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TECHNOLOGY READINESS ASSESSMENT PROCESS ADAPTED TO GEOLOGIC DISPOSAL OF HLW/SNF

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Technology Readiness Assessment (TRA) is a formal process to aid in defining the remaining R&D needed to bring a new, complex technology system to full technical maturity. A geologic repository for high-level radioactive waste is a prototypical complex system, comprised of novel technologies and complex environmental conditions, but because it is intended to function passively and is comprised of both engineered and geologic barriers, the standard, engineered-system ("hardware") TRA process must be modified. Longstanding precedence employs a Safety Case (or Licensing Case) as the preferred vehicle for assembling all facets of knowledge to make a determination of repository system safety and deployment readiness. However, certain modifications to the established TRA process allow it to be applied advantageously in conjunction with the Safety Case. In particular, an adaptation of the established Features, Events, and Processes (FEPs) methodology can serve as a basis for a "TRA-like" maturity evaluation for various major components and subsystems of a deep geologic repository. The newly proposed Knowledge Readiness Assessment (KRA) process combines the best of both methodologies, i.e., of FEPs analysis and standard TRA evaluation, for establishing confidence in the post-closure performance of major repository components and subsystems.

I. INTRODUCTION

Technology Readiness Assessment (TRA) is a metric-based method, similar to decision analysis,[1,2,3] developed by a number of U.S. governmental agencies to aid in defining the remaining research, development, and demonstration (RD&D) activities needed to bring a new technology system to full technical maturity or operational readiness. The TRA process assigns a technology readiness level (TRL) to key components of a system, called Critical Technology Elements (CTEs), whose successful and robust functioning are essential to successful operation of the entire system. The major uses of the TRA process are to not only minimize technical risk associated with deployment and operation of (often) one-of-a-kind complex systems and technologies, but also to inform the assignment of capital and manpower in a logically laid-out project development schedule—i.e., to optimize resource deployment. The TRL rating, combined with some type of risk metric, can be used to help prioritize RD&D within budget constraints.[a]

The TRA process, originally developed by NASA,[5-8] and further by the U.S. Department of Defense (DoD),[9] is a widely accepted technical maturity evaluation method,[b] used in a variety of industries—even in deep geologic repository programs, e.g., the construction and operations phases of the Cigéo repository in France.[10] Within the U.S. Department of Energy (DOE), it has been applied to a number of major projects in the Office of Environmental Management (EM)[11] and several projects within the Office of Fuel Cycle Technologies (FCT), including the Next Generation Nuclear Plant (NGNP)[12] and the development of glass-ceramic waste forms.[13]

A key consideration in the viable application of the DOE TRA process to geologic repository projects is the typical developmental timeline and associated phases of the project, which occur over a period of decades. A sequence of three major phases can be recognized, as indicated in Fig. 1: Concept Evaluation, Site Selection, and Repository Development. The U.S. repository program is currently in the Concept Evaluation phase, during which most of the work is generic in nature and is being conducted to further the understanding of potential disposal concepts and their associated Features, Events, and Processes (FEPs). The preliminary RD&D conducted during the current phase lays the groundwork for making informed decisions and assessments of alternative technologies and concepts that will be required as the timeline progresses towards the later Repository Development phase. Although a formal TRA process is

[a] Although TRLs provide a measure of the maturity (or deployment readiness) of a particular technology, they cannot be used as the sole basis for comparing competing technologies, since, by itself, a TRL does not assess the risks, schedule, or costs of advancing a particular technology to its needed maturity (Ref. 4, Sec. 2.2).

[b] The DoD defines a TRA as "a formal, systematic, metrics-based process and accompanying report that assesses the maturity of technologies called Critical Technology Elements (CTEs) to be used in systems."[9]

not appropriate during the early Concept Evaluation and Site Selection Phases, due to the generic nature of the RD&D activities, TRAs may provide several substantial benefits during later stages of the project, albeit with some necessary modifications arising from the unique nature of a geologic system, as described here.

In particular, TRAs have traditionally been applied to engineered or man-made technologies and systems, primarily to "active" components or systems (e.g., NASA space launch vehicles—see Ref. 5; or the planned hot isostatic press (HIP) calcine HLW disposition facility—see Ref. 14 and Ref. 4, Att. F). A "passive" system, such as a geologic repository, which is designed to function for millennia after permanent closure, requires special considerations for assessing or building confidence in its deployment readiness. A "safety case"[15-21] or licensing case[22] is the recognized, and probably more appropriate, vehicle to establish deployment readiness for the *complete* geologic repository system.[23] However, with certain modifications proposed here, the DOE TRA process may be applied fruitfully to major components of a passive geologic system.

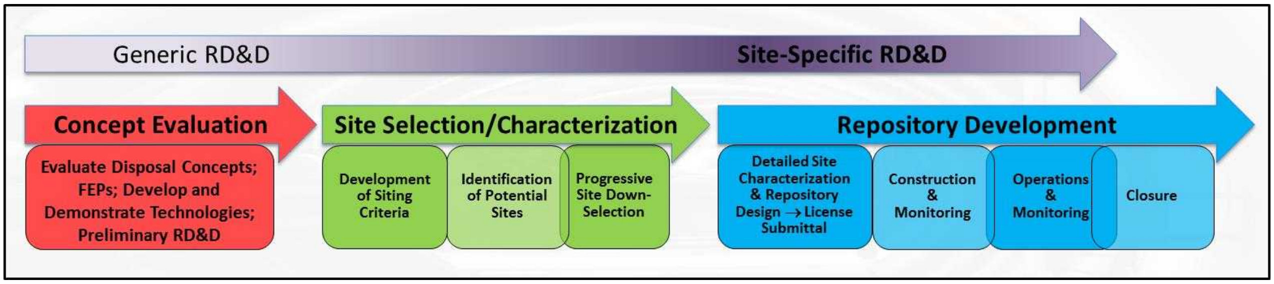

Fig. 1. High-Level Timeline for a Geologic Repository.

Specifically, this paper proposes a union of the traditional Features, Events, and Processes (FEPs) approach[24] with the established TRA process, for the evaluation of technical maturity. The major steps of the TRA process are retained, i.e., definition of CTEs, evaluation of TRLs or a similar RD&D maturity metric, and the development of a technology maturation plan to organize the future RD&D needed to increase the overall system TRL. However, the selection of CTEs is based on FEPs, and the TRL assessment process for the selected repository CTEs is modified for post-closure subsystems[c] influenced strongly by natural processes, to reflect that their technical maturity is based on *knowledge* maturation rather than engineered component maturation.

II. BACKGROUND

In 2007 the U.S. Government Accountability Office (GAO) recommended that the DOE adopt the NASA/DoD TRA methodology for evaluating the maturity of new technologies used in major construction projects because premature application of new technologies had led to cost and schedule overruns in a number of DOE projects.[25] Subsequently, DOE conducted a Root Cause Analysis[26] and issued a Corrective Action Plan[27] regarding cost/schedule overruns for large projects, with part of their findings being that improper assessment of the technology readiness of key components had indeed been a key factor in previous cost/schedule overruns.

As a result of these investigations and analyses, DOE issued formal guidance, *DOE G 413.3-4*,[28] recommending the use of the TRA process for all major DOE projects—those with a total project cost in excess of $750M. This guidance has been further elaborated upon by DOE's Office of Environmental Management.[4] Both the general *DOE TRA Guide*, now updated as *DOE G 413.3-4A*,[29] and the DOE-EM *TRA/TMP Process Implementation Guide*[4] are based on the *DoD Technology Readiness Assessment (TRA) Deskbook*,[30] which grew out of a 1999 GAO recommendation[31] that DoD adopt the NASA TRL methodology (see Ref. 5 and Ref. 32, App. G) for major DoD projects. Although the DOE TRA guidance was formalized for all DOE Offices by *DOE G 413.3-4* in 2009, the TRA process had previously been used by DOE-EM for several of its major projects—for example, in 2007 for both the K Basins Sludge Treatment Process[33] and the Savannah River Site Tank 48H Waste Treatment Project.[34]

[c] "Component," "technology," and "technological element" are generally used interchangeably in the TRA literature and are the basic unit (of a system) to which a maturity or readiness level can be assigned. A "subsystem," or "system" (which may be comprised of several identifiable subsystems), is a combination of technologies, with an overall maturity level that is a function of the maturity and interworking of its individual technologies.

The conduct of a formal TRA for a U.S. DOE project is tied to the guidance in *DOE Order 413.3B*, *Program and Project Management for the Acquisition of Capital Assets*,[35] which requires a TRA prior to certain Critical Decision (CD) points for a Major System Project, *viz.*, one with a Total Project Cost (TPC) greater than or equal to $750M. Specifically, a formal TRA is required prior to "CD-2: Approve Performance Baseline;"[d] but also prior to "CD-3: Approve Start of Construction/Execution," if there is a significant modification to one of the Critical Technology Elements (CTEs) subsequent to CD-2 (Ref. 35, App. C, p. C-27). DOE guidance on the conduct of TRAs[4,29] has extended this requirement to recommend a formal TRA at "CD-1: Approve Alternative Selection and Cost Range." In addition, DOE suggests that a TRA is "highly recommended for smaller projects, as well as Operations Activities, such as technology demonstrations, which involve the development and implementation of new technologies or technologies in new operational environments."[4] The relationship between CD milestones and TRAs is shown in Fig. 2.

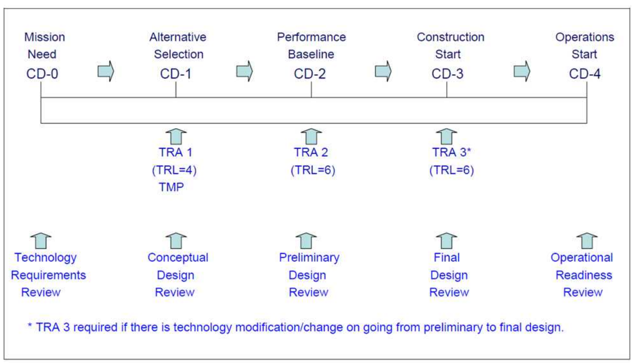

Fig. 2. Suggested Technology Readiness Assessments and Other Reviews for Critical Decisions (same as Ref. 29, Fig. 3 and Ref. 4, Fig. 2)

The approach shown in Fig. 2 is called the "graded approach for TRAs" DOE (Ref. 29, Sec. 2.1). It recommends: (1) conducting a TRA at least 90 days prior to an indicated CD milestone and (2) developing a Technology Maturation Plan (TMP) if some of the CTEs have not reached the TRL rating indicated in Fig. 2 at the given CD. A TMP lays out the additional work needed so that the technologies are matured to TRL 6 by the time of CD-2. As stated in *DOE G 413.3-4A*:[29] "A TMP is a planning document that details the steps necessary for developing technologies that are less mature than desired to the point where they are ready for project insertion. TRAs and TMPs are effective management tools for reducing technical risk and minimizing potential for technology driven cost increases and schedule delays."

[d] DOE defines "CD-2: Approve Performance Baseline" as "completion of preliminary design, and development of a performance baseline that contains a detailed scope, schedule, and cost estimate, and key performance parameters that must be achieved at CD-4." (Ref. 29, Sec. 2.1)

III. KEY ASPECTS OF THE ESTABLISHED TECHNOLOGY READINESS ASSESSMENT (TRA) PROCESS

Both DOE TRA guides[4,29] lay out a formal process and schedule for planning, conducting, and reporting for a TRA, with the DOE-EM guide[4] being the most detailed. Following is a brief summary:

III.A. Major Steps of the TRA Process

The primary conceptual steps in a TRA are few:

1. *Identify Critical Technology Elements* (CTEs) for the system or subsystem that is the subject of the TRA.
2. *Evaluate (or assess) the TRL* of each CTE and document the basis for the assigned level. After the completion of the TRL evaluation for all individual CTEs, various methods (simple or complex) may be used to assign a "system TRL." This step also includes the preparation of a TRA Report summarizing the process followed, including a one-page "TRA Summary" (e.g., see Ref. 4, Att. F).
3. *Develop a Technology Maturation Plan* (TMP) describing the RD&D and engineering activities necessary to mature CTEs rated lower than TRL 6, in order to elevate their TRLs to Level 6 by the time of CD-2 (see Fig. 2). Vienna et al.[13] provide an example of a TMP that has been developed for a project under the purview of DOE Office of Nuclear Energy (NE).

III.B. Critical Technology Elements (CTEs)

A prerequisite to conducting a TRA for a new technology system is the breakdown of the overall system into component parts called Critical Technology Elements (CTEs) (Ref. 30, App. B):

> "A technology element is 'critical' if the system being acquired depends on this technology element to meet operational requirements (within acceptable cost and schedule limits) *and* if the technology element or its application is either new or novel or in an area that poses major technological risk during detailed design or demonstration."

The TRA process was originally designed to assign a TRL to each CTE and then, based on this assessment, to design a set of activities to mature all CTEs in the system to the same level at Critical Decision (CD) points. However, more attention is now being given to the appropriate assignment of an overall *system TRL* (or System Readiness Level—see Sec. III.D) and the role that interactions among CTEs might play in the maturity of the overall system.

Identifying the CTEs for a system is usually imposed as a two-step process wherein an initial pass is made to identify candidate CTEs (erring on the side of conservatism) and then a second pass is made to refine/correct the initial identification (Ref. 4, Sec. 3.5.3; Ref. 29, Sec. 3.0; Ref. 30, Sec. B.3):

1) The initial pass for defining CTEs is based on something similar to a systems engineering functional hierarchy (Ref. 36, Fig. 3; Ref. 30, Fig. B-1), in order to define key components of the system from either a functional standpoint or a physical standpoint. Several methods are suggested depending on the system, including a technical work breakdown structure (WBS) (Ref. 29, Fig. 4), a hardware architecture or software architecture (Ref. 30, App. B), or a process flow diagram (Ref. 29, Fig. 4a).

2) In the second or more detailed pass, two sets of five questions each are asked (i.e., two sets of five criteria are evaluated) to determine if a technology or component is a CTE. These are designed to determine two qualities of the component or technology: (1) is it "critical" to, or does it impose significant uncertainties related to, facility operation, cost, schedule, and/or safety and (2) is it "new or novel" or being used in a new or novel way. A "yes" answer to at least one question in each set of five implies that it must be considered a CTE (Ref. 29, App. E; Ref. 4, Sec. 3.5.2 and App. G).

As discussed below, for many technologies associated with geologic repository projects the second set of questions related to "novelty" almost always results in a "yes" answer, since geologic repositories are currently one-of-a-kind systems.

III.C. Assigning TRLs to CTEs

Evaluation of the technology readiness level (i.e., technical maturity) of each CTE can be made by also using a two-step analysis process (e.g., Ref. 4, Sec. 3.5.3). First, an initial pass to assign the TRL is based on a typical nine-level TRL table, such as that shown here in TABLE 1. During the second pass, a set of detailed questions (different for each TRL) is asked and answered by subject matter experts (SMEs), and possibly other stakeholders, customers, and/or managers. This set of detailed questions can be up to 30 or more for each of the nine levels, e.g., see Ref. 4, Att. H and Ref. 13, Table A.1. To qualify for being rated at or above a given TRL, the answer to every question for that particular TRL must be "yes". This "detail step" is begun at one level lower than the TRL assigned in the initial pass.

A caveat regarding the two-step TRL assignment process is its complexity and the level of effort required in the second pass. This level of effort can be seen in various major DOE-EM projects, such as the Calcine Disposition Project[14] and the K Basins Sludge Treatment Process.[33] However, there are TRL "calculators" available to facilitate the second pass of the TRL assessment, which are spreadsheets containing all the detailed questions for each TRL. The Department of Defense or Department of Homeland Security (DHS) Excel spreadsheet calculators are downloadable from the Internet,[37] although the DOE calculator seems to be readily available only in hardcopy/pdf form—Appendix F in Ref. 29 and Attachment H in Ref. 4.

TABLE 1. General Definitions of Technology Readiness Levels (from Ref. 36, Table 3)

Relative Level of Technology Development	Technology Readiness Level	TRL definition
System operations	TRL 9	Actual system operated over the full range of expected conditions
System commissioning	TRL 8	Actual system completed and qualified through test and demonstration
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment
Technology demonstration	TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
	TRL 5	Laboratory scale, similar system validation in relevant environment
Technology development		
	TRL 4	Component and/or system validation in laboratory environment
Research to prove feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
	TRL 2	Technology concept and/or application formulated
Basic technology research		
	TRL 1	Basic principles observed and reported

III.D. Determining a System TRL

Ultimately, the goal is determine the maturity or deployment readiness of the entire system under development, which is affected by interactions among the CTEs. There are simple, as well as more complex methods, for assigning a TRL to the entire technology system. Major DOE projects to this point have generally used the simple "minimum TRL" method mentioned by Collins et al. (Ref. 12, Sec. 4.1), who proactively applied a TRA process to a major DOE-NE project (the NGNP) before the initial issuance of formal DOE TRA guidance, i.e., before *DOE G 413.3-4*.[28]

In the current revision of the DOE TRA Guide, *DOE G 413.3-4A*,[29] there is no formal assignment or definition of a "system TRL." It is only defined by implication. In particular, *DOE G 413.3-4A* states that all CTEs should reach a certain TRL (and the same TRL) for the project to move to the next Critical Decision (CD) point in the schedule. For example, Sec. 2.1 of DOE G 413.3-4A states that all CTEs should reach TRL=4 at CD-1 ("Alternative Selection") and TRL=6 at CD-2 ("Performance Baseline")—see Figure 2 above. On the other hand, DOE-EM's TRA/TMP Guide (Ref. 4, Sec. 3.5.3) specifically assigns the system TRL to be equal to the lowest CTE TRL: "The overall TRL for the project/program is the lowest TRL for a CTE based on the completed TRL calculators" and "the TRL of the whole is equal to the lowest TRL of the parts."

There is an extensive literature that discusses the assignment of a "system TRL" or System Readiness Level (SRL) based on the TRLs of the underlying CTEs.[38-42] Fernandez[41] gives a good introduction to the variety of system maturity evaluation methods currently in use (as of 2010). As an example, the method of Ramirez-Marquez and Sauser[39] considers the "interplay" between multiple technologies via a table of nine "Integration Readiness Levels" (IRLs) combined with a optimization or search algorithm ("probabilistic solution discovery algorithm") that incorporates cost and schedule (time) constraints (i.e., the "effort" required to reach a certain maturity level). Use of one or more of the system maturity evaluation methods described by Fernandez[41] would address the need for assessing the maturity of integration among CTEs and other system components.

IV. PROPOSED APPLICATION OF THE DOE TRA PROCESS TO A GEOLOGIC DISPOSAL SYSTEM

Geologic repository programs take place over a period of decades (some with a planned timeline of a century or more from initiation to final closure—e.g., as described by Ouzounian et al.[43]) and, therefore, the design, engineering technologies, and knowledge bases continue to evolve through RD&D and fabrication activities during this lengthy period. A coarse timeline for a repository program, as indicated in Fig. 1, is divided into three typical phases: Concept Evaluation, Site Selection, and Repository Development.

Throughout the repository timeline, major milestone dates will be set, either by the project implementer or the national regulator (or both), to evaluate progress. Most of these milestones will be accompanied by reviews of the maturity of the design, engineering, modeling, and knowledge base. For the U.S. repository program, *DOE Order 413.3B* (described above)[35] will impose major milestones and reviews at the Critical Decision (CD) points shown in Fig. 2. However, most of these formal CD points will occur in the later stages of the illustrative timeline in Fig. 1, when major expenditures related to site-characterization, design, construction, and operations are required—just before and during the License Application step, as well as later at the start of construction and the start of operations.

At the current generic stage of repository development in the U.S., it can be considered that even CD-0 has yet to be reached (depending on the exact definition of CD-0), and may not be until a specific repository site is selected. For example, the stage prior to CD-0 is called the "pre-acquisition stage" in *DOE G 413.3-4A* (Ref. 29, Fig. 1) or the Concept Evaluation phase in Fig. 1 above. During this time, the RD&D is generic in nature and is being conducted to further the understanding and formulation of alternative disposal concepts and their underlying Features, Events, and Processes—see detailed FEPs discussion below. The preliminary RD&D conducted during this current phase lays the groundwork for making informed decisions and assessments of alternative technologies and concepts that will be required as the timeline progresses into the Site Selection and Repository Development phases. RD&D during the Concept Evaluation phase also supports stakeholder interactions during the later Site Selection phase and helps build confidence in the safety of potential disposal concepts and technologies, as documented in a Repository Safety Case.[44] CD-1 is not reached until after final site selection and preliminary repository design selection. As implied in its Requirements Document,[45] the Yucca Mountain Project had reached CD-1 but not CD-2 by the time of License Application submittal to the U.S. Nuclear Regulatory Commission (NRC).

Because a repository or geologic disposal system is comprised of both engineered barriers and natural or geologic barriers, the technology maturation process and any associated TRA must be expanded beyond that which is applicable to a strictly engineered facility, e.g., an HLW calcine waste treatment facility[14] or a glass ceramic waste-form fabrication facility.[13] In particular, although it is engineered technologies (such as tunnel construction and waste emplacement) and physical components (such as the waste package and buffer/backfill) that must be assessed and matured for the successful construction and operation of a repository facility prior to permanent closure, it is *knowledge* of the initial state and altered states of the facility that must be assessed and matured to determine its "post-closure" deployment readiness.

An important observation about geologic repositories helps determine how a TRA process may be utilized, and will be discussed in more detail in the following sections. Specifically, technology maturation for geologic repositories has an inherent "temporal" division into RD&D related to the *pre-closure* (construction and operations) time period and RD&D related to the *post-closure* time period. [Some specific repository components (or technologies), such as the waste package, can have both pre-closure functions and post-closure functions, which will be discussed below.]

Pre-closure technologies include those connected with site-characterization, construction, excavation, operations, *in situ* testing, and pre-closure monitoring activities, all of which generally involve some sort of active human intervention. The maturity and readiness of these pre-closure technologies is primarily a matter of controllable equipment/technique design changes. On the other hand, *post-closure* technologies involve the maturation of *knowledge* related to how physical-chemical processes occurring after closure[e] (i.e., after human intervention) can affect the safety functions[46] and performance of the repository. Such knowledge maturation is intimately tied to modeling and simulation methods, along with the knowledge-gathering techniques that provide input data and parameters to these models, such as laboratory and *in situ* testing methods, data collection techniques, and data synthesis technologies, which are model and scale dependent.

IV.A. Application of the TRA Process to Pre-Closure Technologies

Prior to permanent closure of a deep geologic disposal system, a number of complex technologies are employed over a lengthy time period to first evaluate the site for its suitability and later to construct, operate, monitor, and close the repository. Most of these technologies are amenable to a formal TRA process, since they are engineered systems whose uncertainty can be eliminated with reasonable resource expenditure. Many of these technologies, such as *in situ* testing methods, excavation machinery and techniques, waste container emplacement techniques, etc., have been under development for decades, both nationally and internationally, through the extensive use of Underground Research Laboratories (URLs).[47,48] And, although formal TRAs have not been conducted for most of these pre-closure technologies, many of them can be recognized to have already matured to a TRL of 6 to 8 (Ref. 49). This is obvious simply by considering the TRL definitions in TABLE 1. Examples of pre-closure repository technologies developed through URLs include:[49]

- Excavation equipment, developed for boring deposition tunnels and canister holes for vertical emplacement at the ONKALO URL (Finland)
- Machines for horizontal deposition (emplacement) of waste containers, 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

The technologies listed above, and many others, have been demonstrated in URLs at full scale in the applicable environment and expected conditions. However, it should be emphasized that because they have been tested under specific environmental conditions, these technologies cannot be assumed to automatically transfer to other repository projects while retaining the same TRL. Therefore, for other repository programs, many pre-closure technologies, such as waste package and buffer emplacement technologies, are candidates for a formal TRA and associated TMP to layout a path to full deployment readiness in the specific repository under consideration.

If a formal TRA is employed for certain pre-closure technologies, the established DOE TRA method in *DOE G 413.3-4A*, or a modification/simplification thereof, appropriate for the given stage of repository development, is recommended. However, this points to a current deficiency in both DOE TRA guides,[4,29] *viz*., neither of these contains TRL questions for establishing a TRL rating of 8 or higher. *DOE G 413.3-4A*[29] only has TRL rating questions up to TRL 6, while the DOE-EM guide (Ref. 4, App. 1) has proposed (but untried) questions up to TRL 7. Thus, if existing pre-closure technologies have already been matured to TRL 6 in existing or decommissioned URLs, the current DOE TRA procedures are insufficient to rate them at a higher TRL. Furthermore, although it has been suggested that DOE-NE[50] projects do not "generally" go beyond the TRL 6 level, pre-closure repository technologies must certainly go to TRL 9 at some point in a geologic repository developmental timeline.

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[e] Typical post-closure processes include the effect of waste heat on the engineered and natural barriers, and the long-term migration of radionuclides through the host rock.

IV.B. Evaluation of the Technical Maturity of the Post-Closure Repository System

In part, because of inherent uncertainties related to characterization of the initial state and evolution of the natural and engineered barriers, as well as the length of the performance period (one million years or greater), a typical TRA (designed primarily for man-made, engineered technologies) must be modified for assessing the technical maturity and readiness of either the entire geologic repository system or its components that are affected strongly by natural processes. This includes performance or evolution of the disturbed rock zone (DRZ), which is the interface zone between the Engineered Barrier System (EBS) and the Natural Barrier System (NBS). The interface and integration between EBS and NBS "technologies" provides a unique challenge to conducting TRAs and developing a TMP for a geologic repository system.

The Features, Events, and Processes (FEPs) "screening" [f] and analysis process[51] for ensuring completeness of the Repository Safety Case (Ref. 22, Sec. 2.2) and adequacy of the Performance Assessment (or Safety Assessment) Model[52] has been applied to repository projects both nationally and internationally for many years, and also has the approval of regulatory agencies (Ref. 53, Sec. 2.2.1.2.1). A FEPs-based classification and evaluation process[54-56] is a well-established methodology for identifying key performance elements of a geologic repository system and organizing/planning RD&D to address remaining performance uncertainties—see Fig. 3.[55] The following sections describe an adaptation of the established FEPs process as a basis for a "TRA-like" maturity evaluation for technologies/subsystems of a deep geologic repository. The proposed process combines the best of both methodologies, i.e., of FEPs analysis and TRL evaluation.

One of the first key departures from a traditional "total facility" TRA is to divide the repository into manageable subsystems (comprised of sets of CTEs), and choose one or more subsystems for a TRA. The motivation for this departure is, as mentioned, because the Repository Safety Case is viewed as the evidence and plan for the maturity and readiness of the entire system.

Identification of both repository CTEs and subsystems is greatly facilitated by using a "FEPs matrix" approach.[54,57,58] Fig. 4 schematically illustrates this FEPs matrix approach for identifying CTEs (i.e., Features or Components), as well as major subsystems, and is described in more detail in the following sections.

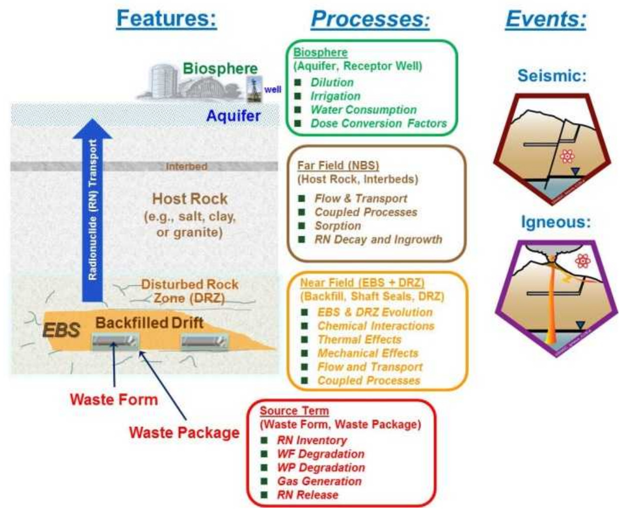


Fig. 3. Schematic of Typical Features, Events, and Processes (FEPs) for a Geologic Disposal System

IV.B.1. CTE Identification for Post-closure Subsystems

If a major post-closure subsystem is recommended for a formal DOE TRA, it will be necessary to follow the basic TRA steps given above in Sec. III, but with the "geologic system" modifications described here. In the context of a FEPs-based approach for organizing and describing the post-closure repository system (and associated RD&D), there are at least two distinct possibilities for identifying a set of CTEs: an individual FEP approach and a "rolled-up" FEP approach.

DOE Guide 413.3-4A (Ref. 29, Sec. 3) recommends that the <u>initial CTE identification step</u> be "conservative," such that any "questionable technology should be identified as a candidate CTE." Thus, as an initial course of action, it is here recommended that the initial CTE identification pass consider all FEPs as potential CTEs. It is further recommended that Features/Components (see Fig. 4) is the appropriate discretization level for conducting one or more TRAs. For example, as shown in Fig. 4, an example candidate subsystem for a TRA might be either (1) the Feature identified as "(WP) Waste Package and Internals" or (2) some Component within the waste package feature category, such as "SNF" Waste Package. Post-closure FEPs related to the waste package, i.e., those mapped into the FEPs matrix cells for the Waste Package Feature or the SNF Component, will be the candidate CTEs for a "Waste Package TRA." The brief FEPs list in the upper right of Fig. 4 is an example of a few such waste package FEPs.

[f] "Screening" is used in the sense of "selection", i.e., whether the FEP is selected for inclusion in the repository safety assessment (or performance assessment) model.

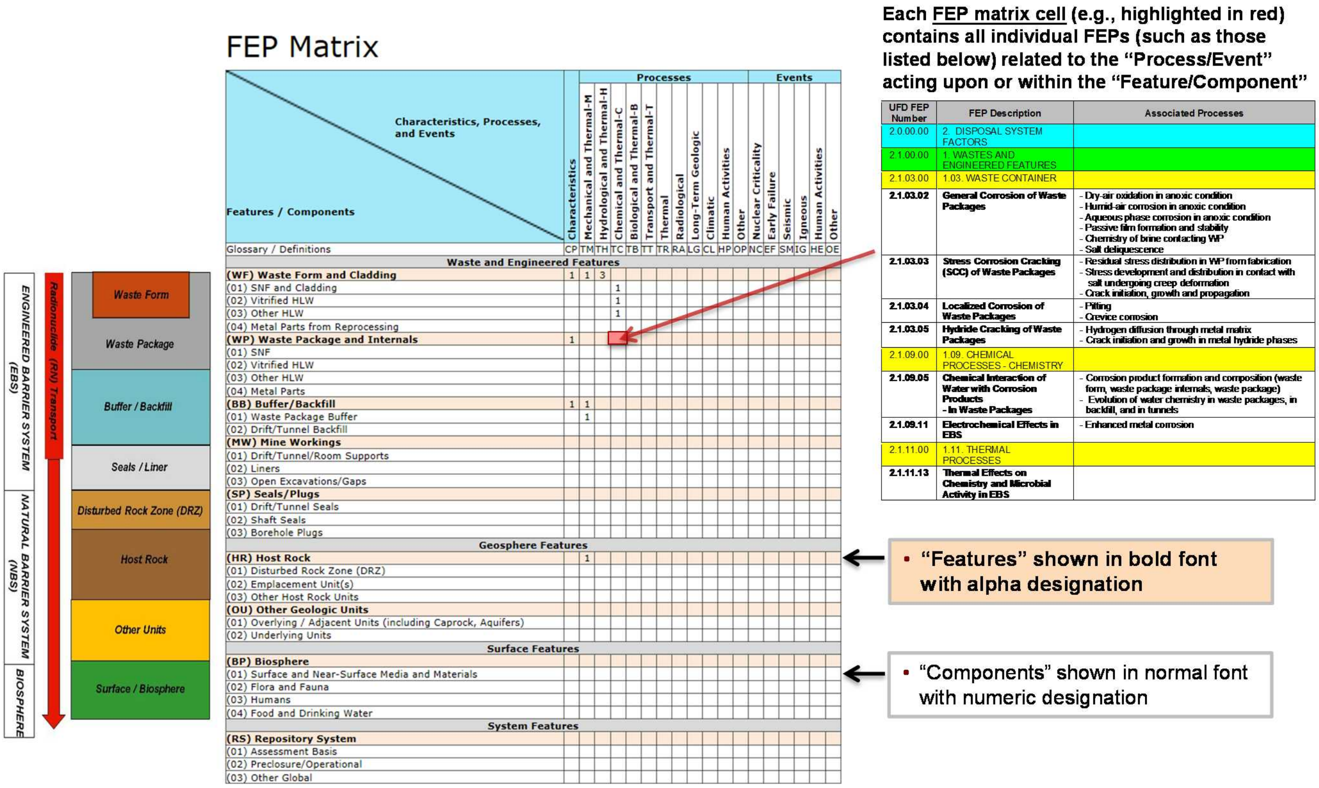


Fig. 4. FEP Matrix Approach for Categorizing and Screening FEPs.[59]

Given that the number of individual FEPs in post-closure performance analysis is usually several hundred,[22] an alternative method that produces a much smaller set of initial-pass CTEs may prove more tractable for managing post-closure technology maturation. A possible example is the method given by Sevougian and MacKinnon[46,60] for identifying remaining areas of RD&D important to the post-closure safety of a geologic repository sited in bedded-salt host rock. To adapt their method to the standard TRA process, post-closure CTEs would be equated to their listed set of 48 "Salt R&D Technical Issues." These "Issues" are effectively "rolled-up" or consolidated FEPs, derived from the much larger, complete set of FEPs by the use of expert opinion.

Another example of the use of expert judgment to formulate the set of key issues or "topics" for post-closure safety, i.e., a set of post-closure issues that could be equated with the TRA concept of CTEs, is given by Hart et al. (Ref. 61, Sec. 4.9.4). Their method includes both an extensive international literature search, as well as the use of expert knowledge specific to their national (Dutch) repository program. It also applies technical considerations, related to the limited heat output of their waste. Their 34 issues are similar to FEPs (or rolled-up FEPs) and they include a screening justification for each issue, i.e., whether to carry it forward in the R&D program. Then they aggregate their individual issues into a set of six primary categories. In the U.S. context, each of these six categories or "topics" might be considered a candidate "subsystem" for a formal TRA-like rating process and the associated technology (or knowledge) maturation plan. Following is their list of six R&D topics for a Dutch repository in salt host rock:

- Influence of Disturbed Rock Zone (DRZ)
- Compaction behaviour of crushed (granular) salt
- (T)HMC effects related to the dissolution of rock salt
- Corrosion of waste container and waste matrix
- Corrosion of cementitious barriers
- Solubility of radionuclides

In the second or detailed step of CTE determination, described in Sec. III.B, a winnowing of potential CTEs occurs based on two sets of criteria: one set of five criteria determines if the technology element is "critical"[g]

[g] Collins et al. (Ref. 12, Sec. 3.2) provide the following definition of a CTE (or "critical SSC," in their terminology): "Critical SSCs, at a minimum, are defined as those components that are not commercially available or do not have proven

and a second set of five criteria determines if it is "new" or "novel." Neither set of traditional CTE determination criteria (Ref. 29, App. E) is tailored specifically for geologic repository projects, i.e., for post-closure "technologies." Of the two sets of CTE criteria, the set determining whether a technology is new or novel must currently be answered in the affirmative for post-closure technologies, since a geologic HLW/SNF repository is a first-of-a-kind project at this time. Thus, it is considered that this second set is probably irrelevant when conducting TRAs for post-closure repository technologies, although some consideration of operating environment, as described in Sec. 3 and Table 5 of *DOE G 413.3-4A*[29], may be needed before finalizing this recommendation.

Of the five criteria in the first set, which determine a status of "critical" or not, it is recommended that "critical" be changed to "important to safety" or something similar, and that this be decided with a methodology similar to what is already in use nationally and internationally for repository projects. In particular, the "important to safety" criterion should be based on either (1) the potential impact of the "technology element" (i.e., the FEP or Issue) on a barrier function or a barrier capability or (2) its potential impact on one or more post-closure safety functions. Typical post-closure safety functions have been proposed by Bailey et al.,[17] and used by Sevougian et al.[60] to determine the importance of remaining RD&D activities for repositories in salt host rock. These safety functions include *waste isolation*, *waste containment*, and *limited or delayed releases or radionuclides*. Typical barrier functions or barrier capabilities are similar to those dictated in 10 CFR Part 63, such as (1) *prevent or substantially reduce the rate of movement of water or radionuclides to the accessible environment* or (2) *prevent or substantially reduce the release rate or radionuclides from the waste* (Ref. 22, Sec. 2.1.1).

An example of the importance rating of individual FEPs based on their effect on post-closure system performance (i.e., whether they should be considered CTEs) can be found in the 2008 Yucca Mountain *Safety Analysis Report* (Ref. 22, Sec. 2.1 and Tables 2.1-2 to 2.1-4), which is supported by the Yucca Mountain *Postclosure Nuclear Safety Design Bases* report (Ref. 62, App. A). This rating method, which was deemed adequate by the U.S. Nuclear Regulatory Commission (Ref. 53, Sections 2.2.1.1.3 and 2.2.1.1.4), evaluated individual FEPs against the two barrier-capability criteria defined above, to decide whether or not each FEP achieves a classification of "important to barrier capability" (ITBC). FEPs deemed to be ITBC then resulted in a higher-level determination that their affected Feature(s) should be rated as "important to waste isolation" or ITWI, which was a classification used in U.S. regulations to decide if a given system element (i.e., feature) was obligatory to prevent exposure of the public to radiation. This type of FEPs rating method could be used for identifying various FEPs as CTEs of major repository subsystems.

A similar, but simpler, method for the second-pass identification of CTEs for repository subsystems was used by Sevougian and MacKinnon[46,60] for the case where candidate CTEs are given by "rolled up" FEPs or "Technical Issues." These potential salt-repository CTEs (i.e., Technical Issues) are assigned one of three possible values on the metric scale "important to post-closure safety" (or ITPS): either "H", "M", or "L", based on the relationship of the Issue (or importance of the Issue) to a set of three post-closure safety functions (*waste isolation*, *waste containment*, and *limited or delayed releases or radionuclides*). The three-level rating could easily be reduced to a "yes/no" binary rating (i.e., it either *is* or *is not* ITPS) by simply considering both "H" and "M" issues to be ITPS and "L" issues to not be ITPS. If a Technical Issue is ITPS, then it would be considered to be a "CTE" in the standard nomenclature of TRAs. This "roll-up" CTE-identification method utilized subject matter experts (SMEs) in an analogous fashion to the recommended TRA process in the DOE-EM *TRA/TMP Process Implementation Guide* (Ref. 4, Sec. 3.2.8), which similarly relies on SMEs to define CTEs (as well as to assess their TRLs). Whether or not a "roll-up" CTE-identification method should be used, or the more straightforward individual-FEPs method, is a decision to be made by those involved in conducting the TRA process for the particular post-closure subsystem or major component.

Another example of FEPs screening[h] (i.e., post-closure CTE determination) is also based on safety

industry experience." [SSC ≡ systems, subsystems, and components]

[h] "FEPs screening" relates to the potential effect of a FEP on the post-closure performance of the repository system. The analogy to a standard TRA process is again the definition of each FEP as a "technology element" of the system and the decision of whether it is a "critical" technology element (CTE). In standard FEPs screening the decision being made is whether to "include" a FEP in the post-closure safety assessment model.[63] For the purposes of prioritizing future RD&D and technology maturation activities, inclusion of a FEP in a post-closure safety assessment model usually implies that it is, in fact, a CTE—in the sense that uncertainty about its effect on performance must be reduced far enough to achieve a certain "level of confidence" prior to regulatory approval for repository licensing and/or construction. However, for the Yucca Mountain Repository not all included FEPs were

functions, rather than barrier functions. This example from the Dutch OPERA program[56] asked a single question to determine if a FEP is important to safety: *"Is it conceivable that a cause-effect chain exists, in which this FEP leads, either directly or indirectly, to damage to one or more safety functions of the Dutch disposal system?"* The considered safety functions were similar to those listed above:

- engineered containment (C)
- delay and attenuation of the releases (R), consisting of
  - R1: limitation of contaminant releases from the waste forms
  - R2: limitation of the water flow through the disposal system
  - R3: retardation of contaminant migration
- isolation (I), consisting of
  - I1: reduction of the likelihood of inadvertent human intrusion
  - I2: ensuring stable conditions for the disposed waste and the system components

Based on this process, 79 of 340 individual FEPs were identified as "safety function hazard" FEPs, i.e., FEPs that are important or "critical" to repository safety.

IV.B.2. Evaluation of Technical Maturity for Post-closure CTEs and Major Post-Closure Subsystems

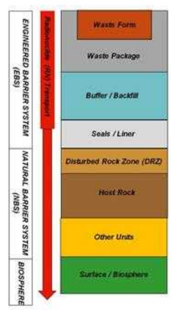
The next TRA step, after identification of either individual FEPs or rolled-up FEPs ("Issues") as CTEs, is the assignment of a maturity level (e.g., a TRL). This evaluation step will depend to some extent on which major subsystem a FEP or Issue belongs to (i.e., the EBS, the NBS, or their interface region, the DRZ), but mostly on whether the maturity being evaluated is manufacturing/emplacement readiness or post-closure performance readiness. For the latter, a new *Knowledge Readiness Assessment (KRA)* process is proposed. TABLE 2 illustrates the maturity evaluation method recommended for each case. In particular,

1) For EBS CTEs (such as the waste package), the standard TRA method may be used for assessing the "emplacement readiness" (and/or *manufacturing readiness*), but a KRA method is recommended for assessing confidence in post-closure performance.

2) For post-closure maturity or readiness of all CTEs (i.e., all EBS, DRZ, or NBS FEPs/Issues), a nine-level *Knowledge Readiness Level (KRL) scale* is proposed.[i]

Knowledge Readiness Levels (KRLs) are proposed for establishing confidence in the performance of CTEs after repository closure because it is knowledge that must be "matured" (or gathered) rather than equipment design that must be altered, and because the long-term geologic environment is not strictly controllable or knowable. [Obviously, there is an aspect of "equipment design" that can be matured for the engineered repository components, through optimization and testing of these engineered components in a simulated and *in situ* post-closure environment (e.g., in a URL). But, given the long-term performance uncertainty associated with a geologic facility, this repository "equipment" maturation is not the same as that for a totally engineered facility or system, such as a waste-form manufacturing facility.[13]]

TABLE 2. Repository CTE Maturity Evaluation as a Function of Spatial Region and Major Subsystems.



Major Post-closure Subsystems (and associated CTEs)	Maturity Evaluation Method
EBS	**TRLs** (and/or **MRLs**§) for emplacement/deployment
	KRLs for performance
DRZ	**KRLs**
NBS	**KRLs**

§ MRLs = "Manufacturing Readiness Levels," are designed to be measures used to assess the maturity of a given technology, component, or system from a manufacturing prospective.[41,65]

For post-closure "maturity" of CTEs (i.e., of FEPs or Issues), two possible scales are proposed. The first recommendation is a nine-point KRL scale not dissimilar to the TRL scale in TABLE 1. This proposed KRL scale is given in TABLE 3 below. However, if this scale proves to be too cumbersome because it requires finer "knowledge discretization" that is normally available for geologic systems, a simpler five-point metric scale can be used, as shown in TABLE 4. This simpler maturity rating method is based on a method developed by DOE[55] wherein "technical maturity" is interpreted as the current "state of the art" regarding knowledge, modeling, and safety assessment of post-closure system performance (i.e., of FEP behavior). This five-point maturity metric is termed the *State-of-the-Art Level (SAL)*.

determined to be CTEs, i.e., not all were given the ITBC rating (Ref. 62, App. A).

[i] "KRL" was first coined by NASA,[64] but for engineered systems and with only five discrete levels.

TABLE 3. Nine-Level Knowledge Readiness Level (KRL) Scale (adapted from Tables 1 and 4 in Ref. 29).

Knowledge Readiness Level	KRL Definition	Description
KRL 9	Actual system operated over the full range of expected conditions	Probably not feasible/applicable for a major post-closure geologic repository subsystem.
KRL 8	Actual system completed and qualified through test and demonstration	Probably not feasible/applicable for a major post-closure geologic repository subsystem.
KRL 7	Full-scale, similar (prototypical) (sub)system demonstrated in a relevant environment	The major difference between KRL 7 and KRL 6 is in the scale of the (sub)system and the fidelity of the actual or simulated operating environment. KRL 7 represents a higher degree of confidence in the actual initial and operating conditions than KRL 6, based on more complete site investigations and testing. This KRL should be reached prior to submittal of a license application to the national regulatory agency. Therefore, this represents a departure from the required readiness levels in *DOE Order 413.3B*, in the sense that a repository cannot begin performing till it is completed and closed off from human intervention. Thus, a higher degree of confidence is required to begin construction (CD-3), as compared to a strictly engineered facility.
KRL 6	Engineering-scale, similar (prototypical) (sub)system operated in a relevant environment	Entails a major step in the level of integration and in the fidelity of the technology, or knowledge, demonstration. A representative (sub)system has been tested or simulated in a relevant environment at a relatively large ("engineering") scale over an appropriate time scale, and including full process coupling. A full suite of uncertainty and sensitivity analyses would be expected at this level. The prototype system may be an *in situ* test in a URL and/or a full computer simulation that has been informed by site-specific data and testing, or both.[a] Long time-scale computer simulations are necessary at this level to simulate post-closure performance. Some input data and initial conditions regarding the actual operating environment may still be under investigation at this level.
KRL 5	Reduced-scale (sub)system validation in a relevant environment	Requires the validation of the (sub)system in a relevant environment (i.e., one that represents critical FEPs of the expected operational environment). Initial, but formal, uncertainty and sensitivity analyses are appropriate at this point, to develop understanding of how to progress to KRL 6. Experiments and/or computer models of the (sub)system are important in demonstrating understanding of the concept, but may be formulated at a reduced temporal-spatial scale, and possibly with reduced order models (i.e., with few process couplings or simpler representations/models of some processes).
KRL 4	Reduced-scale (sub)system validation in a simulated or generic environment	The basic components or processes involved in a technology or concept must be integrated, or investigated in a coupled manner, to establish that the pieces will work together, but not necessarily at the expected spatial-temporal scale or full process coupling of the final operating environment. Uncertainty characterization should be conducted, or at least planned, at this point. Experiments, modeling, and/or computer simulations of the concept are conducted, but may use generic data input or environmental conditions, to establish validity of the concept.
KRL 3	Analytical and/or experimental proof-of-concept investigations	Active R&D is initiated. This includes analytical studies, and experiments if appropriate, and/or process-level computer simulations to test and gather knowledge regarding the validity of the concept.
KRL 2	Technology or knowledge application formulated	New practical applications of physical principles or scientific ideas are formulated or invented. This step represents the creation of a new concept or technology based on a new or existing physical or mathematical principle. Applied research and development activities are identified.
KRL 1	Basic principles observed and reported	At this initial level, basic scientific research has resulted in the observation and reporting of basic principles that might lead to a novel technology or novel application of the principles. Theoretical, experimental, and/or computational studies have been initiated.

[a] Many of the laboratory and *in situ* testing methods necessary to prove a certain KRL rating for repository CTEs have been tabulated by the NEA (Ref. 67, Table 5.1), who describe the use of URLs for technical maturation of pre-closure and post-closure repository technologies.

TABLE 4. Five-Level State-of-the Art (Readiness) Scale (adapted from Ref. 55, Sec. 2.2.3)

State-of-the-Art Level	SAL Definition	Description
SAL 5	*Well Understood*	The representation of an issue (process) is well developed, has a strong technical basis, and is defensible. Additional R&D would add little to the current understanding.
SAL 4	*Improved Defensibility*	Related to confidence, but focuses on improving the technical basis, and defensibility, of how an issue (process) is represented.
SAL 3	*Improved Confidence*	Methods and data exist, and the representation is technically defensible but there is not widely-agreed upon confidence in the representation (scientific community and other stakeholders).
SAL 2	*Improved Representation*	The representation of an issue may be technically defensible, but improved representation would be beneficial (i.e., lead to more realistic representation).
SAL 1	*Fundamental Gaps in Method or Fundamental Data Needs*	The representation of an issue (conceptual and/or mathematical, experimental) is lacking, or the data or parameters in the representation of an issue (process) is lacking.

A maturity scale with a similar purpose to the proposed KRL and/or SAL scales described above is the *Scientific Readiness Level* scale, which was designed to evaluate the maturity of a scientific project or mission. This scale was developed and defined in detail by the European Space Agency in their *Scientific Readiness Levels (SRL) Handbook*.[66] However, as with the original definition of KRLs by Chiaramonti and Justin,[64] the original Scientific Readiness Level definitions are very specific to engineered systems (satellite development or other space applications). Thus, they are not particularly useful, as originally defined, for geologic systems. [Furthermore, the "SRL" acronym is an already established acronym for "System Readiness Level",[38,41] so it is a bit confusing to reuse it in the literature for another concept.]

Another recommendation when adapting the traditional TRA process to geologic systems is to only use a single-pass maturity evaluation method for assigning KRLs (i.e., TABLE 3 or TABLE 4). In other words, for post-closure repository maturity evaluation, it may be excessive to utilize multi-question readiness-level tables for each KRL, as are described for the second-pass TRL rating step discussed in Sec. III.C. However, this recommendation can be revisited during the course of the first such KRA, and a first attempt at devising such questions may wish to consider the questions in Ref. 50 or Ref. 66.

As discussed above in Sec. IV.B.1 (see Fig. 4), individual Features or Components may be considered candidates for a formal readiness assessment. However, based on program priorities and management judgment, bigger combinations of Features/Components (e.g., perhaps even the entire EBS) may be better candidates for a formal TRA or KRA—as the CD-1 decision point is approached (see Fig. 2). Regardless of how the assessment is structured, the recent modification of existing TRL rating questions/criteria[50] is a better starting point for designing new TRL or MRL criteria specifically applicable to a repository component or subsystem.[j]

Another consideration that is important when choosing a subsystem for a formal TRA or KRA is to recognize, as mentioned earlier, that some subsystems have both pre-closure functions and post-closure functions. A good example is the emplacement waste package, which must serve during the pre-closure period as a barrier to isolate and contain the waste from worker exposure (including perhaps as a radiation shield), and also as a containment barrier during the post-closure period, depending on the geologic host rock.[16] For example, in a granitic host rock, it would have a safety function of long-term containment of the waste. From a TRA perspective, the waste package might reach a pre-closure maturity of TRL 9 but only a KRL 7 for post-closure (see TABLE 3).

For establishing the manufacturing (or emplacement) readiness of the engineered repository components (see TABLE 2), it is recommended that the DOE (or repository "implementer") consider adapting or incorporating some version of the MRL scale and rating process.[41,65,68] The current MRL method[k] uses only a single-pass rating method (with MRLs between 1 and 10).

[j] The TRL questions proposed in DOE (2014) are intended to be generally applicable to most DOE-NE projects, so even they require some modification, especially for NBS FEPs.

[k] As noted in Ref. 65, Sec. 2.2: "Manufacturing readiness and technology readiness go hand-in-hand. MRLs, in conjunction with TRLs, are key measures that define risk when a technology or process is matured and transitioned to a system."

However, a typical two-pass maturity evaluation method (Ref. 4, Sec. 3.5.3) could be attempted instead, if the questions for each level are appropriately modified to be specific to a geologic system.

The final, but perhaps most important, step in a repository TRA is the establishment of a (sub)system TRL or System Readiness Level (SRL). As described in Sec. III.D, a commonly used, but very simple, measure of the SRL is the minimum CTE TRL/KRL. However, as discussed by Rameriz-Marquez and Sauser,[39] and many others,[41] interactions and integration among CTEs or technologies is an important facet of overall system readiness and should verified through testing.[67] A number of measures for system integration and readiness have been developed to account for these interactions.[40,41] One or more of these methods could be adapted to a geologic repository system to provide a higher fidelity system readiness metric than simply using the minimum CTE TRL. This will be the topic of a future paper.

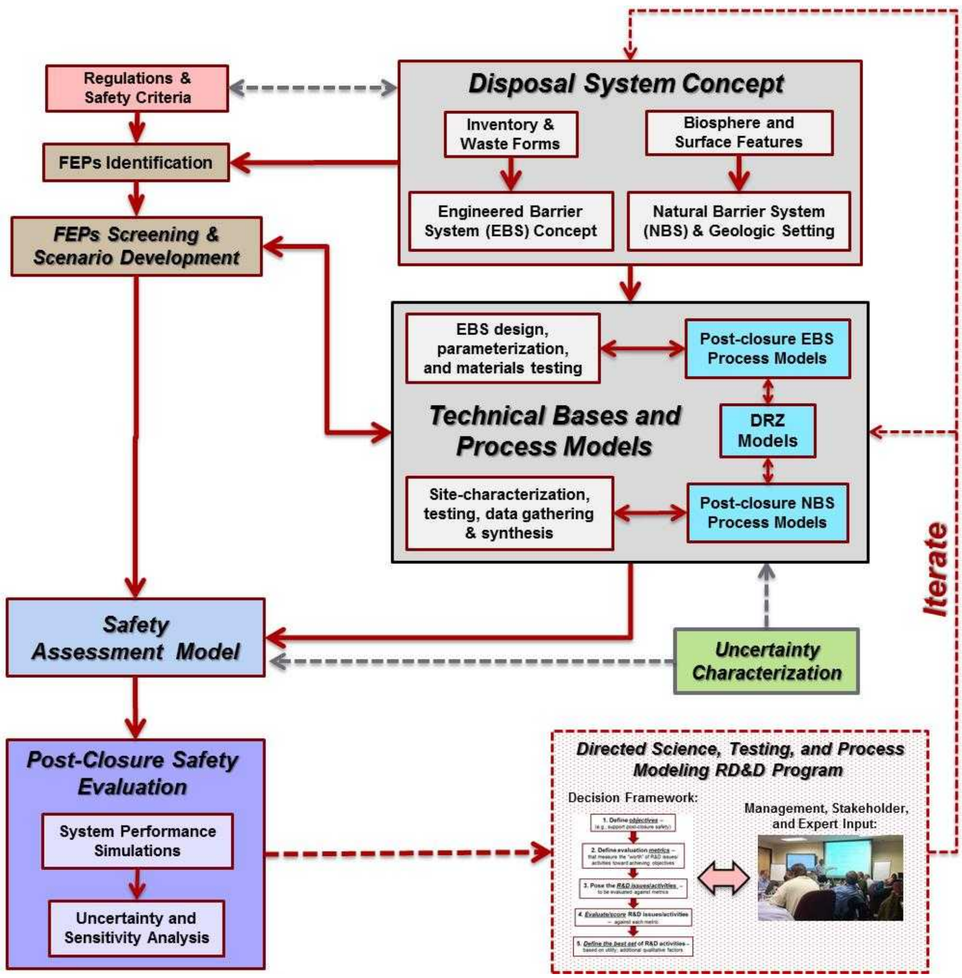


Fig. 5. Evolution and Iteration of Technical Bases (Knowledge and Design) and Safety Assessment Modeling for Technology Maturation of a Geologic Repository System.

IV.B.3. Repository Technologies Maturation Plan

Examples of Technology Maturation Plans (TMPs) and/or Technology Roadmaps abound in the literature. For DOE-NE, a good TMP example is provided by Vienna et al.[13] A typical Technology Roadmap, with correlations to TRLs, is given by Collins et al.[12] A repository TMP (for either individual CTEs or major subsystems) may be similar to either of the foregoing examples, or may be like that presented in the U.S. DOE's *Used Fuel Disposition Campaign Disposal Research and Development Roadmap*,[55] or may take some other yet-to-be-determined form. However, one unique quality of a repository TMP will be the interaction between maturity evaluation and system (computer) modeling. In particular, because of inherent uncertainties related to natural processes, a probabilistic Performance Assessment (or Safety Assessment) model and associated system performance analyses (comparison with national radiation standards) will be crucial to prioritizing future RD&D and establishing confidence in the deployment readiness of the entire repository system. This is codified in regulations of many countries that are considering geologic disposal of nuclear waste[69] and has been important in the U.S. (10 CFR 63). This iterative interaction between knowledge gathering (via testing), component design, and system modeling is illustrated schematically in Fig. 5, and has been discussed elsewhere.[46,70]

IV.B.4. Treatment of Uncertainties

As indicated in Fig. 5, a key component of RD&D prioritization, technology maturation, and system performance assessment is the characterization and treatment of uncertainties. Consideration of uncertainty in the evaluation of safety after repository closure is a well-developed science[19,71-73] that categorizes uncertainty into two major types: uncertainty related to the inherent randomness of the problem (such as random external events that affect safety, e.g., seismicity) and uncertainty related to lack of measurement data (such as the uncertain composition of the current inventory of spent fuel and high-level waste). The former type of inherent or irreducible uncertainty is often called *aleatory* uncertainty and the latter type of measurement or reducible uncertainty is often called *epistemic* uncertainty.[71] Epistemic uncertainties can be reduced by data-gathering methods, including additional site characterization, design studies, fabrication and other demonstration tests, and other experiments both in the laboratory and in underground test facilities (all of which are part of the box entitled "Technical Bases and Process Models" in Fig. 5).

Probabilistic sensitivity analysis based on the results of the post-closure safety assessment provide the basis for defining the types of tests and studies needed to reduce epistemic uncertainty and for assigning priorities for further RD&D work in each subsequent stage of repository development. This iteration between repository stages (which are defined in a TMP, schedule, or roadmap) is a key feature of the system maturation methodology indicated in Fig. 5, wherein the current safety assessment informs the RD&D agenda necessary for the next phase of system characterization, design, and/or implementation. This iterative principle for reducing uncertainties has been applied to several quite different U.S. disposal concepts that have advanced to the regulatory licensing stage: the Waste Isolation Pilot Project (WIPP),[74] the Yucca Mountain Project,[22] and Greater Confinement Disposal.[75] As recommended by the U.S. Nuclear Waste Technical Review Board (Ref. 76, p. 53): "Future repository programs should use probabilistic performance assessments throughout the life of a program to help set priorities among site-characterization activities, i.e., to guide the research portfolio."

IV.B.5. Relationship to the Safety Case

A *safety case* is a formal compilation of evidence, analyses, and arguments that substantiate and demonstrate the safety, and the level of confidence in the safety, of a deep geologic repository, and is in widespread use internationally as a means of documenting system deployment readiness.[16-22] A safety case also provides the necessary structure for organizing and synthesizing existing knowledge in order to help the repository implementing organization prioritize its future RD&D activities toward those that are more important for enhancing confidence.[46,60] Although the specific scope of a safety case, and the definitions and terminology used therein, differ somewhat across the various international programs, they all have the same goal of understanding and substantiating the short- and long-term safety of a geologic disposal system. Major elements of a safety case are shown in Fig. 6 and are defined in various documents.[18,20,44,46]

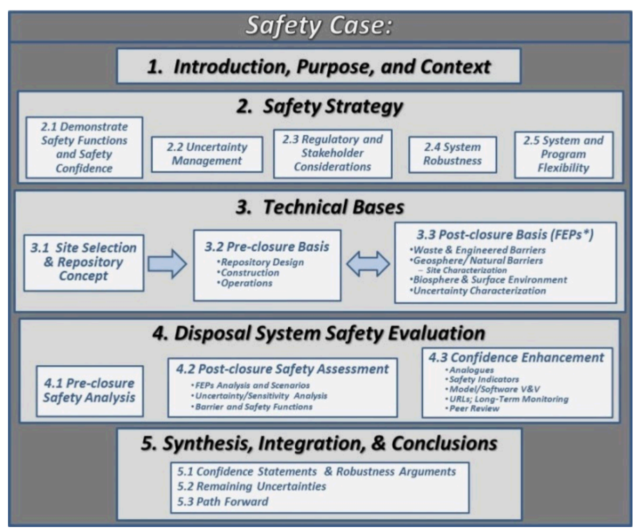


Fig. 6. Major Elements of a Post-Closure Safety Case.

As described in Sec. I, the Safety Case (or Licensing Case) document (or collection of documents) will likely be used as the ultimate basis for making a final decision regarding feasibility and construction of the geologic repository system. However, there is no formal metric scale associated with the "degree of confidence" embodied in a Safety Case at any given time. The

TRA/KRA concept applied to repository CTEs and major subsystems could be used to assign a "degree of confidence" to the deployment readiness of the various repository CTEs and subsystems, and through the definition of an appropriate SRL could be used to assign a quantitative rating to overall system readiness, if this is felt to be valuable by either the implementer or the regulator. In any case, the current *DOE Order 413.3B*[35] necessitates the use of the TRA process at later stages in the timeline of a U.S. geologic repository. If this process is adapted appropriately (as described herein), it should be effective for guiding the RD&D and manufacturing activities necessary to achieve a successful post-closure repository system; and, in conjunction with the full Safety Case, provide a reasonable expectation of long-term safety.

V. CONCLUSIONS

Technology Readiness Assessment (TRA) is a formal process to aid in defining the remaining research, development, and demonstration (RD&D) effort to bring a new, complex technology system to full technical maturity. A geologic repository for high-level radioactive waste is a prototypical complex system, comprised of novel technologies and complex environmental conditions, but because it is intended to function passively and because it is comprised of both engineered and geologic barriers, the standard engineered-system ("hardware") TRA process must be modified. In particular, although it is engineered technologies (such as waste package and buffer emplacement) and physical components (such as shaft seals) that must be assessed, matured, and deployed for the human-designed engineered barrier system (EBS), it is knowledge of the initial state and altered states (e.g., the disturbed rock zone) that must be assessed and matured for establishing confidence in the post-closure performance of both the EBS and the natural barrier system (NBS). Although manufacturing readiness of engineered repository technologies and components is amenable to a standard TRA method, using "standard" Technology Readiness Level (TRL) definitions (or a similar metric called Manufacturing Readiness Level (MRL)), *post-closure* (i.e., long-term) system, subsystem, and component performance for a geologic repository should be evaluated on a metric scale based on "knowledge readiness," which takes into account the inherent uncertainties in system performance over a period of tens of thousands to millions of years.

Longstanding precedence employs a Safety Case (or Licensing Case) as the preferred vehicle for assembling all facets of knowledge to make a determination of repository system safety and deployment readiness. However, certain modifications to the established TRA process allow it to be applied advantageously to many or all of the major repository subsystems and technologies. In particular, an adaptation of the established Features, Events, and Processes (FEPs) methodology can serve as a basis for a "TRA-like" maturity evaluation for various major components and subsystems of a deep geologic repository. The newly proposed *Knowledge Readiness Assessment (KRA)* process combines the best of both methodologies, i.e., of FEPs analysis and standard TRA/TRL evaluation, for establishing confidence in the post-closure performance of major repository components and subsystems. However, the Safety Case (or Licensing Case in some countries) is still recommended as the final product for establishing integrated safety confidence in the specific repository design and site. Also, the Safety Case may be used at all stages of a repository program, from the early conceptual development stage through the operations stage, whereas a formal TRA is only necessary in the advanced stages of the program, after a specific site and associated design are selected, and the funding profile is ramped up (at least in the U.S.).

The major steps of the standard TRA process are retained, i.e., definition of Critical Technology Elements (CTEs), evaluation of a "TRL-like" RD&D maturity metric, and the development of a technology maturation plan (TMP) to organize the future RD&D needed to increase the overall system maturity. However, the selection of CTEs is based on FEPs, and the maturity assessment process for the selected repository CTEs and their associated subsystems is modified to reflect that their technical maturity is based on knowledge maturation rather than engineered component maturation. The Knowledge Readiness Level (KRL) for assessing post-closure readiness is based in part on the remaining degree of uncertainty surrounding the safety functions associated with these components, such as their perceived ability to retard the transport of radionuclides. This in turn is based to a substantial degree on probabilistic computer models that represent the current state of knowledge (i.e., a state-of-the-art uncertainty assessment) of all key features/components and processes.

Most major *pre-closure* technologies (e.g., excavation, construction, and testing technologies) are still recommended for a standard TRA, with CTEs defined and rated according to the well-established TRA process for equipment-based technologies. Also, it is recognized that many such technologies already have a high TRL rating based on their past usage and demonstration in Underground Research Laboratories (URLs) scattered throughout the world.

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