Technology Readiness Assessment Process Applied to Post-closure Performance of Deep Geologic Repositories

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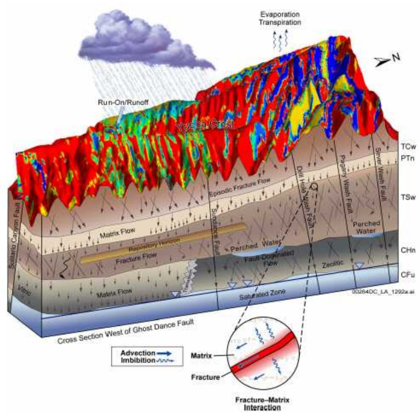
Novel Technology Development

- **Evolution of a novel technology or complex engineering project, from conception to deployment—e.g., a geologic repository:**

Data gathering; conceptual model development and simulations:



Deployment:

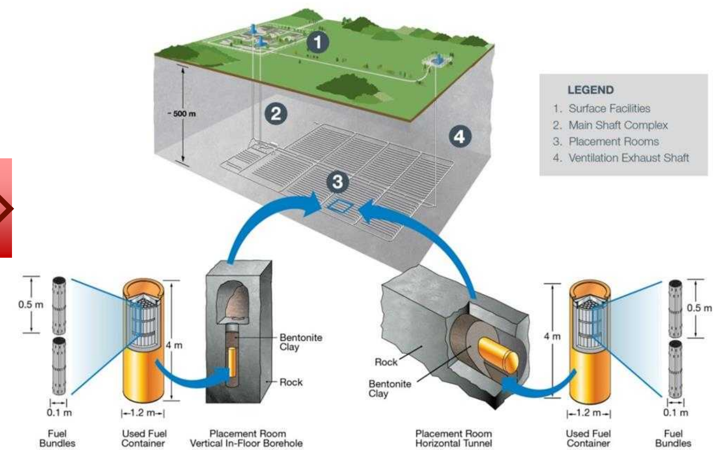


Figure Source: https://www.cnsc-ccsn.gc.ca/eng/waste/high-level-waste/cnsc-role-in-nwmo-apm-project/index.cfm

Deep Geologic Repository Development Timeline

Concept Evaluation
- Evaluate Disposal Concepts; FEPs; Develop and Demonstrate Technologies; Preliminary RD&D

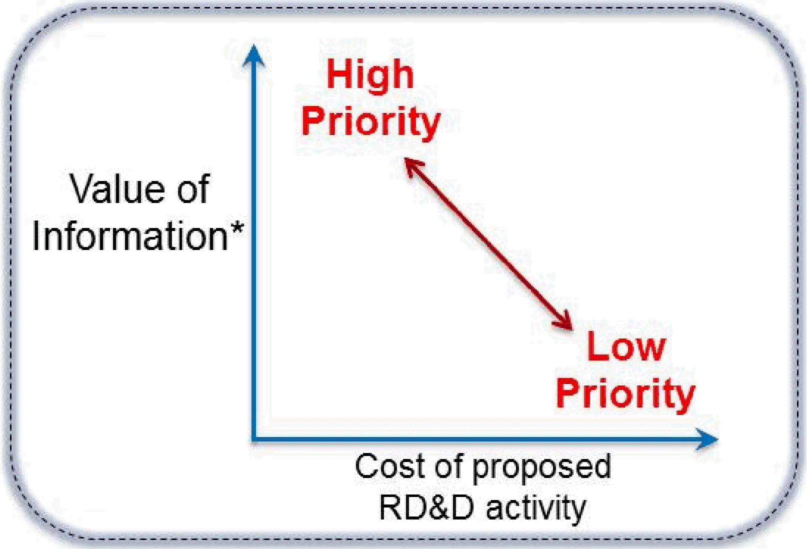
Site Selection/Characterization
- Development of Siting Criteria
- Identification of Potential Sites
- Progressive Site Down-Selection

Repository Development
- Detailed Site Characterization & Repository Design → License Submittal
- Construction & Monitoring
- Operations & Monitoring
- Closure

Generic RD&D → **Site-Specific RD&D**

Managing Technology Development

1. **Periodically *evaluate* the current technical maturity (or deployment readiness) of a new and complex technology system**
2. **Systematically *plan and evolve* such a system to reach full maturity and deployment, e.g.,**
   - **Formal *decision analysis* methods (mathematically based, with expert judgment) to help prioritize future RD&D**

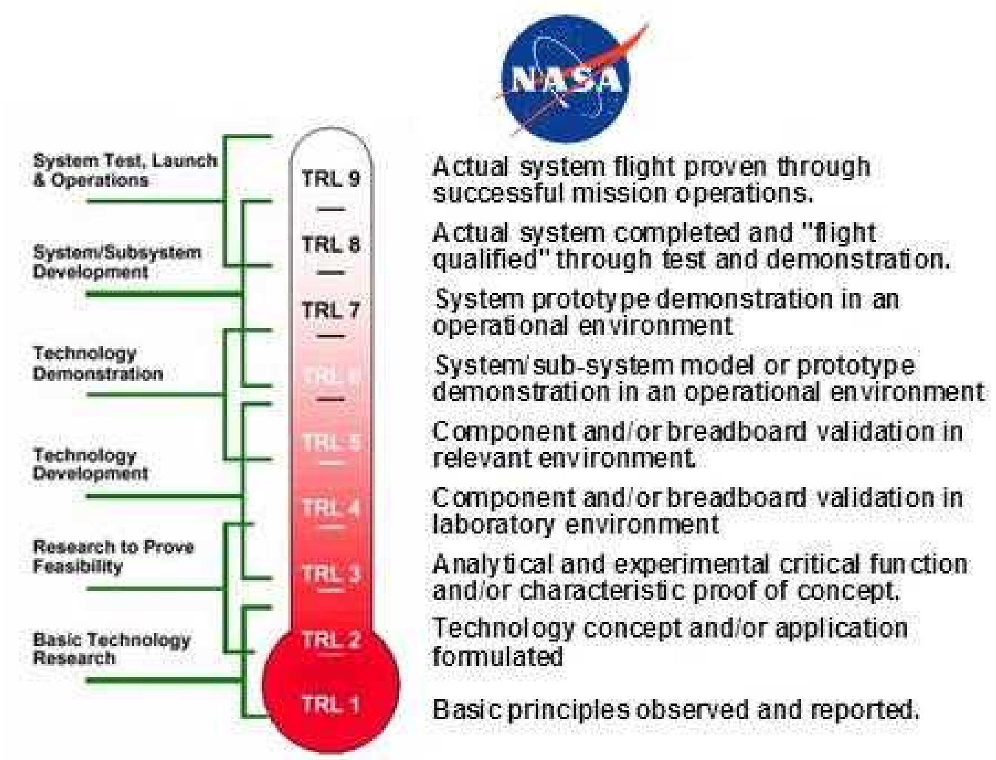


* = *Func* {sensitivity of performance to the information obtained; uncertainty reduction potential (TRL)}

Maturity Evaluation Using Technology Readiness Assessment (TRA)

- An evaluation (or “grading”) and planning process to help define the remaining RD&D effort to bring a new technology (or system) to full maturity or operational readiness
- Maturity “grade” assigned at any point in time is the ***TRL (Technology Readiness Level):***

Original NASA TRL “Thermometer”



Some TRA History and Uses

- Formally defined and used by NASA in 1989 but conceived by NASA in 1974: used to assess readiness of JPL Jupiter Orbiter spacecraft and many other projects
- Used by U.S. Air Force in the '90s
- In 1999 the U.S. GAO recommended the that U.S. DoD adopt the TRA approach; resulted in the 2003 *DoD TRA Deskbook*
- In 2007, the U.S. GAO recommended that the U.S. DOE adopt the TRA approach for major projects, based on past cost/schedule overruns (caused by premature application of new technologies)
- DOE-EM has been using TRA for several major facility projects since 2007, e.g., Savannah River Site Tank 48H Waste Treatment Project
- Currently used by many technology, manufacturing, and scientific organizations involved in developing complex new systems, including DOE, DoD, DHS, NASA, European Space Agency, Andra (Cigéo Project)—construction and operations phases, the American Petroleum Institute (API 17N), and others

Adaptation of the Usual TRA Process to Geologic Systems

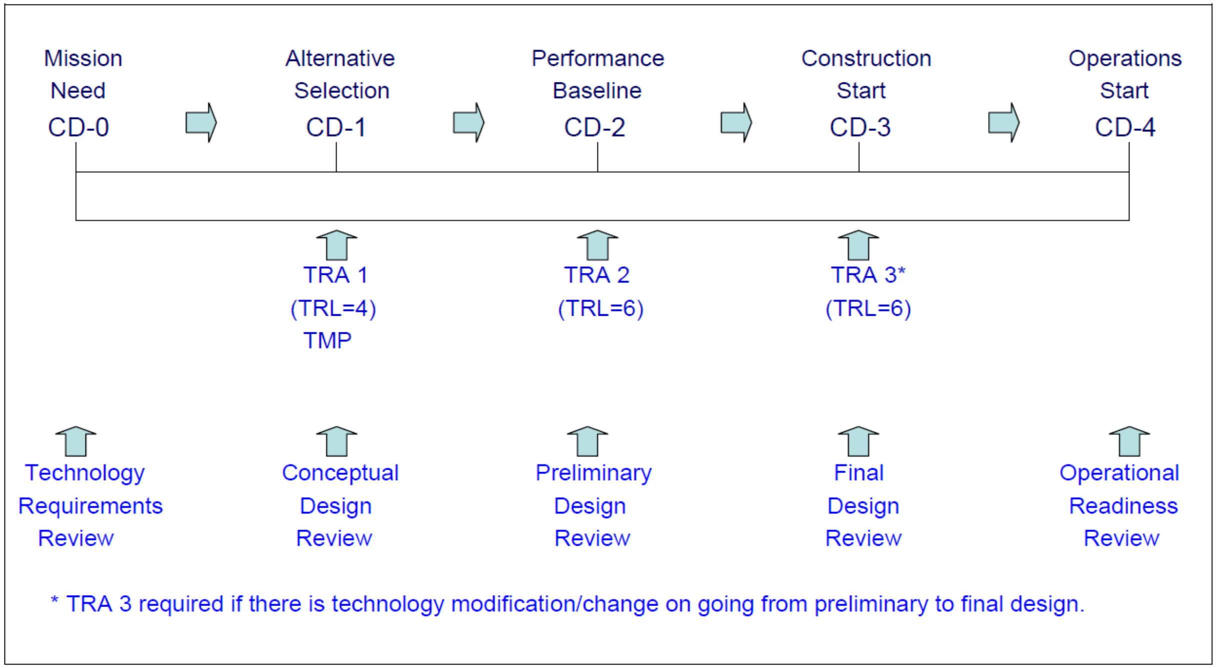
1. **TRAs are traditionally applied to engineered or man-made technologies and systems, primarily to "active" components or systems (e.g., NASA space launch vehicle; HIP calcine HLW disposition facility)**
2. **The *Safety Case* or *Licensing Case* is the recognized, and appropriate, vehicle to establish deployment readiness for an entire deep geologic repository *system* (a "passive" system designed to function for millennia)**
3. **However, in conjunction with a Safety Case, the traditional TRA process can be modified to formally evaluate the post-closure* maturity of repository *subsystems* (comprised of features and components)**
   - *Use the FEPs (features, events, and processes) methodology to identify novel technologies and subsystems*
   - *Use a KRL (Knowledge Readiness Level) metric to evaluate post-closure maturity, in part because of*
     - Inherent (and irreducible) uncertainties in the natural system and the long-time evolution of natural processes

**Pre-closure* technologies (construction; waste emplacement) are still amenable to the usual TRA process

TRA Applicability vs. DOE Project Stage

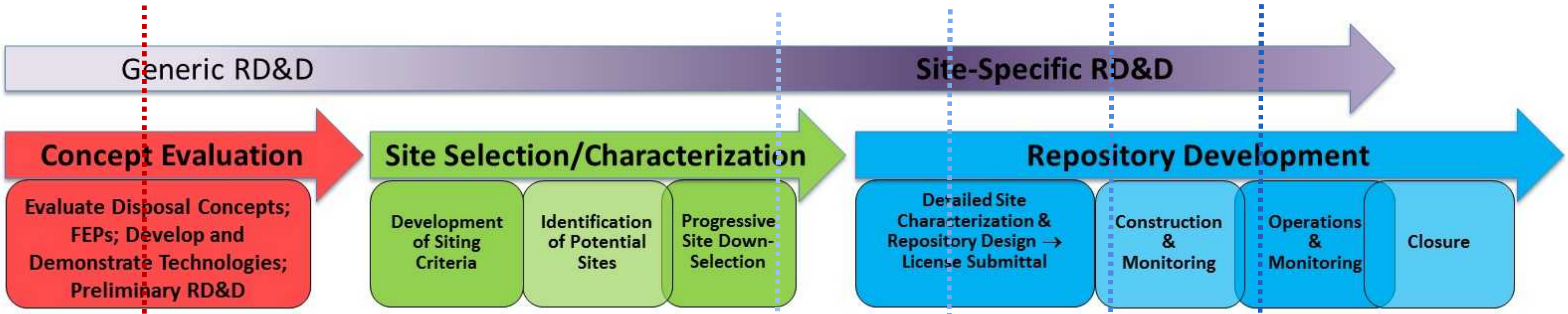
- **DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets:***
  - **TRA <u>required</u> prior to Critical Decision (CD) points for a Major System Project—one with a Total Project Cost (TPC) greater than or equal to $750 M**

"Graded Approach" for TRAs (DOE TRA Guide 413.3-4A):

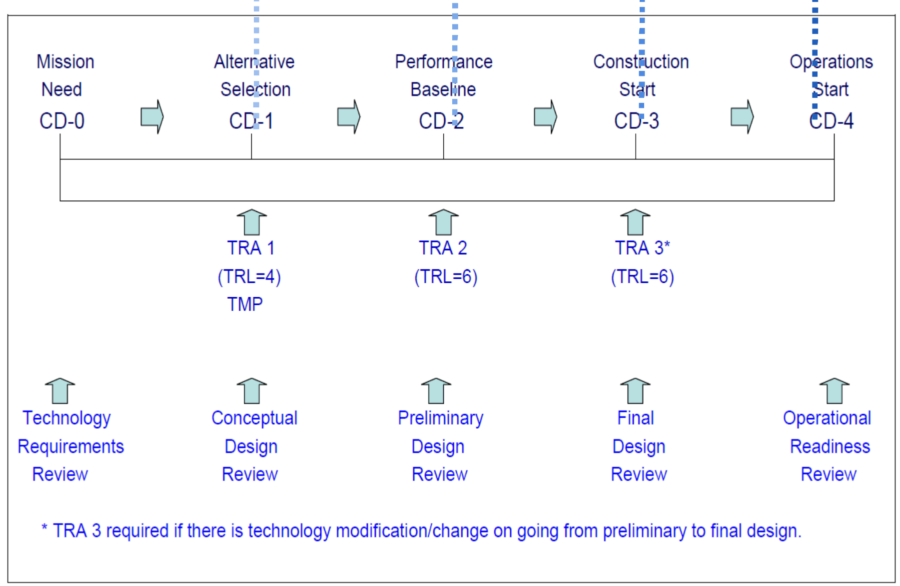


- **CD-1 (TRL=4): Alternative Selection and Cost Range**
- **CD-2 (TRL=6): Performance Baseline (preliminary design; detailed scope, schedule, cost through CD-4)**
- **CD-3 (TRL=6): Construction Start (TRA only needed if one or more CTEs are significantly changed)**

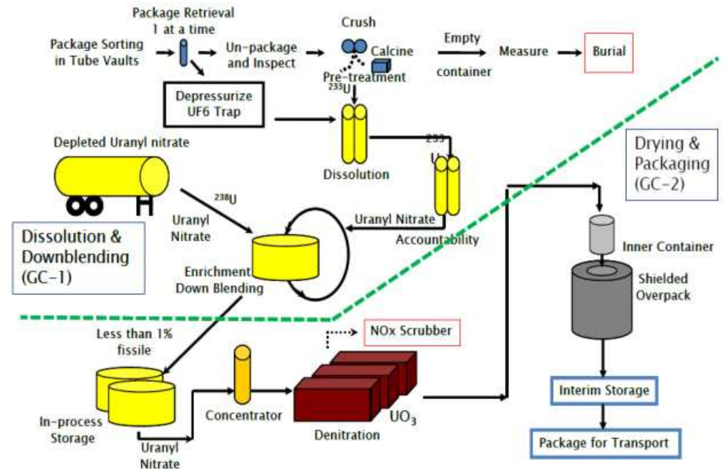
TRA Applicability vs. Repository Phase



- “Generic” stage
- Before site-selection
- “Pre- CD-0”
- **TRA not needed at ≤ CD-0**



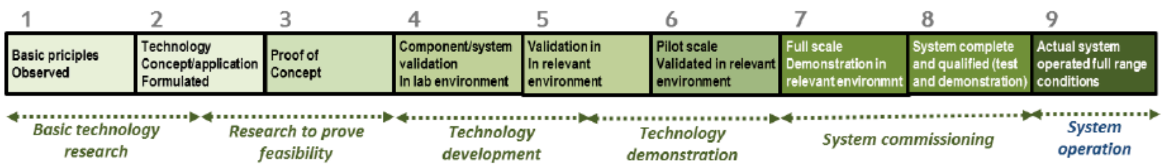
Major Steps of TRA Process



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

1. **Identify:**
   a. Technology system or subsystem to be considered
   b. Critical technical elements (CTEs) of the considered (sub)system

2. **Evaluate (or assess):**
   a. Assign a technology readiness level for each CTE:



   b. Assign a system readiness level

3. **Plan (or evolve):**
   a. Develop a formal Technical Maturity Plan (TMP) to evolve the TRL to the next major program milestone
   b. Prioritize RD&D within the TMP, based on TRLs–formal decision analysis (DA) may be used
   c. Execute the plan over a multi-year period

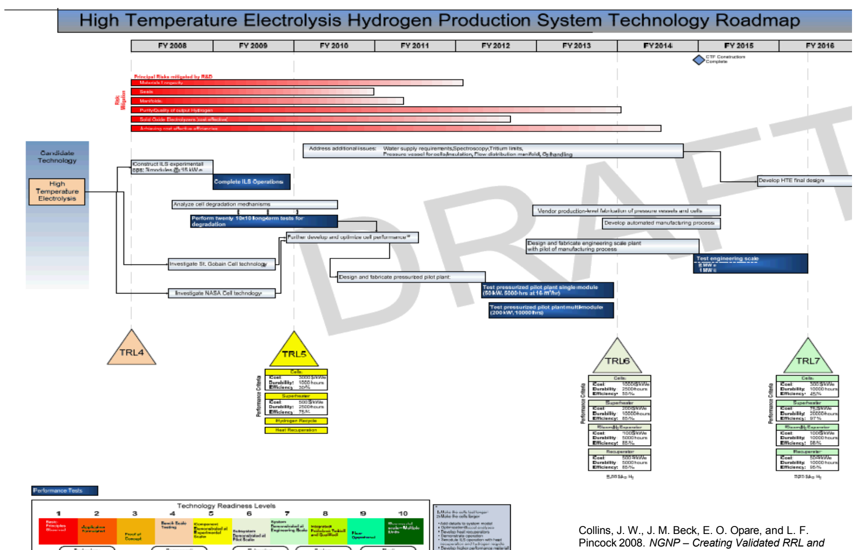
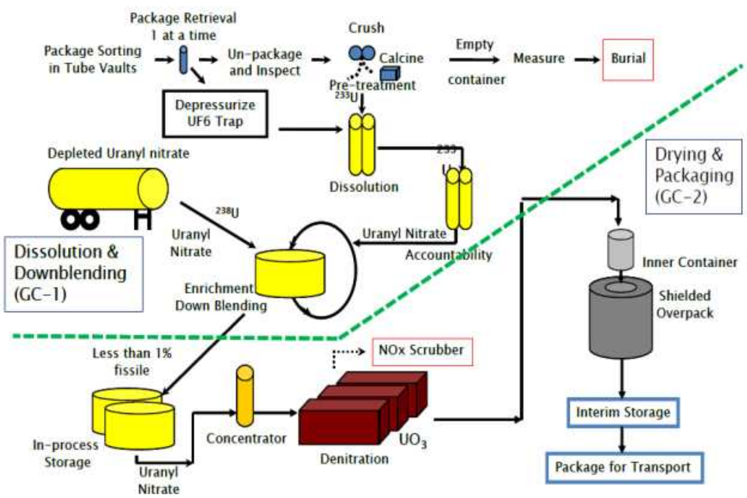


Figure B-2. HTE Hydrogen Production Technology Development Roadmap

Collins, J. W., J. M. Beck, E. O. Opare, and L. F. Pincock 2008. *NGNP – Creating Validated RRL and TRDMs for Critical Systems, Subsystems and Components*, INL/EXT-08-14842, Idaho National Laboratory, Idaho Falls, Idaho 83415, September 2008.

Typical TRA Process – “Identify CTEs”

- ***Common*** **two-step CTE identification procedure for *engineered* technologies:**
  1. High-level (conservative) pass based on:
     - Process flow diagram, or
     - Systems engineering functional hierarchy, or
     - Technical work breakdown structure (WBS), or
     - Software architecture
  2. Detailed pass, with two sets of five questions:
     - Is it “critical” to, or does it impose significant uncertainties related to, facility operation, cost, schedule, and/or safety?
     - Is it “new or novel” or being used in a new or novel way?



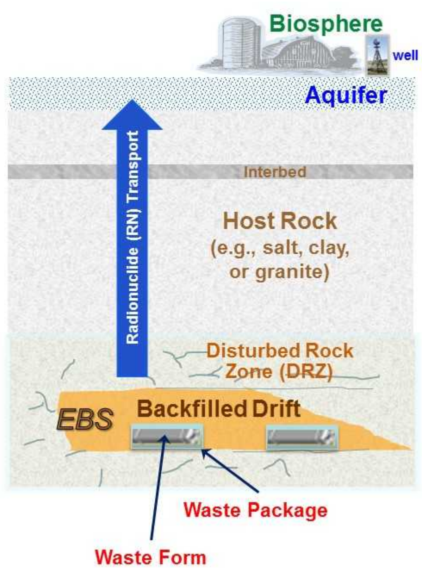
DOE (U.S. Department of Energy) 2011. *Technology Readiness Assessment Guide*, DOE G 413.3-4A, 9-15-2011, Fig. 4a, U.S. Department of Energy, Washington, D.C. 20585, www.directives.doe.gov

Set 1 - Criteria	Yes	No
• Does the technology have a significant impact on a functional requirement of the process or facility?		
• Do limitations in the understanding of the technology result in a potential schedule risk, i.e., the technology may not be ready for insertion when required?		
• Do limitations in the understanding of the technology result in a potential cost risk, i.e., the technology may cause significant cost overruns?		
• Are there uncertainties in the definition of the end state requirements for this technology?		
• Do limitations in the understanding of the technology impact the safety of the design?		

Set 2 - Criteria	Yes	No
• Is the technology new or novel?		
• Is the technology modified?		
• Has the technology been repackaged so a new relevant environment is realized?		
• Is the technology expected to operate in an environment and/or achieve performance beyond its original design intention or demonstrated capability?		
• Does the technology represent new hazards or safety-related issues that have not been assessed and/or mitigated?		

Repository TRA/KRA Process – "Identify CTEs"

- **Use the Features, Events, and Processes (FEPs) approach to *identify* both CTEs and candidate *subsystems*, for maturity evaluation: :**



FEP Matrix:

Characteristics, Processes, and Events / Features / Components		Processes											Events		
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic
Glossary / Definitions	CP	TM	TH	TC	TB	TT	TL	RA	LG	CL	HP	OP	NC	EF	SM
Surface Features															
(BP) Biosphere															
(01) Natural Surface and Near-Surface Environment															
(02) Flora and Fauna															
(03) Humans															
(04) Food and Drinking Water															
(05) Dwellings and Other Man-Made Surface Features/Materials															
Geosphere Features															
(OU) Other Geologic Units															
(01) Overlying / Adjacent Units (including Caprock, Aquifers)															
(02) Underlying Units															
(HR) Host Rock															
(01) Disturbed Rock Zone (DRZ)															
(02) Emplacement Unit(s)															
(03) Other Host Rock Units															
Waste and Engineered Features															
(BB) Buffer/Backfill															
(01) Waste Package Buffer															
(02) Drift/Tunnel Backfill															
(WP) Waste Package and Internals															
(01) SNF															
(02) Vitrified HLW															
(05) Other HLW															
(06) Metal Parts															
(WF) Waste Form and Cladding															
(01) SNF and Cladding															
(02) Vitrified HLW															
(05) Other HLW															
(06) Metal Parts from Reprocessing															

Candidate CTEs (e.g., individual FEPs):

Each FEP matrix cell (e.g., highlighted in red) contains all individual FEPs (such as those listed below) related to the "Process/Event" acting upon or within the "Feature/Component"

UFD FEP Number	FEP Description
2.0.00.00	2. DISPOSAL SYSTEM FACTORS
2.1.00.00	1. WASTES AND ENGINEERED FEATURES
2.1.03.00	1.03. WASTE CONTAINER
2.1.03.02	**General Corrosion of Waste Packages**
2.1.03.03	**Stress Corrosion Cracking (SCC) of Waste Packages**
2.1.03.04	**Localized Corrosion of Waste Packages**
2.1.03.05	**Hydride Cracking of Waste Packages**
2.1.09.00	1.09. CHEMICAL PROCESSES - CHEMISTRY
2.1.09.05	**Chemical Interaction of Water with Corrosion Products**
2.1.09.11	**Electrochemical Effects in EBS**

Candidate Subsystems:

- **"Features" shown in bold font with alpha designation**
- "Components" shown in normal font with numeric designation

Repository TRA Process – "Identify CTEs" (cont.)

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Step 1. *High-level (conservative)* CTE identification pass based on either:

a. All individual FEPs:

UFD FEP Number	FEP Description	Associated Processes
2.0.00.00	2. DISPOSAL SYSTEM FACTORS	
2.1.00.00	1. WASTES AND ENGINEERED FEATURES	
2.1.03.00	1.03. WASTE CONTAINER	
2.1.03.02	**General Corrosion of Waste Packages**	- Dry-air oxidation in anoxic condition - Humid-air corrosion in anoxic condition - Aqueous phase corrosion in anoxic condition - Passive film formation and stability - Chemistry of brine contacting WP - Salt deliquescence
2.1.03.03	**Stress Corrosion Cracking (SCC) of Waste Packages**	- Residual stress distribution in WP from fabrication - Stress development and distribution in contact with salt undergoing creep deformation - Crack initiation, growth and propagation
2.1.03.04	**Localized Corrosion of Waste Packages**	- Pitting - Crevice corrosion
2.1.03.05	**Hydride Cracking of Waste Packages**	- Hydrogen diffusion through metal matrix - Crack initiation and growth in metal hydride phases
2.1.09.00	1.09. CHEMICAL PROCESSES - CHEMISTRY	
2.1.09.05	**Chemical Interaction of Water with Corrosion Products - In Waste Packages**	- Corrosion product formation and composition (waste form, waste package internals, waste package) - Evolution of water chemistry in waste packages, in backfill, and in tunnels
2.1.09.11	**Electrochemical Effects in EBS**	- Enhanced metal corrosion
2.1.11.00	1.11. THERMAL PROCESSES	
2.1.11.13	**Thermal Effects on Chemistry and Microbial Activity in EBS**	
. . . . .	. . . .	. . . . .

or

$\sum$ *FEPs*

b. "Rolled-up" FEPs/issues or topics:

Sevougian et al. (2013):

Salt RD&D Technical Issue	Issue Importance Rating
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues	
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)
17. The formation and evolution of the EDZ	H (= D,P)
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)
19. Chemical characteristics of brine in the host rock	L (= I,S)
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)
22. Radionuclide transport in the host rock and EDZ	L (= D,S)
Repository System (EBS and Geosphere combined) Feature/Process Issues	
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)
24. Buoyancy of the waste packages	L (= W,P)
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)
28. Performance of seal system	H (= D,P)
29. Performance of ground support	L = (W,P,S)
30. Performance and effects of ventilation	M (= I,P)

Hart et al. (2015):

1. Influence of Disturbed Rock Zone (DRZ)
2. Compaction behaviour of crushed (granular) salt
3. (T)HMC effects related to the dissolution of rock salt
4. Corrosion of waste container and waste matrix
5. Corrosion of cementitious barriers
6. Solubility of radionuclides

Repository TRA Process – "Identify CTEs" (cont.)

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Step 2. ***Detailed*** **CTE identification pass, based on** ***importance*** **of FEP, "RD&D issue", or "topic" to long-term performance, using either of two metrics:**

a. Importance to post-closure safety (ITPS), i.e., to safety functions, such as isolation, containment, delayed/limited releases (Sevougian and MacKinnon 2014):

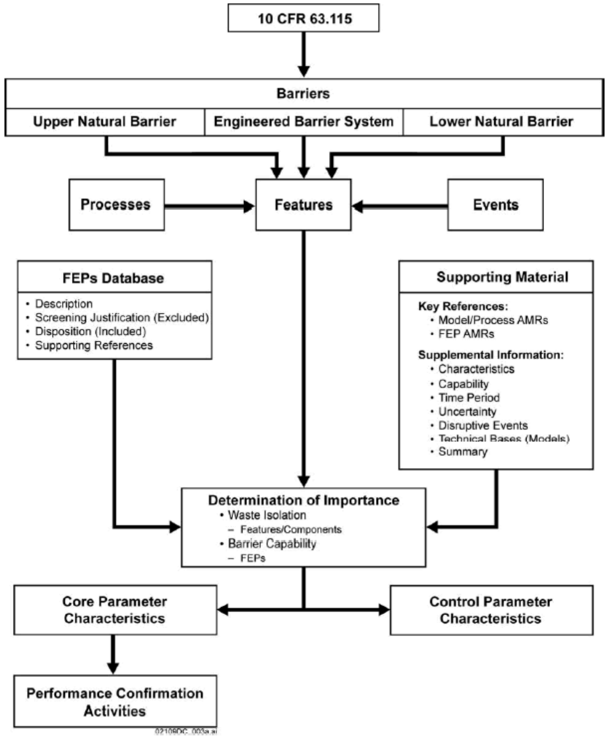
Importance of RD&D Issue = **Impact of RD&D Issue on a Safety Function** ∪ **Function Level of the Safety Function**

- "***Impact***" of an RD&D Issue on *performance* or *success* of a safety/design function: direct, indirect, weak
- "***Function level***" for any safety function is defined as either *primary* or *secondary:*
  - A *primary* safety function operates from the time of closure to prevent transfer of radionuclides to the biosphere
  - A *secondary* safety function is only operative if a primary function fails, for whatever reason

Importance Value Rating	= Impact	+ Function Level
High: H=(D,P)	Direct (D)	Primary (P)
Medium: M=(I,P)	Indirect (I)	Primary (P)
Low: L=(W,P)	Weak (W)	Primary (P)
Low: L=(D,S)	Direct (D)	Secondary (S)
Low: L=(I,S)	Indirect (I)	Secondary (S)
Low: L=(W,S)	Weak (W)	Secondary (S)

or

b. Importance to barrier capability (ITBC)— see Yucca Mountain License Application (DOE 2008) and Post-closure Nuclear Safety Design Bases document (SNL 2008):



NOTE: Processes and/or events, acting on features within a barrier are described by FEPs. The ITBC evaluations are tabulated in Appendix A. Corresponding core parameter characteristics and control parameter characteristics, and Performance Confirmation activities are also tabulated in this appendix.

Figure 6-4. Schematic of ITBC/ITWI Process with Ties to Performance Confirmation Activities

Typical TRA Process – "Evaluate CTEs"

- ***Common*** **two-step CTE evaluation procedure for *engineered* technologies:**
  1. High-level (initial guess) pass based on:
     - Common nine-level TRL table (like NASA table) →
     - Nine-level TRL table adapted to engineered repository technologies (if necessary)
  2. Detailed pass, with multi-question tables for each TRL:
     - Begin with the table just below the initial TRL guess
     - All questions in the "TRL minus 1" table must be answered in the affirmative to confirm the initial guess:

Table A-1. Example TRL 1 Questions for CTEs.

Y/N	Question/Criterion	Basis and Supporting Documentation
	1. Has a scientific fact, phenomenon, or principle been discovered that suggests one or more potentially useful new capabilities?	
	2. Is the new fact or principle described?	
	3. Are the new capabilities described?	
	4. Are the capabilities useful in an application relevant to program goals?	
	5. For a useful new, relevant capability, is there a fundamental, perhaps newly discovered scientific fact and/or principle that suggests a technically feasible path to implementation?	
	6. For the scientific phenomena involved, is further scientific research possible in the foreseeable future?	
	7. Has the required research path forward been identified?	

Table 1 Technology Readiness Levels

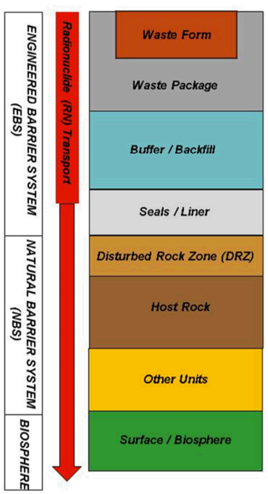
Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	TRL 9	Actual system operated over the full range of expected conditions.	Actual operation of the technology in its final form, under the full range of operating conditions. Examples include using the actual system with the full range of real wastes.
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with real waste in hot commissioning.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in a relevant environment	Prototype[a] full scale system. Represents a major step up from TRL 6, requiring demonstration of a system prototype in a relevant environment. Examples include testing the prototype in the field with a range of simulants and/or real waste and cold commissioning.
Technology Demonstration	TRL 6	Engineering scale, similar (prototypical) system validation in a relevant environment	Representative engineering scale system, which is well beyond the scale tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness and system integration. Examples include testing a prototype with real waste and a range of simulants.
Technology Development	TRL 5	Laboratory/bench 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. Examples include testing a high-fidelity system in a simulated environment and/or with a range of real wastes and simulants.
	TRL 4	Component and/or system validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in a laboratory and testing with a range of simulants.[b] Laboratory/bench scale testing may not be appropriate for all systems. For example, mechanical systems, such as robotic retrieval technologies, may require full scale prototype testing to meet TRL 4.
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory/bench scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants. For some applications, such as mechanical systems, this may include computer and/or physical modeling to demonstrate functionality.
	TRL 2	Technology concept and/or application formulated	Invention begins. 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	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.

[a] A prototype is defined as a physical or virtual model used to evaluate the technical or manufacturing feasibility or utility of a particular technology or process, concept, end item, or system.
[b] If feasible, it is recommended to include tests on a limited range of real waste prior to achieving TRL 4.

DOE (US Department of Energy) 2013. *Technology Readiness Assessment (TRA)/Technology Maturation Plan (TMP) Process Implementation Guide, Revision 1*, U.S. Department of Energy Office of Environmental Management, Washington, D.C., August 2013.

Repository TRA/KRA Process – “Evaluate CTEs”

- **For *post-closure* maturity of *all* CTEs and (sub)systems (i.e., all EBS, DRZ, or NBS features/components), use a *“Knowledge Readiness Assessment” (KRA)***
  - **= Maturity of knowledge, or level of confidence, about future performance**
    - **Based on modeling and simulation; and in consideration of:**
      - **Data and model uncertainties; scale dependencies**
      - **Inherent (aleatory) uncertainties regarding the timing and effect of future events**
      - **Very long performance time-scales**
      - **No human intervention or access—“passive” systems**



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

EBS = Engineered Barrier System
DRZ = Disturbed Rock Zone
NBS = Natural Barrier System

§ 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 (Fernandez 2010).

Repository KRA Process – “Evaluate CTEs” (cont.)

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Step 1. *High-level* CTE evaluation pass for subsystem *post-closure* maturity:

- Use Knowledge Readiness Levels (KRLs)* metric, a “modified TRL” metric
- Probably “overkill” to use a *detailed* 2nd pass, with multi-question tables, for each KRL (but can be decided at the time of the first such KRA)

Table 1. Possible Nine-Level Knowledge Readiness Scale (for post-closure readiness)

Knowledge Readiness Level	KRL Definition	Description
KRL 9	*Actual system operated over the full range of expected conditions*	Not feasible/applicable for a major *post-closure* geologic repository subsystem.
KRL 8	*Actual system completed and qualified through test and demonstration*	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. 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.

Repository KRA Process – "Evaluate CTEs" (cont.)

1. Alternative for *high-level* CTE evaluation pass:

- As a simpler alternative to KRLs, one could possibly use a "state-of-the-art" knowledge scale ("SALs")—adapted here from the DOE Used Fuel Disposition Roadmap (DOE 2012):

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.

TRA or KRA Process – "Evaluate System TRL"

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- **Determine a (sub)system TRL—or "(sub)system readiness level (SRL)"**
  - A commonly used SRL is the minimum CTE TRL for the system being evaluated
- **Should consider interactions among CTEs and subsystems or Integration Readiness Level (IRL)—currently an active area of research**

Table 4. Definitions for TRLs, MRLs, IRLs, SRLs (for Levels 1 to 9) and SRL Values (compiled from Gove 2007; Ramirez-Marquez and Sauser 2009; Sauser et al. 2010; AFManTech 2008).

LEVEL	TRL Definition	MRL Definition	IRL Definition	SRL Definition	SRL Value
1	Basic principles observed and reported.	Basic manufacturing implications identified.	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship.	Concept Refinement	0.10 to 0.39
2	Technology concept and/or application formulated.	Manufacturing concepts identified.	There is some level of specificity to characterize the interaction between technologies through their interface.		
3	Analytical and experimental critical function and/or characteristic proof of concept.	Manufacturing proof-of-concept developed.	There is compatibility between technologies to orderly and efficiently integrate and interact.		
4	Component and/or breadboard validation in laboratory environment.	Capability to produce the technology in a laboratory environment.	There is sufficient detail in the quality and assurance of the integration between technologies.		
5	Component and/or breadboard validation in relevant environment.	Capability to produce prototype components in a production relevant environment.	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.	Technology Development	0.40 to 0.59
6	System/subsystem model demonstration in relevant environment.	Capability to produce a prototype system or subsystem in a production relevant environment.	The integrating technologies can accept, translate, and structure information for its intended application.		
7	System prototype demonstration in relevant environment.	Capability to produce systems, subsystems, or components in a production representative environment (MRL 7). Pilot line capability demonstrated; ready to begin low-rate, initial production (MRL 8).	The integration of technologies has been verified and validated with sufficient detail to be actionable.	System Development and Demonstration	0.60 to 0.79
8	Actual system completed and qualified through test and demonstration.	Low-rate production demonstrated; capability in place to begin full-rate production (MRL 9).	Actual integration completed and mission qualified through test and demonstration in the system environment.		
9	Actual system proven through successful mission operations.	Full-rate production demonstrated and lean production practices in place (MRL 10).	Integration is mission proven through successful mission operations.	Production Operations and Support	0.80 to 0.89 0.90 to 1.00

Fernandez, J. A. 2010, *Contextual Role of TRLs and MRLs in Technology Management*, SAND2010-7595, Sandia National Laboratories, Albuquerque, NM 87185.

Typical TRA process – “Maturation Plan”

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Technology Maturation Plan Format*

Table of Contents

1.0 Introduction

2.0 Technology Assessments of the Project

3.0 TMPs For Individual CTEs

4.0 Plan To Mature System Integration

5.0 Technology Maturity Schedule

6.0 Summary Technology Maturity Budget

7.0 References

* DOE (US Department of Energy) 2013. *Technology Readiness Assessment (TRA)/Technology Maturation Plan (TMP) Process Implementation Guide, Revision 1*, U.S. Department of Energy Office of Environmental Management, Washington, D.C., August 2013, Att. E.

- **Example of a Technology Maturation Plan (TMP) or Technology Development Roadmap (TDRM) for an engineered subsystem in the DOE Next Generation Nuclear Plant (NGNP):**

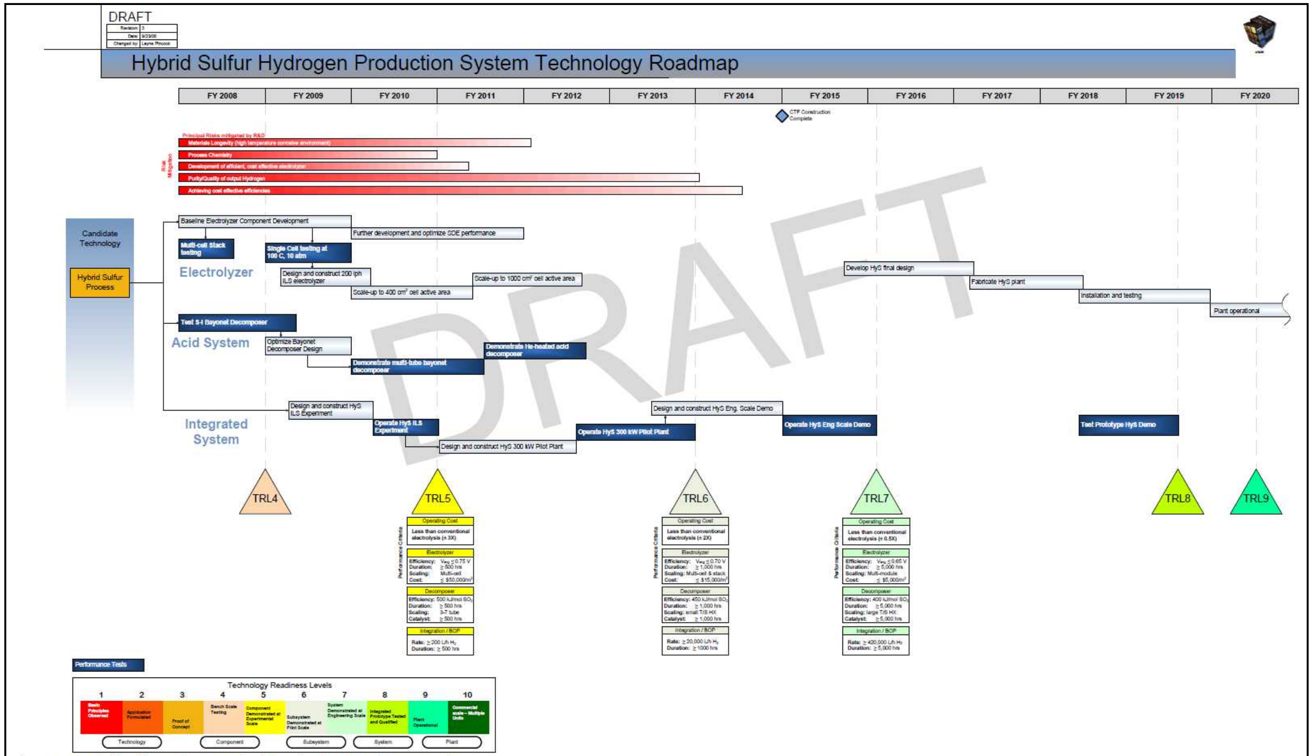


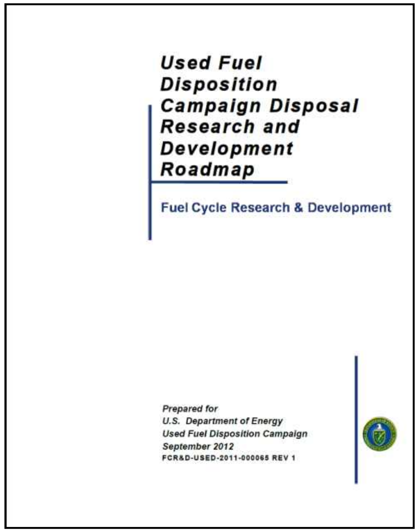
Figure B-3. Hybrid Sulfur Hydrogen Production Technology Development Roadmap

Collins, J. W., J. M. Beck, E. O. Opare, and L. F. Pincock 2008. *NGNP – Creating Validated RRL and TRDMs for Critical Systems, Subsystems and Components*, INL/EXT-08-14842, Idaho National Laboratory, Idaho Falls, Idaho 83415, September 2008

Repository KRA process – "Example of a Partial Maturation Plan"

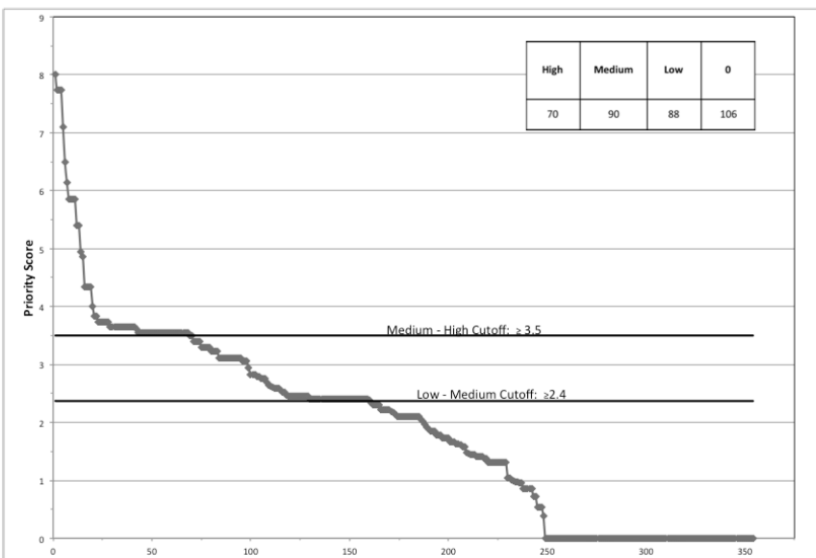
2012 UFD R&D Roadmap

- Budget and schedule not considered—premature at the generic stage


Used Fuel Disposition Campaign Disposal Research and Development Roadmap

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
September 2012
FCR&D-USED-2011-000065 REV 1



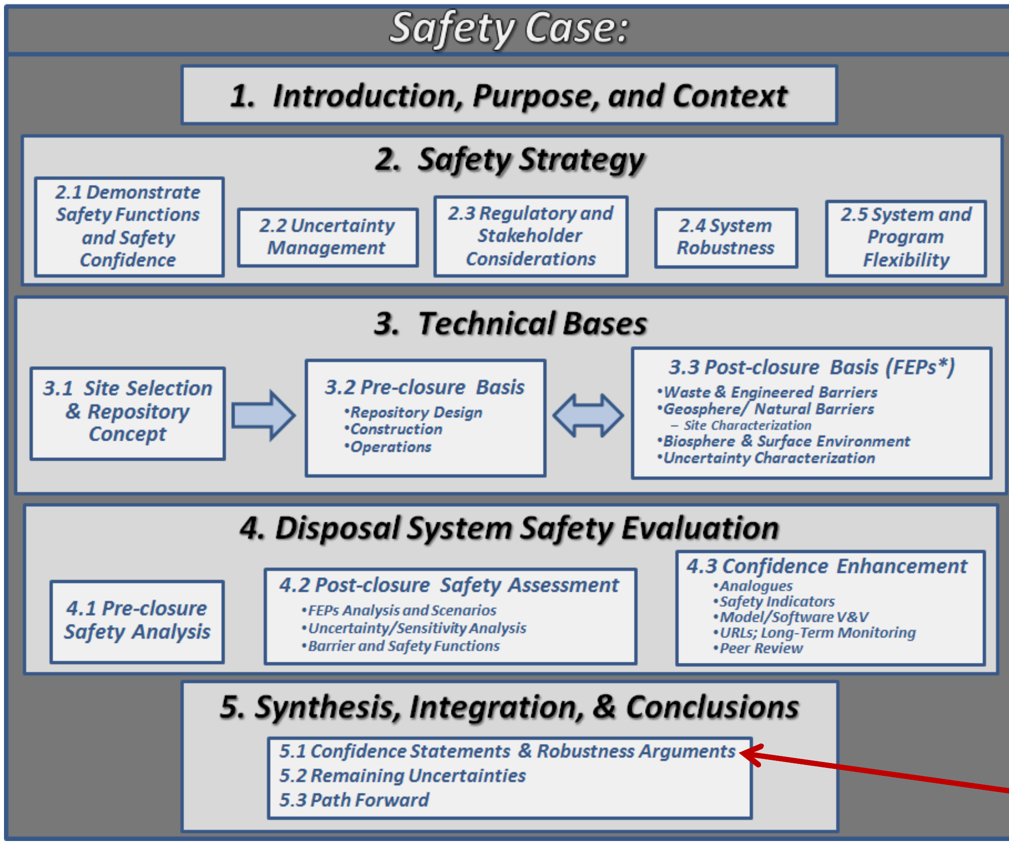
Appendix B

UFD FEP ID No., Title, and Media	Overall Priority Score
2.2.01.01 - Evolution of EDZ - Clay/Shale	8.00
2.2.08.01 - Flow Through the Host Rock - Salt	7.73
2.2.08.02 - Flow Through the Other Geologic Units - Confining units - Aquifers - Salt	7.73
2.2.08.06 - Flow Through EDZ - Salt	7.73
2.2.08.04 - Effects of Repository Excavation on Flow Through the Host Rock - Salt	7.10
2.2.08.07 - Mineralogic Dehydration - Salt	6.49
2.2.01.01 - Evolution of EDZ - Deep Boreholes	6.13
2.2.09.01 - Chemical Characteristics of Groundwater in Host Rock - Deep Boreholes	5.86
2.2.09.02 - Chemical Characteristics of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers - Deep Boreholes	5.86
2.2.09.05 - Radionuclide Speciation and Solubility in Host Rock - Deep Boreholes	5.86
2.2.09.06 - Radionuclide Speciation and Solubility in Other Geologic Units (Non-Host-Rock) - Deep Boreholes	5.86
2.2.09.03 - Chemical Interactions and Evolution of Groundwater in Host Rock - Deep Boreholes	5.40
2.2.09.04 - Chemical Interactions and Evolution of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers - Deep Boreholes	5.40
1.2.03.01 - Seismic Activity Impacts EBS and/or EBS Components -	4.94
2.1.09.13 - Radionuclide Speciation and Solubility in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel -	4.86
2.1.03.02 - General Corrosion of Waste Packages -	4.34
2.1.03.03 - Stress Corrosion Cracking (SCC) of Waste Packages -	4.34
2.1.03.04 - Localized Corrosion of Waste Packages -	4.34
2.1.03.05 - Hydride Cracking of Waste Packages -	4.34
2.1.02.01 - SNF (Commercial, DOE) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Radionuclide Release -	4.01
2.2.07.01 - Mechanical Effects on Host Rock - Salt	3.83
2.2.07.01 - Mechanical Effects on Host Rock - Clay/Shale	3.83
2.2.02.01 - Stratigraphy and Properties of Host Rock - Granite/Crystalline	3.74
2.2.02.01 - Stratigraphy and Properties of Host Rock - Deep Boreholes	3.74
2.2.02.01 - Stratigraphy and Properties of Host Rock - Salt	3.74
2.2.02.01 - Stratigraphy and Properties of Host Rock - Clay/Shale	3.74

Used Fuel Disposition Campaign Disposal Research and Development Roadmap
FCRD-USED-2011-000065 Rev. 1

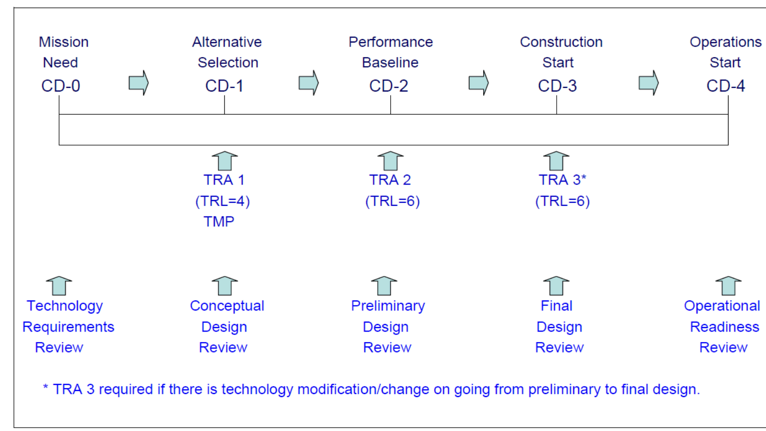
Role of the *Safety Case* for Readiness of Total Geologic System

- **The *Safety Case(s)* is the internationally recognized vehicle to establish and document *total system* (i.e., repository) post-closure technical maturity at various development phases, including final deployment readiness:**



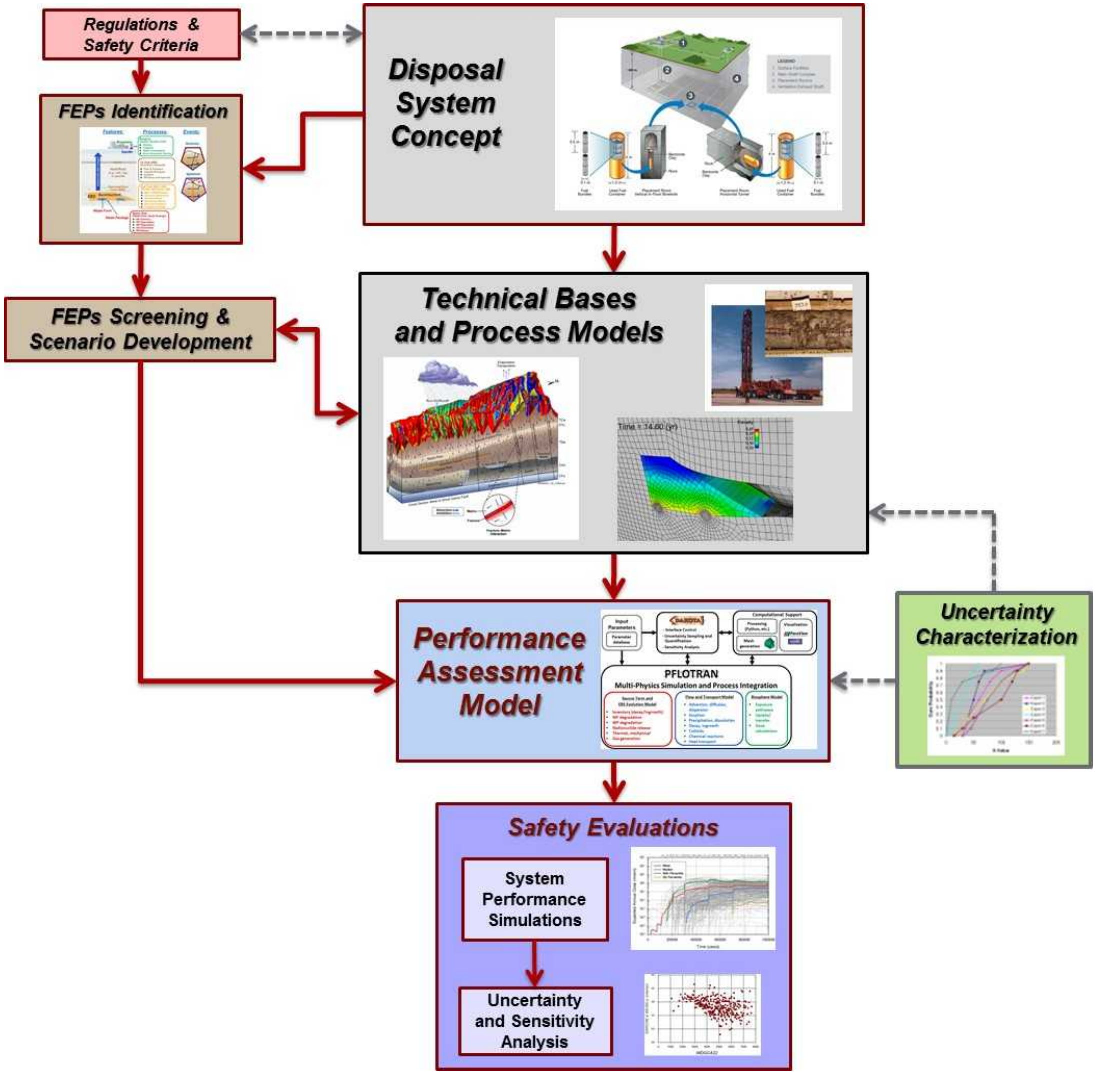
*FEP = Feature, Event, or Process

- **TRAs/KRAs for a new geologic repository would be components of the Safety Case beginning at least at CD-2, according to the current DOE Order 413.3B:**

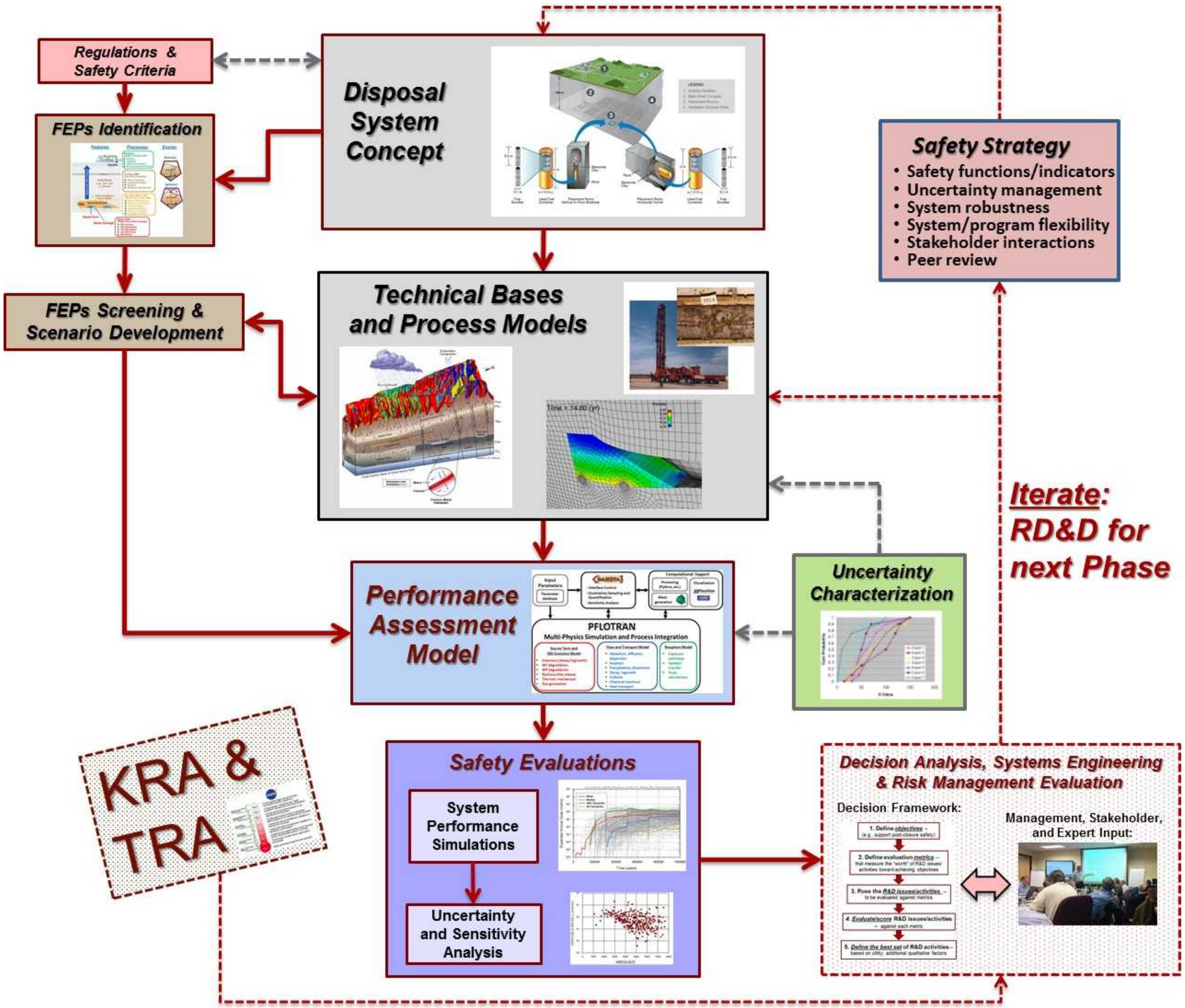


- ***KRAs/TRAs could aid in defining a "degree of confidence" metric for deployment readiness***

Information Flow Between Key Elements of Safety Case



Iterative Use of Performance Assessment and Decision Analysis for Technology Maturation



Questions?

Backup Slides

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Pre-Closure Technologies and Systems

- **Excavation and emplacement methods/equipment, or *in situ* testing and monitoring methods/equipment:**
  - Use traditional TRA process, if deemed beneficial or necessary
  - Much previous experience exists in URL construction, operations, and *in situ* testing—maturity level can be inferred to be from TRL 6 to 8 for many technologies
  - Although TRL > 6 implies testing in the site-specific, relevant environment, many URL-developed technologies may be directly transferable to other programs

Boring of deposition holes

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

Buffer emplacement

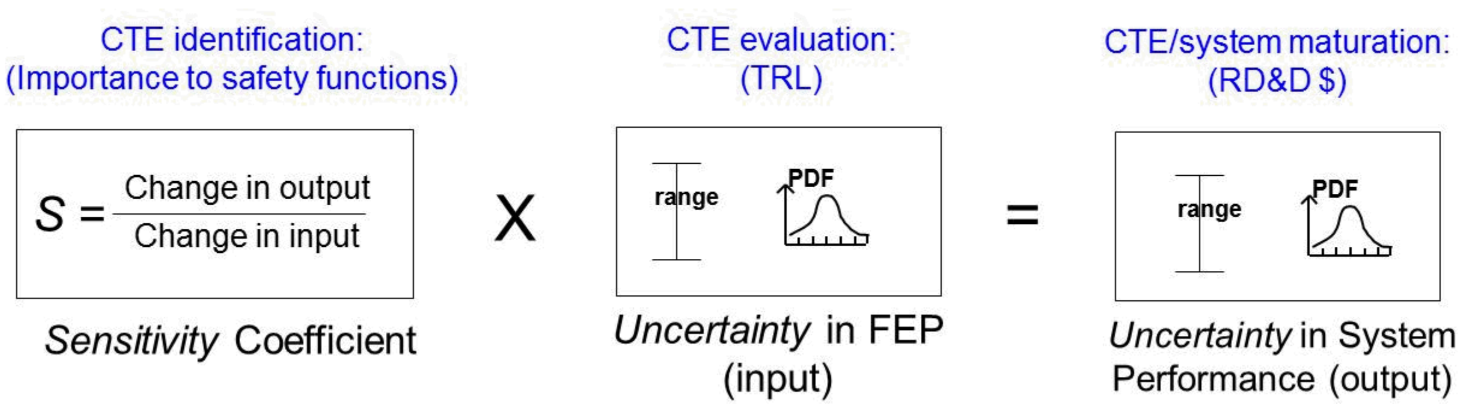
Some Limitations of TRA Process

(from Fernandez 2010)

- TRL scale is non-linear, especially when considering cost and schedule
- Does not address uncertainty (and difficulty) in technology development
- Lacks focus on system-to-system integration as the TRLs focus on a particular element of technology
- Not well integrated into cost and risk modeling tools or does not give a complete picture of risk in integrating a technology into a system
- Captures only a small part of the information that stakeholders need to support their decisions

Uncertainty Considerations

- ***Identification*** **of CTEs is based on the degree to which a CTE is capable of influencing system performance (or safety functions):**
  - How *sensitive* might the system be to the given CTE (or FEP)?
- ***Evaluation*** **of CTEs (i.e., the TRLs or KRLs) is based on the current state of knowledge regarding the CTE, i.e., what is the *uncertainty* reduction potential of further RD&D**
- **Both are important when making RD&D decisions:**



Summary: Adaptation of the Usual TRA Process to Geologic Systems

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1. **For post-closure critical technical element (CTE) *identification*…**
   - For first-pass, high-level CTE identification, the traditional FEPs identification process has significant value and precedence:
     - Individual FEPs and/or possibly "rolled-up" FEPs/issues or topics
   - For second-pass, detailed CTE identification (i.e., those that are "critical") the use of safety functions or barrier functions (barrier capabilities) is appropriate
2. **For CTE and/or subsystem maturity *evaluation*…**
   - For *pre-closure* technologies, as well as the manufacture of post-closure EBS components (e.g., the waste package), use the traditional TRA process
   - For *post-closure* performance of both natural and engineered CTEs, use a Knowledge Readiness Assessment (KRA) process
3. **For CTE and subsystem *maturation*….**
   - Use various RD&D prioritization methods (e.g., formal decision analysis that includes fiscal/personnel constraints), based on information from quantitative safety assessments
   - Re-evaluate according to major program stages (licensing, construction, operations)
     - ➢ Iterate between technical bases and safety assessment