection, site characterization, safety assessment, and License Application Continue development of Post Processing and Presentation Methods for Stakeholder Interactions	If necessary, use data collected in site characterization and understanding of FEPs, generic reference cases, radionuclide screening, and simplified tools to conduct Site evaluations to support identification of candidate sites Continue development of safety assessment tools and analyses conducted in preceding phases as necessary to support site selection, site characterization, safety assessment, and License Application	Using site-specific data develop input parameters for simplified safety assessments and site evaluations Update radionuclide screening assessment as needed. Develop simplified representations of repository designs Conduct site evaluations to support selection of preferred site(s) Continue development of safety assessment tools and analyses conducted in preceding phases as needed to support site selection, site characterization, safety assessment, and License Application Develop site evaluation presentations for communication to stakeholders	Using site-specific data develop input parameters for simplified safety assessments and site evaluations Revisit generic FEPs analyses and reassess for site specific conditions Develop appropriately detailed representations of conceptual repository designs Update radionuclide screening assessment as needed Revise and tailor conceptual and computational TSPA models for site-specific conditions Conduct Site Selection Analyses incorporating site-specific conceptual repository design and important site specific FEPs Preliminary uncertainty quantification, sensitivity analyses to inform site characterization planning Continue development of safety assessment tools and	. Continue development of safety assessment tools and analyses conducted in preceding phases as needed to support site selection, site characterization, safety assessment, and License Application TSPA analyses conducted to guide site characterization activities, laboratory testing programs, URL activities, and to support repository LA design studies Conduct Post-Closure Safety Assessments Develop site evaluation presentations for communication to decision makers and stakeholders to support site characterization	Complete total system performance assessment (TSPA) repository and geosphere conceptual models for LA Complete Features, Events, and Processes (FEPs) analysis, define evolution of system and scenarios and excluded FEPs Complete database and input parameters for LA Finalize TSPA mathematical and computational methodology for probabilistic TSPA simulations, uncertainty quantification, and sensitivity analysis Complete development of post-closure computational safety assessment models for implementation in TSPA	Perform final PA prior to waste emplacement including data and knowledge gathered during construction (including any design changes and construction impacts) and URL Use PA and UA/SA as basis for finalizing monitoring program during operational phase	Final PA for Closure; updates to Safety Case, as necessary including data and knowledge gathered during operations and monitoring	

APPENDIX B. IAEA URF NETWORK WORKSHOP: NEED FOR AND USE OF GENERIC AND SITE-SPECIFIC UNDERGROUND RESEARCH LABORATORIES TO SUPPORT SITING, DESIGN, AND SAFETY ASSESSMENT DEVELOPMENTS

In October 2014, a three-day workshop was held in Albuquerque, New Mexico to identify and compare the understanding of URF Network members on the place and role of a generic or site-specific underground research laboratory (URL) in the overall, iterative geological disposal development process, including repository siting, design, and post-closure safety assessment. Attention was also given to the need for URLs in salt host rock, since there is currently no such facility in operation in the world. The primary goals or proposed "outcomes" of the workshop were presented to the participants as follows:

- Develop a better understanding of the role of URLs to support the phased development of the safety case for a geological disposal facility for HLW/SNF.
- Develop a better understanding of the link between research and development (R&D) conducted in URLs and the overall science and technology programme.
- Develop a better understanding of how existing and new information from closed and operating generic and site-specific URLs can support program R&D needs.
- Gain a better understanding of how to develop a plan for incorporating a URL and/or URL studies into a disposal program.
- Gain a better understanding of the role a generic salt URL would play in international disposal programmes and its potential benefits.

To achieve these overall goals, presentations and workshop discussions first reviewed the role of the safety case as a management and communication framework for integrating siting, design and safety assessment. The workshop then proceeded through a succession of existing URL case studies (see Table B.1) from various national programs in different phases of development to elicit the potential scientific and engineering contributions from generic URLs in different host formations, as well as from site-specific URLs (in more advanced repository programs that have already chosen a repository site). These case studies included the role of URLs in advancing the technical knowledge base, in validating conceptual and numerical models of repository behavior, and in building confidence with stakeholders. Given also the associated cost, design and operational considerations for a URL, group discussions further addressed the place and role of a generic or site-specific URL compared to other types of research, development, and demonstration (RD&D) activities, as well as their prioritization. Finally, these considerations were revisited for the specific case of a URL sited in a salt host rock, to elicit the need and urgency, if any, to establish such a facility, as there is currently not one in operation around the world. The major product of the three-day workshop is expected to be an IAEA report that can be used as a basis for training on how to effectively use URLs to support a geological disposal program.

Table B.1. Presentations give at the IAEA URF Network workshop on "Need for and use of generic and site-specific underground research laboratories to support siting, design, and safety

assessment developments." (Workshop presentations may be accessed at: http://connect.iaea.org/sites/connect-members/URF/2014-URF-Use_SandiaVenue/default.aspx [2])

Presentation Title	Presenter	Affiliation
Introductions, Workshop Objectives, Structure, and Approach	Mr. Robert MacKinnon	SNL
Overview of International URLs	Mr. Stefan Mayer	IAEA
Role of URLs in Support of the Safety Case	Mr. S. David Sevougian	SNL
Importance of URLs in Safety Assessment with Focus on Licensing Processes in Canada	Ms. Karina Lange	CNSC
Overview of the U.S. DOE's International Collaborations in Disposal R&D	Mr. Peter Swift	SNL
Case Study: The Grimsel Test Site	Mr. Stratis Vomvoris	NAGRA
Case Study: The Mont Terri Rock Laboratory	Mr. Paul Bossart	swisstopo
Case Studies: Currently Operating Generic URLs in Crystalline and Sedimentary Host Rocks (Mizunami and Horonobe)	Mr. Naotaka Shigeta	JAEA
Case Study: ONKALO Underground Rock Characterization Facility	Mr. Kimmo Kemppainen	Posiva
Extension of the KURT and its Role for the Geological Disposal Programme in Korea	Mr. Geon Young Kim	KAERI
URL Cost and Design Considerations	Mr. Ernest Hardin	SNL
Lessons Learned from Canada's Underground Research Laboratory	Mr. Paul Thompson	AECL
Preliminary Plans for In-DEBS Experiment in KURT	Ms. InYoung Kim	KAERI
Plans for a URF to Support Czech Republic's National Disposal Program	Mr. Lukas Vondrovic	SURAO (RAWRA)
An Underground Laboratory in the Context of Salt Disposal RD&D	Mr. Frank Hansen	SNL
TSDE Thermal Test: Post-test Evaluation of Instrumentation and Considerations for Future Test	Mr. Gerald-Hans Nieder-Westermann	DBE-TEC
Results from the Preliminary Safety Analysis of Gorleben	Mr. Klaus Wieczorek	GRS
State of RD&D, Design & Site Characterization in Salt Host Rock	Mr. Kris Kuhlman	SNL

WORKSHOP GOALS AND OUTCOMES

During the course of the three-day workshop, focus sessions comprised of all participants were held to generate ideas for each of the five workshop goals, based on the in-depth URL experiences of the assembled participants. These discussions generated useful outcomes for each goal, described below, which can help guide future uses and planning for both generic and site-specific URLs.

Goal #1: Develop a better understanding of the role of URLs to support the phased development of the safety case for a geological disposal facility for HLW/SNF.

This goal applies to all phases of the repository development/RD&D timeline shown in Figure 2.2 but is particularly important to the first indicated step of the Repository Development phase—the development and submittal of a safety case for licensing construction. Several important observations were noted by workshop participants as regards the importance and role of URLs with respect to safety case development:

a) A very long-term (decades) perspective should be adopted for the uses of both generic and site-specific URLs. The final, "as-built" safety case differs from the preliminary safety case in the amount and type of required information, which will be reflected in the type and complexity of testing supported by URLs in each repository phase. This should be incorporated into the initial planning of URLs, recognizing that their role and usage will evolve over a multi-decade period, but their usefulness will not generally diminish. Appropriate milestones should be built into both the repository development program and the associated URL studies to reflect the required maturity of

R&D at the end of a particular phase or milestone. This could be quantified by associating specific and increasing TRL values with each of the milestones. It is recommended that an example milestone schedule be formulated showing TRL values and associated example technologies for a generic repository development program.

b) A comprehensive knowledge retention program is important on both a national and an international basis. For example, in Canada many of the technical lessons learned from the AECL Whiteshell URL have been lost in the organizational transition from AECL to NWMO, due to a break in organizational continuity [15]. One of the main purposes of URLs is to ensure a vehicle for transferring knowledge and experience between generations of scientists and engineers in a multi-decade repository program. This is important not only from a technical standpoint but from a confidence-enhancement and integrity perspective with the public and other stakeholders. It is recommended that a cooperative international effort be initiated to develop an easily accessible URL knowledge base that is populated with currently available data from existing and/or closed URLs.

c) Stakeholder input and involvement is important for both URL siting and operation. This includes the general public, the regulator, and technical advisors (such as universities). Outreach and knowledge centers built at URLs (whether generic or site-specific) increase transparency, confidence, and national participation in solving the nuclear waste disposal problem. It is recommended that successful examples of stakeholder participation from several national programs be assembled into a summary training document.

<u>Goal #2</u>: Develop a better understanding of the link between R&D conducted in URLs and the overall science and technology programme.

This goal is again important to all phases of a repository program and requires an understanding of the economics involved in constructing and operating both generic and site-specific URLs [4]. During the Concept Development and Site Selection phases (Figure 2.2), this issue should help guide the decision of whether or not to build a generic URL. After site selection, this issue combined with budgetary constraints, should determine the allocation of resources between *in situ* R&D and surface-based R&D. Figure 2.3 identifies in situ R&D activities supported by URLs in the context of R&D for the overall science and technology program supporting the safety case. Two important observations were noted by workshop participants regarding the relationship between these R&D activities in URLs versus R&D activities conducted at the surface (e.g., laboratory investigations):

a) Several URL programs, e.g., AECL's Whiteshell [15] and Nagra's Grimsel [8], have found that laboratory measurements of certain parameters and processes may result in parameter values that are not representative of repository conditions. For example, due to mechanical stress relief and the resulting increases in porosity, laboratory core measurements may incorrectly estimate *in situ* diffusive transport coefficients in crystalline rock. It is recommended that training documentation include known examples where lab-derived parameters differ from *in situ* estimations.

b) Retrievability, which is a licensing requirement in most national programs (e.g., [17]), is an issue that still remains to be demonstrated. Given that a URL is probably the only venue for confident demonstration, a program must either use its own site-specific URL (preferable) or must arrange with another program (in a similar host rock) to design and conduct a demonstration.

<u>Goal #3</u>: Develop a better understanding of how existing and new information from closed and operating generic and site-specific URLs can support program R&D needs.

Again, this goal is important throughout the timeline of repository development (Figure 2.2). Some of the related issues are whether a site-specific URL is always necessary for a repository program, or can a program's R&D needs be satisfied with information from URLs in other countries. This is strongly related to the stage of the repository program, which requires more site-specific information as it progresses towards a license for construction. The question then becomes how much technical information is necessary from a purpose-built URL at the repository site in order to support both the technical and non-technical aspects of a safety case (Figure 2.3) Workshop participants made the following observation in this regard:

a) Transferability of information [3] is the key concept here and some metric(s) should be proposed to help determine the degree of transferability from generic or site-specific URLs in one repository program to other repository programs. Mining and operational techniques will have different metrics for transferability than FEPs, modeling, and safety assessment information. The former may be transferable among different media and concepts but the latter perhaps only transferable if the medium (e.g., clay, granite, salt) is sufficiently similar for the different programs. For transferability with respect to FEPS and modeling for a given medium, the key point may be transference of modeling tools and methodologies among national programs. It is recommended the transference criteria be outlined and incorporated into the early stages of a repository program, which is facilitated by a robust international cooperation effort. In addition, any newly built generic URLs that are envisioned to include a significant international collaboration aspect should consider transference criteria at the beginning of their R&D planning.

Goal #4: Gain a better understanding of how to develop a plan for incorporating a URL and/or URL studies into a disposal program.

The role of URLs has been described above at a high level in the context of an overall repository development or disposal program. The first step in developing a plan for incorporating a URL into a program would be to take a similar but more detailed approach as outlined above that would include developing an overall program schedule, identifying specific near-term and long-term objectives to be achieved, and including milestones in the schedule that correspond to achieving these objectives. Cost estimates for completing the different milestones would also need to be made to have an understanding of potential future costs and to adjust expectations if needed. An early working draft of such a plan should be developed during an early phase of repository development such as the Concept Evaluation phase and/or the Site Selection phase because significant technical, economic, and political planning is required prior to actual initiation of a URL, whether generic or site-specific—as discussed above in Outcome 1(a). Workshop participants made the following observations in this regard:

a) A generic or site-specific URL can serve as both a research and an operational "playground" [7] that produces important lessons for repository construction and operation. Examples derive from the Finnish program at the ongoing ONKALO URL [9] and the Canadian program at the closed AECL URL [15]. These programs found that early mining techniques needed improvement to produce both consistent excavation speeds and consistent development of the EDZ. Also, mining contractors needed training for repository mining, which has different requirements than mineral extraction. A bonus should be placed on quality rather than quantity of excavations. Thus, the URL can serve as a training or test facility for mining optimization in the actual repository but only if continuity and retention is maintained in a robust institutional memory program.

b) When planning for a site-specific URL, an important consideration is whether it might eventually become part of the same underground tunnel system as the eventual waste repository (i.e., co-location). This has several important implications: (1) Regulatory requirements for the repository may impose greater operational and documentation constraints that result in higher URL costs and reduced timeliness and amount of *in situ* experimentation, (2) a potential accident in either the URL or in the operating repository (during emplacement) may have an adverse effect (e.g., the recent WIPP accident has shut down *in situ* physics experiments), (3) the URL funding profile may be affected by the repository funding profile, if there is a limited funding stream, (4) costs for construction and access infrastructure will be optimized when the URL and repository are co-located, (5) success (or vice-versa, problems and accidents) with the URL can raise/lower public acceptance of the co-located repository, and (6) transferability of information about processes and parameters is generally enhanced through co-location.

c) Hidden benefits of a URL are sometimes not considered in the planning and budget profile. These are the economic benefits related to building safety confidence, which are more difficult to quantify in dollars than immediate costs related to operations and capital expenditures, but can result in much higher actual expenditures later in the repository development and licensing process. These benefits include reduction of uncertainties and enhancement of confidence in safety assessments, attained through the unique modeling, testing, and operational work conducted in URLs. These "intangible" benefits might be measured by assigning a dollar value to increased TRLs for various elements of the safety case, including both technical elements and non-technical elements.

<u>Goal #5</u>: Gain a better understanding of the role a generic salt URL would play in international disposal programmes and its potential benefits.

Salt repository investigations have been ongoing for decades [25, 26], particularly related to the US WIPP repository for disposal of transuranic wastes in bedded salt [27] and the proposed Gorleben salt-dome repository for disposal of high-level waste [28, 29]. Thus, although this workshop goal is applicable to all phases of the repository development timeline (Figure 2.2), it has significant input from mature R&D studies that have been carried out in the license application development and submittal phase. Despite the significant degree of available past information from *in situ* R&D studies in salt, the workshop participants made the following observations:

a) There are definable benefits for establishing a generic salt URL, including (1) investigating heat dissipation for large waste packages—those containing a significant heat load, such as dual-purpose canisters (DPCs) in the US program, (2) retrievability of waste packages in salt, including the issue of vertical movement (which appears to not follow currently available constitutive laws), (3) how neutron absorption is improved by salt (i.e., criticality control), (4) the effect of brine movement in the EDZ and its potential impact on gas generation, (5) hoisting and handling of large waste containers, (6) full-scale demonstrations of shaft sealing technology, and (7) maintaining long-term technical competence in salt repository research and operations. Model validation in salt media would also clearly benefit from full-scale *in situ* experimentation [29].

b) It is more likely that an HLW repository must first be sited in salt media before a new salt URL will be funded by a national program. The best opportunity for a generic salt URL is probably WIPP, after it is reopened.

c) The similarity of potential salt host rock at various locations throughout the world should lead to a higher degree of transferability for salt as compared to other media, which implies a greater benefit for establishing a generic salt URL in a willing host country.

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