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Application of the Technology Readiness Assessment (TRA) Process to Deep Geologic Repository Systems

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DAEF
Deutsche Arbeitsgemeinschaft Endlagerforschung

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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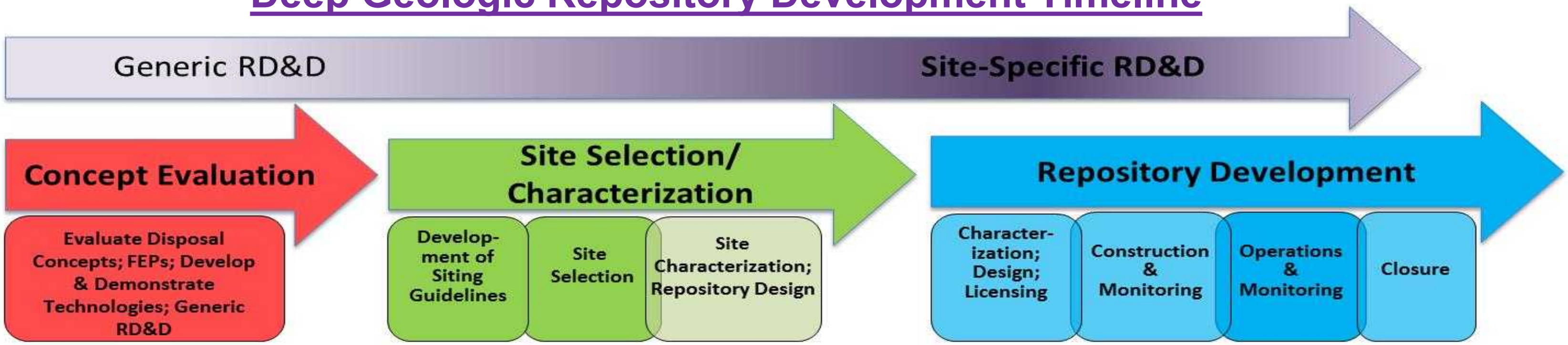
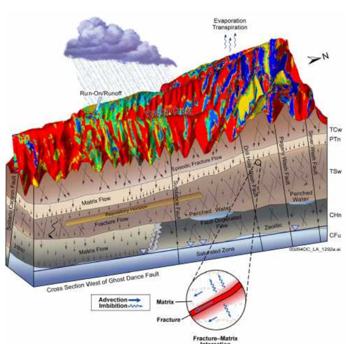
Novel Technology Development

- **Evolution of a novel technology or a novel complex engineering project, from conception to deployment, with research at the beginning and full-scale engineering at the end:**

Deep Geologic Repository Development Timeline



Initial conceptual model



Characterization

Full deployment

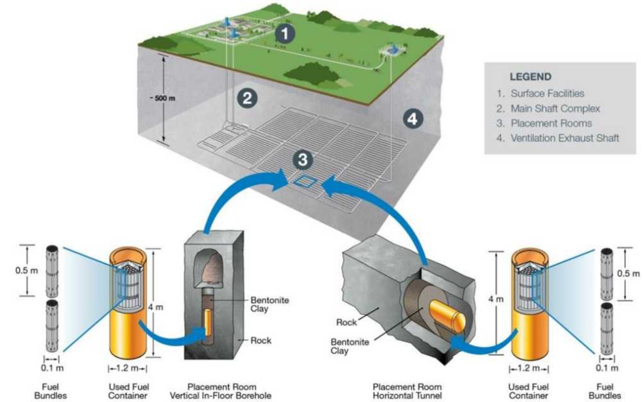
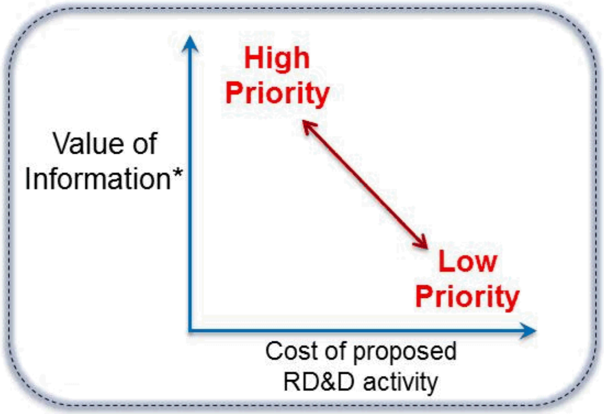


Figure Source: https://www.cnsc-ccsn.gc.ca/eng/waste/high-level-waste/cnsc-role-in-nwmo-apm-project/index.cfm

Major Tasks in Technology Evolution

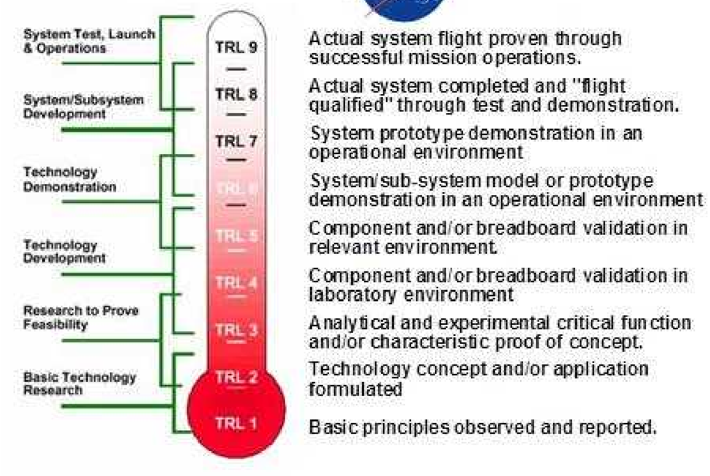
1. How to *evaluate* the technical maturity (or deployment readiness) of a new and complex technology system, at any stage of development
2. How to systematically *plan and evolve* such a system to reach full maturity and deployment (various such methods are in use):
   - **Formal planning and technology maturation methods usually lead to prioritization of RD&D (to a degree dependent on the program stage):**
     - Constraints are often part of the RD&D prioritization process ($, 🕴)
     - Formal decision analysis methods (mathematically based, with expert judgment) are appropriate for prioritization



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

TRA Definition and Value

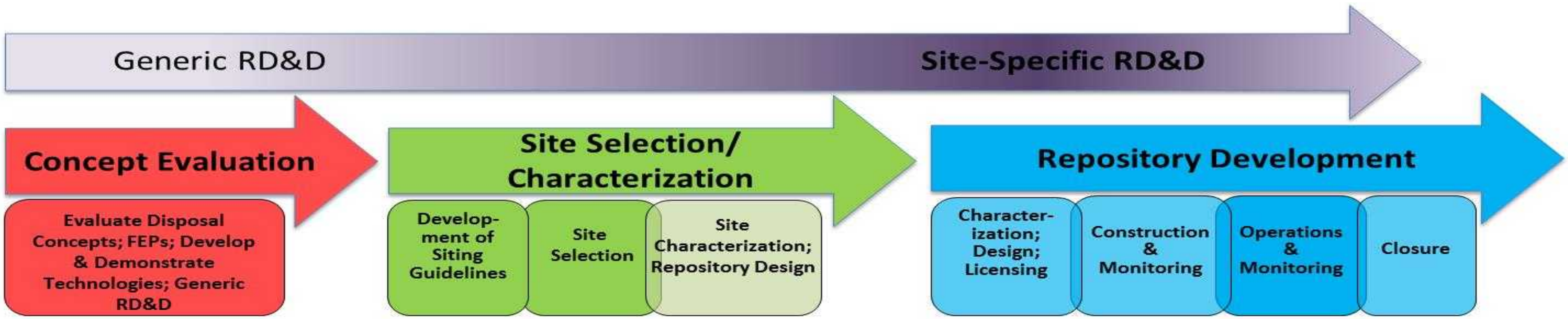
- **The Technology Readiness Assessment (TRA) process, originally developed by NASA, and later by the US DoD, is a formal or structured technical maturity evaluation and evolution method, currently in wide use (even in deep geologic repository programs, e.g., Cigeo in France)**



- <u>**Definition**</u>**:** a formal process to aid in defining the remaining research and development (R&D) effort and related activities to bring a new technology system to full maturity or operational readiness

- <u>**Value**</u>**:**
  - *minimize technical risk* associated with deployment and operation of (often) one-of-a-kind complex systems and technologies
  - *optimize resource deployment and usage,* by informing the assignment of capital ($) and manpower (🕴) in a logically laid-out project schedule

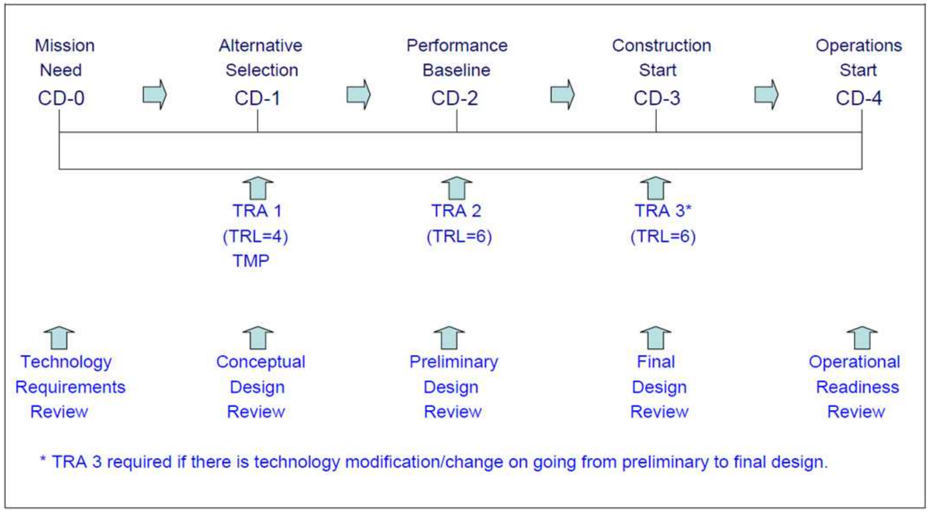
TRA Applicability vs. DOE Project Stage



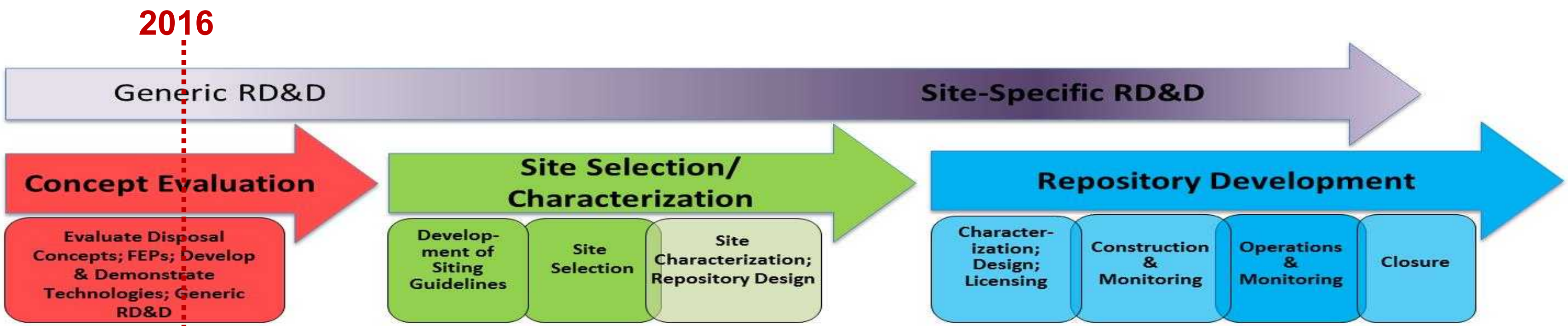
DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets, and*
DOE Guide 413.3-4A, *Technology Readiness Assessment Guide*:

- TRA 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
- 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)

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



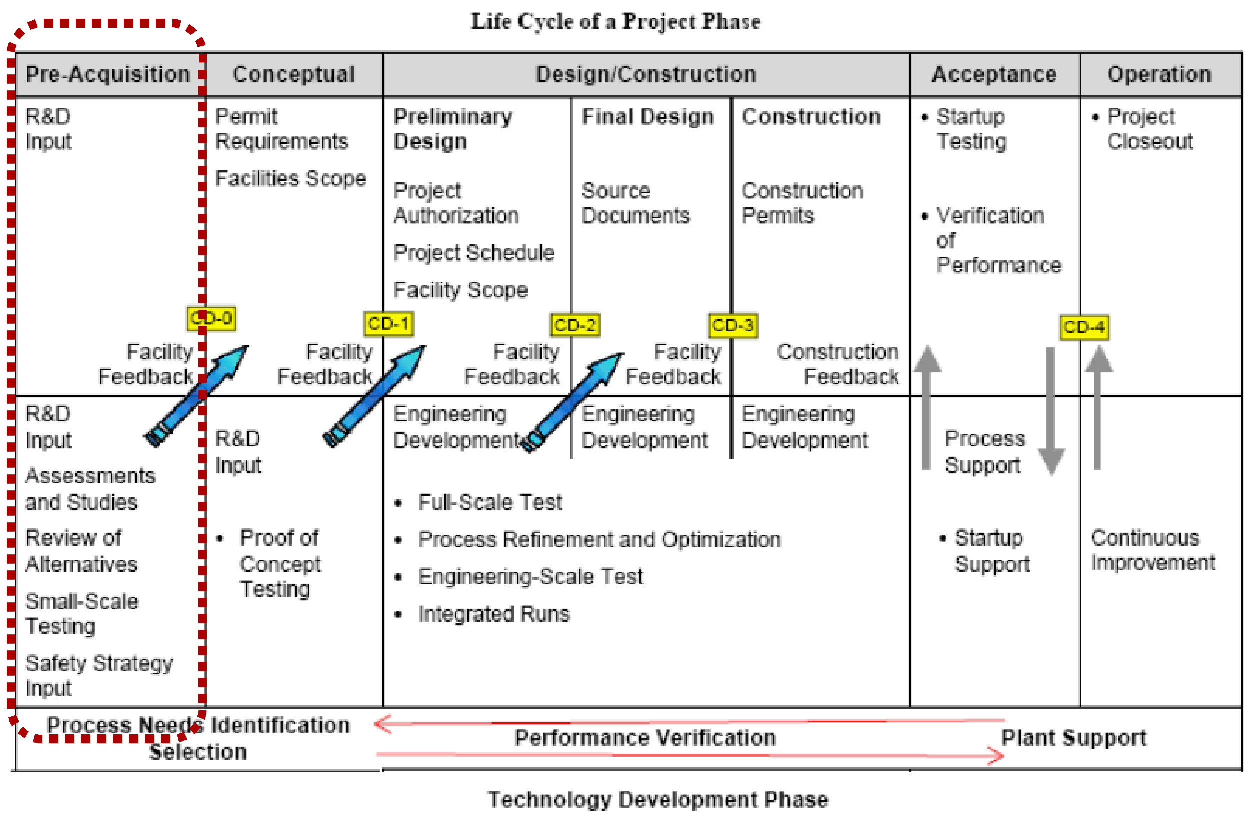
TRA Applicability vs. current U.S. Repository Stage



U.S. Program currently

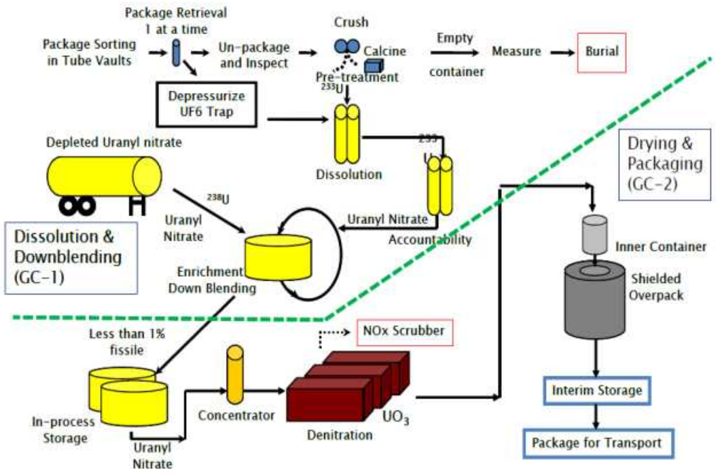
- Concept Evaluation stage
- "Generic" stage
- Before site-selection
- "Pre-acquisition"
- "Pre- CD-0"

● **TRA not needed at ≤ CD-0** ●



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

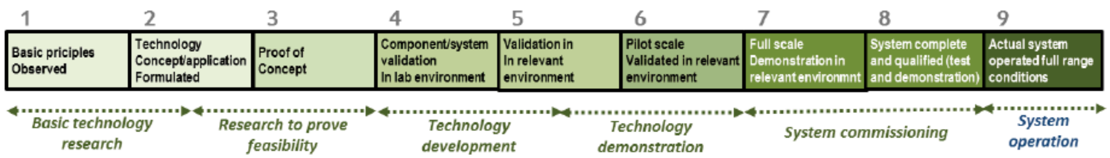
Major Steps of TRA Process



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.

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 (EARTO 2014):



   b. Assign a technology readiness level to the total (sub)system

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.

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 the TRL of a CTE (with consideration of the stage of the program): formal decision analysis (DA) may be used
   c. Execute the plan over a multi-year period

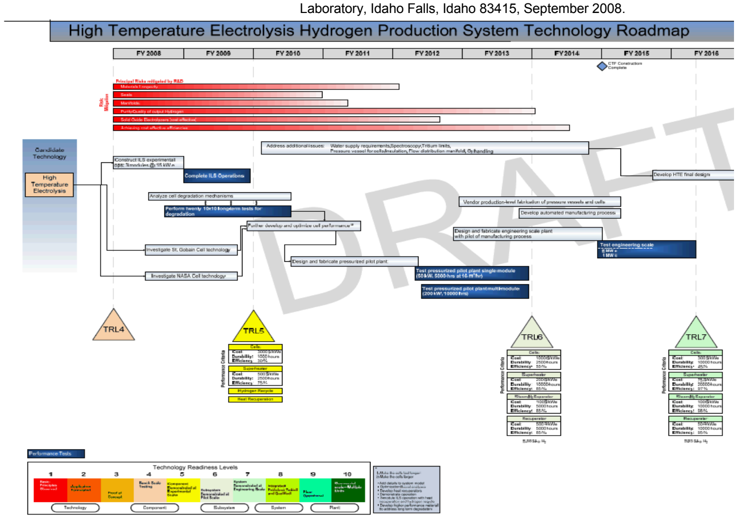


Figure B-2. HTE Hydrogen Production Technology Development Roadmap

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 probably more appropriate, vehicle to establish deployment readiness for a *complete* geologic repository system**
3. **However, the traditional TRA process is useful for key repository subsystems and components, with modifications based on the following:**
   - Inherent "temporal" division into (1) technologies and/or subsystems related to *pre-closure* activities and (2) those related to *post-closure* system evolution
   - Technologies and/or subsystems related to *post-closure* performance of geologic repositories have an inherent "spatial" or physical division into two key subsystems: engineered barriers and natural barriers.
     - Natural components and/or passive engineered components must be evaluated differently than the traditional TRA process
     - *"Knowledge readiness assessment" (KRA)* is a more applicable concept than "technology readiness assessment " for natural components

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

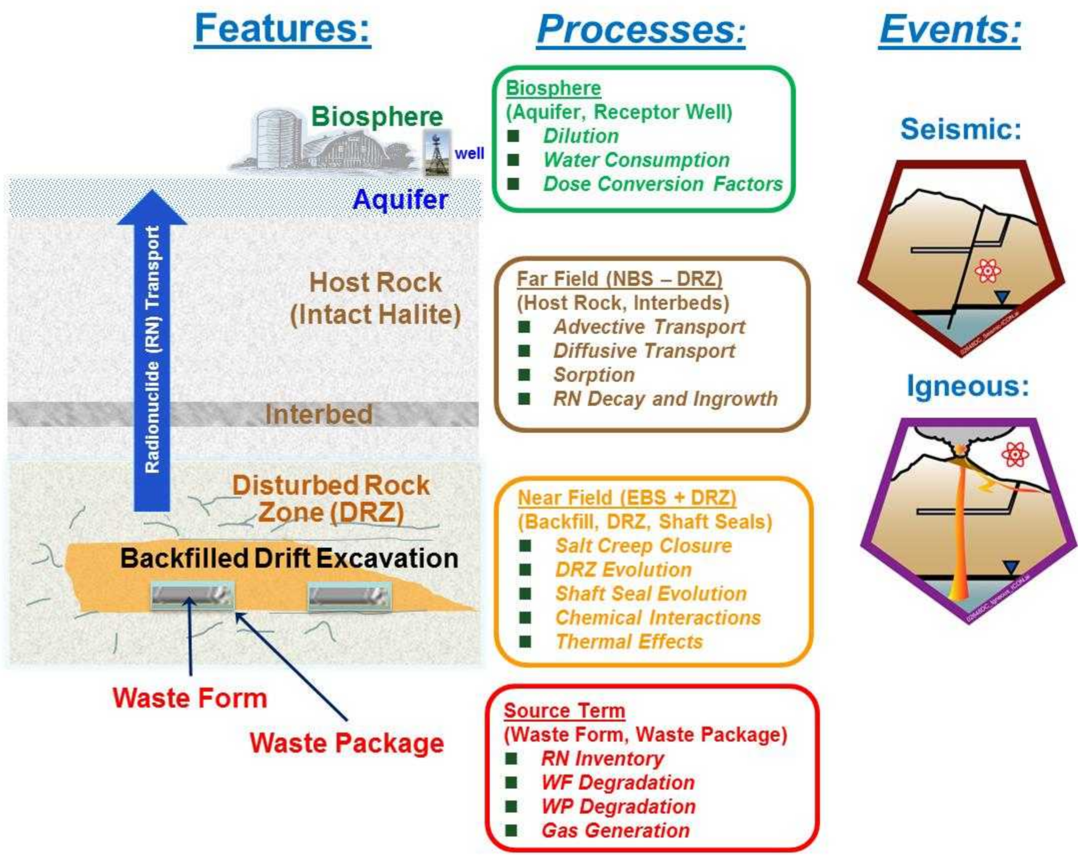
Boring of deposition holes

Buffer emplacement

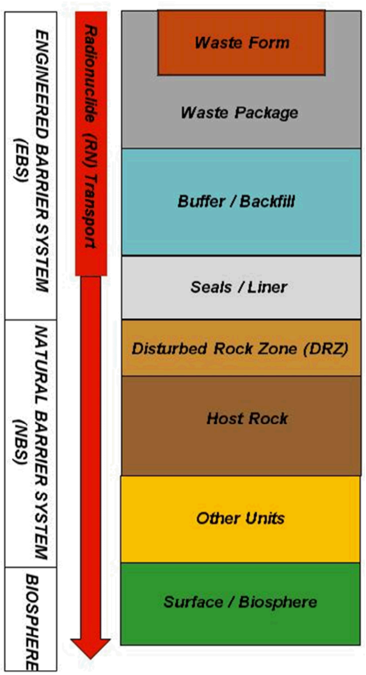
Kemppainen K. 2014. "Case Study: ONKALO Underground Rock Characterization Facility," in *Proceedings of the IAEA Workshop on Need for and Use of Generic and Site-Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments*, Oct. 7-9, 2014, Albuquerque, NM,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

Repository TRA Process – "Choose a Subsystem"

- Identify post-closure repository *subsystems* to be separately evaluated
- Use the Features, Events, and Processes (FEPs) approach to identify CTEs and subsystems:



Post-closure FEP Matrix Approach
(for subsystem and CTE identification)



FEP Matrix

Features / Components \ Characteristics, Processes, and Events	Characteristics	Processes: Mechanical and Thermal-M	Hydrological and Thermal-H	Chemical and Thermal-C	Biological and Thermal-B	Transport and Thermal-T	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities	Other	Events: Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities	Other
Glossary / Definitions	CP	TM	TH	TC	TB	TT	TR	RA	LG	CL	HP	OP	NC	EF	SM	IG	HE	OE
Waste and Engineered Features																		
(WF) Waste Form and Cladding	1	1	3															
(01) SNF and Cladding				1														
(02) Vitrified HLW				1														
(03) Other HLW				1														
(04) Metal Parts from Reprocessing																		
(WP) Waste Package and Internals	1																	
(01) SNF																		
(02) Vitrified HLW																		
(03) Other HLW																		
(04) Metal Parts																		
(BB) Buffer/Backfill	1	1																
(01) Waste Package Buffer		1																
(02) Drift/Tunnel Backfill																		
(MW) Mine Workings																		
(01) Drift/Tunnel/Room Supports																		
(02) Liners																		
(03) Open Excavations/Gaps																		
(SP) Seals/Plugs																		
(01) Drift/Tunnel Seals																		
(02) Shaft Seals																		
(03) Borehole Plugs																		
Geosphere Features																		
(HR) Host Rock		1																
(01) Disturbed Rock Zone (DRZ)																		
(02) Emplacement Unit(s)																		
(03) Other Host Rock Units																		
(OU) Other Geologic Units																		
(01) Overlying / Adjacent Units (including Caprock, Aquifers)																		
(02) Underlying Units																		
Surface Features																		
(BP) Biosphere																		
(01) Surface and Near-Surface Media and Materials																		
(02) Flora and Fauna																		
(03) Humans																		
(04) Food and Drinking Water																		
System Features																		
(RS) Repository System																		
(01) Assessment Basis																		
(02) Preclosure/Operational																		
(03) Other Global																		

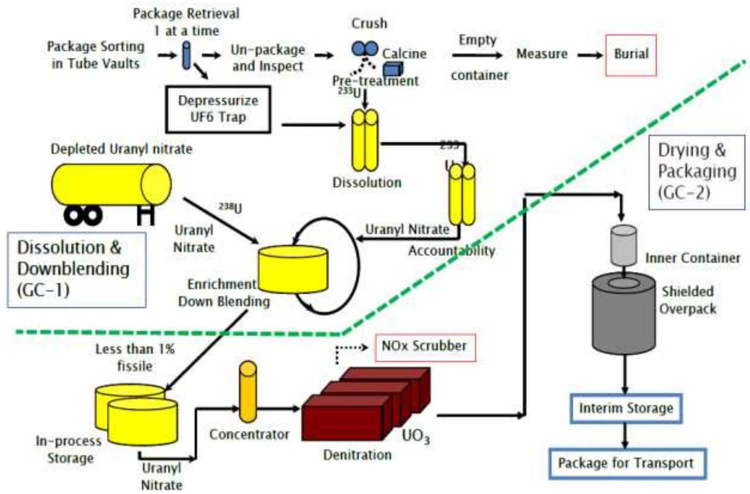
UFD FEP Number	Description	Associated Processes
2.0.00.00	2. DISPOSAL SYSTEM FACTORS	
2.1.00.00	1. WASTES AND ENGINEERED FEATURES	
2.1.03.00	1.03. WASTE CONTAINER	
2.1.03.02	**General Corrosion of Waste Packages**	- Dry-air oxidation in anoxic condition - Humid-air corrosion in anoxic condition - Aqueous phase corrosion in anoxic condition - Passive film formation and stability - Chemistry of brine contacting WP - Salt deliquescence
2.1.03.08	**Evolution of Flow Pathways in Waste Packages**	- Evolution of physical form of waste package degradation - Plugging of cracks in waste packages
2.1.08.00	1.08. HYDROLOGIC PROCESSES	
2.1.08.02	**Flow In and Through Waste Packages**	- Saturated / Unsaturated flow - Movement as thin films or droplets
2.1.08.03	**Flow in Backfill**	- Saturated / Unsaturated flow - Fracture / Matrix flow – fracture flow does not occur in crushed salt - Preferential flow pathway as crushed salt backfill undergoes consolidation
2.1.08.04	**Flow Through Seals**	- Saturated / Unsaturated flow - Fracture / Matrix flow - Gas transport (in UFD, Appendix A list) - Preferential flows in non-salt portion - Brine formation by salt deliquescence

Each <u>FEP matrix cell</u> contains all individual FEPs related to the "Process/Event" acting upon or within the "Feature"

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

Typical TRA Process – “Identify CTEs”

- ***Common*** **two-step CTE <u>identification</u> 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 (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.

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 Process – "Identify CTEs"

- **Two-step CTE <u>identification</u> procedure adapted to *post-closure* repository (engineered & natural) technologies:**

1. High-level (conservative) pass based on either:
    a. FEPs matrix and full FEPs list (100s of FEPs) (Freeze et al. 2014)

    or

    b. "Rolled-up" FEPs/issues, e.g., SNL/LANL 2013 Salt RD&D Workshop (Sevougian et al. 2013) or Dutch COVRA "topics" (Hart et al. 2015)

2. Detailed pass, based on <u>*importance*</u> of FEPs, RD&D "issue", or "topic" to post-closure performance, using either of two metrics:
    a. Importance to safety functions, such as isolation, containment, delayed/limited releases (see Sevougian and MacKinnon 2014)

    or

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

Repository TRA Process – “Identify CTEs” (cont.)

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

a. FEPs matrix and full FEPs list (Freeze et al. 2014):

UFD FEP Number	Description	Associated Processes
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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
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2.1.08.04	**Flow Through Seals**	- Saturated / Unsaturated flow - Fracture / Matrix flow
2.1.08.05	**Flow Through Liner / Rock Reinforcement Materials in EBS**	- Saturated / Unsaturated flow - Flow pathways along rock bolts - Fracture / Matrix flow
2.1.08.06	**Alteration and Evolution of EBS Flow Pathways**	- Drift collapse - Degradation/consolidation of EBS components - Plugging of flow pathways
⋮	⋮	⋮

$\sum$ *FEPs*

FEP Matrix

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(RS) Repository System																		
(01) Assessment Basis																		
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(03) Other Global																		

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.)

2. Detailed CTE <u>identification</u> pass, based on *importance* of FEPs, RD&D "issue", or "topic", using either of two metrics:

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

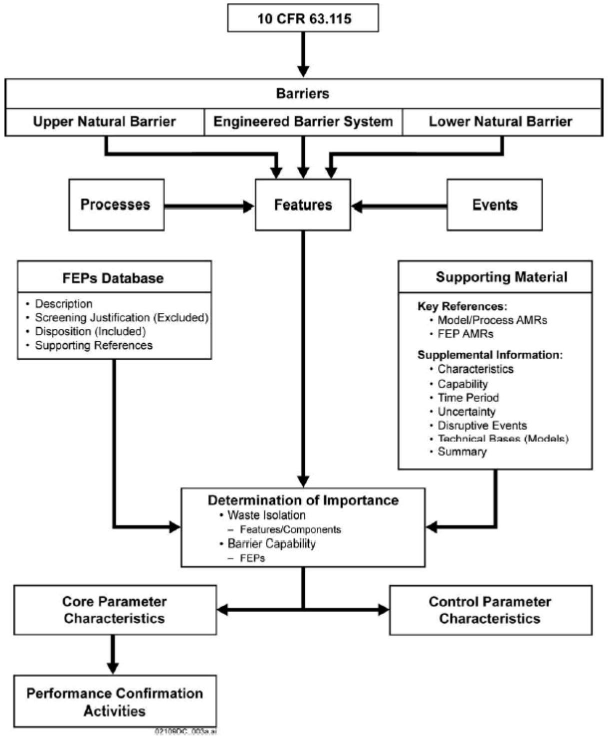
<u>or</u>

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

***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)



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.

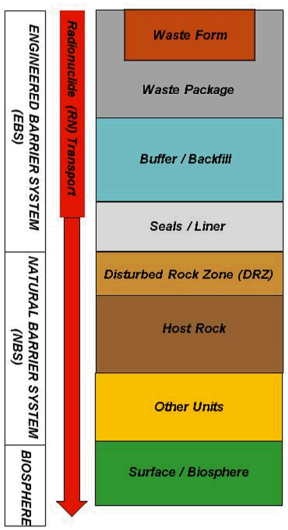
[a] A prototype is defined as a physical or virtual model used to evaluate the technical or manufacturing feasibility or utility of a particular technology or process, concept, end item, or system.
[b] If feasible, it is recommended to include tests on a limited range of real waste prior to achieving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

2. Detailed CTE evaluation pass depends on the nature of the CTE:

- Post-closure EBS* vs. post-closure NBS† (with consideration of their interface, the DRZ‡)
- For post-closure passive EBS CTEs, the standard TRA method could be used
- For post-closure DRZ (interface) CTEs and natural barrier system CTEs, use a nine-level *Knowledge Readiness Scale (KRL) scale* (see next slide)



Major Post-closure Subsystems (and associated CTEs)	Maturity Evaluation Method
EBS (and its components)	TRLs
DRZ	KRLs
NBS (and its components)	KRLs

*EBS = Engineered Barrier System
‡DRZ = Disturbed Rock Zone
†NBS = Natural Barrier System

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

2. Detailed CTE evaluation pass for natural system CTEs:

- Use Knowledge Readiness Levels (KRLs)*, since it is knowledge that must be matured (gathered)—perhaps similar to Scientific Readiness Levels†
- Probably “overkill” to use detailed, 2nd pass, multi-question tables for each KRL

Table 1. Possible Nine-Level Knowledge Readiness Scale

Knowledge Readiness Level	KRL Definition	Description
KRL 9	Actual system operated over the full range of expected conditions	May not be feasible/applicable for a major post-closure geologic repository CTE or subsystem.
KRL 8	Actual system completed and qualified through test and demonstration	May not be feasible/applicable for a major post-closure geologic repository CTE or subsystem.
KRL 7	Full-scale, similar system demonstrated in a relevant environment	Not completely defined as of yet. Major difference between TRL 7 and TRL 6 is in the scale of the system and the operating environment, in the sense that a TRL 7 system should be demonstrated “in the field,” i.e., *in situ*.
KRL 6	Prototypical system operated	Entails a major step in the level of integration and the fidelity of the technology, or process knowledge, demonstration. A representative prototype system, beyond just a series of discrete component-level trials, has been tested in a relevant environment at a relatively large (“engineering”) scale. A full suite of uncertainty and sensitivity analyses would be expected at this level. The prototype system may be either an *in situ* test in a URL or a full computer simulation that has been informed by site-specific data and testing.
KRL 5	Component and subsystem validation in a relevant environment	Requires the validation of a CTE and its sub-system(s) in a relevant environment (i.e., one that represents critical features of the expected operational environment). This means that the components must be integrated to a sufficient degree so that the system or sub-system can be tested or simulated realistically. Initial, but formal, uncertainty and sensitivity analyses are appropriate at this point, to develop understanding of how to progress to KRL 6. Computer models of the subsystem are important in demonstrating understanding of the concept.
KRL 4	CTE and/or subsystem validation	The basic components or processes involved in a technology must be integrated, or investigated in a coupled manner, to establish that the pieces will work together. Uncertainty characterization should be conducted, or a plan formulated, at this point. Computer simulations of the concept are conducted but may be conducted with generic data input.
KRL 3	Analytical and/or experimental proof-of-concept investigations	Active R&D is initiated. This includes both analytical studies and experiments, if appropriate, plus process-level computer simulations to validate predictions and to gather knowledge regarding the validity of the concept.
KRL 2	Technology/knowledge concept and application formulated	Practical applications of new physical principles or new scientific ideas are identified or invented. This step represents the creation of a new concept 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 level, basic scientific research has resulted in the observation and reporting of basic principles that can lead to a novel technology or novel application of the principles.

* “KRL” first coined by Chiaramonte and Joshi (2004), but for engineered systems and only at five levels.

† *Scientific Readiness Levels* defined in detail in ESA (European Space Agency) 2015, *Scientific Readiness Levels (SRL) Handbook*, but again this is primarily for engineered systems (satellite development or other space applications)

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

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2. ***Alternative* for detailed CTE evaluation pass:**
   – As a simpler alternative to KRLs, one could possibly use a "state-of-the-art" knowledge scale—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 Process – "Evaluate System TRL"

- **Determine a (sub)system TRL or system readiness level (SRL)**
- **Should consider interactions among CTEs and subsystems or Integration Readiness Level (IRL)**

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	IRL Definition	SRL Definition	SRL Value
1	Basic principles observed and reported.	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.	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.	There is compatibility between technologies to orderly and efficiently integrate and interact.		
4	Component and/or breadboard validation in 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.	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.	The integrating technologies can accept, translate, and structure information for its intended application.		
7	System prototype demonstration in relevant environment.	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.	Actual integration completed and mission qualified through test and demonstration in the system environment.		
9	Actual system proven through successful mission operations.	Integration is mission proven through successful mission operations.	Production	0.80 to 0.89
			Operations and Support	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"

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

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

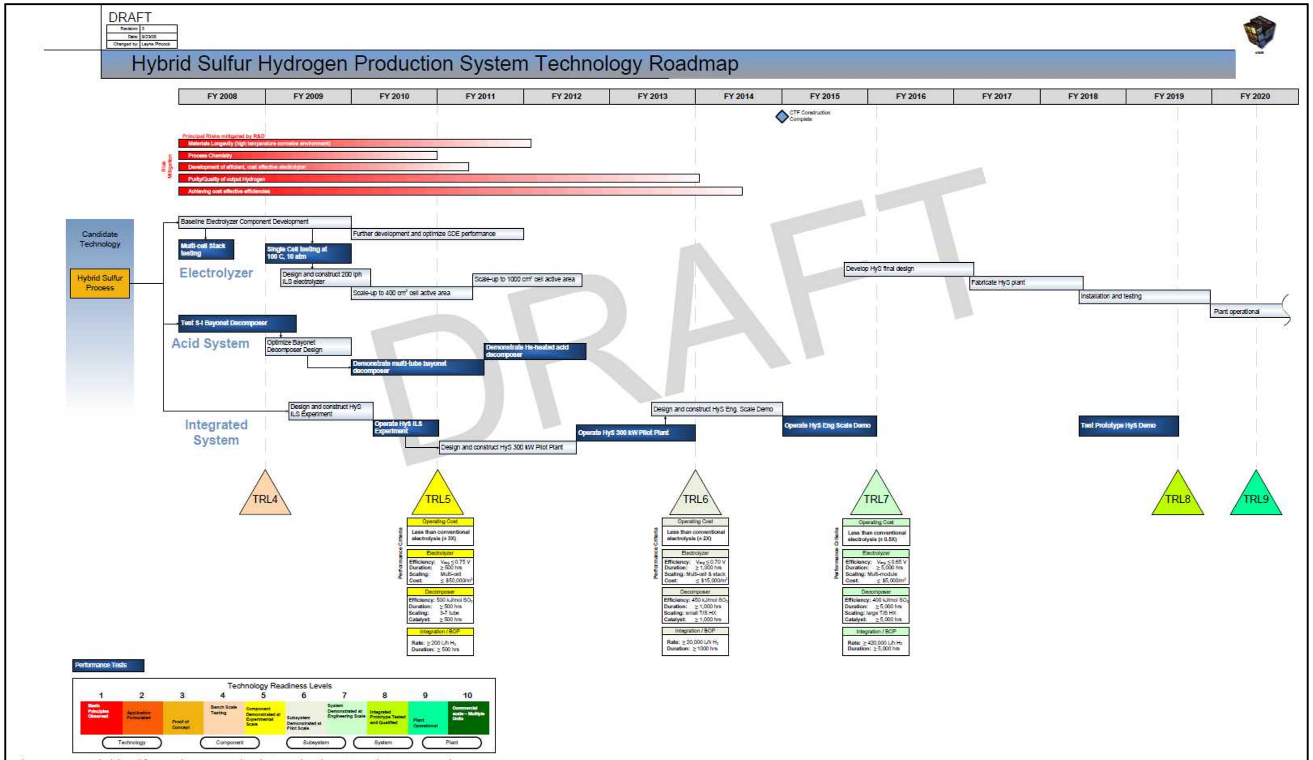
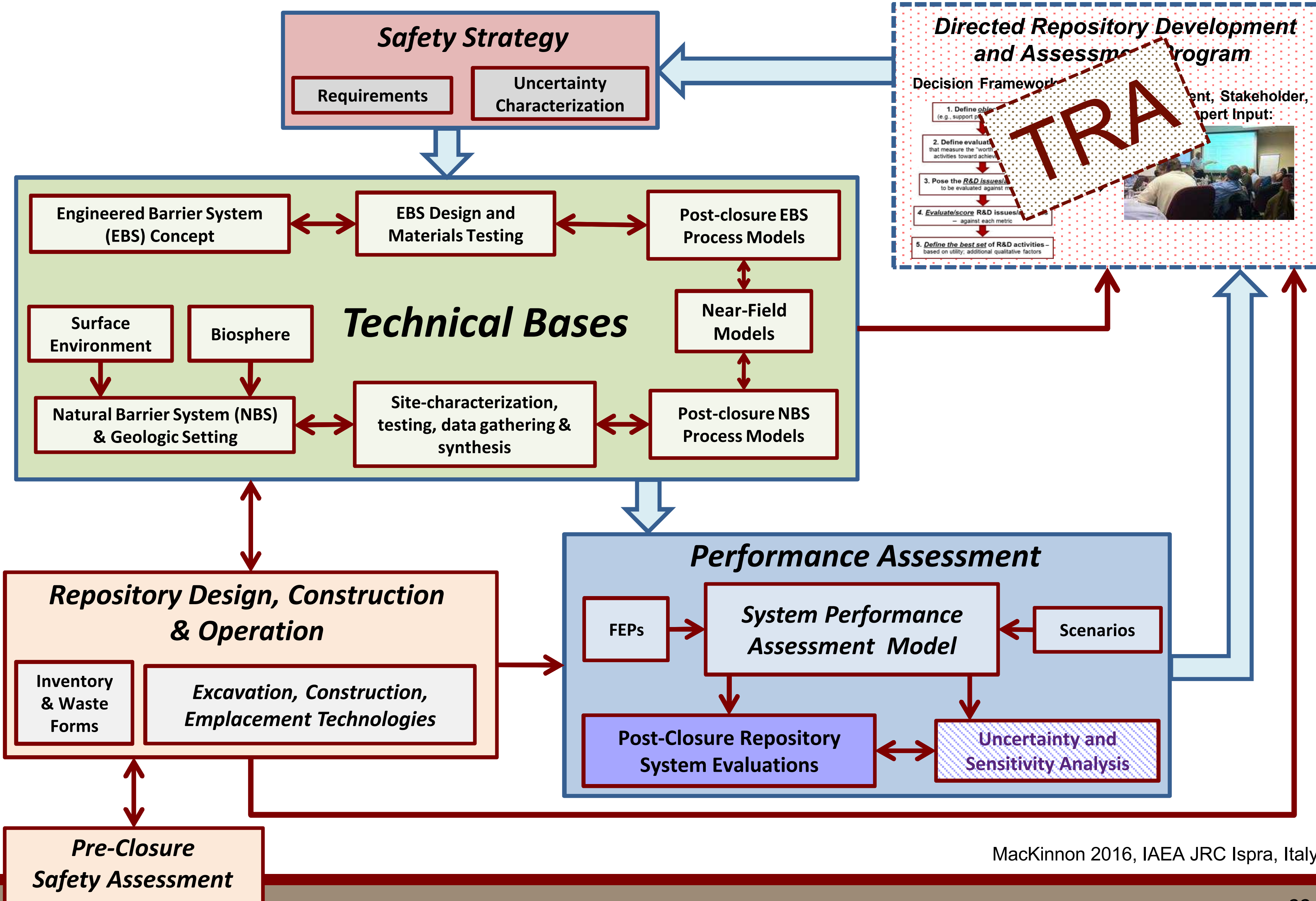


Figure B-3. Hybrid Sulfur Hydrogen Production Technology Development Roadmap

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 TRA process – “Maturation Plan”



MacKinnon 2016, IAEA JRC Ispra, Italy

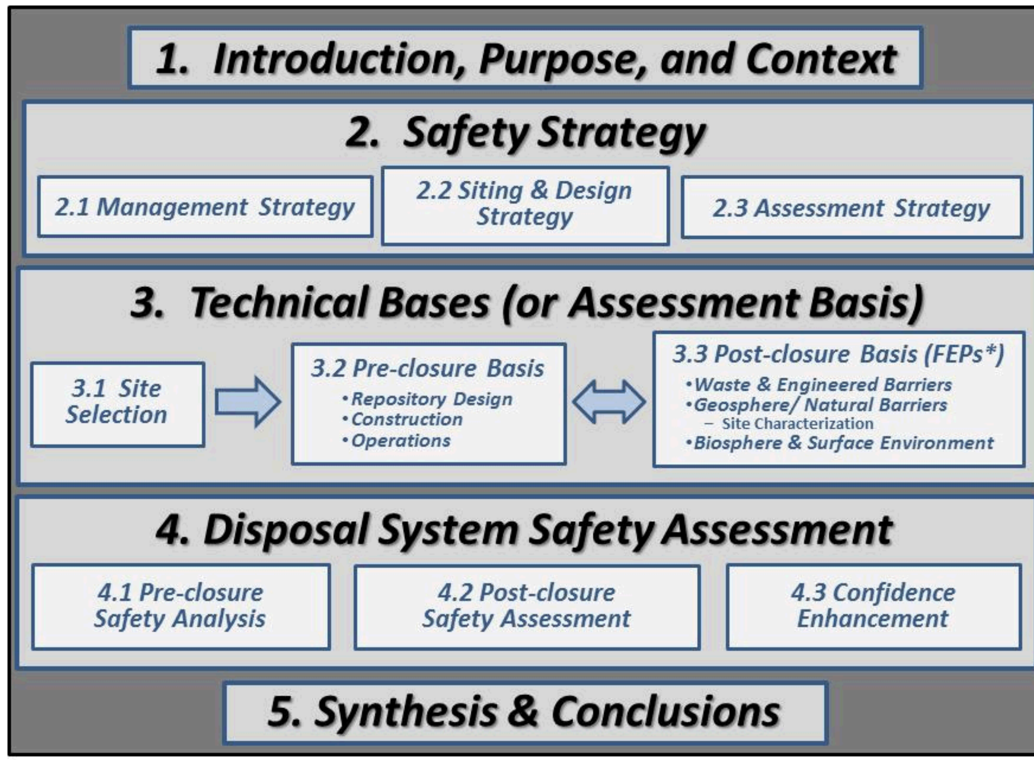
Some Limitations of TRA Process

(from Fernandez 2010)

- **TRL scale is non-linear, especially when considering cost and schedule**
- **Does not address uncertainty (and difficulty) in technology development**
- **Provides a subjective assessment of maturity**
- **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**

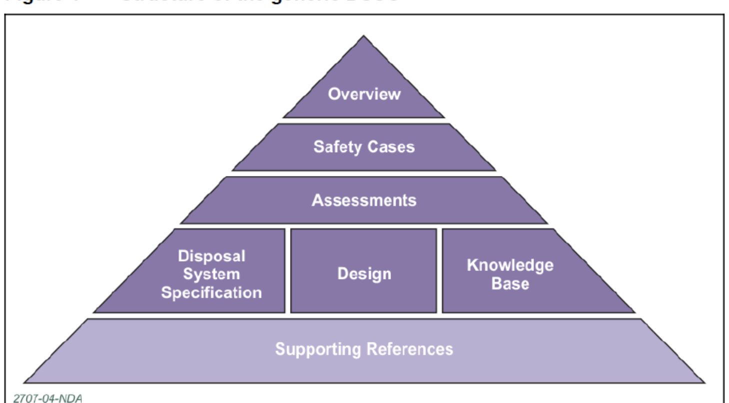
Safety Case for Readiness of Total Geologic System

- **The *Safety Case(s)* or *Licensing Case* is the recognized, and probably more appropriate, vehicle to establish total system readiness at different stages, especially at closure, because of:**
  - Inherent (and not fully reducible) uncertainties related to characterization of the initial state and evolution of the natural and engineered barriers
  - Length of the performance period (one million years or greater)
  - Interaction of engineered technologies with natural system



*FEP = Feature, Event, or Process

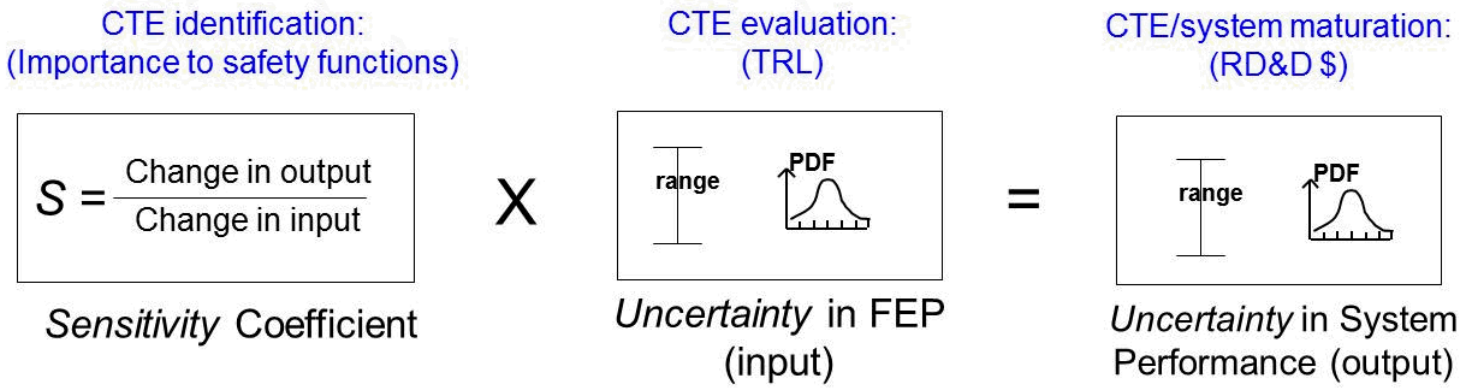
Figure 1 Structure of the generic DSSC



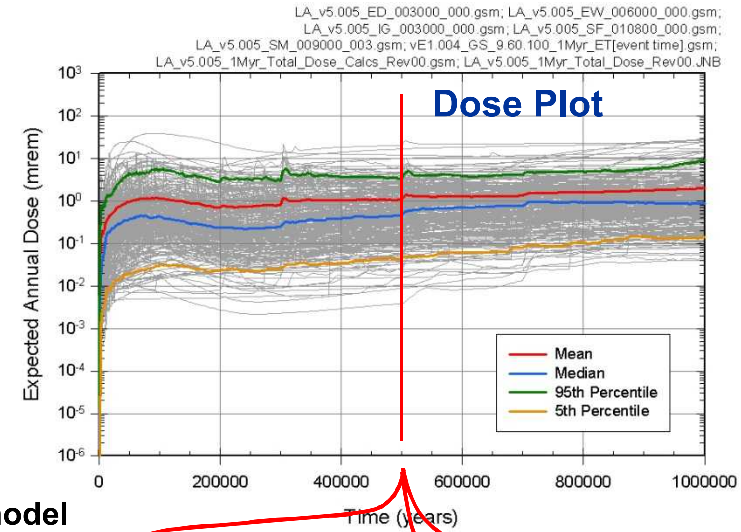
RWM (Radioactive Waste Management LTD) 2016. *Geological Disposal: Generic Environmental Safety Case,* DSSC/203/01, in preparation, Harwell Oxford, Didcot OX11 0RH

Uncertainty Considerations

- ***Identification*** **of CTEs is mostly based on how the CTE might influence system performance (or safety functions):**
  - How *sensitive* is the system 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:**



Uncertainty in YM Total Expected Dose
(Sum over All Scenario Classes and RNs)



IGRATE – Frequency of igneous events

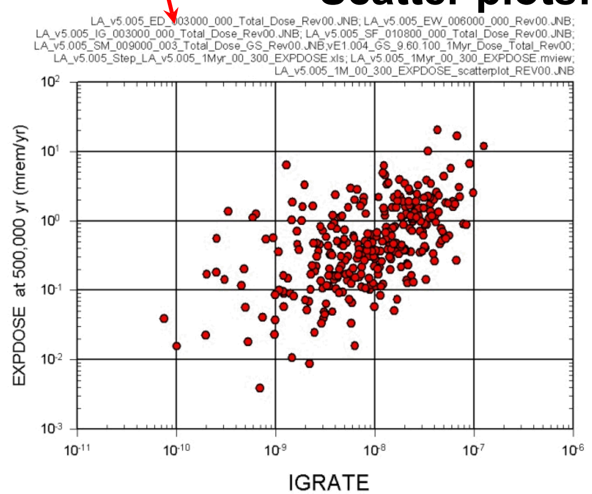
WDGCA22 – Temperature dependence in A22 corrosion rate

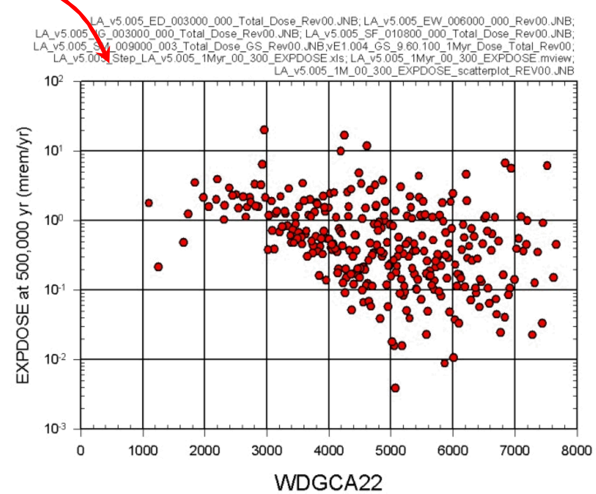
SZGWSPDM – Uncertainty factor for groundwater specific discharge rate

Linear regression model
Output = f (inputs)

EXPDOSE: 500,000 Years		
Variable	R^2	SRRC
IGRATE	0.29	0.54
WDGCA22	0.46	−0.38
SZGWSPDM	0.53	0.24
EP1LOWNU	0.56	0.19
MICNP237	0.59	0.16
EP1L0WPU	0.61	0.17
SZCONCOL	0.64	0.15
SZFISPVO	0.66	0.15
INFIL	0.67	0.11
GOESITED	0.68	−0.10
SZKDCSVO	0.69	−0.10
HFOSITED	0.69	−0.09
SZDIFCVO	0.70	−0.09

Scatter plots:





Summary: Adaptation of the Usual TRA Process to Geologic Systems

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1. For post-closure CTE *identification*…

- For first-pass CTE identification, the traditional FEPs process has significant value and precedence
  - Individual FEPs and/or possibly "rolled-up" FEPs/issues or topics
- For second-pass CTE identification, the use of safety functions or barrier functions (or barrier capabilities) is appropriate

2. For CTE and/or subsystem *evaluation*…

- For post-closure engineered technologies (as well as pre-closure technologies) use traditional high-level (first-step) TRL scale, followed by detailed (second-step) TRL question tables
- For post-closure natural system technologies, use a single-step, nine-level KRL scale

3. For CTE and subsystem *maturation*….

- Use a variety of RD&D prioritization methods (e.g., formal DA, if fiscal/personnel constraints are present), including information from safety assessments
- Re-evaluate according to major program stages (licensing, construction, operations)

Thank you for your attention!!

Backup Slides

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Some Aspects of Uncertainty Characterization

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- **Nature of uncertainty: aleatory (inherent randomness) vs. epistemic (lack of knowledge)**
- **Sources of model and prediction uncertainty, e.g.:**
  - Parameter (input) uncertainty (epistemic)
  - Model structural uncertainty (epistemic—lack of knowledge of true physics)
  - Experiment or data measurement uncertainty (aleatory or variability)
  - Numerical approximation uncertainties, arising from spatial-temporal discretization error, statistical sampling error, iterative convergence error
- **How to upscale data (from lab to field; from core data to numerical grid blocks)—how to handle associated variance reduction**