

Safety Case for Geologic Disposal of Radioactive Waste

PRESENTED BY

S. David Sevougian, Peter Swift

**NEFC Knowledge Management Deep Dive
Sandia National Laboratories
Albuquerque, NM
January 29, 2020**



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Outline – Geologic Disposal Safety Case



■ Background:

- what is “safe”
- Geologic disposal safety case, the nuclear fuel cycle, and status of geologic disposal worldwide

■ Components of a Safety Case

■ Detailed discussion of Features, Events, and Processes Analysis

■ Information Flow Among Components of a Safety Case: Building Confidence

■ Phased repository development: Iteration of safety case and R&D activities

■ Technology Readiness Assessment and the Safety Case

Who Defines Safe and Safety?



■ Mission statement of the U.S. Environmental Protection Agency

The mission of EPA is to protect human health and the environment.
(<http://www2.epa.gov/aboutepa/our-mission-and-what-we-do>)

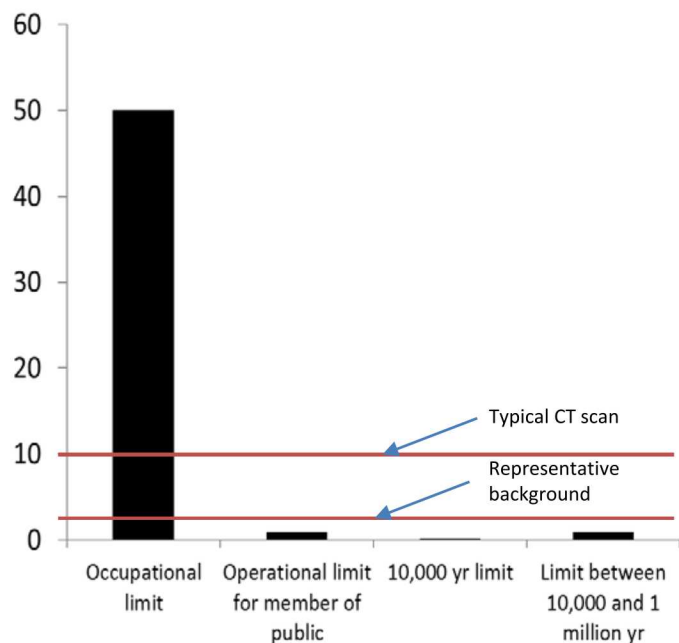
■ Mission statement of the U.S. Nuclear Regulatory Commission

The NRC licenses and regulates the Nation's civilian use of radioactive materials to protect public health and safety, promote the common defense and security, and protect the environment.
(<http://www.nrc.gov/about-nrc.html>)

How is Safety Defined?



NRC's Radiation Dose Limits for Yucca Mountain (mSv/yr)



■ Annual dose limits for operating nuclear facilities (NRC's 10 CFR part 20)

- 20.1201 Occupational dose limits for adults.
 - (a) *The licensee shall control the occupational dose to individual adults, except for planned special exposures under 20.1206, to the following dose limits.*
 - (1) *An annual limit, which is the more limiting of--*
 - The total effective dose equivalent being equal to 5 rems (50 mSv) ... [additional requirements follow]
- 20.1301 Dose limits for individual members of the public.
 - (a) *Each licensee shall conduct operations so that -*
 - *The total effective dose equivalent to individual members of the public from the licensed operation does not exceed 0.1 rem (1 mSv) in a year, exclusive of the dose contributions from background radiation*

■ Annual dose limits for long-term repository performance (NRC's 10 CFR part 63, derived from EPA's 40 CFR part 197; specific to Yucca Mountain)

- 63.311 Individual protection standard after permanent closure.
 - (a) *DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than the following annual dose from releases from the undisturbed Yucca Mountain disposal system:*
 - (1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and
 - (2) 1.0 mSv (100 mrem) after 10,000 years, but within the period of geologic stability.

Who Makes the Determination of Safety?



- **The Nuclear Waste Policy Act of 1982 (Section 121) assigns licensing responsibility for repositories containing spent nuclear fuel and high-level radioactive waste to the NRC**

“the Commission, pursuant to authority under other provisions of law, shall, by rule, promulgate technical requirements and criteria that it will apply, under [applicable laws] in approving or disapproving—

- (i) applications for authorization to construct repositories;*
- (ii) applications for licenses to receive and possess spent nuclear fuel and high-level radioactive waste in such repositories; and*
- (iii) applications for authorization for closure and decommissioning of such repositories.”*

What is the Basis for Evaluating Safety?



- 10 CFR 63.311: “DOE must demonstrate, **using performance assessment**, that there is a reasonable expectation that [estimated doses are below the stated limits]...”
- 10 CFR 63.2: “*Performance assessment* means **an analysis that:**
 - (1) Identifies the features, events, processes (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring;
 - (2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and
 - (3) **Estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence.**
- 10 CFR 63.303: “Compliance is based on the arithmetic mean of the projected doses...”

(emphasis added)

Safety Case – Definition & Roles



- **“The safety case is the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility.” (IAEA 2012)**
 - Quantitative information – e.g., safety assessment or performance assessment (PA)
 - Qualitative information – supporting evidence that builds confidence (e.g., peer review, corroborating lines of evidence, natural analogues)
- **Major roles:**
 - Management: a structured framework to assist in prioritizing the technical work (R&D) to reduce uncertainties and enhance confidence
 - Communication: transparently explain current safety understanding to stakeholders
- **Vis-à-vis a “license application” – see later slides for comparison**

Components of the Safety Case (international usage)



from IAEA 2012, No. SSG-23

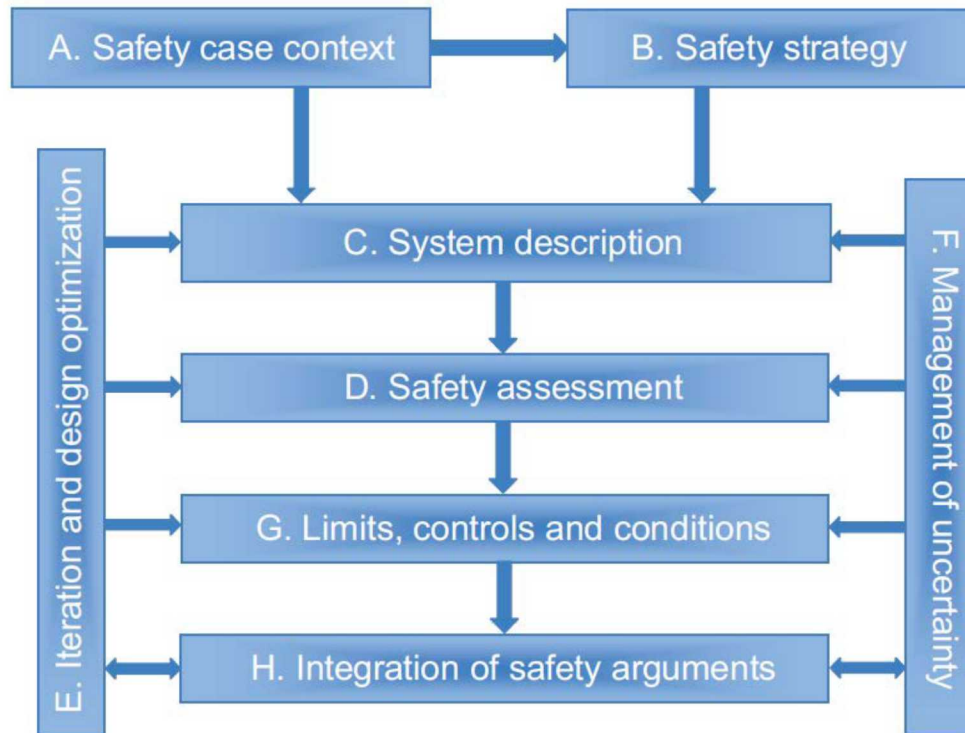
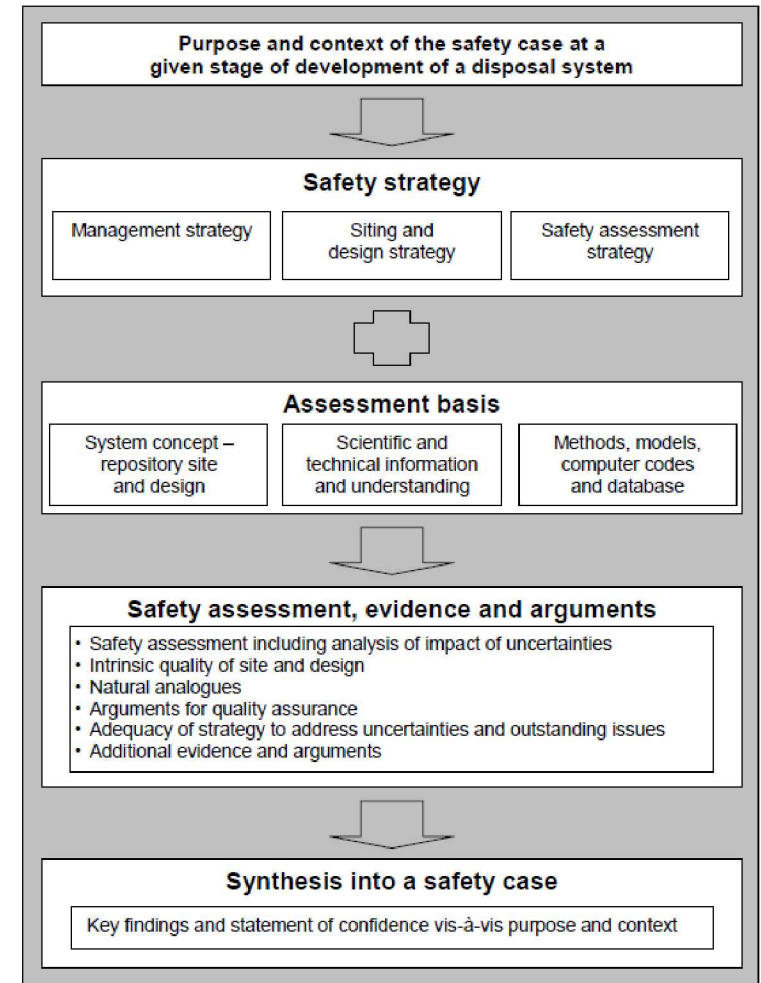


FIG 2. Components of the safety case.

from NEA 2013a, No. 78121

Figure 2.1: An overview of the relationship between the different elements of a safety case

Modified from Figure 1 of (NEA, 2004a)



Geologic Safety Case and the Nuclear Fuel Cycle

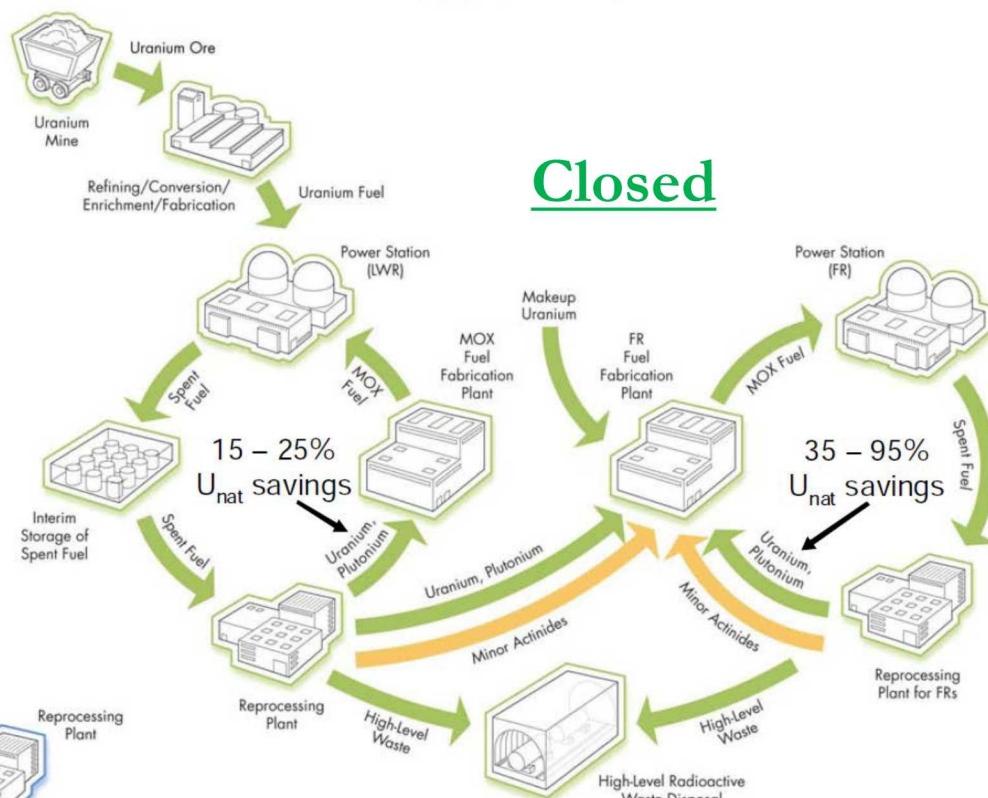


- The Geologic Disposal Safety Case demonstrates safety for the end of both open and closed nuclear fuel cycles, and includes:

- Transportation of the waste
- Packaging of the waste
- Construction of the waste repository
- Operation of the waste repository
- Long-term period after closure of the repository

Closed Fuel Cycles {
■ Partially Closed Fuel Cycle
■ Fully Closed Fuel Cycle

Closed



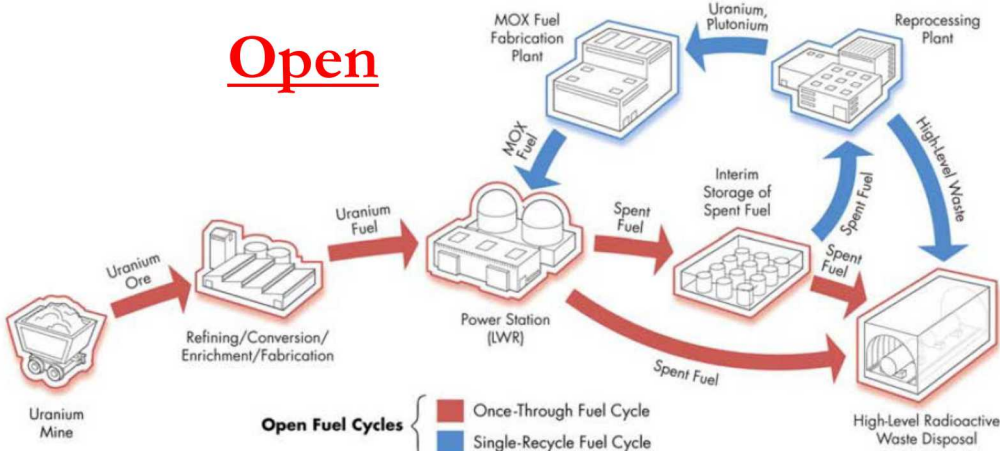
Repository

Repository

figures from EPRI (2010)

Open

Open Fuel Cycles {
■ Once-Through Fuel Cycle
■ Single-Recycle Fuel Cycle



Current SNF Disposition for the Once-Through Cycle in the U.S.: The Reality

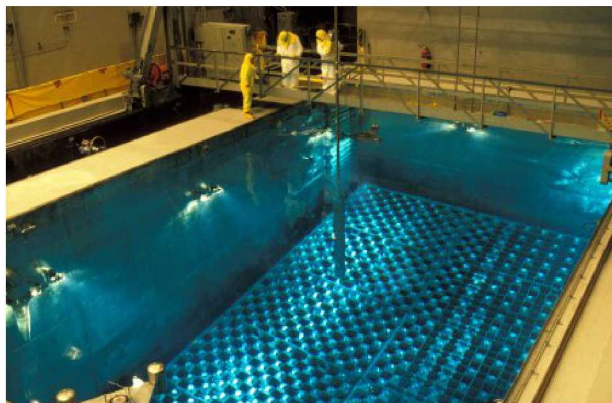


Temporary Storage at 75 commercial reactor sites in 33 States

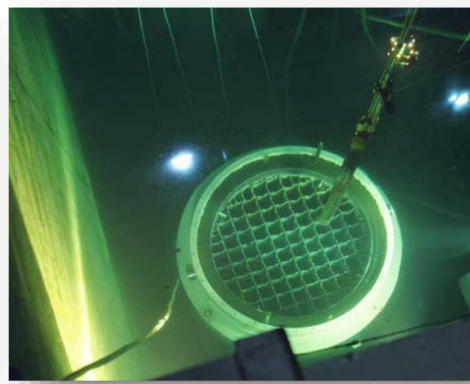


Map of the US commercial SNF storage from Bonano et al. 2018

- Pool storage provides cooling and shielding of radiation
 - Primary risks for spent fuel pools are associated with loss of the cooling and shielding water
- US pools have reached capacity limits and utilities have implemented dry storage
- Some facilities have shutdown and all that remains is “stranded” fuel at an independent spent fuel storage installation (ISFSI):



January 29, 2020



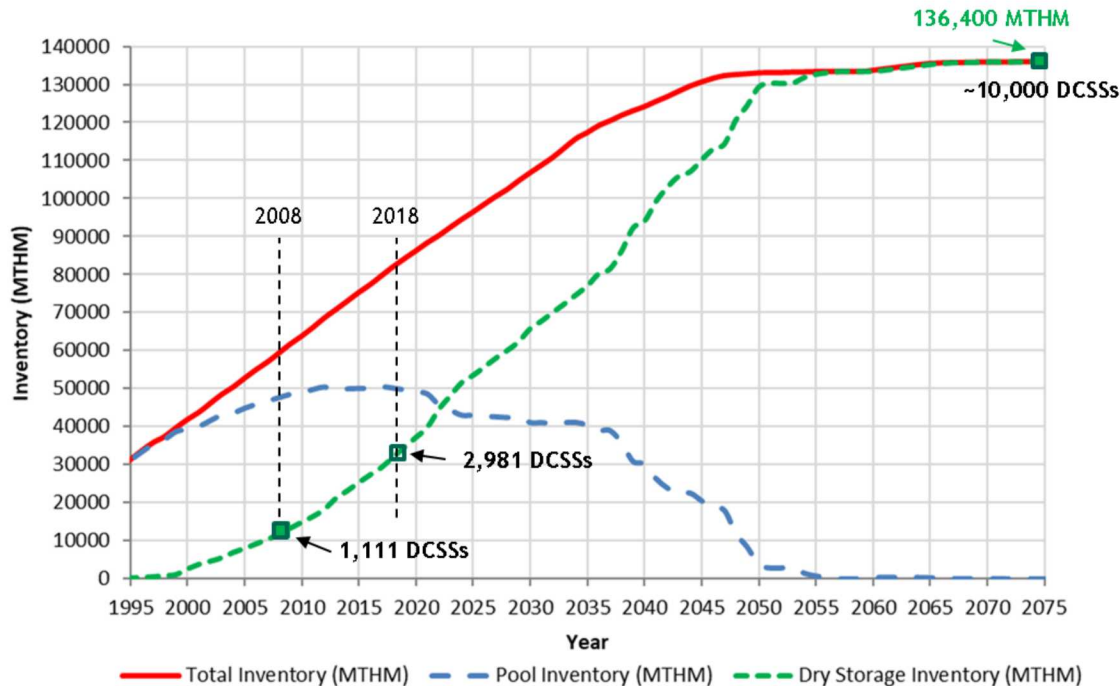
Safety Case NEFC Knowledge Management Deep Dive



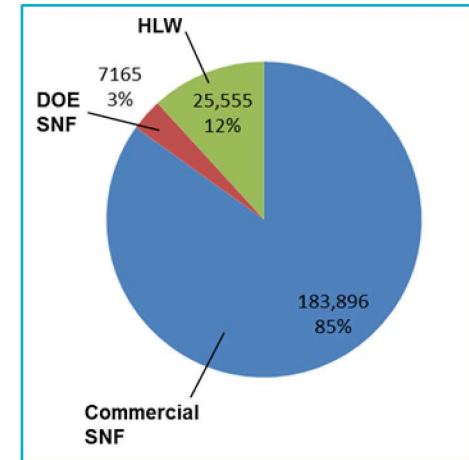
US Projections of Spent Nuclear Fuel (SNF) and High-Level Radioactive Waste (HLW)



Projections assumes full license renewals and no new reactor construction or disposal (updated from Bonano et al., 2018)



Projected Volumes of SNF and HLW in 2048



Volumes shown in m^3 assuming constant rate of nuclear power generation and packaging of future commercial SNF in existing designs of dual-purpose canisters.

- Approx. 80,000 MTHM (metric tons heavy metal) of commercial SNF in storage in the US as of Dec. 2017
- 30,000 MTHM in dry storage at reactor sites, in approximately 2,981 cask/canister systems as of Dec. 2018
 - Balance in pools, mainly at reactors
- Approx. 2200 MTHM of SNF generated nationwide each year
 - Approximately 160 new dry storage canisters are loaded each year in the US

Could the U.S. Re-Process Existing Spent Nuclear Fuel and Reuse It (e.g., in a closed cycle)?



- The US has no commercial reprocessing capability
 - Operations at West Valley, New York, ceased in 1972
 - Savannah River Site, South Carolina retains the capability to reprocess for defense purposes
- The US has more than 80,000 metric tons of spent fuel and generates an additional 2,200 metric tons each year
- The largest reprocessing facility in the world (Sellafield, UK) had a nominal capacity of 1,200 metric tons per year
 - La Hague in France has a capacity of at least 1100 metric tons per year
- The US would need at least two of the world's largest reprocessing facilities just to keep up with current discharges

To date there has not been a viable economic model in which existing spent fuel gets reprocessed in the U.S.

OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2012/308
FCRD-FCT-2012-000232

Categorization of Used Nuclear Fuel
Inventory in Support of a Comprehensive
National Nuclear Fuel Cycle Strategy

December 2012

Prepared by
John C. Wagner, ORNL
Joshua L. Peterson, ORNL
Don E. Mueller, ORNL
Jess C. Gehin, ORNL
Andrew Worrall, ORNL
Temitope Taiwo, ANL
Mark Nutt, ANL
Mark A. Williamson, ANL
Mike Todosow, BNL
Roald Wigeland, INL
William G. Halsey, LLNL
Ronald P. Omberg, PNNL
Peter N. Swift, SNL
Joe T. Carter, SRNL



*“98% of the total current U.S.
inventory by mass can proceed to
permanent disposal without the need
to ensure retrievability for reuse or
research”*

*(Wagner et al., 2012)**

** This assessment does not assume any decision about future fuel cycle options or preclude any potential options, including those with potential recycling of commercial UNF, since the ~2000 MTHM that is generated annually could provide the feedstock needed for deployment of alternative fuel cycles....*



La Hague, France

Bottom line



- **Geologic disposal will be necessary in the U.S., unless....**
 - Permanent storage is adopted (e.g., permanent monitored retrievable storage)
 - But, storage (underground or above ground) will still require a safety case / licensing process

Deep Geological Disposal for SNF and HLW

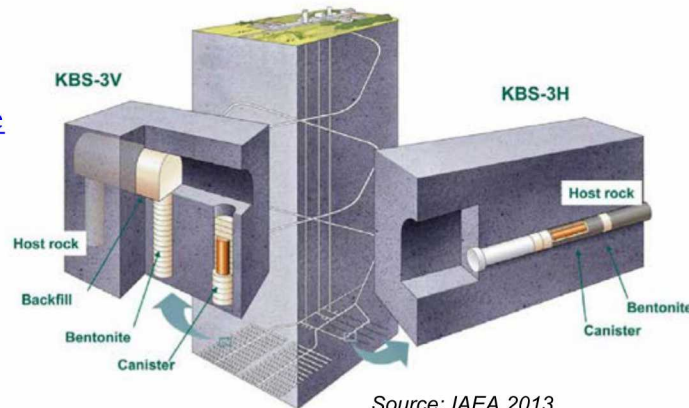


“There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF).”

“Geological disposal remains the only long-term solution available.”

National Research Council, 2001

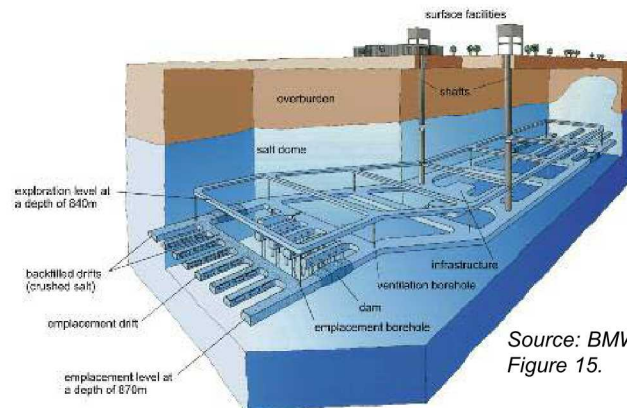
Crystalline rock:
Sweden,
Finland



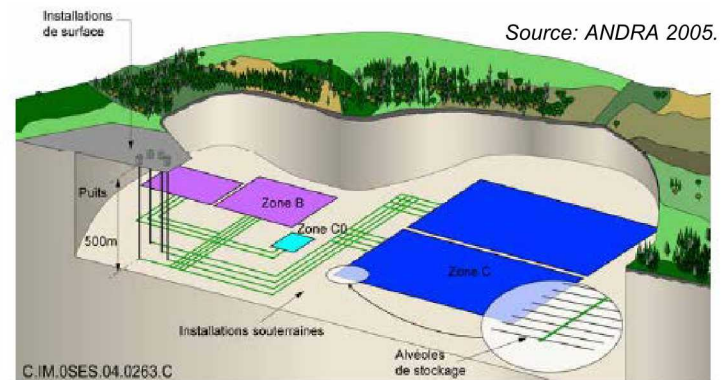
Source: IAEA 2013

Deep geologic disposal
(primarily, mined disposal) has
been planned since the 1950s

Salt:
Germany



Source: BMWi 2008,
Figure 15.



Argillite:
France

Status of Deep Geologic Disposal Programs

World-Wide



Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015. Operations application to be submitted in 2020
Sweden	Granite	License application submitted 2011
France	Argillite	Disposal operations planned for 2025
Canada	Granite, sedimentary rock	Candidate sites being identified
China	Granite	Repository proposed in 2050
Russia	Granite, gneiss	Licensing planned for 2029
Germany	Salt, other	Uncertain
USA	Salt (transuranic waste at the Waste Isolation Pilot Plant) Volcanic Tuff (Yucca Mountain)	WIPP: operating Yucca Mountain: suspended

Others: Belgium (clay), Korea (granite), Japan (sedimentary rock, granite), UK (uncertain), Spain (uncertain), Switzerland (clay), Czech Republic (granitic rock), all nations with nuclear power.

Source: Information from Faybishenko et al., 2016

Socio-Political Issues “Rule” SNF Management and Final Disposition Regardless of the Fuel Cycle



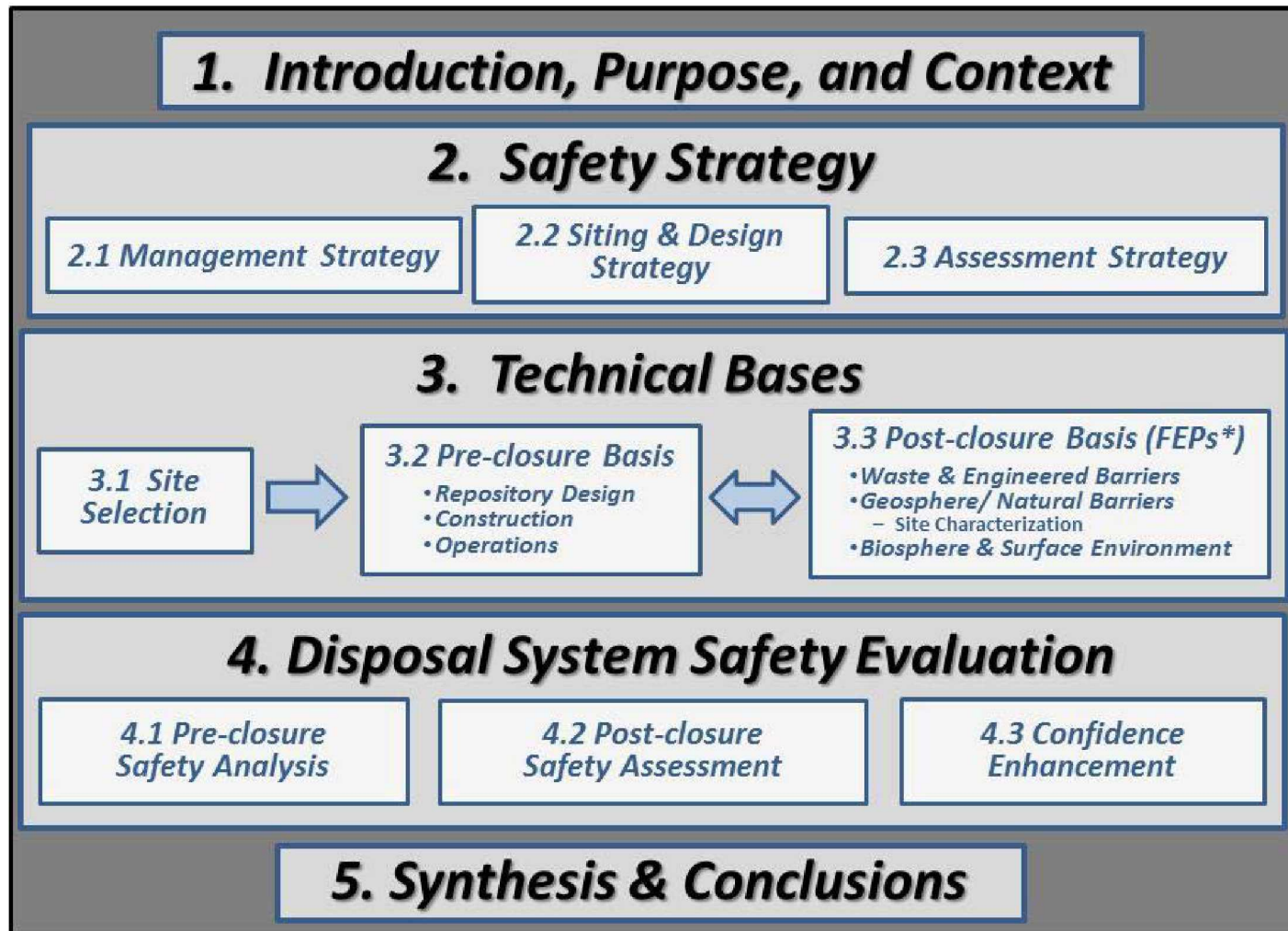
Example: Brief History of the U.S. SNF Disposal Program*

- **1982:** Nuclear Waste Policy Act (NWPA) defines Federal responsibility for permanent disposal of spent fuel and high-level waste, and leaves responsibility for storage at reactor sites with private sector
- **1987:** Congress amends NWPA to focus solely on disposal at Yucca Mountain, Nevada
- **2002:** Congress overrides Nevada’s veto of the site and directs the Department of Energy and the Nuclear Regulatory Commission to proceed with the licensing process
- **2008:** DOE submits Yucca Mountain license application to the NRC
- **2009-10:** DOE determines Yucca Mountain is “unworkable” and Congress terminates funding for the project
- **2013:** DOE proposes to “facilitate the availability of a geologic repository by 2048”
- **2015:** NRC staff completes its Safety Evaluation Report for Yucca Mountain, concluding that “DOE has met the applicable regulatory requirements” related to safety
- **2016-19:** Private sector applications to the NRC for consolidated interim storage of spent fuel
- **Present:** Funding for Yucca Mountain licensing process remains suspended. Approximately 300 technical contentions remain to be adjudicated before a licensing board can reach a decision regarding construction authorization

* from Swift 2017; Bonano 2019

Components of a Safety Case

Typical Major Components of a Safety Case



**FEP = Feature, Event, or Process*

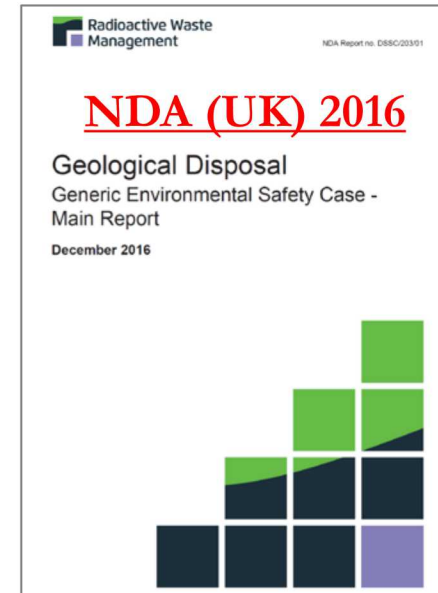
Safety Case vs. License Application

Safety Case

- “The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety of the geological disposal facility and the associated level of confidence....A safety case is the compilation of underlying evidence, models, designs and methods that give confidence in the quality of the scientific and institutional processes as well as the resulting information and analyses that support safety... In fact, not all programmes use the term ‘safety case’ to describe the broader range of arguments and evidence of which safety assessment forms one part; they may alternatively call such products a ‘safety report’, ‘safety dossier’ or (part of a) ‘license application’, for example.” (NEA 2012)

License Application (LA) for Construction

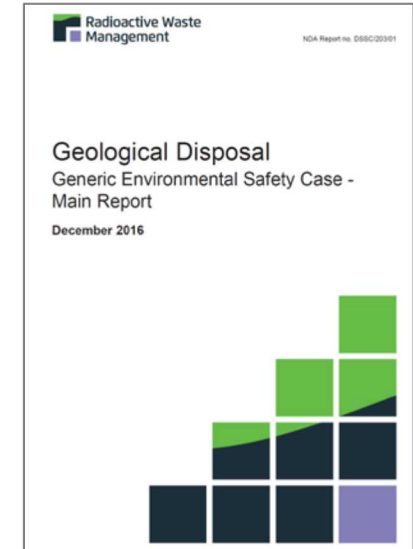
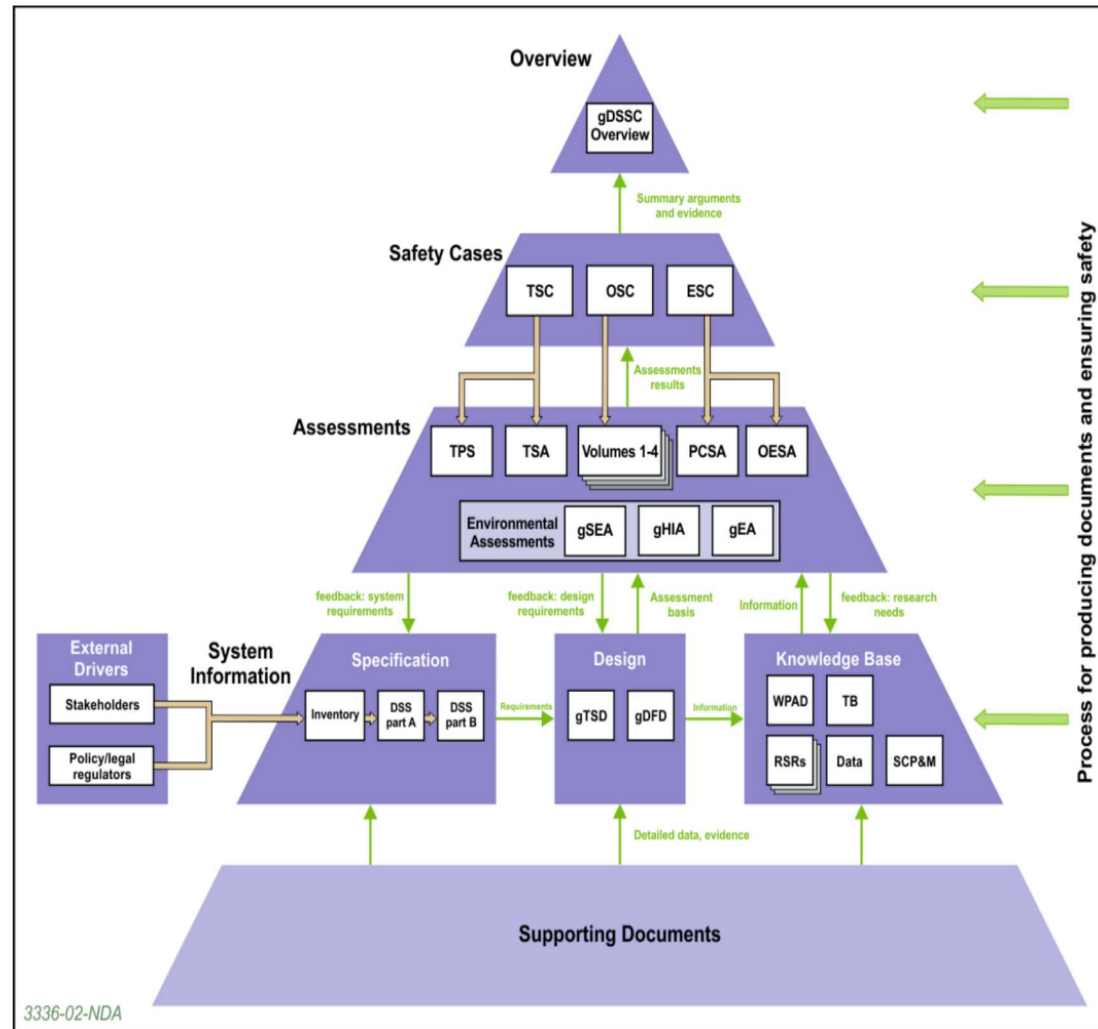
- Documentation that demonstrates the repository implementer (e.g., DOE; SKB) satisfies all regulatory and technical requirements applicable to the disposal facility and which constitutes an adequate basis for the regulator (e.g., NRC; SSM) to exercise its statutory licensing authority.
- E.g., “SKB’s license application is structured to meet Swedish regulations, and long-term safety is reported in detail in the SR-Site (safety assessment) main report (SKB 2011c). Most elements of a *safety case* according to the NEA definition (OECD/NEA 2004) appear in the SR-Site report hierarchy, whereas a few remaining elements are found elsewhere in the license application.” (Hedin and Andersson in NEA 2013b; SKB 2011b)



Example Documentation Structure of a Generic Safety Case – Recent (2016) Example from UK



*from RWM (2016)



What does a Repository License Application Look Like?



The 2008 Yucca Mountain License Application (LA) included

- 17 volumes; 8,646 pages
- 198 supporting documents (~38,000 pages) submitted with the application

Nuclear Regulatory Commission (NRC) staff issued approximately 673 formal requests for additional information

Approximately 305 contentions admitted for adjudication by the NRC Atomic Licensing and Safety Board (nearly all remain unresolved)

NRC Licensing process originally anticipated to take 3-4 years for a decision on construction authorization



Michael Weber (on left), Director, NRC Office of Nuclear Material Safety and Safeguards and Ward Sproat, Director, DOE Office of Civilian Radioactive Waste Management (June 2008)



The DOE's 1996 Compliance Certification Application to the Environmental Protection Agency (EPA) for the Waste Isolation Pilot Plant (WIPP) was ~72,000 pages, including appendices and supporting references

What is in a License Application?

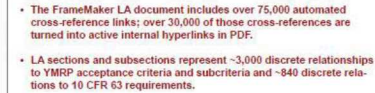


- **General Information**
 - General Description
 - Proposed Schedules for Construction, Receipt and Emplacement of Waste
 - Physical Protection Plan
 - Material Control and Accounting Program
 - Site Characterization
- **Safety Analysis Report**
 - Repository Safety Before Permanent Closure
 - Repository Safety After Permanent Closure
 - Research and Development Program to Resolve Safety Questions
 - Performance Confirmation Program
 - Management Systems

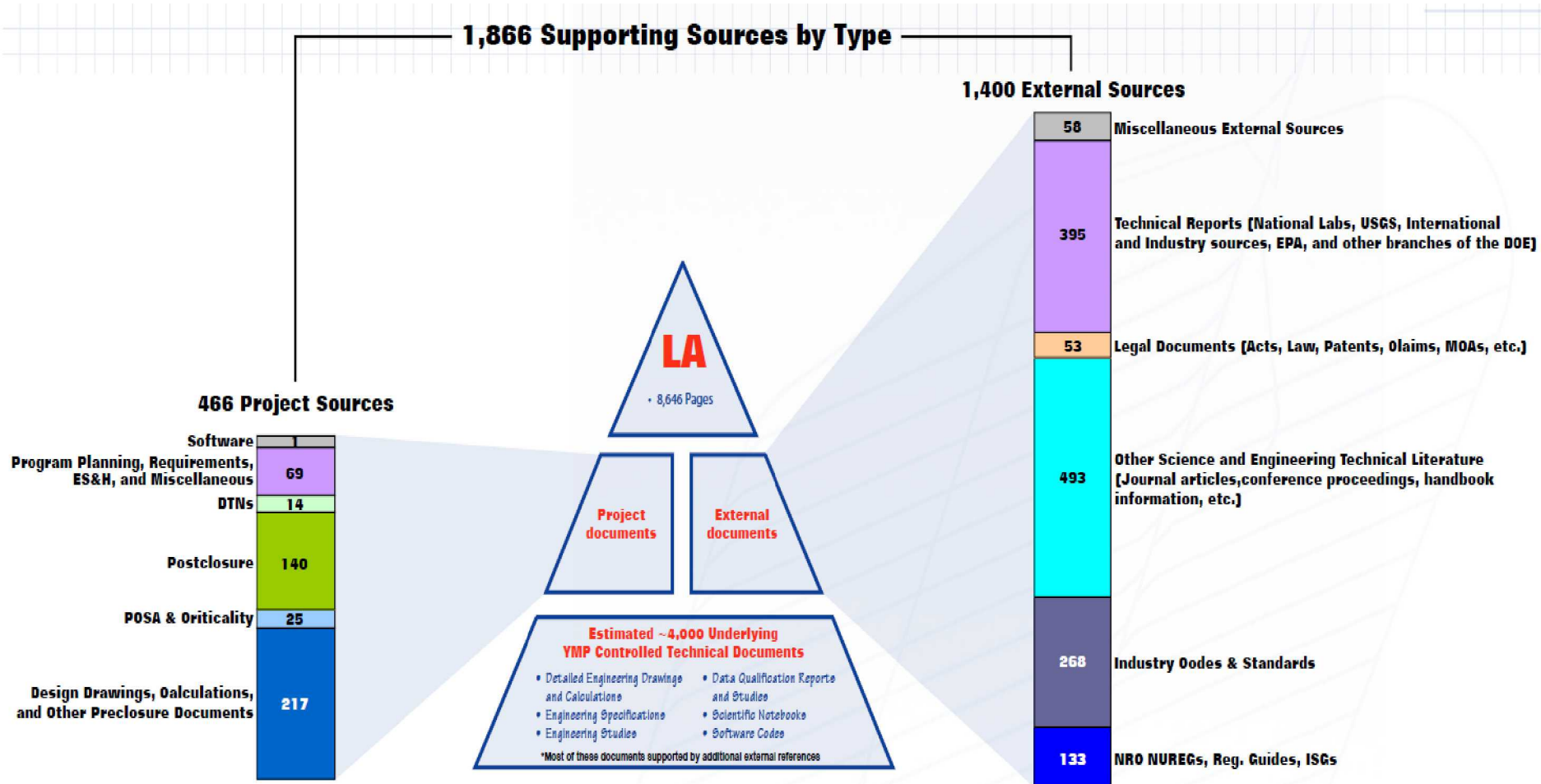
Repository Safety after Permanent Closure is addressed in 3,456 of the 8,646 pages in the 2008 Yucca Mountain License Application



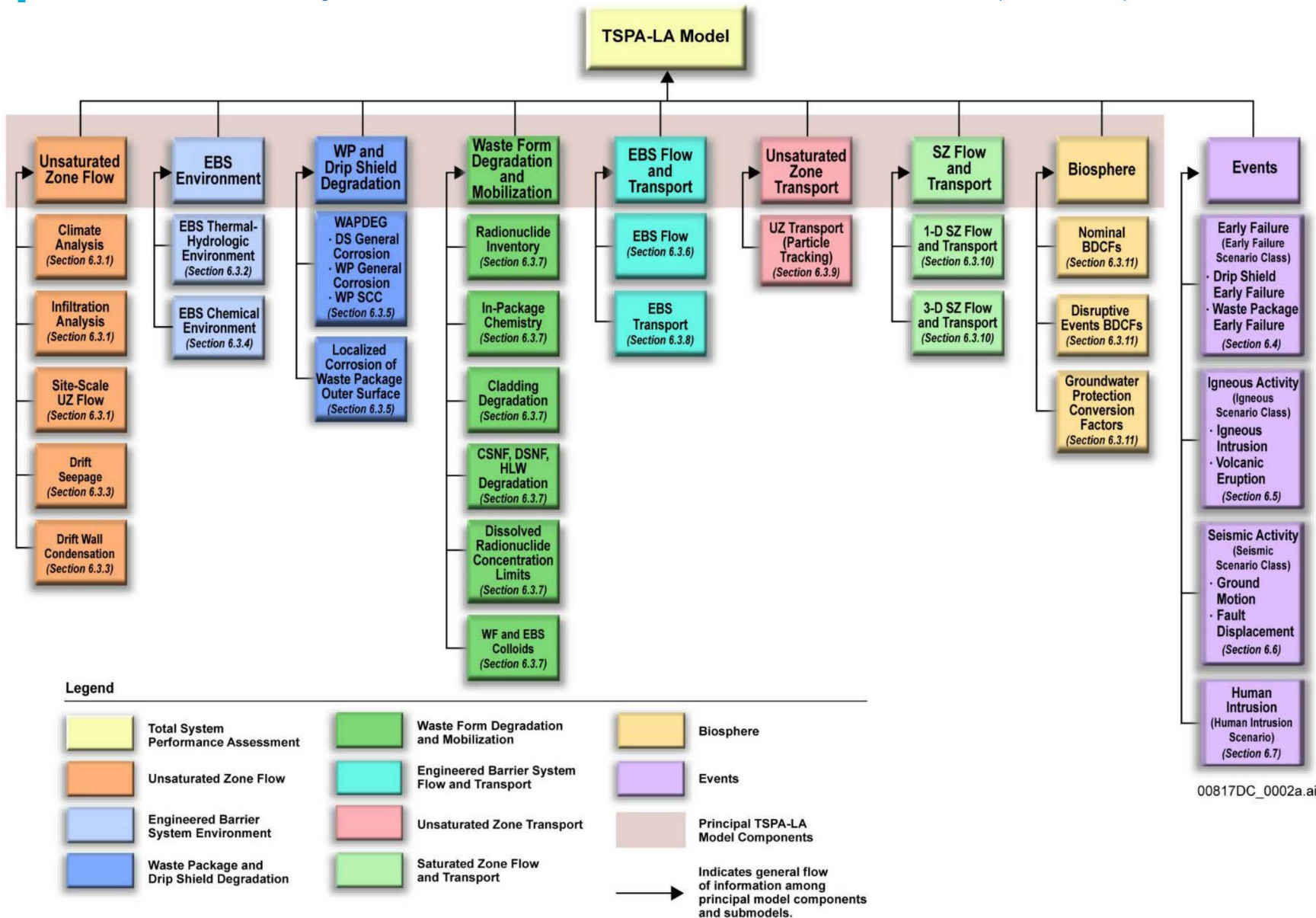
Swift NEFC Knowledge Management Workshop December 17-19 2019



Example Documentation from the Yucca Mountain License Application (Detail)



Example Documentation Supporting the Yucca Mountain Total System Performance Assessment (TSPA)



00817DC_0002a.ai

* from DOE 2008

Detail on One Component of a Safety Case: Features, Events and Processes Analysis

Detailed Elements of the Safety Case*



1. Introduction, Purpose, and Context

2. Safety Strategy

2.1 Management Strategy

- a. Organizational/mgmt. structure
- b. Safety culture & QA
- c. Planning and Work Control
- d. Knowledge management
- e. Oversight groups

2.2 Siting & Design Strategy

- a. National laws
- b. Site selection basis & robustness
- c. Design requirements
- d. Disposal concepts
- e. Intergenerational equity

2.3 Assessment Strategy

- a. Regulations and rules
- b. Performance goals/safety criteria
- c. Safety functions/multiple barriers
- d. Uncertainty characterization
- e. RD&D prioritization guidance

3. Technical Bases

3.1 Site Selection

- a. Siting methodology
- b. Repository concept selection
- c. FEPs Identification
- d. Technology development
- e. Transportation considerations
- f. Integration with storage facilities

3.2 Pre-closure Basis

- a. Repository design & layout
- b. Waste package design
- c. Construction requirements & schedule
- d. Operations & surface facility
- e. Waste acceptance criteria
- f. Impact of pre-closure activities on post-closure

3.3 Post-closure Bases (FEPs)

3.3.1 Waste & Engineered Barriers Technical Basis

- a. Inventory characterization
- b. WF/WP technical basis
- c. Buffer/backfill technical basis
- d. Shafts/seals technical basis
- e. UQ (aleatory, epistemic)

3.3.2 Geosphere/Natural Barriers Technical Basis

- a. Site characterization
- b. Host rock/DRZ technical basis
- c. Aquifer/other geologic units technical basis
- d. UQ (aleatory, epistemic)

3.3.3 Biosphere Technical Basis

- a. Biosphere & surface environment:
 - Surface environment
 - Flora & fauna
 - Human behavior

4. Disposal System Safety Evaluation

4.1 Pre-closure Safety Analysis

- a. Surface facilities and packaging
- b. Mining and drilling
- c. Underground transfer and handling
- d. Emplacement operations
- e. Design basis events & probabilities
- f. Pre-closure model/software validation
- g. Criticality analyses
- h. Dose/consequence analyses

4.2 Post-closure Safety Assessment

- a. FEPs analysis/screening
- b. Scenario construction/screening
- c. PA model/software validation
- d. Barrier/safety function analyses and subsystem analyses
- e. PA and Process Model Analyses/Results
- f. Uncertainty characterization and analysis
- g. Sensitivity analyses

4.3 Confidence Enhancement

- a. R&D prioritization
- b. Natural/anthropogenic analogues
- c. URL & large-scale demonstrations
- d. Monitoring and performance confirmation
- e. International consensus & peer review
- f. Verification, validation, transparency
- g. Qualitative and robustness arguments

5. Synthesis & Conclusions

- a. Key findings and statement(s) of confidence
- b. Discussion/disposition of remaining uncertainties
- c. Path forward

Features, Events, and Processes (FEPs) Analysis Supports the Safety Case



- **Documents the comprehensiveness of the safety case**
 - Proof of completeness is impossible for analyses of future performance, but comprehensive and iterative documentation of a FEP process provides objective evidence answers to questions of “Have you thought of everything?” and “What about...?”
 - Iteration is essential; a project must be willing to add new FEPs to the analysis as they are identified
- **Provides a structure to ensure that all important FEPs are captured in the safety assessment models**
 - All FEPs that can't be screened out using defined criteria must be included in one or more scenarios for quantitative modeling
- **FEP analysis is inherently a soft component of the safety case that defines the boundaries of the quantitative assessment**
 - There is no unique right way to do FEPs analyses
 - Thirty-plus years of experience and regulatory interactions in the US provides insight

Regulatory Basis for the Analysis of Features, Events, and Processes in the United States



The definition of Performance Assessment

From EPA 40 CFR 197.12: “*Performance assessment* means an analysis that

- (1) Identifies the features, events, processes, (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring;
- (2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and
- (3) Estimates the annual committed effective dose equivalent incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence.”

“All significant features, events, and processes, and sequences of events and processes” do not include very unlikely events and events of low consequence on overall performance

From NRC 10 CFR Part 63.342(a): “DOE’s performance assessments conducted to show compliance with §§ 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring. In addition, DOE’s performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurring if the results of the performance assessments would not be changed significantly in the initial 10,000-year period after disposal.” *(Emphasis added)*

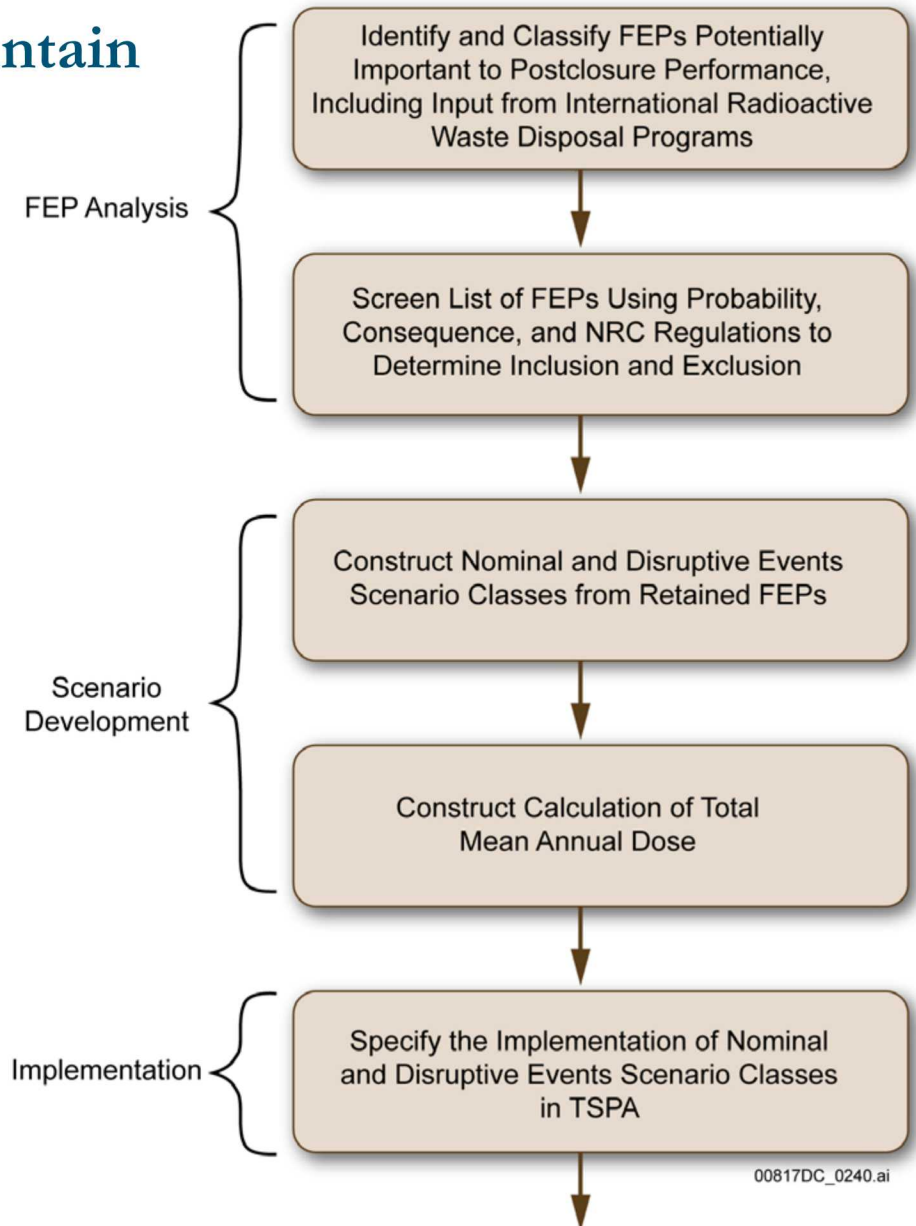
FEP Screening and Scenario Development for Yucca Mountain

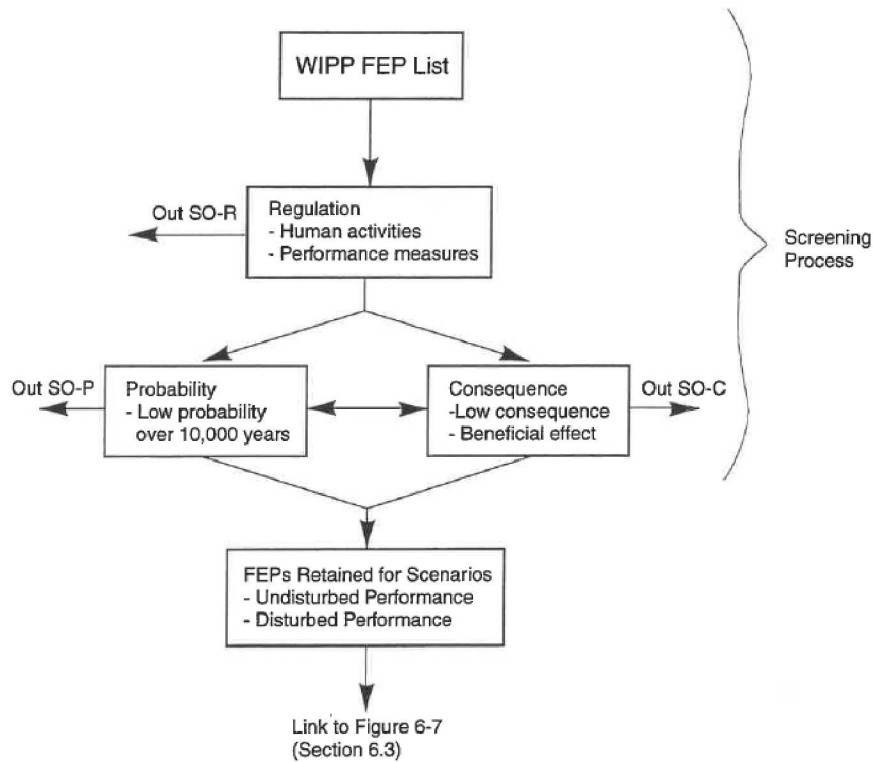
■ 374 FEPs evaluated for the YM License Application (SNL 2008a,b)

- 222 excluded from the TSPA
- 152 included in the TSPA

■ Four scenario classes defined for TSPA analysis

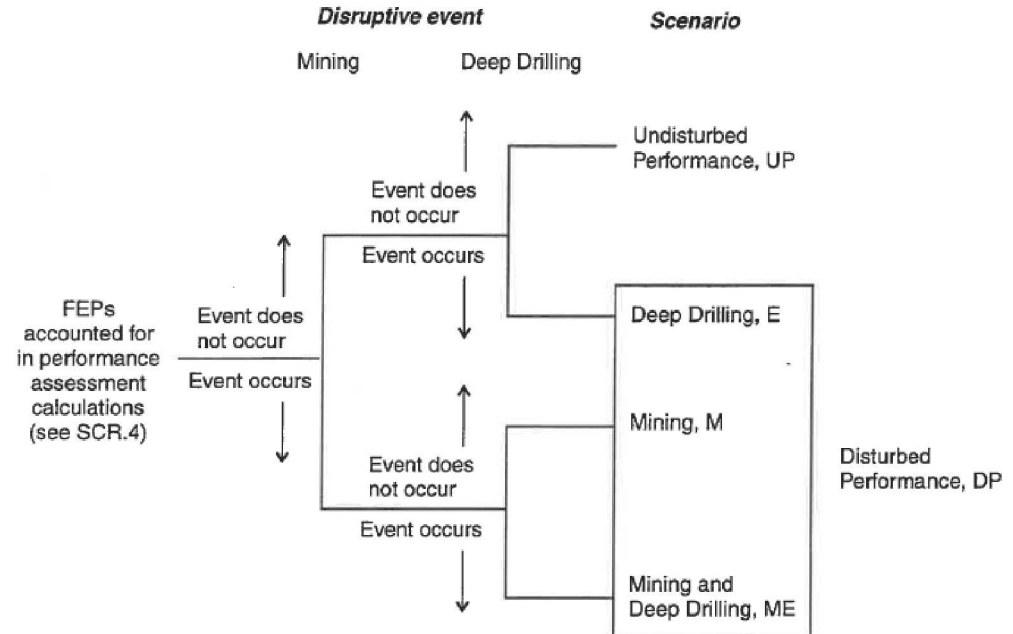
- Nominal Performance
- Early Failure
- Igneous Disruption
- Seismic Disruption





Approximately 240 FEPs evaluated, 89 included in the performance assessment

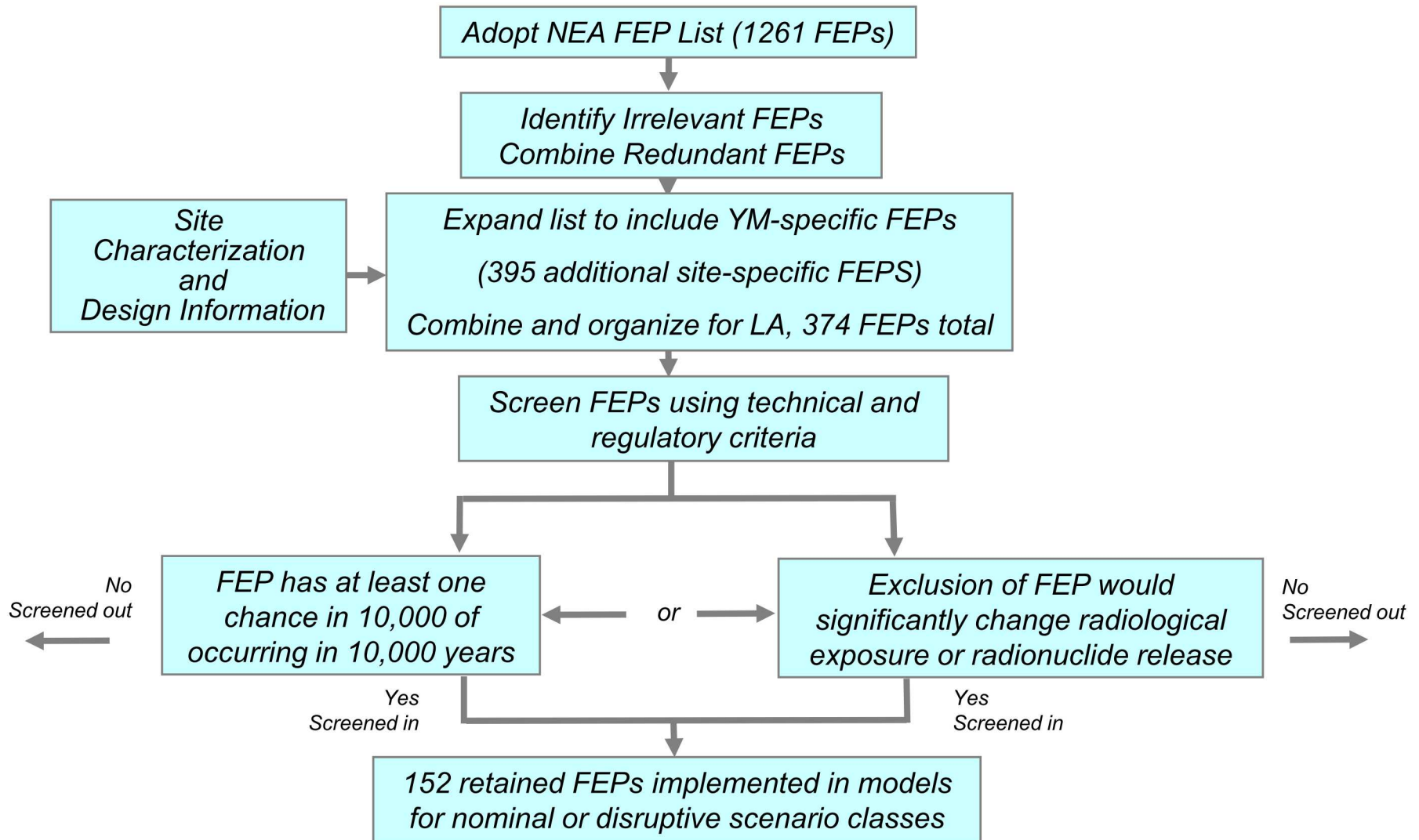
Occurrence or nonoccurrence of two disruptive events (mining and drilling) used to construct scenarios for analysis (below)



DOE 1996 Figures 6-6 (above) and 6-7 (right)

WIPP FEP analyses documented in CCA Appendix SCR (DOE 1996 and subsequent CRA analyses)

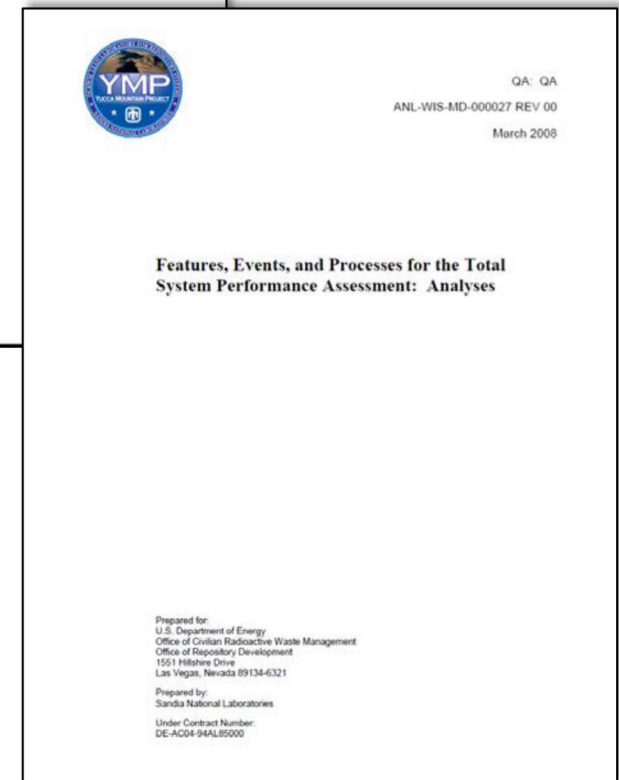
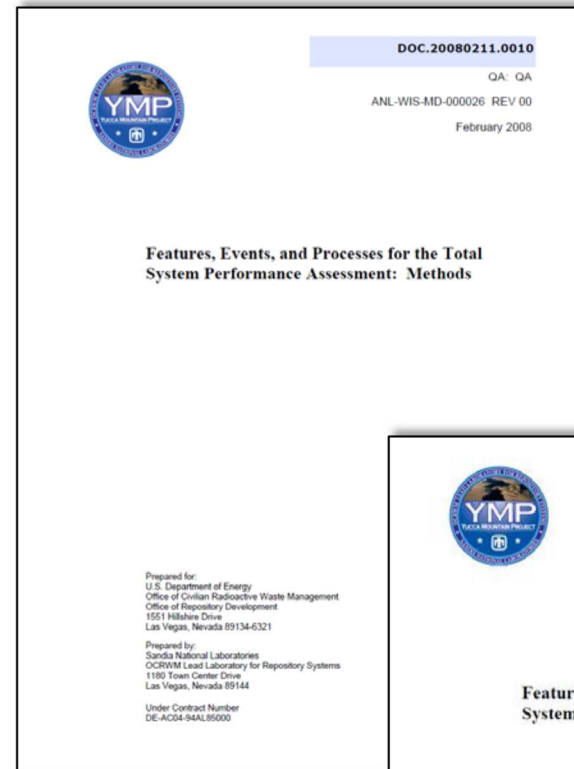
The FEP Process for Yucca Mountain



FEP Analysis for Yucca Mountain



- **YM FEP analysis summarized in Section 2.2 of the LA Safety Analysis Report (DOE 2008)**
- **Details provided in two supporting documents**
 - “*Methods*” (SNL 2008a) provides an 80-page summary of the process
 - “*Analyses*” (SNL 2008b) provides 2,042 pages of detailed screening arguments for all 374 FEPs
 - *For the 222 “excluded” FEPs, this document provides the only documentation of the basis for exclusion, and is therefore a critical supporting document for the License Application*



Representative portion of the YM FEP list



Table 7-1. Yucca Mountain Project Features, Events, and Processes List (Continued)

FEP Number	FEP Name
2.1.03.06.0A	Internal Corrosion of Waste Packages Prior To Breach
2.1.03.07.0A	Mechanical Impact on Waste Package
2.1.03.07.0B	Mechanical Impact on Drip Shield
2.1.03.08.0A	Early Failure of Waste Packages
2.1.03.08.0B	Early Failure of Drip Shields
2.1.03.09.0A	Copper Corrosion in EBS
2.1.03.10.0A	Advection of Liquids and Solids Through Cracks in the Waste Package
2.1.03.10.0B	Advection of Liquids and Solids Through Cracks in the Drip Shield
2.1.03.11.0A	Physical Form of Waste Package and Drip Shield
2.1.04.01.0A	Flow in the Backfill
2.1.04.02.0A	Chemical Properties and Evolution of Backfill
2.1.04.03.0A	Erosion or Dissolution of Backfill
2.1.04.04.0A	Thermal-Mechanical Effects of Backfill
2.1.04.05.0A	Thermal-Mechanical Properties and Evolution of Backfill
2.1.04.09.0A	Radionuclide Transport in Backfill
2.1.05.01.0A	Flow Through Seals (Access Ramps and Ventilation Shafts)
2.1.05.02.0A	Radionuclide Transport Through Seals

From SNL 2008a, "Features, Events, and Processes for the Total System Performance Assessment: Methods"

Example FEP Analysis for Yucca Mountain: Exclusion on Low Consequence



■ FEP 2.2.02.08.0A: Pyrophoricity from DSNF

■ FEP Description

“DSNF can contain pyrophoric material. Pyrophoric material could ignite and produce an adverse effect on repository performance. Pyrophoric events could affect the thermal behavior of the system and could contribute to degradation of the waste package, waste form, and cladding.”

■ Screening Decision: Excluded – low consequence

■ Screening Justification

“The adverse consequences for such a pyrophoric event are expected to be small because the TSPA model uses a bounding instantaneous degradation rate for DOE SNF (BSC 2004 [DIRS 172453], Section 8.1), and because a very conservative bounding estimate of the overall temperature increase (i.e., the adiabatic estimate discussed above) is sufficiently small that it is not expected to melt or otherwise degrade the codisposed glass waste forms.”

■ Ten-page technical analysis supports estimates of peak temperature rise associated with a pyrophoric event, based on oxygen availability through assumed breaches in the waste package and canister overpack

From SNL 2008b, “Features, Events, and Processes for the Total System Performance Assessment: Analyses”

Example FEP Analysis for Yucca Mountain: Exclusion on Low Probability



■ FEP 1.5.01.01.0A Meteorite Impact

■ FEP Description

“Meteorite impact close to the repository site might disturb or remove rock to such an extent that radionuclide transport to the surface is accelerated. Possible effects include alteration of flow patterns (by re-activation or formation of faults and fractures), changes in rock stress, cratering, and exhumation of waste.”

■ Screening Decision: Excluded – low probability

■ Screening Justification

“The fracturing of the PTn [Paintbrush Tuff nonwelded unit] can, therefore, be excluded based on low probability because the probability of a cratering event sufficiently large to cause fracturing the PTn to less than 10-m thick is less than 10^{-8} per year.”

Justification also addresses direct exhumation, hydrologic effects, and direct exhumation of the waste; in all cases cratering of sufficient size is of low probability.

■ Three-page technical analysis summarizes 30-page appendix to the FEPs analysis report, analysis based on planetary cratering frequency and site geology

From SNL 2008b, “Features, Events, and Processes for the Total System Performance Assessment: Analyses”

Example FEP Analysis for Yucca Mountain: Exclusion by Regulation



■ FEP 1.1.03.01.0A Error in Waste Emplacement

■ FEP Description

“Deviations from the design and/or errors in waste emplacement could affect long-term performance of the repository. A specific example of such an error would be erroneously emplacing the waste packages in a saturated or wet zone of the repository. Errors of this type would impact repository performance by affecting waste package corrosion and radionuclide transport.”

■ Screening Decision: Excluded – by regulation

■ Screening Justification

“Inherent in the approach to FEP evaluation is the expectation that the repository be constructed, operated, and closed according to the design used as the basis for FEP screening and in accordance with NRC license requirements. Repository construction, operation, and closure will be subject to a quality assurance program and quality control procedures that will evaluate and disposition any deviations from the design.”

■ Three-page summary of relevant programmatic documentation

From SNL 2008b, “Features, Events, and Processes for the Total System Performance Assessment: Analyses”

Example FEP Analysis for Yucca Mountain: Exclusion on Probability-weighted Consequence



■ FEP 1.2.04.07.0B Ash Redistribution in Groundwater

■ FEP Description

“Following deposition of contaminated ash on the surface, contaminants may leach out of the ash deposit and be transported through the subsurface to the compliance point.”

■ Screening Decision: Excluded – low consequence

■ Screening Justification

“Thus, the probability-weighted consequences of leaching from ash would be less than the probability-weighted consequences of exposing the same number of waste packages to direct seepage.”

■ Three-page reasoned argument

See also FEP 1.4.07.03.0A, “Recycling of Accumulated Radionuclides from Soils to Groundwater”, for which the low consequence argument was supported by a full-scale stand-alone analysis. The NRC staff did not accept the irrigation recycling analysis and performed their own, simpler analysis, and came to the same conclusion (NRC 2014, section 2.2.1.2.1.3.2): the process has the potential to cause an increase in estimated dose but the increases are small and not significant.

From SNL 2008b, “Features, Events, and Processes for the Total System Performance Assessment: Analyses”

References for Safety & Licensing Cases – Generic and Actual Cases



- International and national experience lessen the technical challenges:
 - ANDRA (French National Radioactive Waste Management Agency) 2016. *Safety Options Report – Post-closure Part (DOS-AF)*, CG-TE-D-NTE-AMOA-SR2-0000-15-0062/A, July 11, 2016, 466 pp., https://international.andra.fr/sites/international/files/2019-03/Safety%20Options%20Report%20-%20Post-Closure_1.pdf
 - DOE (U.S. Department of Energy) 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184
 - DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1. Available at <https://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/yucca-lic-app-safety-report.html#1>
 - Freeze, G., M. Voegelé, P. Vaughn, J. Prouty, W.M. Nutt, E. Hardin, and S.D. Sevougian 2013. *Generic Deep Geologic Disposal Safety Case*, FCRD-UFD-2012-000146 Rev. 1, SAND2013-0974P, Sandia National Laboratories, Albuquerque, NM, August 2013
 - IAEA (International Atomic Energy Agency) 2012. *The Safety Case and Safety Assessment for the Disposal of Radioactive Waste*, Specific Safety Guide, IAEA Safety Standards Series No. SSG-23, International Atomic Energy Agency, Vienna, 2012.
 - IAEA 2016. *International Peer Review on the “Safety Options Dossier” of the Project of Disposal of Radioactive Waste in Deep Geological Formations: Cigéo*, Peer Review Report, November 2016, Paris France, Final Report, <https://www-ns.iaea.org/downloads/rw/waste-safety/cigeo-final-report2016.pdf>
 - MacKinnon, R. J. 2016. *Safety Case – Iterations from Generic Studies to License Application*, SAND2016-8636PE, presented to JRC (EU Joint Research Centre), Ispra, Italy, September 12-16, 2016.
 - NAGRA (Nationale Genossenschaft für die Lagerung Radioactiver Abfälle [National Cooperative for the Disposal of Radioactive Waste]), 2002. *Project Opalinus Clay Safety Report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis)*, Technical Report 02-05.
 - NEA (Nuclear Energy Agency) 2004. *Post-closure safety cases for geological repositories. Nature and purpose*. OECD/NEA report 3679. Paris.

References for Safety & Licensing Cases – Generic and Actual Cases (cont.)



- NEA 2009a. *Considering timescales in the post-closure safety of geological disposal of radioactive waste*. OECD/NEA report 6424. Paris.
- NEA 2009b. *International Experiences in Safety Cases for Geological Repositories (INTESC): Outcomes of the INTESC Project*. NEA Report No. 6251. Paris, France: OECD 2009.
- NEA (Nuclear Energy Agency) 2012. *Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative*. NEA No. 6923. Organisation for Economic Co-operation and Development, Nuclear Energy Agency, OECD 2012, ISBN 978-92-64-99190-3.
- NEA 2013a. *The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories*, NEA Report No. 78121, Radioactive Waste Management, NEA/RWM/R(2013)1, February 2013, www.oecd-neo.org, Paris, France: OECD 2013.
- NEA 2013b. *The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art Symposium Proceedings*, 7-9 October 2013, OECD-NEA, Paris, France.
- Posiva 2012. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Synthesis 2012*, Posiva Report 2012-12, Posiva Oy, Olkiluoto. FIN-27160 Eurajoki, Finland, December 2012, ISBN 978-951-652-193-3, https://www.posiva.fi/files/2987/Posiva_2012-12web.pdf.
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- SKB 2011a. *The Post-closure Radiological Safety Case For A Spent Fuel Repository In Sweden: An International Peer Review of the SKB License Application Study of March 2011* (Final report)
- SKB 2011b. *Application for Licence Under the Nuclear Activities Act*, Stockholm, 16 March 2011, Svensk Kärnbränslehantering AB, <http://www.skb.com/future-projects/the-spent-fuel-repository/our-applications/>
- Smith, P., B. Cornelis, M. Capouet, C. Depaus, and M. Van Geet 2009. *The Long-Term Safety Assessment Methodology for the Geologic Disposal of Radioactive Waste*, SFC1 level 4 report: second full draft, NIROND-TR Report 2009-14 E, ONDRAF/NIRAS, Brussels, Belgium, June 2009, www.nirond.be

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- SNL (Sandia National Laboratories), 2008b. Features, Events, and Processes for the Total System Performance Assessment: Analyses. ANL-WIS-MD-000026, Rev 00. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management
- SNL (Sandia National Laboratories), 2008c. Total system performance assessment model/analysis for the license application. MDL-WIS-PA-000005 Rev00, AD 01. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management
- U.S. DOE (U.S. Department of Energy), 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, Carlsbad, NM, U.S. Department of Energy Carlsbad Area Office
- U.S. DOE (U.S. Department of Energy), 2008. Yucca Mountain repository license application safety analysis report. DOE/RW-0573, Update no. 1. Las Vegas, NV: U.S. Department of Energy
- U.S. DOE (U.S. Department of Energy), 2014. Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant
- U.S. Nuclear Regulatory Commission (NRC), 2014. Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 3, Repository Safety after Permanent Closure. NUREG-1949, Vol. 3
- U.S. Nuclear Regulatory Commission (NRC), 2015. Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 2, Repository Safety Before Permanent Closure, and Volume 5, Proposed Conditions on the Construction Authorization and Probable Subjects of License Specifications. NUREG-1949, Vol. 2 and Vol. 5
- Key Websites: <http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html>;
<http://www.wipp.energy.gov/library/caolib.htm>

Information Flow Among the Components of a Safety Case: Building Confidence

Detailed Elements of the Safety Case*



1. Introduction, Purpose, and Context

2. Safety Strategy

2.1 Management Strategy

- a. Organizational/mgmt. structure
- b. Safety culture & QA
- c. Planning and Work Control
- d. Knowledge management
- e. Oversight groups

2.2 Siting & Design Strategy

- a. National laws
- b. Site selection basis & robustness
- c. Design requirements
- d. Disposal concepts
- e. Intergenerational equity

2.3 Assessment Strategy

- a. Regulations and rules
- b. Performance goals/safety criteria
- c. Safety functions/multiple barriers
- d. Uncertainty characterization
- e. RD&D prioritization guidance

3. Technical Bases

3.1 Site Selection

- a. Siting methodology
- b. Repository concept selection
- c. FEPs Identification
- d. Technology development
- e. Transportation considerations
- f. Integration with storage facilities

3.2 Pre-closure Basis

- a. Repository design & layout
- b. Waste package design
- c. Construction requirements & schedule
- d. Operations & surface facility
- e. Waste acceptance criteria
- f. Impact of pre-closure activities on post-closure

3.3 Post-closure Bases (FEPs)

3.3.1 Waste & Engineered Barriers Technical Basis

- a. Inventory characterization
- b. WFI/WP technical basis
- c. Buffer/backfill technical basis
- d. Shafts/seals technical basis
- e. UQ (aleatory, epistemic)

3.3.2 Geosphere/Natural Barriers Technical Basis

- a. Site characterization
- b. Host rock/DRZ technical basis
- c. Aquifer/other geologic units technical basis
- d. UQ (aleatory, epistemic)

3.3.3 Biosphere Technical Basis

- a. Biosphere & surface environment:
 - Surface environment
 - Flora & fauna
 - Human behavior

4. Disposal System Safety Evaluation

4.1 Pre-closure Safety Analysis

- a. Surface facilities and packaging
- b. Mining and drilling
- c. Underground transfer and handling
- d. Emplacement operations
- e. Design basis events & probabilities
- f. Pre-closure model/software validation
- g. Criticality analyses
- h. Dose/consequence analyses

4.2 Post-closure Safety Assessment

- a. FEPs analysis/screening
- b. Scenario construction/screening
- c. PA model/software validation
- d. Barrier/safety function analyses and subsystem analyses
- e. PA and Process Model Analyses/Results
- f. Uncertainty characterization and analysis
- g. Sensitivity analyses

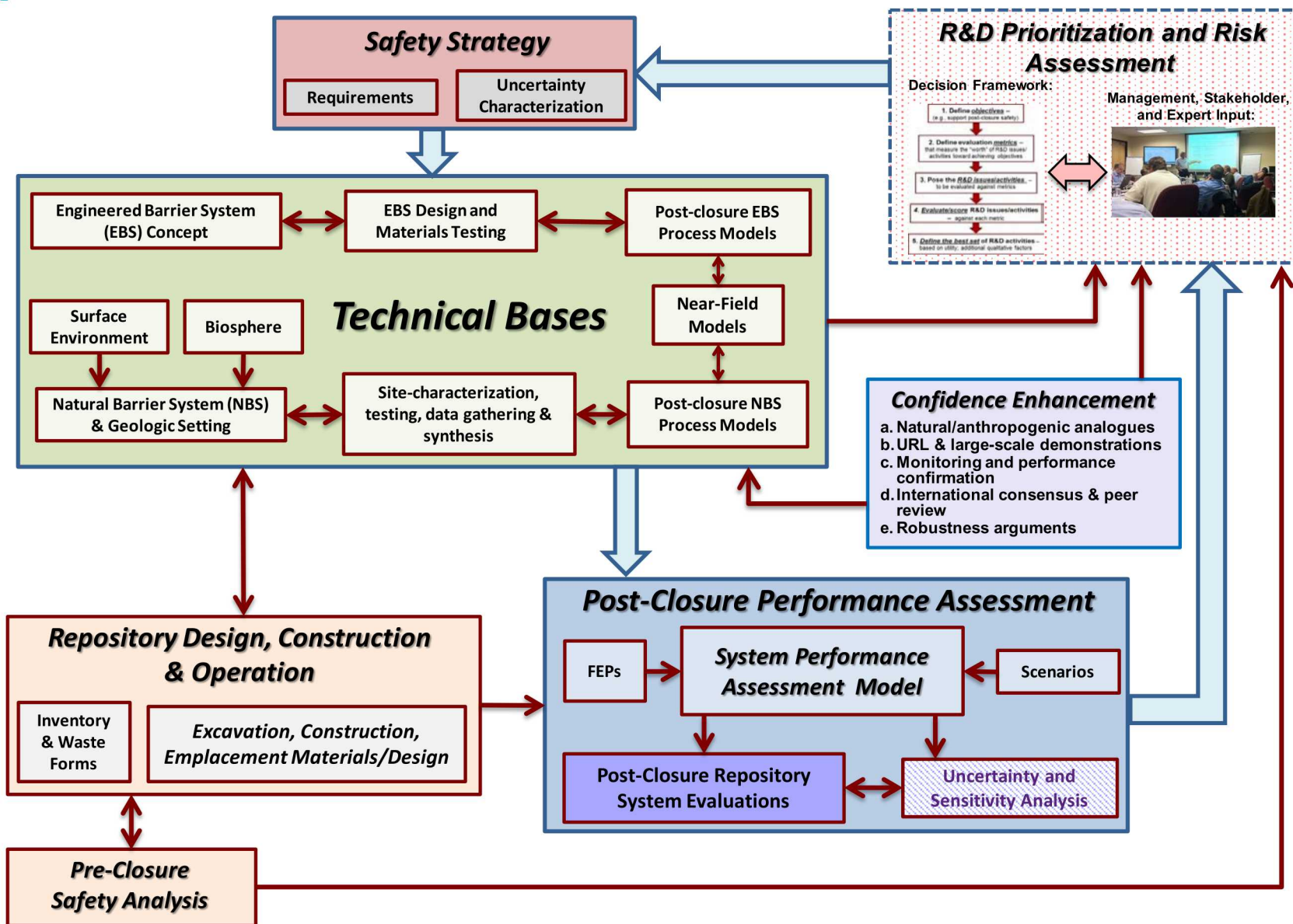
4.3 Confidence Enhancement

- a. R&D prioritization
- b. Natural/anthropogenic analogues
- c. URL & large-scale demonstrations
- d. Monitoring and performance confirmation
- e. International consensus & peer review
- f. Verification, validation, transparency
- g. Qualitative and robustness arguments

5. Synthesis & Conclusions

- a. Key findings and statement(s) of confidence
- b. Discussion/disposition of remaining uncertainties
- c. Path forward

Information Flow Between Components of a Safety Case



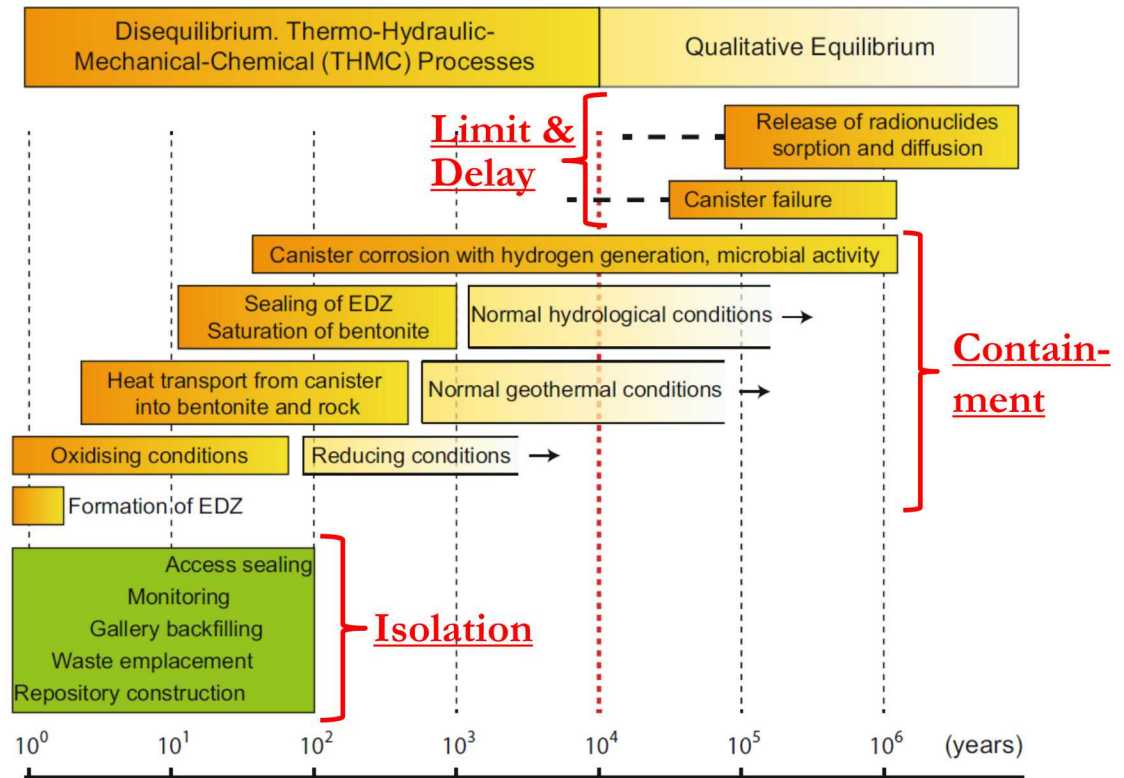
Physical Safety Strategy for a Geologic Repository – Safety Functions



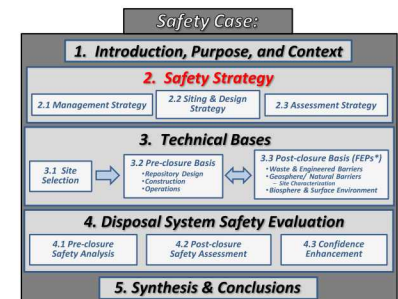
Safety Functions:

- Design and construct an engineered repository sufficiently deep beneath the ground surface to ensure **isolation** of the waste from external changes, events, and non-purposeful human intrusion.
- The underground facility typically comprises multiple engineered and geologic barriers that act together to **contain** the waste within the facility.
- After loss of full containment (breach of waste packages), the multiple engineered and natural barriers act to **limit and delay** the release and transport of radionuclides to and within the geosphere.

Fig. 5 The possible evolution of a potential high-level waste repository in the Opalinus Clay based on the Swiss disposal concept. *



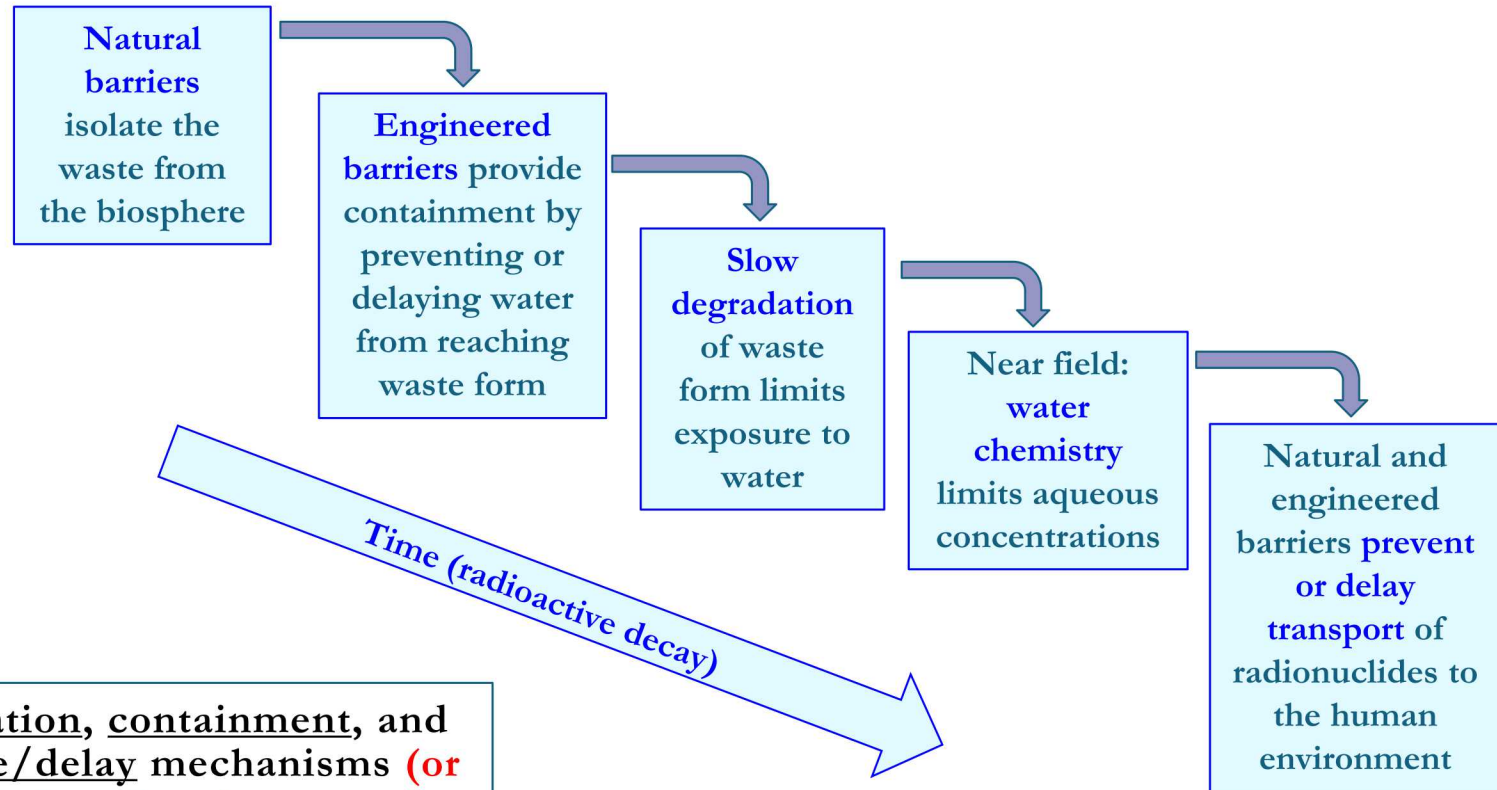
*from Bossart et al. (2017)



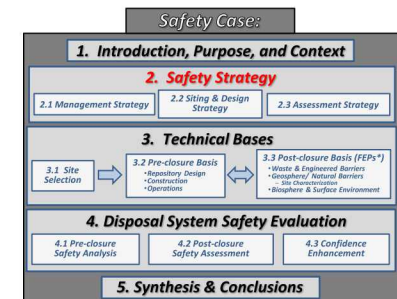
Safety Functions and Barriers – Interplay



Overall performance and safety relies on multiple functions/barriers – different disposal concepts emphasize different functions/barriers:

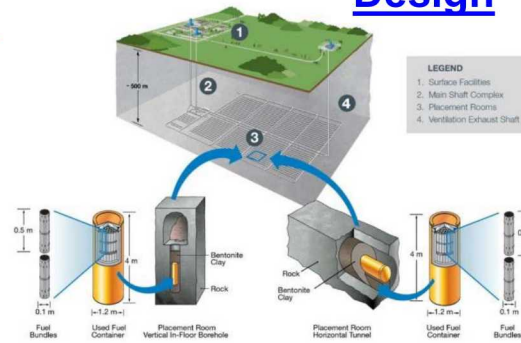


Isolation, containment, and dilute/delay mechanisms (or safety functions) may differ for different nuclides in different disposal concepts.



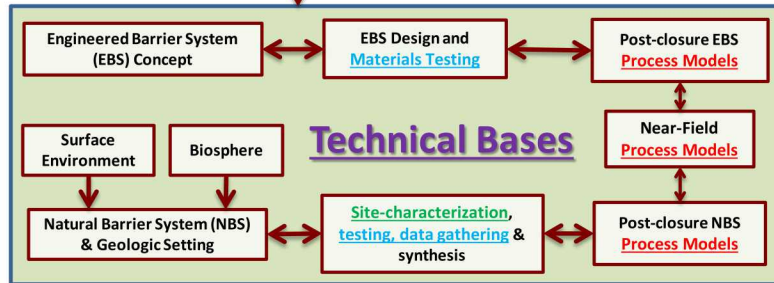
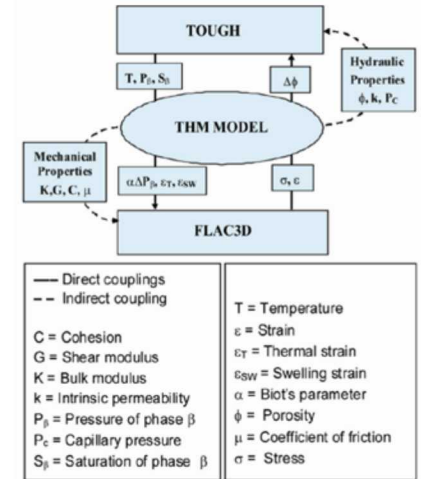
Technical Bases (Assessment basis)

Design



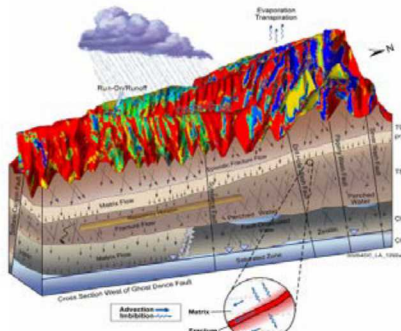
Process Model Development*

TOUGH-FLAC



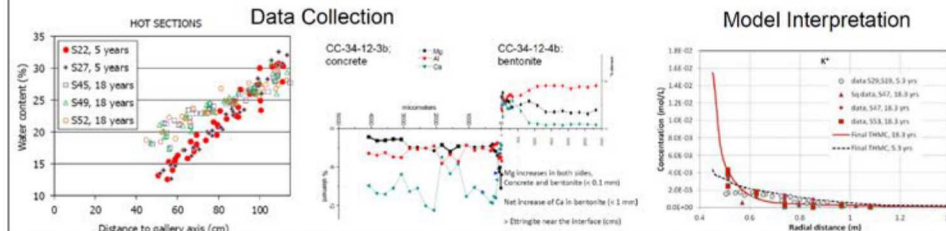
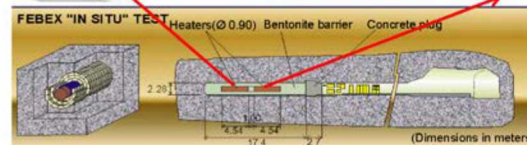
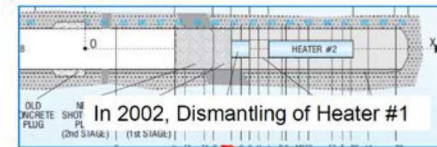
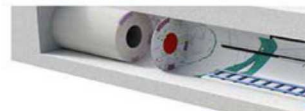
Testing & Data Gathering**

Site-characterization



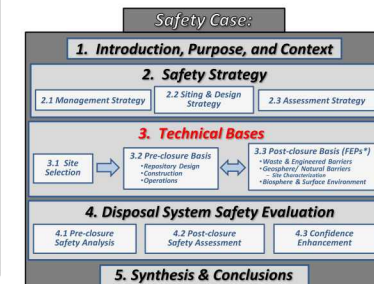
FEBEX-DP (Full-scale Engineering Barriers Experiment Dismantling Project): Demonstration of feasibility, study THMC process, validate model

In 2015, Dismantling of Heater #2



*from Rutqvist et al. (2018)

**from Zheng et al. (2018)



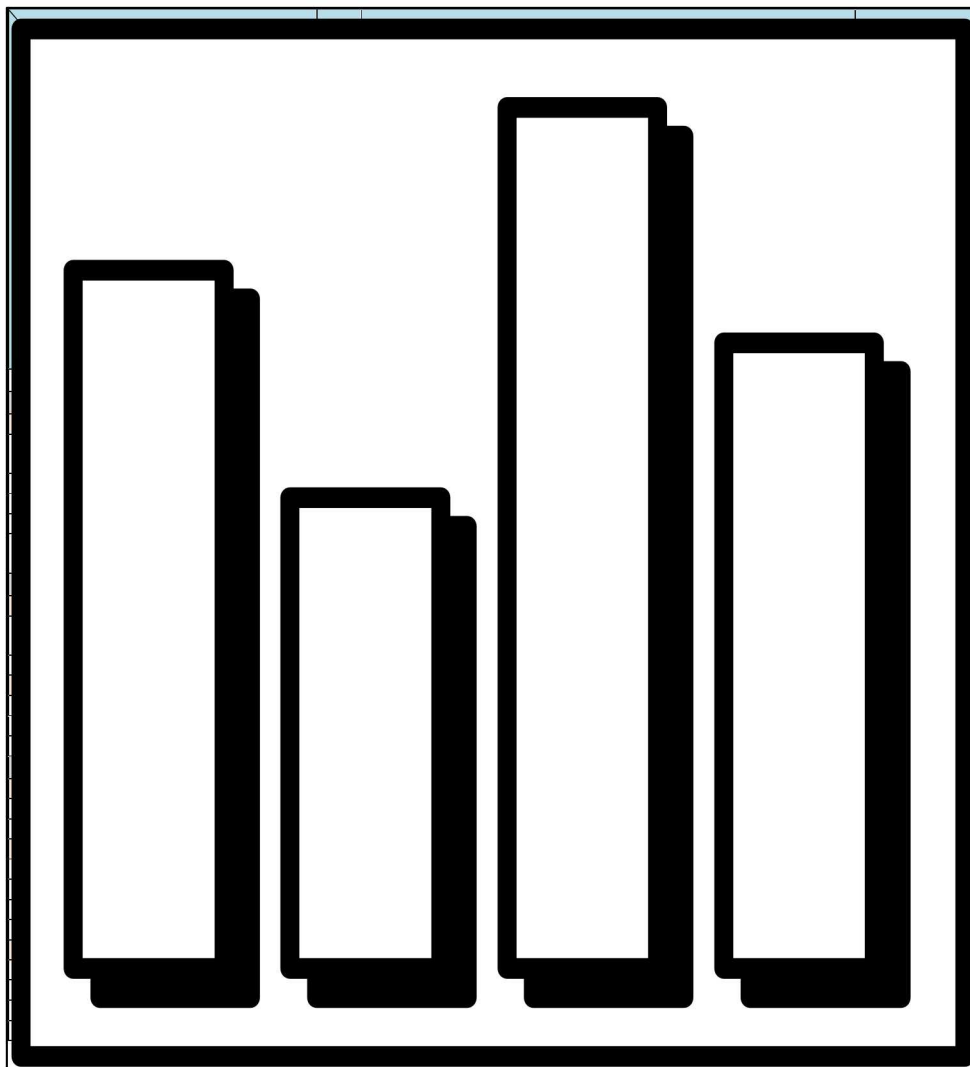
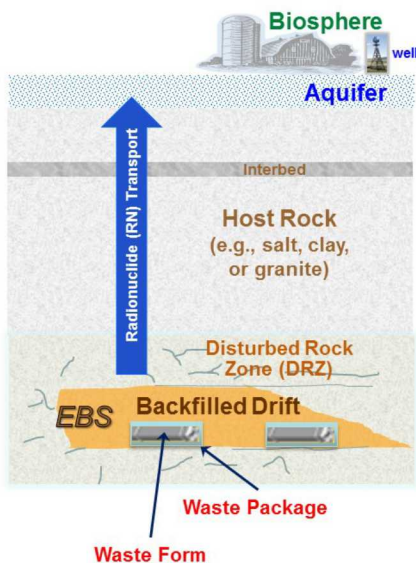
Detailed Evidence for Post-closure Technical Bases



- Evidence can be organized by FEPs, or at least a FEPs completeness check must be cross-referenced:*

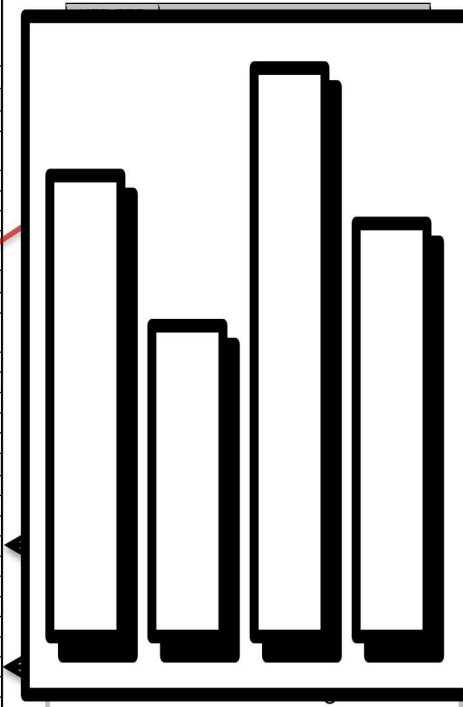
FEP Matrix:

Physical Features & Components:



Individual FEPs:

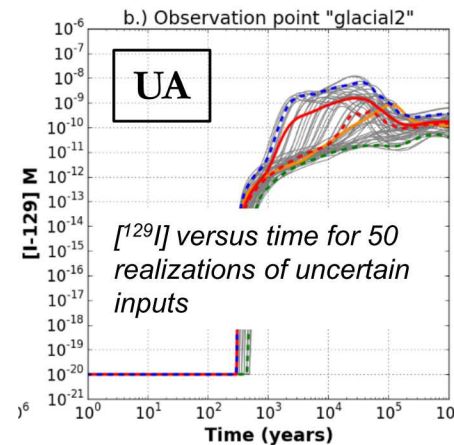
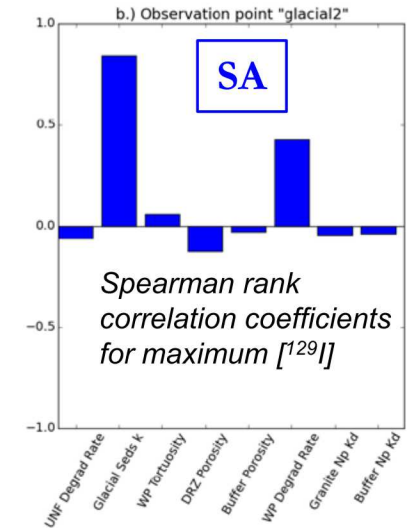
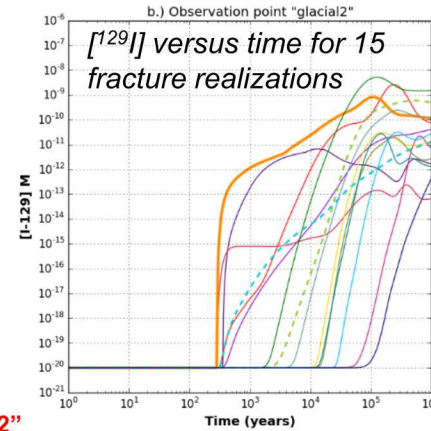
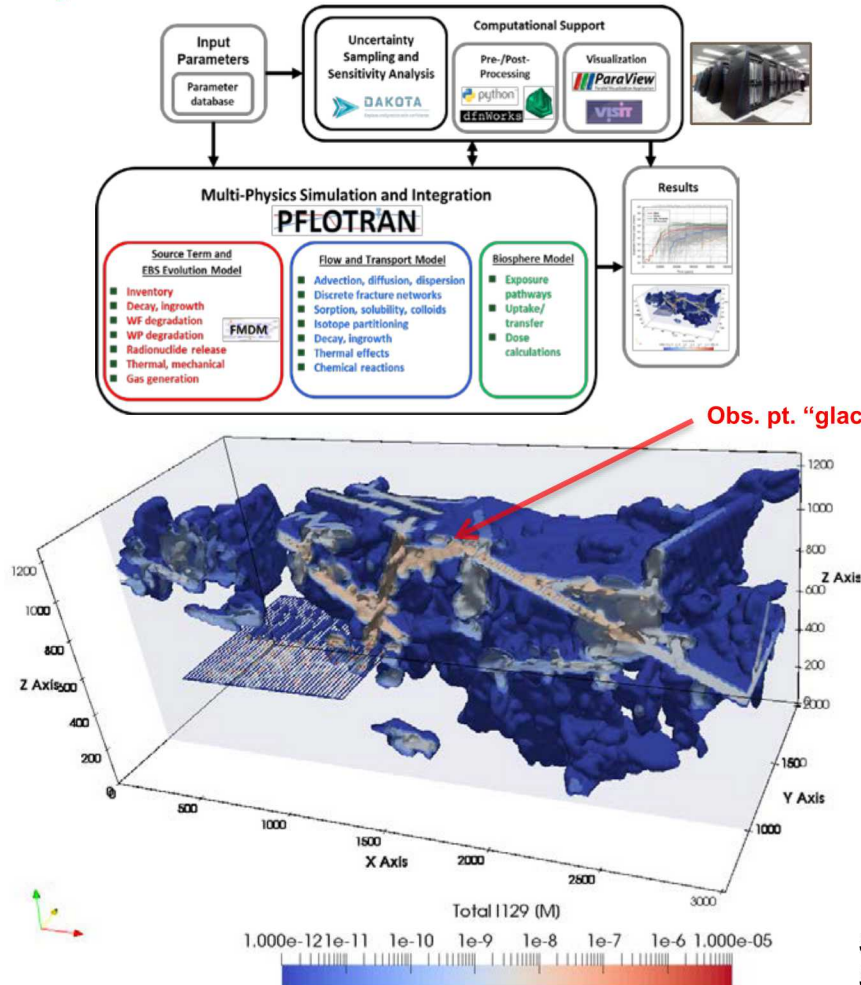
Each FEP matrix cell (e.g., highlighted in red) contains all individual FEPs (such as those listed below) related to the “Process/Event” acting upon or within the “Feature/Component”



Safety or Performance Assessment



GDSA Framework



Parameter	Range	Units	Distribution
UNF Dissolution Rate	$10^{-8} - 10^{-6}$	yr^{-1}	log uniform
Mean Waste Package Degradation Rate	$10^{-5.5} - 10^{-4.5}$	yr^{-1}	log uniform
Waste Package τ	0.01 - 1.0		log uniform
Bentonite ϕ	0.3 - 0.5		uniform
DRZ ϕ	0.005 - 0.05		uniform
Np K_d bentonite	0.1 - 702	m^3kg^{-1}	log uniform
Np K_d natural barrier	$1.26 \times 10^5 - 5.37 \times 10^7$	m^3kg^{-1}	log uniform

Crystalline Repository Simulations

- Breakthrough of ^{129}I (at surface) *highly* sensitive to fracture distribution
- Also sensitive to sediment permeability and waste package degradation rate

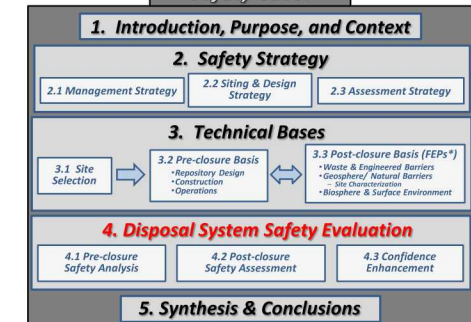
Source: Mariner et al., 2016

SA = sensitivity analysis

UA = uncertainty analysis

UQ = uncertainty quantification

Safety Case:



Synthesis – Belgium Safety (Confidence) Statements



Examples of the hierarchical structure of Ondraf/Niras safety statements (Smith et al. 2009, Table 1):

The assessment basis provides evidence that the safety functions will be fulfilled as described by the safety concept

Indeed, the disposal system and its geological coverage isolate the wastes for as long as required in such a way as to minimise the probability and consequences of human intrusion and humans actions and to protect the wastes and system components against internal and external geodynamic events and processes (I)

Indeed, ...

and the supercontainer of vitrified high-level waste and spent fuel provides complete containment of the radionuclides and other contaminants at least through the thermal phase (C)

Indeed, ...

and the disposal system delays and attenuates releases of radionuclides and other contaminants to the environment for as long as required (R)

Indeed, the release of radionuclides and other contaminants from the waste forms is spread in time (R1)

Indeed, ...

and the properties of the disposal system limit the water flow, ensuring a diffusion-dominated transport (R2)

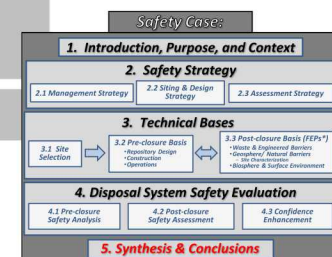
Indeed, the characteristics of the host formation ensure a diffusion-dominated transport which is not jeopardised by the disturbances related to waste emplacement

Indeed, the host formation has a fine homogeneous pore structure and a low hydraulic conductivity

which is true because the host formation has a fine homogeneous pore structure

and because the host formation has a low hydraulic conductivity

Note: Statements at the same level are given the same colour. Statements directly supported by phenomenological evidence from the assessment basis are shown in grey.

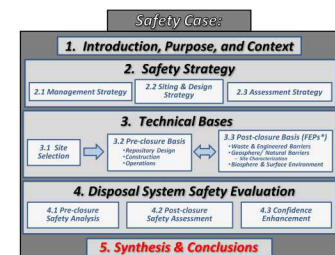




The confidence in the results obtained is in the SR-Site safety report (SKB, 2011) assessed as sufficient for the decision at hand based on the following:*

- Knowledge of the Forsmark site from the completed, surface-based investigations is sufficient for the assessment of long-term safety...
- The reference design is well-established, with specified and achievable production and control procedures yielding an initial state of the repository system with properties favourable for long-term safety at the Forsmark site...
- The scientific understanding of issues relevant for long-term safety is mature as a result of decades of research both within Swedish and other national programmes and in international collaboration projects...
- The SR-Site [post-closure safety] report and its supporting documents have been comprehensively peer reviewed...
- A complete analysis of issues identified as relevant to long-term safety (SKB, 2010j) was carried out for the SR-Site according to an established assessment methodology (SKB, 2011), comprising e.g. cautious approaches when addressing uncertainties...
- Documented quality assurance routines have been applied in the assessment of the initial state, in the development of the site description and in the analysis of long-term safety...

***from Hedin and Andersson in NEA (2013)**

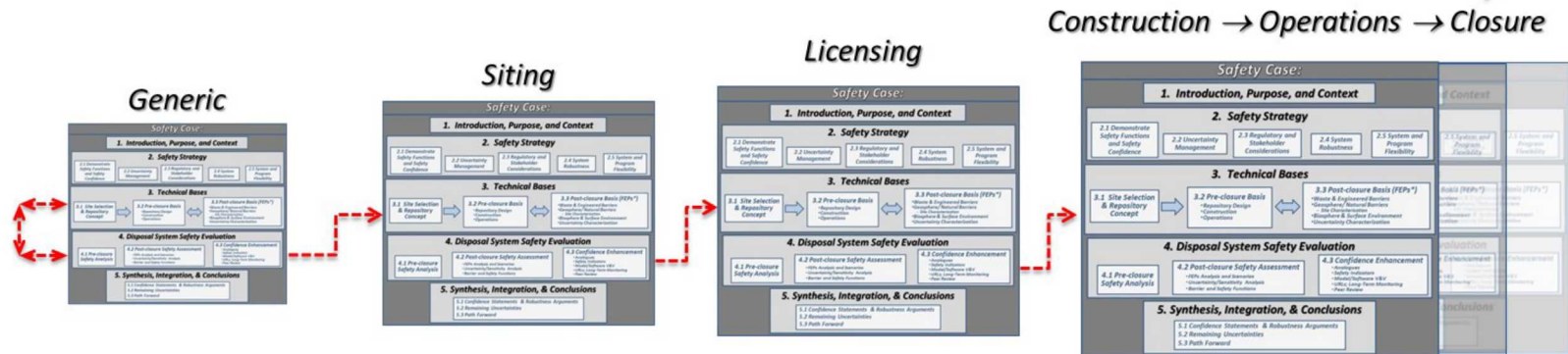
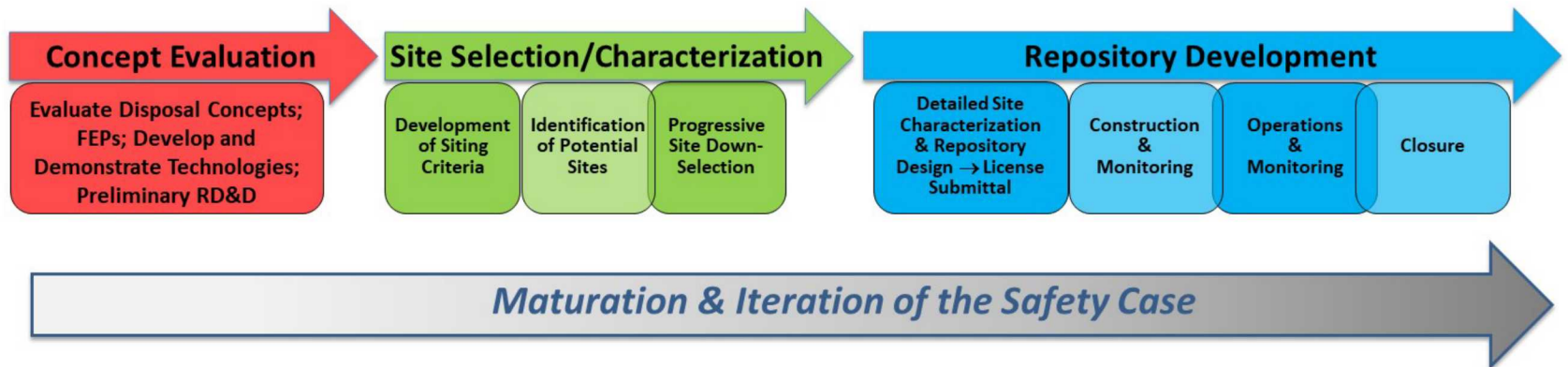


Phased repository development: Iteration of safety case and R&D activities

Iteration (and Maturation) of the Safety Case



- Safety case confidence and associated technical bases *evolve* in phases

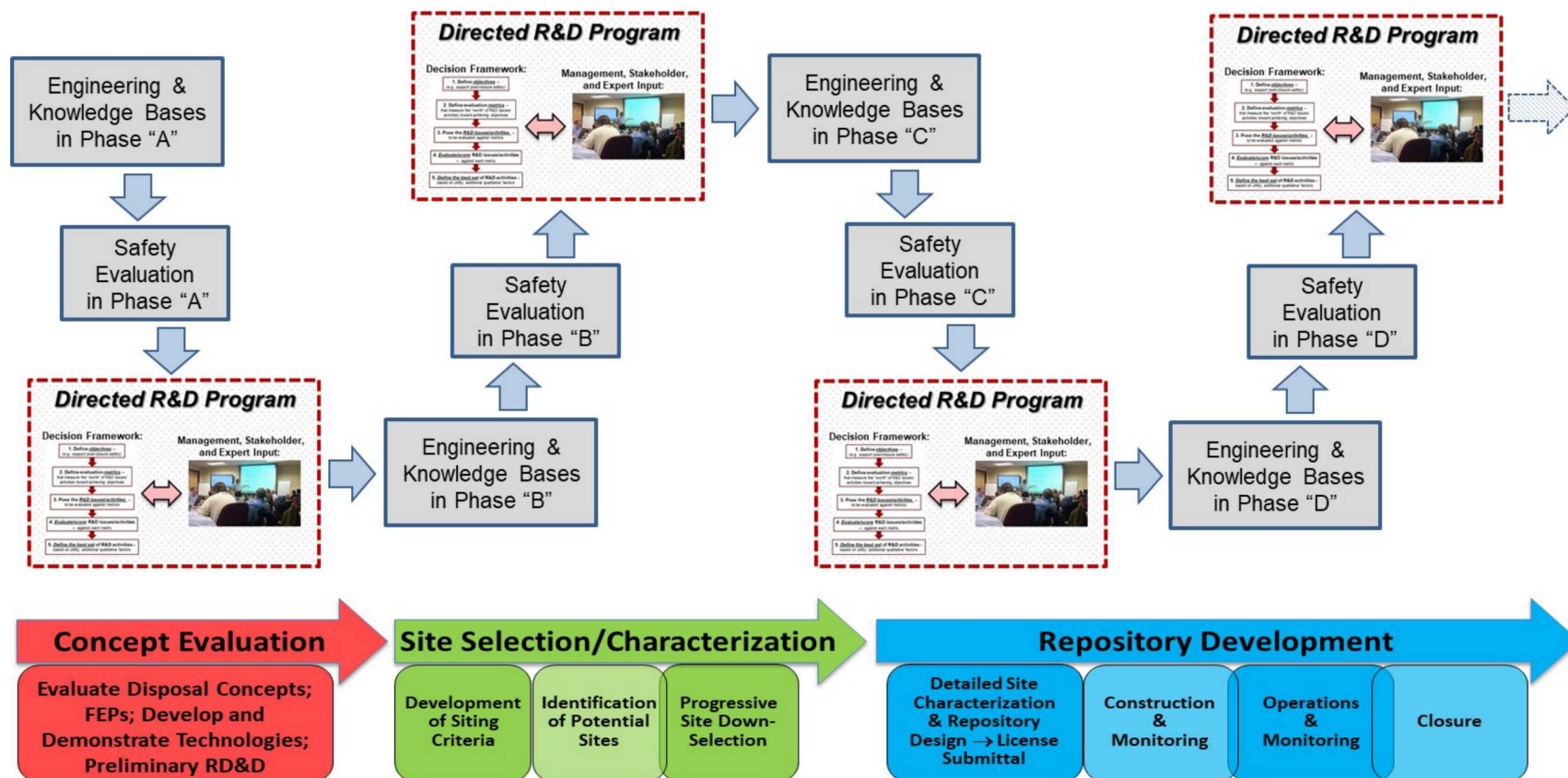


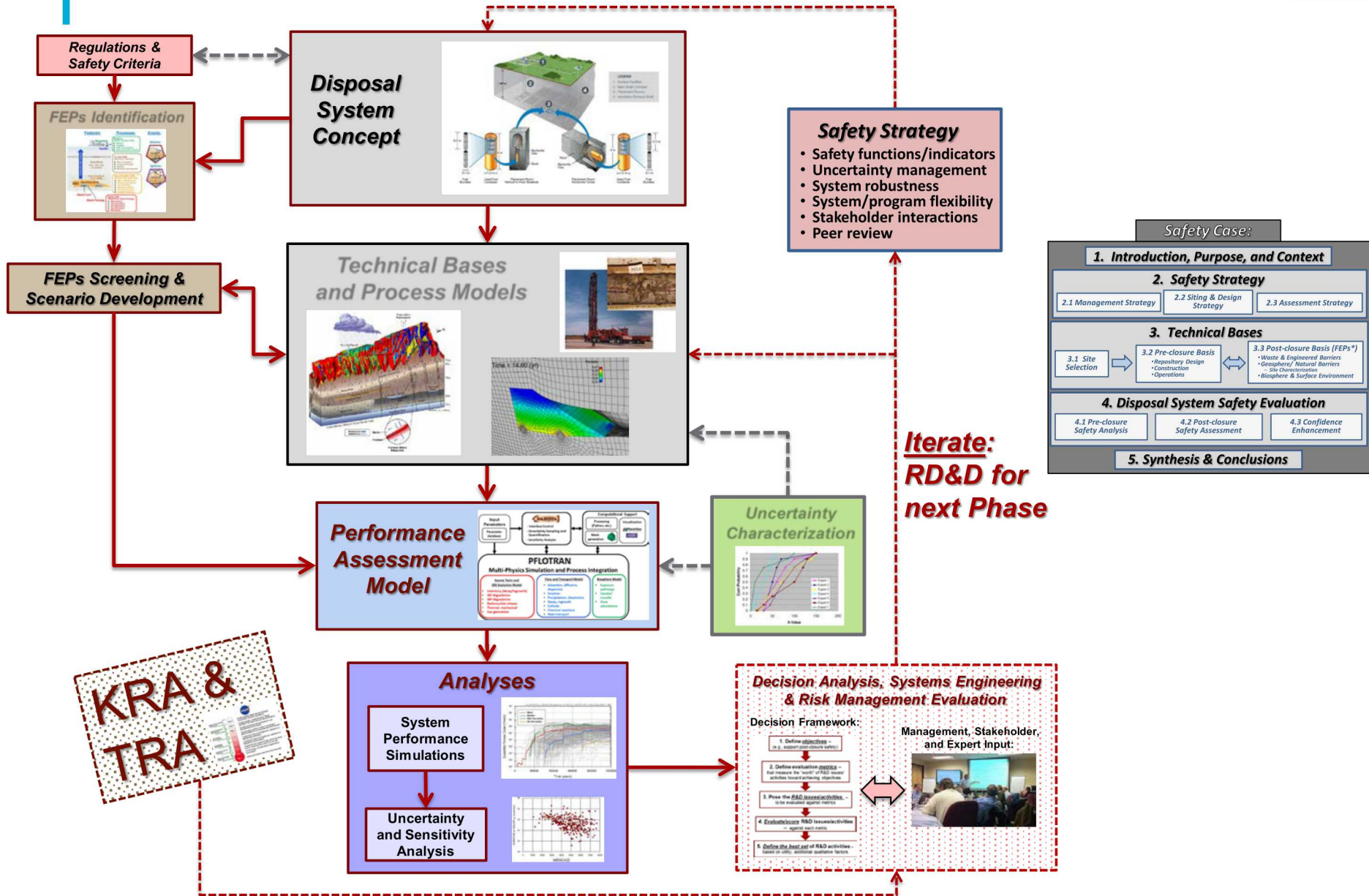
Iteration of Technical Bases (design & FEPs) with Safety Evaluation



■ How does safety confidence improve through time?

- Iteration of two major elements of the safety case—**technical bases** (engineering and knowledge) and **safety evaluation**
- Feeds directed R&D decisions/scope to reduce uncertainties and resolve “issues”





Safety Understanding Evolves Through “Issue Resolution” (or “Uncertainty Reduction”)



■ In a safety or licensing case, *all* outstanding “issues” must ultimately be addressed

- Designation of remaining R&D issues (or “uncertainties”) is based on inferences from the existing technical knowledge base — including lab, field, and *in situ* testing, as well as prior performance assessment modeling and process modeling
- During most phases of the safety case, finite resources (funding, personnel, time) require prioritization of R&D issues/activities
- For the Construction LA, it may be possible to simply acknowledge “remaining issues” with a plan to resolve them, e.g., YMP SAR Chapter 3, *Research and Development Program to Resolve Safety Questions*

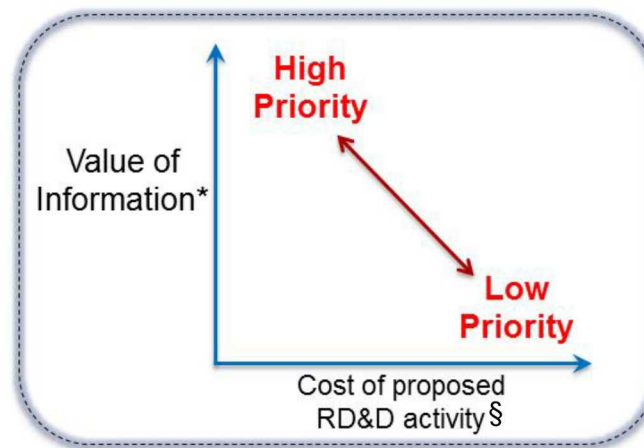
■ Typical broad R&D issue “categories”:

- Feature/process issues (FEPs) – “technical bases”
- Modeling issues
- Confidence-building issues
- *In-situ* design/operations/testing issues

R&D Issue/Activity Prioritization Process



- **Prioritization process can be formalized (e.g., 2012 UFD Disposal R&D Roadmap [Nutt, 2012])**
 1. Identify a set of **items** (or “quanta”) to be evaluated (e.g., options, activities, or issues)
 2. Identify **criteria** and associated **metrics** for assessing the set of items:
 - Potential to reduce key *uncertainties*, i.e., to change the SAL (or TRL)*
 - *Importance* to the safety case
 - Other factors, e.g., *cost*, redundancies and/or synergies
 3. **Evaluate** each R&D item against the metrics
 4. Define a “**utility function**” (or ranking function) to combine the metric values and produce an overall ranking or score for each R&D item



* SAL = State-of-the-Art Level

* TRL = Technology Readiness Level

§ Cost not formally considered in the 2019 Roadmap Update Workshop (Sevougian et al. 2019b)

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

Generic R&D “Completion” State



Two criteria for “ending” or transitioning to next phase:

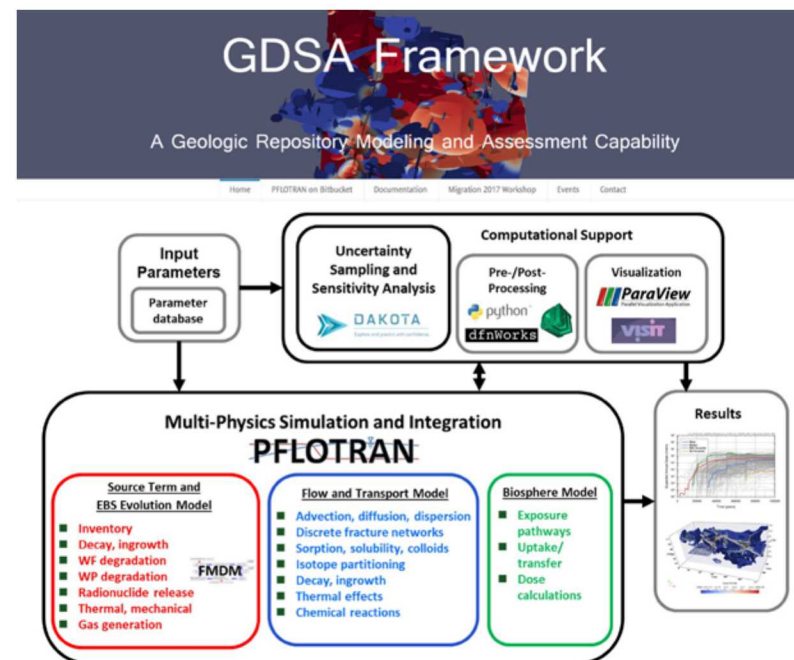
1. Change in State-of-the-Art Level (or Knowledge)

- R&D necessary to move the state-of-the-art to the next level (defined later in SAL table) for the given R&D item (i.e., activity) – analogous to a change in TRL*

* Sevougian and MacKinnon 2017. “Technology Readiness Assessment Process Adapted to Geologic Disposal of HLW/SNF” IHLRWM 2017, Charlotte, NC.

2. Time constraint:

- PA “baseline” capability: Process models and their implementation in the PA system model (*GDSA Framework*) will have a certain “fidelity” that allows for a full PA calculation, i.e., a PA simulation that includes important post-closure FEPs
- Achieved by a specified date on the repository timeline



A Recent Example of R&D Prioritization: 3-Day DOE-NE SFWST Roadmap Update Workshop*



Goals/Tasks of January Workshop:

- 1) Review pre-Workshop R&D Activities (i.e., the “items” to be evaluated and prioritized)—revise as warranted
- 2) Decide upon the SAL rating and its justification for each R&D Activity
- 3) Determine the generic R&D still needed to improve the SAL for each R&D Activity
- 4) Brainstorm and add “Gap” Activities, as appropriate
- 5) Decide upon the Importance to the Safety Case (ISC) rating and its justification for each assigned R&D Activity
- 6) Discuss ongoing and “unresolved” integration issues



* from Sevougian et al. (2019b)

R&D Activity Priority Score (using $ISC \times SAL$ product)



ISC (importance to safety case) value:

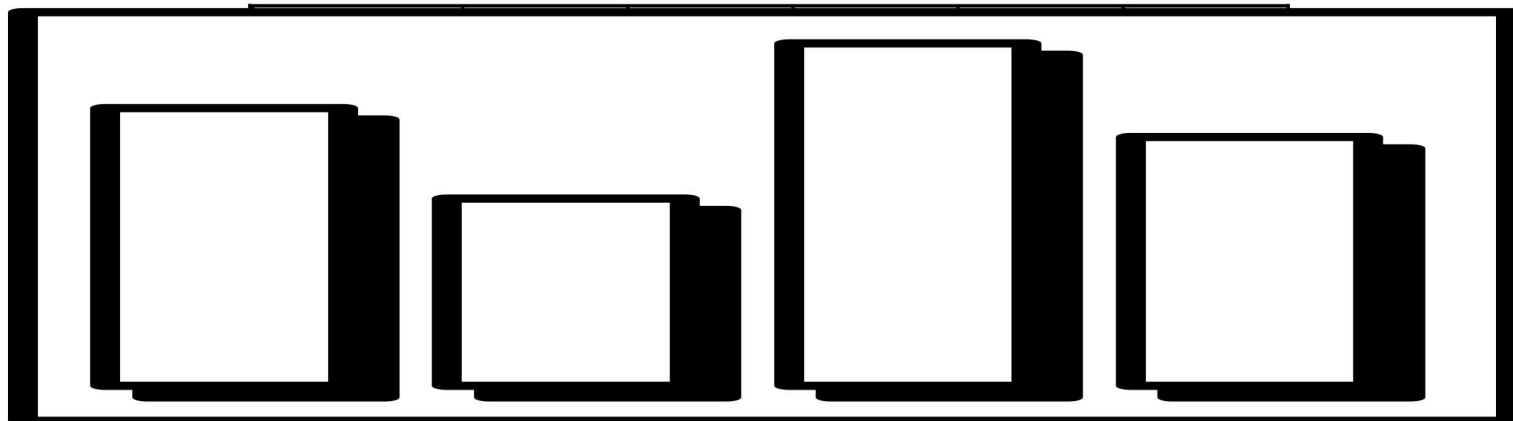
ISC Numerical Value	ISC Descriptive Value
5	<i>High Importance to SC</i>
3	<i>Medium Importance to SC</i>
1	<i>Low Importance to SC</i>

×

SAL (state of the art) value

SAL Numerical Value	SAL Descriptive Value
5	<i>Fundamental Gaps in Method or Fundamental Data Needs, or Both</i>
4	<i>Improved Representation</i>
3	<i>Improved Defensibility</i>
2	<i>Improved Confidence</i>
1	<i>Well Understood</i>

Final R&D Priority Score for an Activity

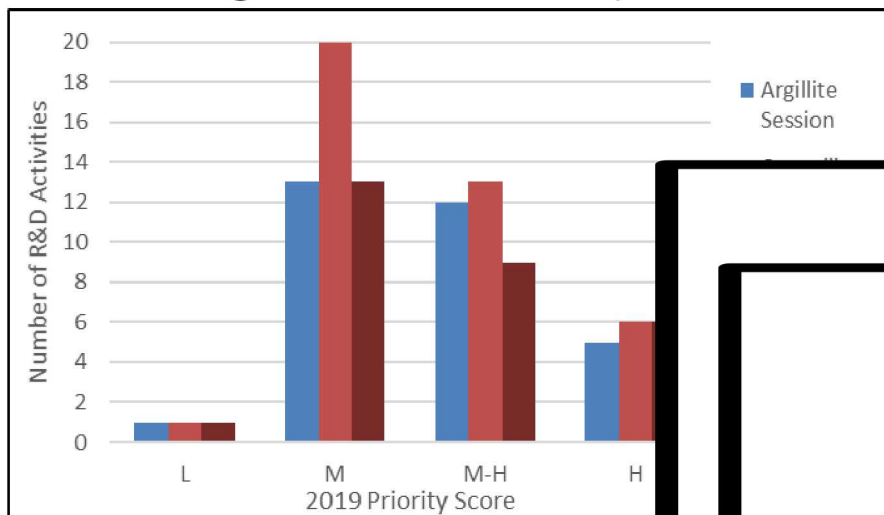


Sevougian et al. (2019b)

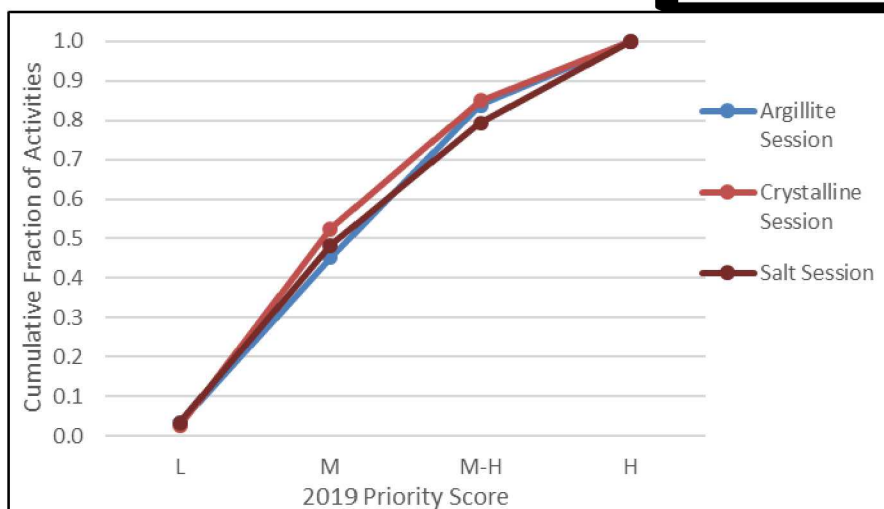
R&D Activity Priority Scores by Host-Rock Sessions



Histogram of R&D Activity Scores



Cumulative Fraction of R&D Activities



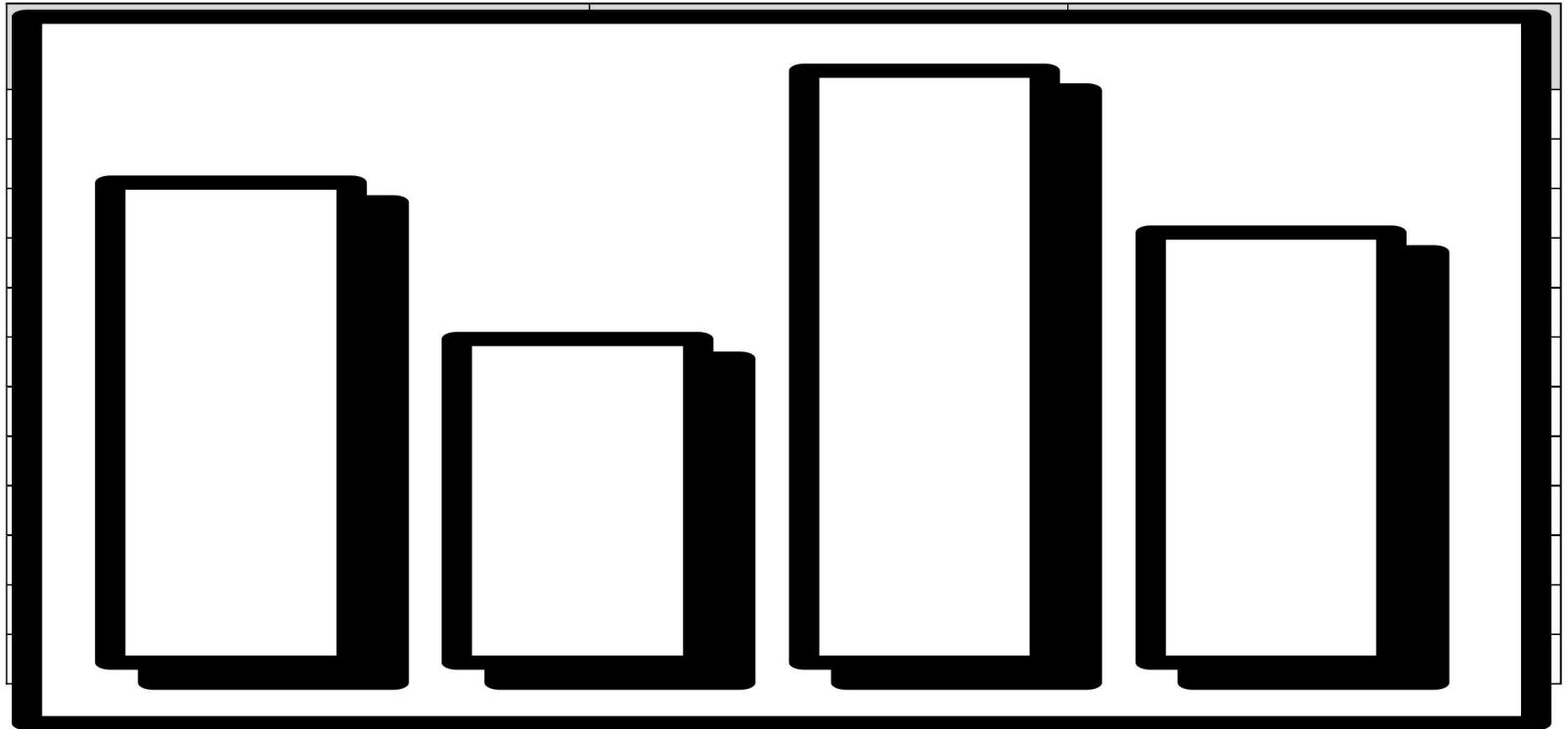
- Apparent uniformity of scoring among host-rock breakout groups
- Good “calibration” of the process?

Sevougian et al. (2019b)

“High Impact R&D Topics”



- Groupings of similar R&D Activities with High and Medium-High Priority Scores:



- Helpful snapshot of overall R&D program; can help focus future R&D work



Technological Readiness Assessment and the Safety Case



TRA – Another Potentially Important Role of the *Safety Case* in the U.S.

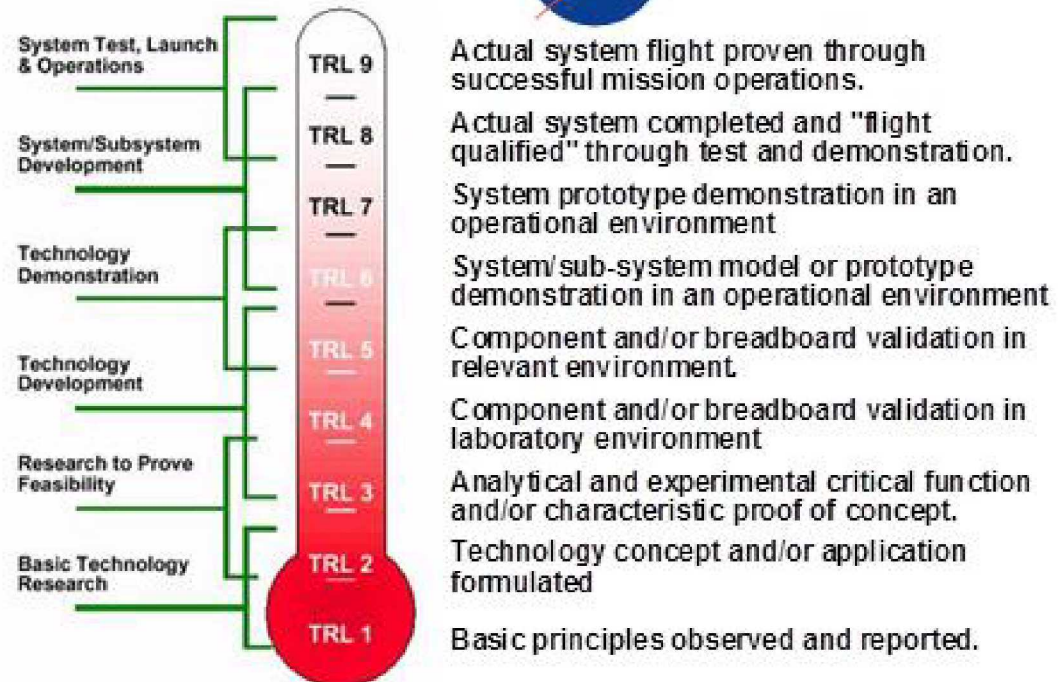
- The *Safety Case* is the internationally recognized vehicle to establish and document total system (i.e., repository) post-closure technical maturity at various development phases, including final deployment readiness
- However, what about existing U.S. DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*:
 - A **Technology Readiness Assessment (TRA)** is required prior to Critical Decision Point 2 (CD-2) for a Major System Project—one with a Total Project Cost (TPC) greater than or equal to \$750 M (see Table 2.2)
 - It is strongly encouraged for use by the Acquisition Executive for projects with a TPC less than \$750M.
 - **Technology Readiness Assessment.** An assessment of how far technology development has proceeded. It provides a snapshot in time of the maturity of technologies and their readiness for insertion into the project design and execution schedule.

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/deployment readiness
- The maturity “grade” assigned at any point in time is the **TRL** (**Technology Readiness Level**):

Original NASA TRL “Thermometer”



Some TRA History and Uses

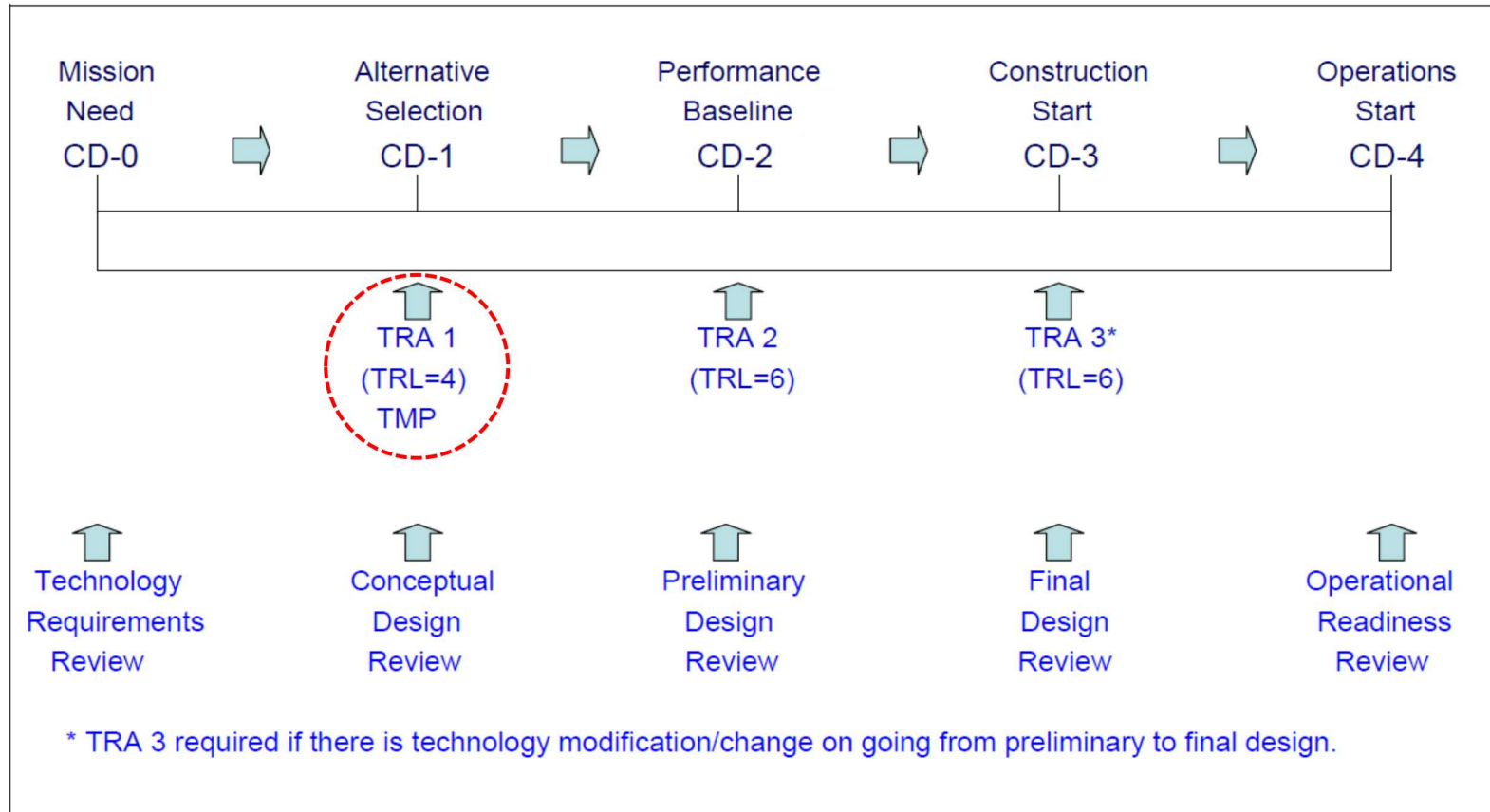


- Formally defined and used by NASA in 1989 but conceived by NASA in 1974: used to assess readiness of JPL Jupiter Orbiter spacecraft and many other projects
- Used by U.S. Air Force in the '90s
- In 1999 the U.S. GAO recommended that U.S. DoD adopt the TRA approach; resulted in the 2003 *DoD TRA Deskbook*
- 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 Geologic Repository Project) – for the construction and operations phases; the American Petroleum Institute (API 17N); and others

TRA Applicability vs. DOE Project Stage

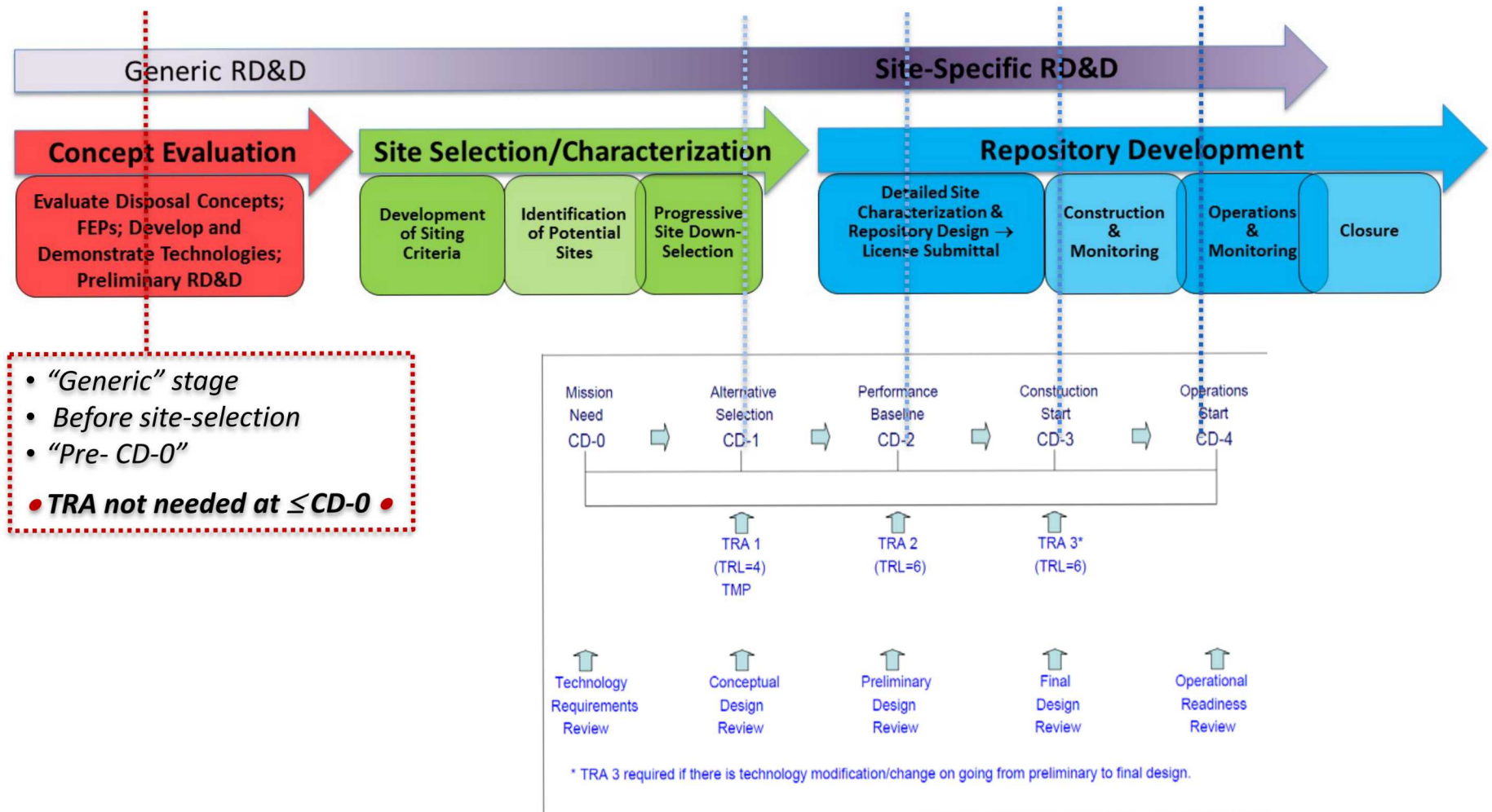


“Graded Approach” for TRAs (DOE TRA Guide 413.3-4A):



- ***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



Adaptation of the Usual TRA Process to Geologic Disposal 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; DOE-EM 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 (i.e., Critical Technical Elements (CTEs)) and the associated (sub)system
 - Use a KRA (Knowledge Readiness Assessment) metric to evaluate post-closure maturity, in part because of
 - Inherent (and irreducible) uncertainties in the natural system and the associated long-time evolution of natural processes

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

Repository KRA Process – Evaluate Readiness of Critical Technical Elements (CTEs)



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

- Use **Knowledge Readiness Level (KRL)*** metric, a “modified TRL” metric

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

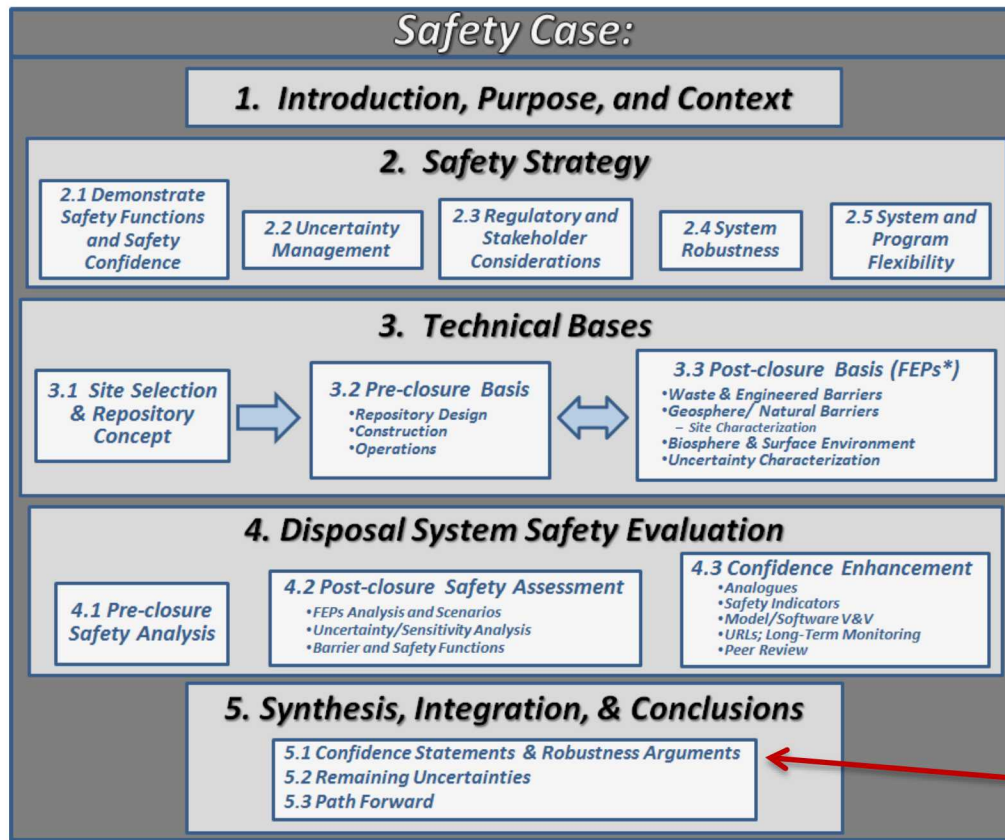
Knowledge Readiness Level	KRL Definition	Description
KRL 9	<i>Actual system operated over the full range of expected conditions</i>	Not feasible/applicable for a major post-closure geologic repository subsystem.
KRL 8	<i>Actual system completed and qualified through test and demonstration</i>	Not feasible/applicable for a major post-closure geologic repository subsystem.
KRL 7	<i>Full-scale, similar (prototypical) (sub)system demonstrated in a relevant environment</i>	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 until 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	<i>Engineering-scale, similar (prototypical) (sub)system operated in a relevant environment</i>	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	<i>Reduced-scale (sub)system validation in a relevant environment</i>	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	<i>Reduced-scale (sub)system validation in a simulated or generic environment</i>	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	<i>Analytical and/or experimental proof-of-concept investigations</i>	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	<i>Technology or knowledge application formulated</i>	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	<i>Basic principles observed and reported</i>	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.

* “KRL” first coined by NASA (Chiaramonte and Joshi, 2004), but for engineered systems and only at five levels, and not used since then.

Role of the Safety Case for Readiness of Total Geologic System

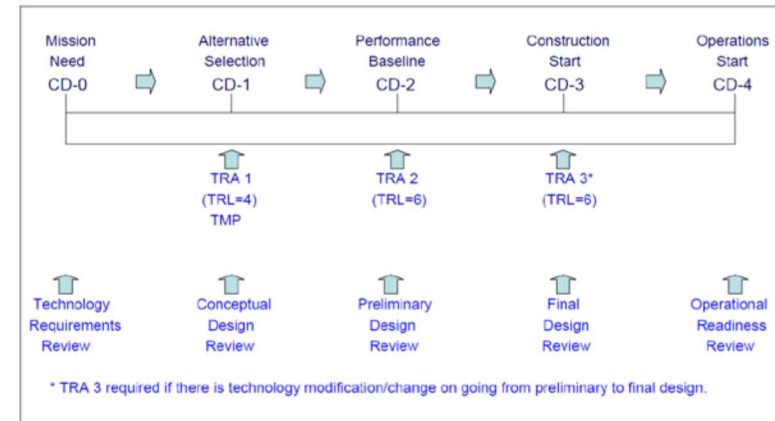


- The *Safety Case(s)* is the internationally recognized vehicle to establish and document *total system* (i.e., repository) post-closure technical maturity at various development phases, including final deployment readiness:



*FEP = Feature, Event, or Process

- TRAs/KRAs for a new geologic repository would be addendums to 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**

Discussion? Questions?



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Back-Up Slides

R&D Activity Access® Database

~ 100 R&D Activities



SFWST Integration REV00 : Database- C:\SDS data files\UFD\GDSA FY19\Roadmap Update Workshop Jan 2019\M2 Roadmap deliverable\SFWST Integration REV00.accdb (Access 2007)

File Home Create External Data Database Tools Tell me what you want to do

View Paste Cut Copy Filter Ascending Descending Selection Advanced Refresh All Delete More Find Replace Go To Select Text Formatting

SAVE CHANGES Save your changes to the server. Save to SharePoint Site

All Access Objects

Search...

Tables
Queries
Forms

Data - All Activities

Data - New or Selected Activities

Map FEPs to All Activities

Map FEPs to Selected Activity

Reports

Activities Binned by Score

Activities w/Related FEPs

Activity Comments

Activity Descriptions

Activity Descriptions w/o PICS

Activity Descriptions, Scores, etc

Activity Roadmap Session

Activity Scores, Rationale, & R&D

FEPs w/Arg-Related Activities

FEPs w/Crys-Related Activities

FEPs w/Related Activities

FEPs w/Salt-Related Activities

FEPs without Activities

H/M FEPs without Activities

H/M FEPs without Current Activities

Activity Information

1. Scroll (◀▶) to Activity record (at bottom of window ↓)
2. Modify as needed or append a new record
3. Save/close by right clicking on Data window tab

Act. ID: A-04 Activity Name: Argillite Coupled THM processes modeling including host rock, EBS, and EDZ (TOUGH-FLAC)

Description

- Coupled thermal-hydrological-mechanical processes in Argillite host rock repository, including EBS (bentonite and backfill), and excavation disturbed zone (EDZ)
- Integration with GDSA/PA

Personnel/Labs	Type (L, PA, ...)	Codes	Safety Case Elem.	Status	Level of Effort	Time Frame
Gap Activity Rutqvist, Xu LBNL	PM, MA	TOUGH-FLAC	SC elements 3.3, 4.2, & 4.3	H	M - F	

SAL 4

SAL Rationale

The basic framework for these modeling activities is the TOUGH-FLAC simulator. This basic framework has been modified to incorporate Bentonite and Shale constitutive models, i.e. BBM and BExM. EDZ models have been developed including:

- Empirical stress-permeability model
- Non-linear elastic and brittle failure model
- Anisotropic continuum damage model

These models are being validated by activities evaluating data from the Mont Terri FE

R&D Needed

FY19 workscope: R&D for (1) confident modeling bentonite dual-structure behavior on permeability and resaturation, (2) confident modeling of EDZ evolution, including long-term sealing and healing and (3) model development for gas migration in bentonite and clay host rocks. Continued model validation of large scale field experiments related to international activities (Mont Terri Project and DECOVALEX 2019). Expand for modeling of fault activation and fluid migration along faults. Linking of new TOUGH3 code with new FLAC3D V6 for more efficient simulations.

ISC High

ISC Rating Rationale

PICS WBS and WP Numbers

1.08.01.03.01 SF-19LB01030103 Argillite Disposal R&D – LBNL1.08.01.03.01 SF-19LB01030107 Rev 0 Argillite International Collaborations – LBNL1.08.01.03.08 SF-19LB01030802 Rev 0 Engineered Barrier System R&D – LBNL

Deliverables

Comments

- Response surface suggested (permeability and porosity fields/surfaces for EDZ and backfill).
- Cross-cuts with EBS & GDSA integration needed

Prioritization Metrics: SAL and ISC



- The breakout group chairs and the R&D work-package technical leads made a pre-Workshop draft of ISC and SAL values and rationales

- There was an initial cut only – to facilitate discussion
- The main task for Workshop participants was to reach consensus on SAL and ISC in the breakout sessions

■ State-of-the-Art Level (SAL):

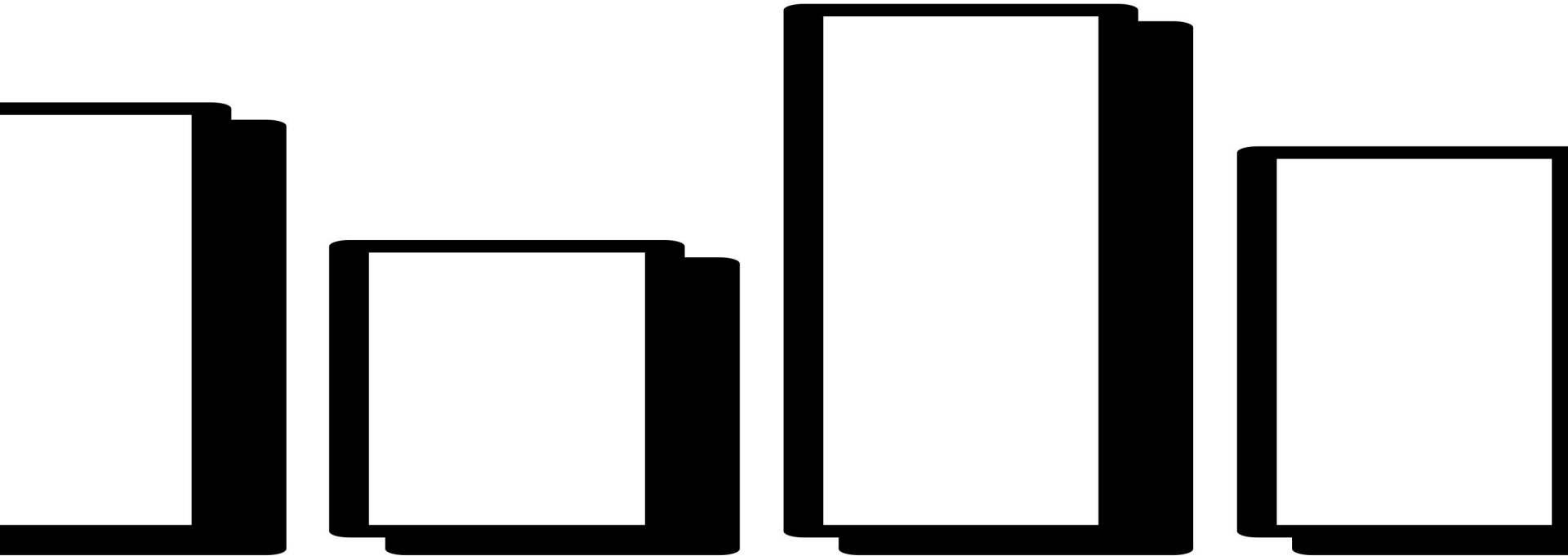
- five SAL or knowledge levels, based fairly closely on the “State-of-the-Art” categories used in the original 2012 Roadmap, but simplified and scaled

SAL Numerical Value	SAL Descriptive Value
5	<i>Fundamental Gaps in Method or Fundamental Data Needs, or Both</i>
4	<i>Improved Representation</i>
3	<i>Improved Defensibility</i>
2	<i>Improved Confidence</i>
1	<i>Well Understood</i>

■ Importance to the Safety Case (ISC):

ISC Numerical Value	ISC Descriptive Value
5	<i>High Importance to SC</i>
3	<i>Medium Importance to SC</i>
1	<i>Low Importance to SC</i>

Importance to the Safety Case – ISC Metric Table





Safety Case Components

1. Introduction, Purpose, and Context

2. Safety Strategy

2.1 Management Strategy

- a. Organizational/mgmt. structure
- b. Safety culture & QA
- c. Planning and Work Control
- d. Knowledge management
- e. Oversight groups

2.2 Siting & Design Strategy

- a. National laws
- b. Site selection basis & robustness
- c. Design requirements
- d. Disposal concepts
- e. Intergenerational equity

2.3 Assessment Strategy

- a. Regulations and rules
- b. Performance goals/safety criteria
- c. Safety functions/multiple barriers
- d. Uncertainty characterization
- e. RD&D prioritization guidance

3. Technical Bases

3.1 Site Selection

- a. Siting methodology
- b. Repository concept selection
- c. FEPs Identification
- d. Technology development
- e. Transportation considerations
- f. Integration with storage facilities

3.2 Pre-closure Basis

- a. Repository design & layout
- b. Waste package design
- c. Construction requirements & schedule
- d. Operations & surface facility
- e. Waste acceptance criteria
- f. Impact of pre-closure activities on post-closure

3.3 Post-closure Bases (FEPs)

3.3.1 Waste & Engineered Barriers Technical Basis

- a. Inventory characterization
- b. WFI/WP technical basis
- c. Buffer/backfill technical basis
- d. Shafts/seals technical basis
- e. UQ (aleatory, epistemic)

3.3.2 Geosphere/Natural Barriers Technical Basis

- a. Site characterization
- b. Host rock/DRZ technical basis
- c. Aquifer/other geologic units technical basis
- d. UQ (aleatory, epistemic)

3.3.3 Biosphere Technical Basis

- a. Biosphere & surface environment:
 - Surface environment
 - Flora & fauna
 - Human behavior

4. Disposal System Safety Evaluation

4.1 Pre-closure Safety Analysis

- a. Surface facilities and packaging
- b. Mining and drilling
- c. Underground transfer and handling
- d. Emplacement operations
- e. Design basis events & probabilities
- f. Pre-closure model/software validation
- g. Criticality analyses
- h. Dose/consequence analyses

4.2 Post-closure Safety Assessment

- a. FEPs analysis/screening
- b. Scenario construction/screening
- c. PA model/software validation
- d. Barrier/safety function analyses and subsystem analyses
- e. PA and Process Model Analyses/Results
- f. Uncertainty characterization and analysis
- g. Sensitivity analyses

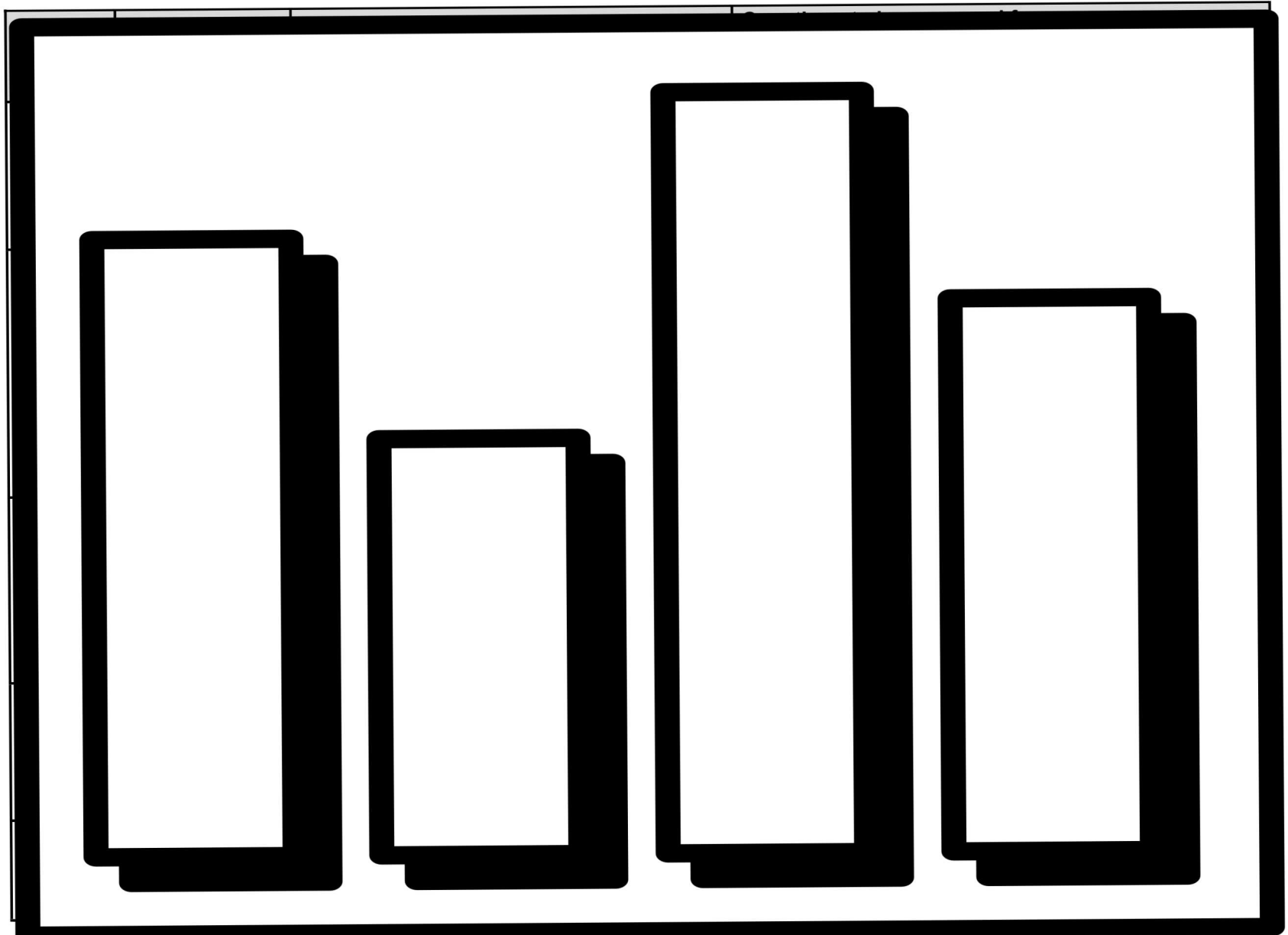
4.3 Confidence Enhancement

- a. R&D prioritization
- b. Natural/anthropogenic analogues
- c. URL & large-scale demonstrations
- d. Monitoring and performance confirmation
- e. International consensus & peer review
- f. Verification, validation, transparency
- g. Qualitative and robustness arguments

5. Synthesis & Conclusions

- a. Key findings and statement(s) of confidence
- b. Discussion/disposition of remaining uncertainties
- c. Path forward

SAL Metric Table



Some Workshop Results – Expert Consensus on SAL and ISC Values



ID (*gap) Activity

Microsoft Access® Database

2019
Score
M-H

E-03 *THC processes in EBS*

Desc • Engineered barrier (metal-clay-rock) material interactions & experimental data
• Modeling (thermodynamic & reactive transport) Includes temperatures relevant to DPC. Provide chemical constraints for SNF degradation/radionuclide transport.

Type PM, LT, EA

Codes PFLOTRAN, CHNOSZ, EQ3/6

Elements SC element 3.3.1, 4.2 b, 3.2

ISC High

Rationale High importance for design/construction arguments affecting disposal system design that utilize backfill/buffer as an engineered barrier and potential generation of preferential pathways through the EDZ- Note this source term model/testing is more important in crystalline case; less important in case of Salt concept AND NOT directly applicable in brine conditions

SAL 4 Improved Representation

Rationale • Chemical processes still under development, particularly at elevated temperature conditions.
• Gained improved understanding of phase mineralogy & modeling methods.

R&D Needed May be of high importance for performance in certain environments and disposal concepts that utilize backfill/buffer as an engineered barrier - governs "source term" release upon failure of waste packages for certain designs in certain environments.
High importance for design/construction - could effect disposal system design that utilize backfill/buffer as an engineered barrier, how it is constructed, and emplacement of waste and backfill/buffer (i.e., size of waste packages and spacing).
High importance for overall confidence - secondary isolation barrier and long-term barrier performance.

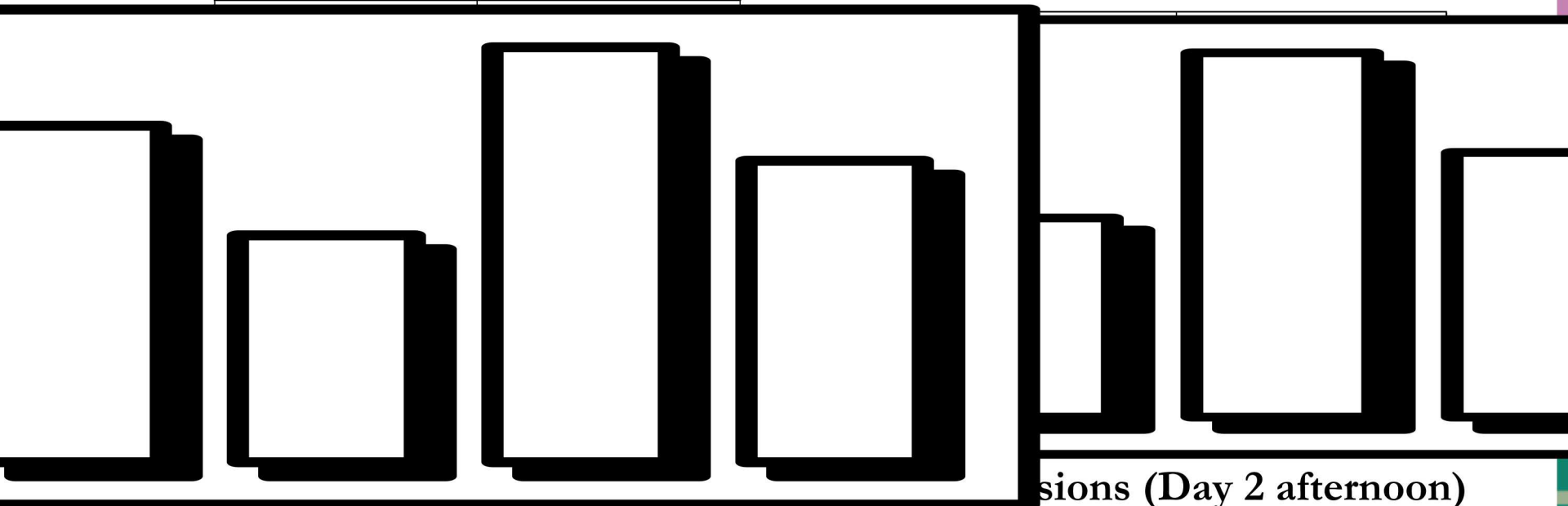
Some Workshop Results – R&D Activity Count



- Three host-rock breakout sessions in January workshop (also considered EBS, International, DPC, and PA activities relevant to their host rock concept):

Number of R&D Activities included in each
R&D Activity “Group” or Type (e.g., EBS)

Number of R&D Activities considered
in each host-rock breakout session

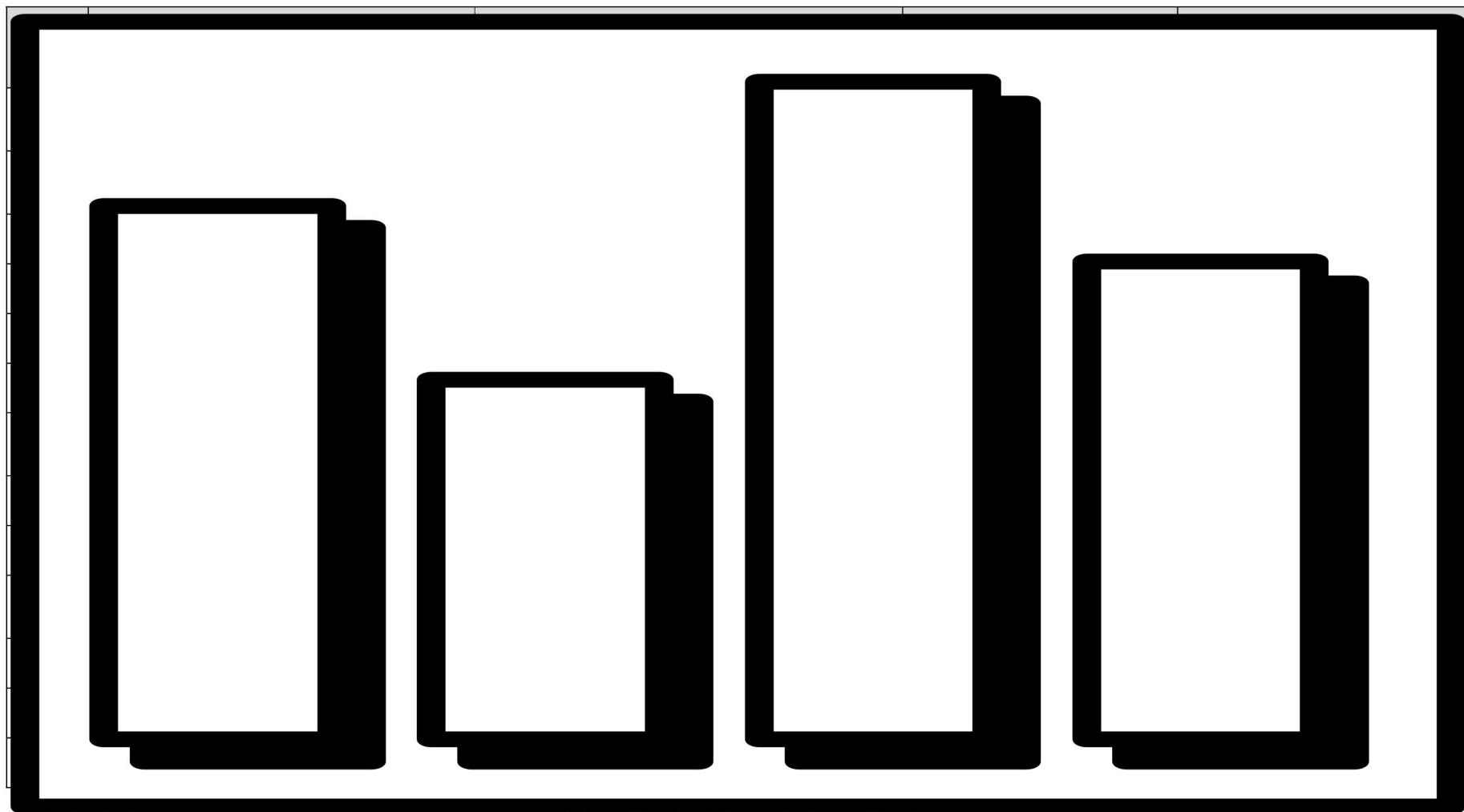


resolved different ISC and SAL values for their R&D Activities, given in the three host-rock sessions, if any

Evolution of State-of-the-Art Knowledge



- Comparison of 2012 “State-of-the-Art” (for “primary FEPs”) with 2019 SAL Values for R&D Activities:



Some Workshop Results – Expert Consensus on SAL and ISC Values



ID (*gap) Activity

Microsoft Access® Database

2019
Score
M-H

E-03 *THC processes in EBS*

Desc • Engineered barrier (metal-clay-rock) material interactions & experimental data
• Modeling (thermodynamic & reactive transport) Includes temperatures relevant to DPC. Provide chemical constraints for SNF degradation/radionuclide transport.

Type PM, LT, EA

Codes PFLOTRAN, CHNOSZ, EQ3/6

Elements SC element 3.3.1, 4.2 b, 3.2

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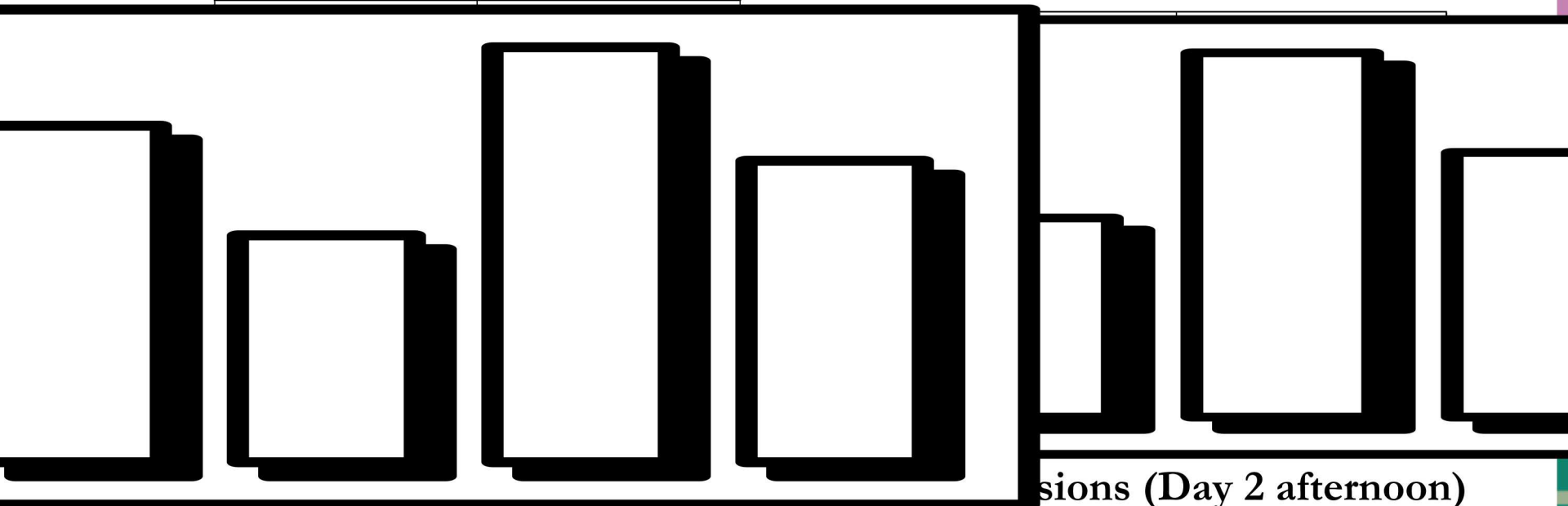
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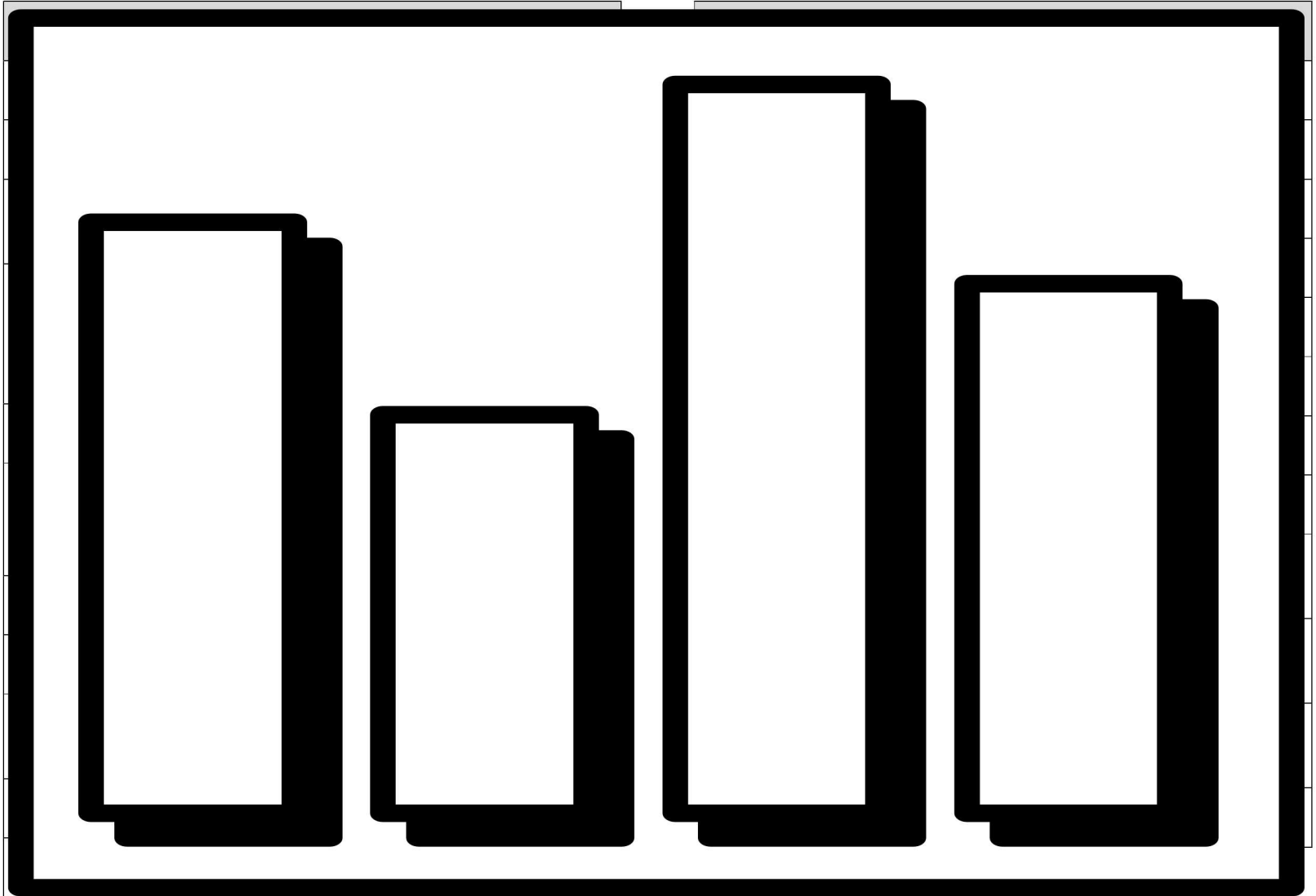
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R&D Activity “Group” or Type (e.g., EBS)

Number of R&D Activities considered
in each host-rock breakout session

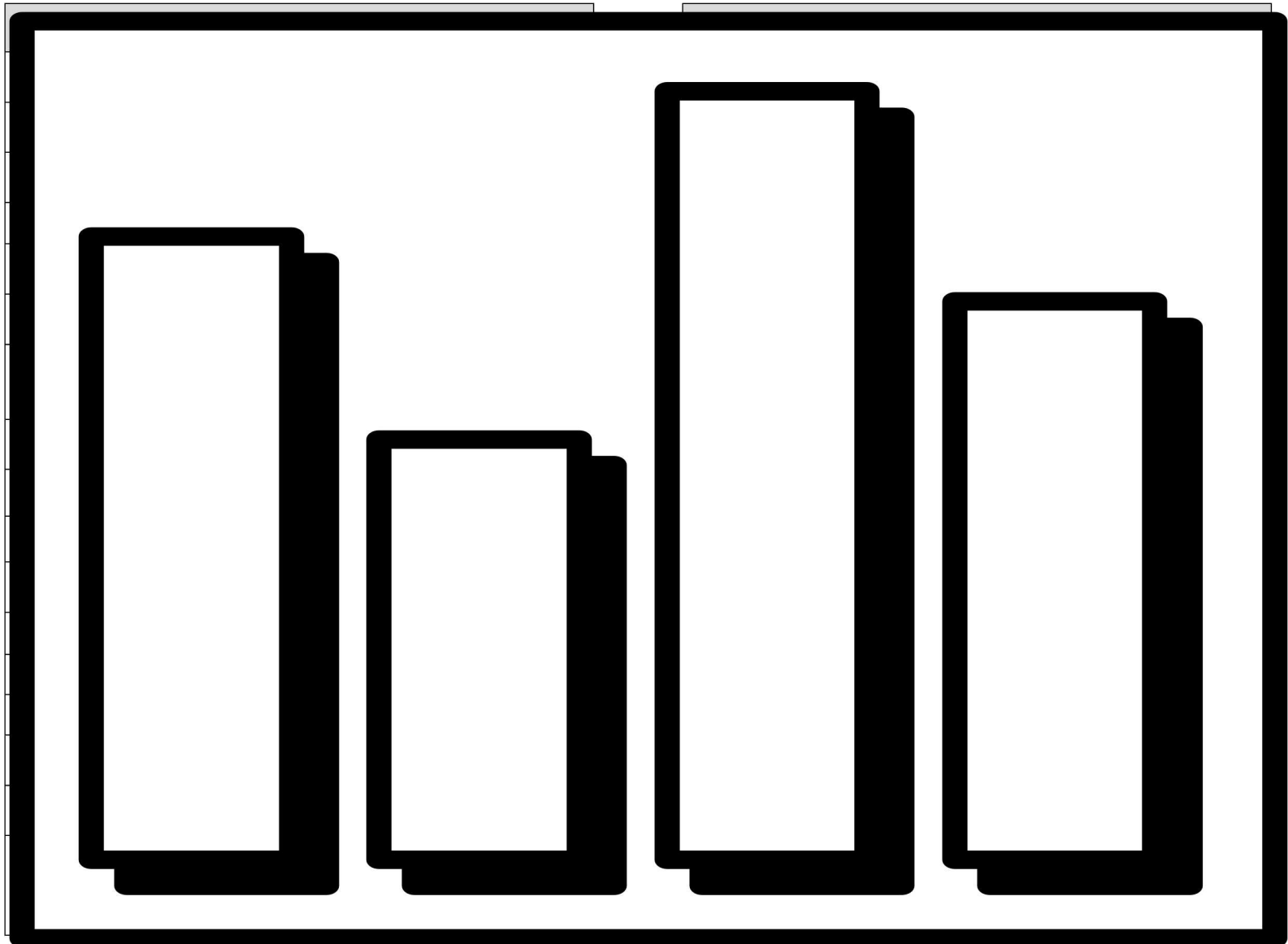


resolved different ISC and SAL values for their R&D Activities, given in the three host-rock sessions, if any

High-Priority R&D Activities



Medium-High-Priority R&D Activities



Some Insights (continued)



■ Completeness check (2012 FEPs vs. 2019 R&D Activities):

- A number of High and Medium priority FEPs from 2012 Roadmap do NOT map to current R&D Activities – nineteen in total
- Nine of these are for “Other Geologic Units,” meaning they are site-specific and cannot really be addressed in a generic R&D program
- The other ten are either “Host Rock” or “Host Rock and Other Geologic Units,” which again are mostly site-specific
 - But most of these ten FEPs are related to chemistry and solubility, which are being incorporated into the Campaign’s generic reference cases via literature searches

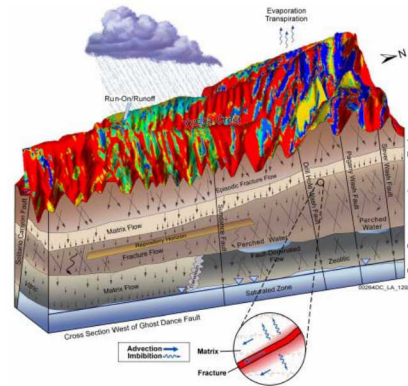
■ Thus, we did a “good job” since 2012 in addressing important FEPs in our R&D program

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:

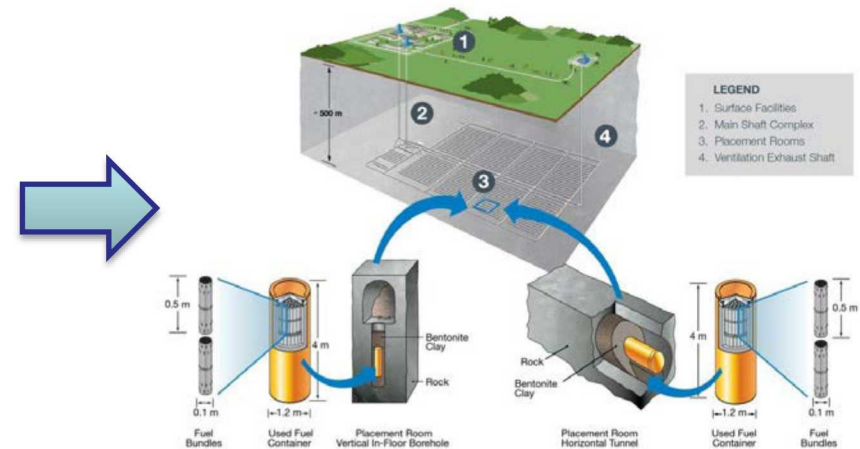
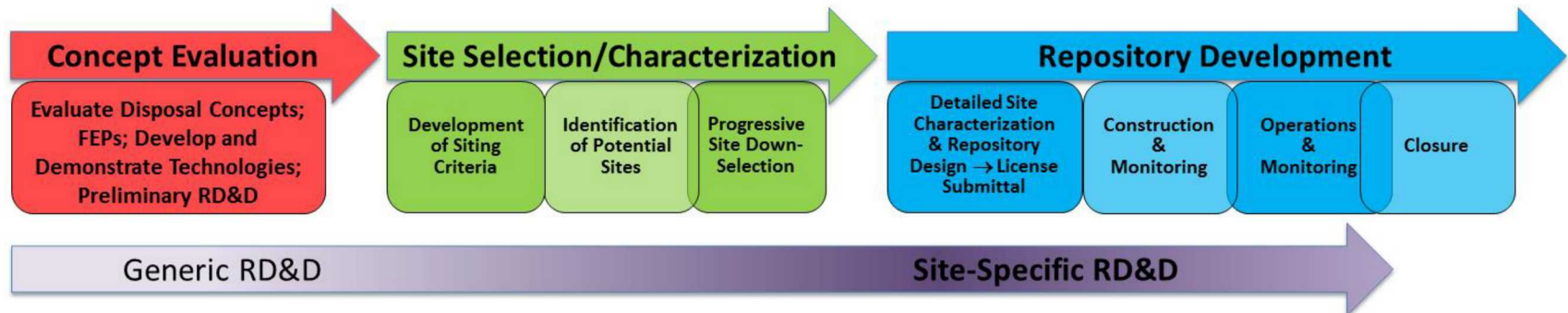


Figure Source: <https://www.cnsccsn.gc.ca/enq/waste/high-level-waste/cnsc-role-in-nwmo-apm-project/index.cfm>

Deep Geologic Repository Development Timeline



Major Steps of TRA Process

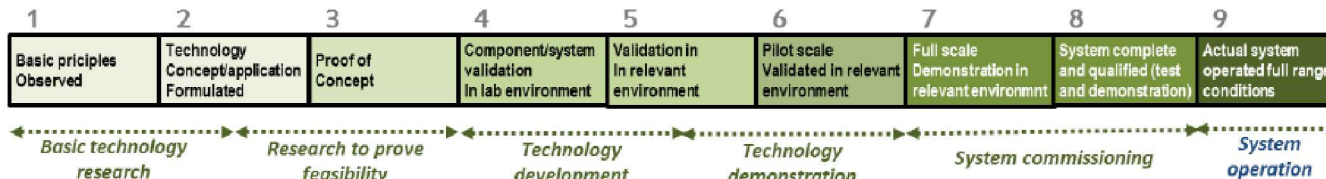
DOE (U.S. Department of Energy) 2011. Technology Readiness Assessment Guide, DOE G 413.3-4A, 9-15-2011, Fig. 4a, U.S. Department of Energy, Washington, D.C. 20585, www.directives.doe.gov

1. Identify:

- Technology system or subsystem to be considered
- Critical technical elements (CTEs)* of the considered (sub)system

2. Evaluate (or assess):

- Assign a TRL for each CTE:



EARTO (European Association of Research and Technology Organisations) 2014. The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations, Rue Joseph II 36-38, 1000 Brussels, Belgium
http://www.earto.eu/fileadmin/content/03_Publications/The_TRL_Scale_as_a_R_I_Policy_Tool_-_EARTO_Recommendations_-_Final.pdf

- Assign a system readiness level (SRL)

3. Plan (or evolve):

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

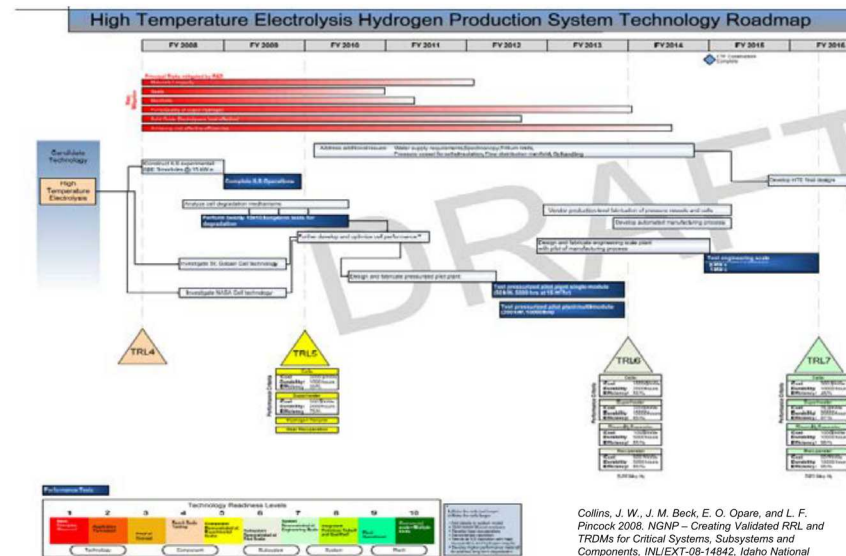
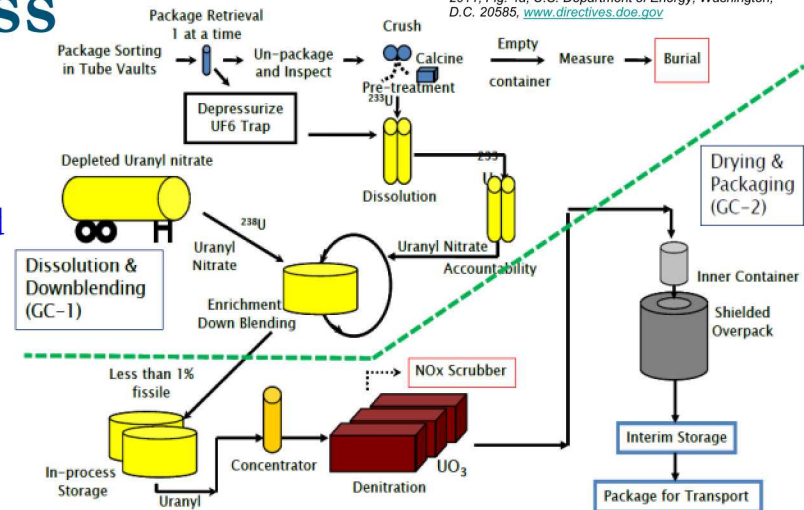


Figure B-2. HTE Hydrogen Production Technology Development Roadmap

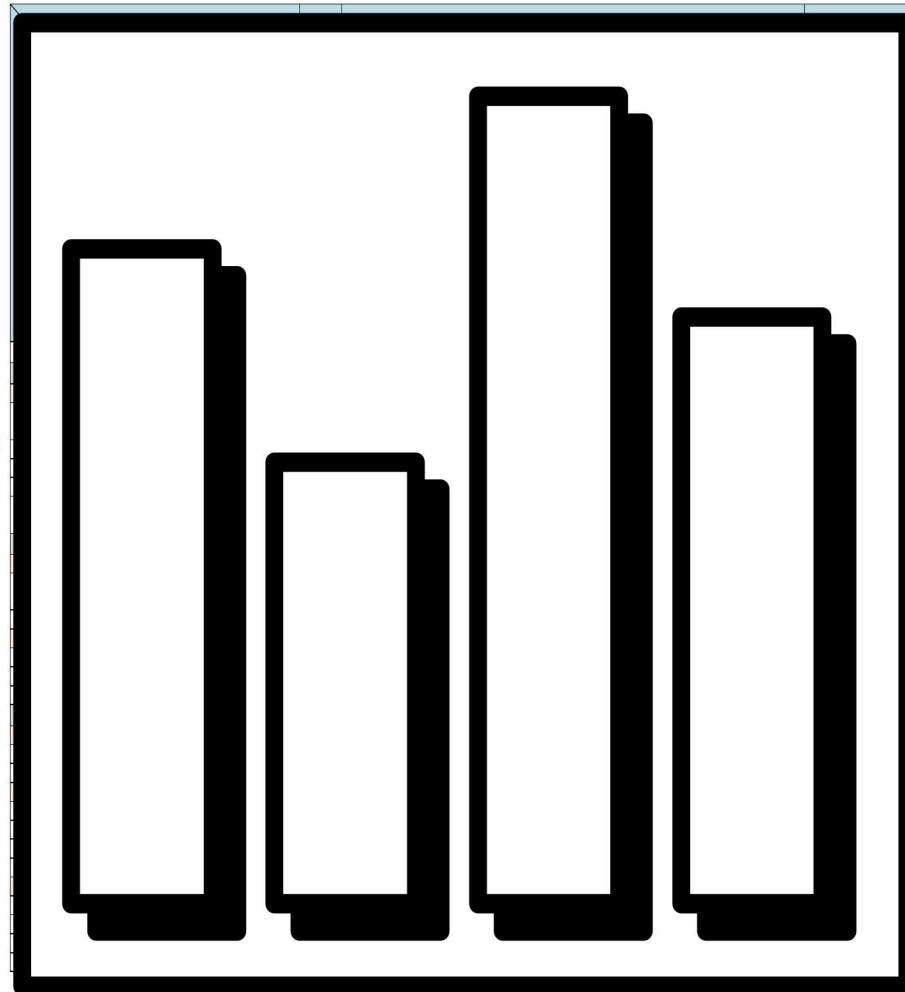
Collins, J. W., J. M. Beck, E. O. Opare, and L. F. Pincock 2008. NGNP - Creating Validated RRL and TRDMs for Critical Systems, Subsystems and Components. INL/EXT-08-14942. Idaho National Laboratory, Idaho Falls, Idaho 83415, September 2008.

Repository TRA/KRA Process – “Identify CTEs”



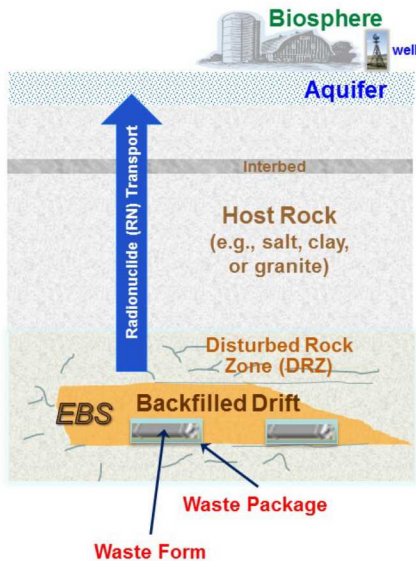
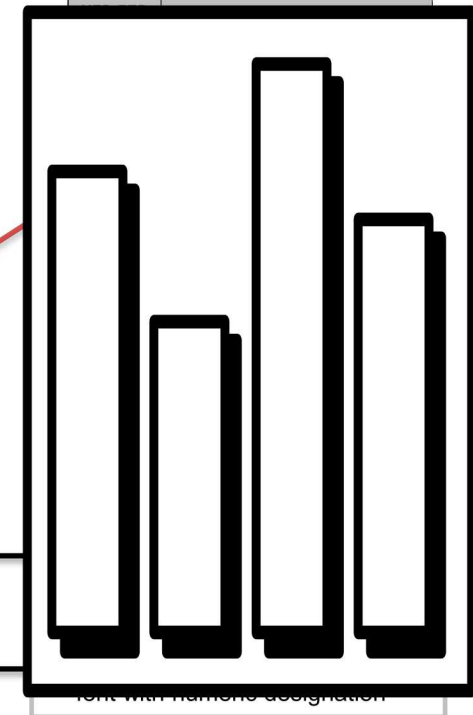
- Use the Features, Events, and Processes (FEPs) approach to *identify* both CTEs and candidate *subsystems*, for maturity evaluation:

FEP Matrix:



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”



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



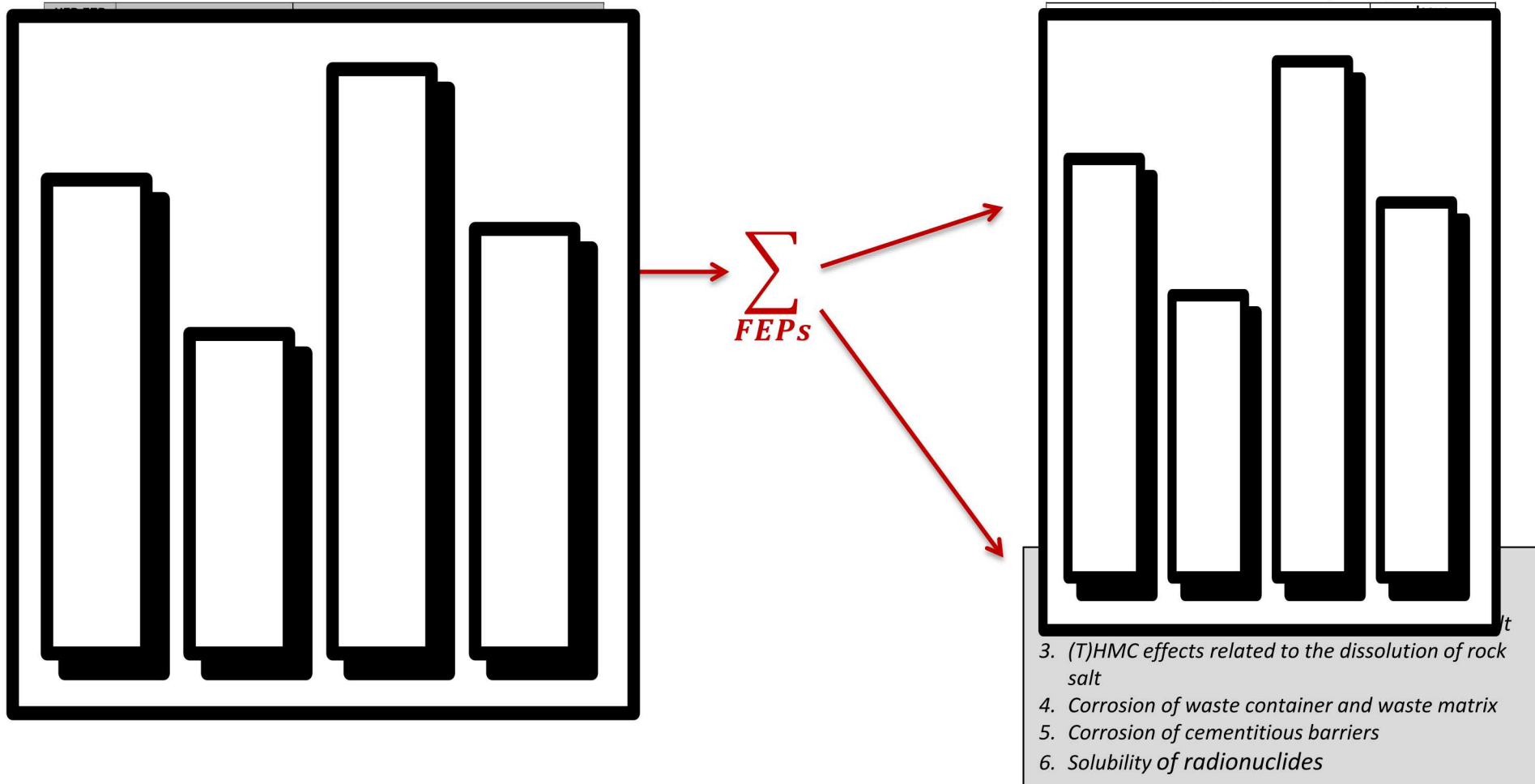
Step 1. High-level (conservative) CTE identification pass based on **either**:

a. All individual FEPs:

or

b. “Rolled-up” FEPs/issues or topics:

Sevougian et al. (2013):



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



Step 2. Detailed CTE identification pass, based on *importance* of CTE (i.e., FEP, “RD&D issue”, or “topic”) to post-closure performance:

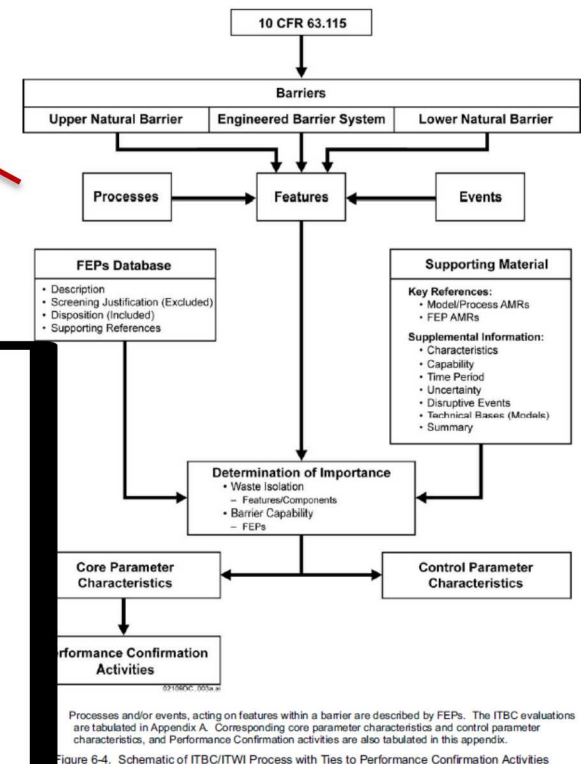
a. Importance to post-closure safety (ITPS), i.e., to *safety functions*, such as isolation, containment, delayed/limited releases (Sevougian and MacKinnon 2014):

Importance
of RD&D Issue

$$= \text{Impact of RD\&D Issue on a Safety Function} \cup \text{Function Level of the Safety Function}$$

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

or **c. Importance to the Safety Case (ISC)**—see SFWST R&D Roadmap Update (Sevougian et al. 2019b):



Typical TRA Process – “Evaluate CTEs”



Common two-step CTE evaluation procedure for engineered technologies:

1. High-level pass (initial guess) 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:

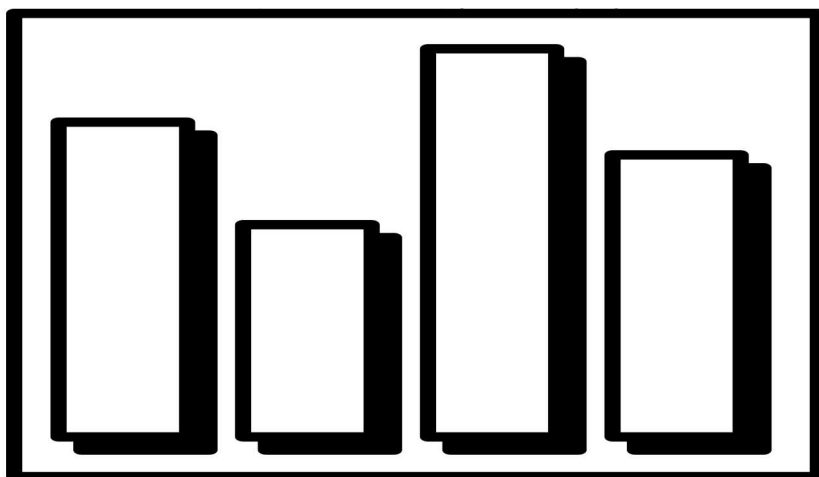


Table 1 Technology Readiness Levels

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.

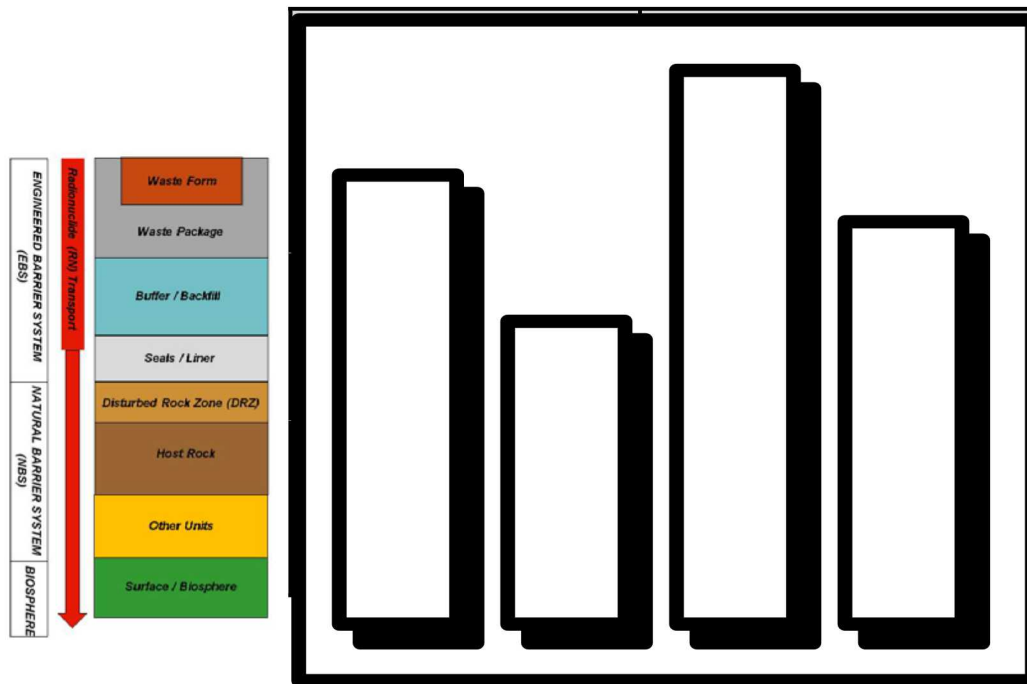
Repository TRA/KRA Process – “Evaluate CTEs”



- 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 in large degree 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



EBS = Engineered Barrier System

DRZ = Disturbed Rock Zone

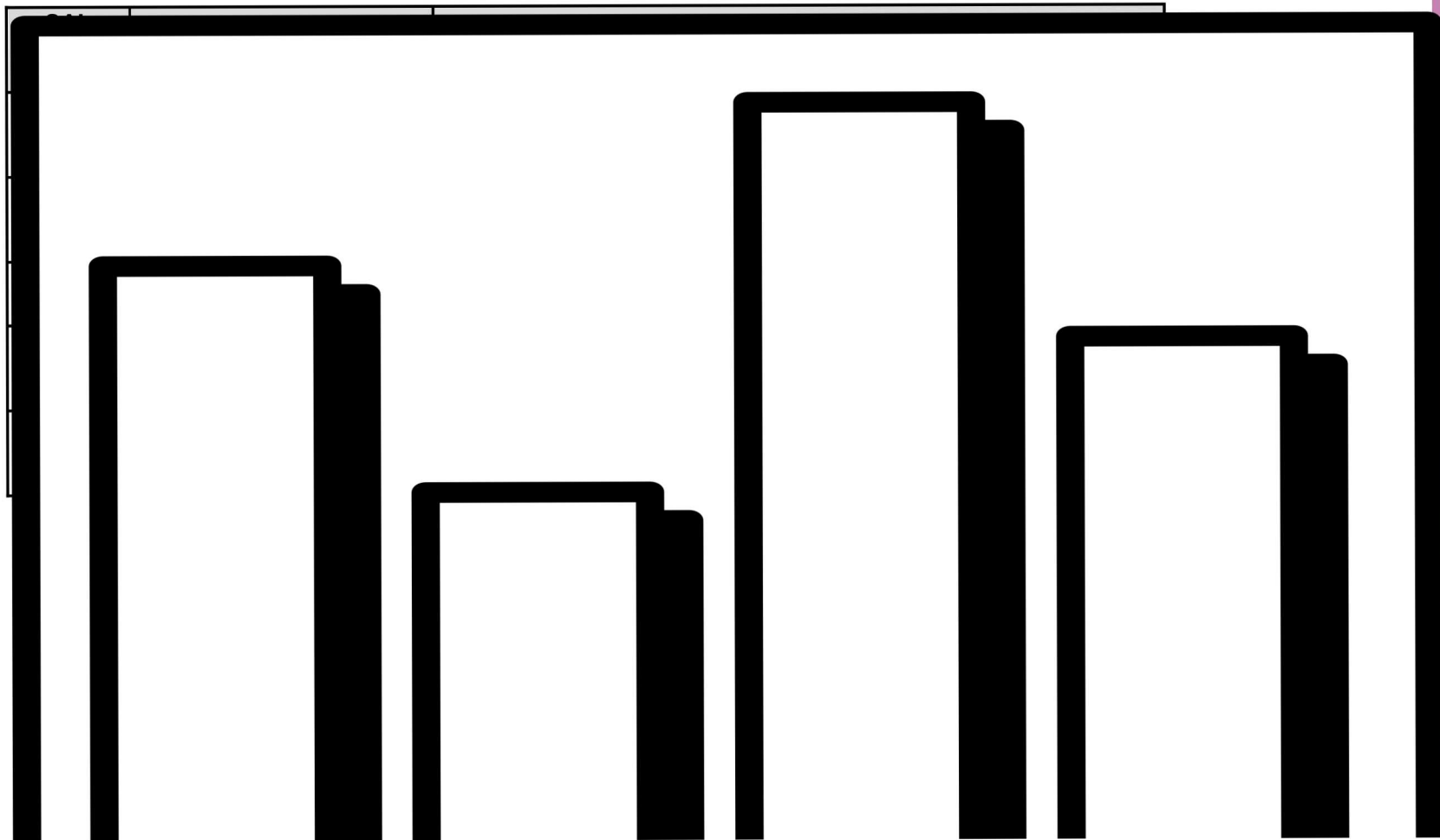
NBS = Natural Barrier System

to assess the maturity of a given technology, component, or system from a manufacturing perspective (Fernandez 2010).

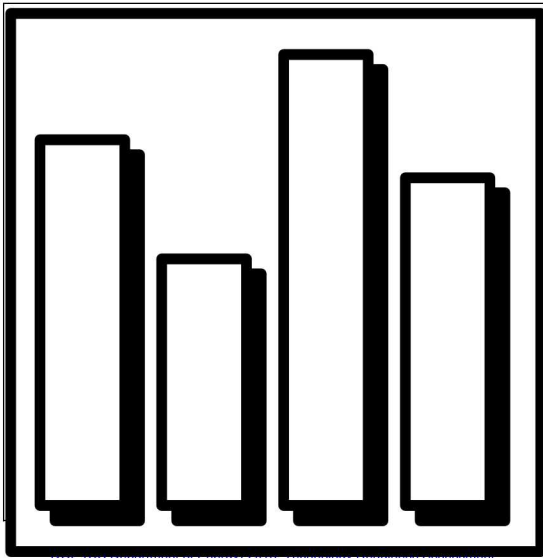


1. **Alternative** for *high-level* CTE evaluation pass:

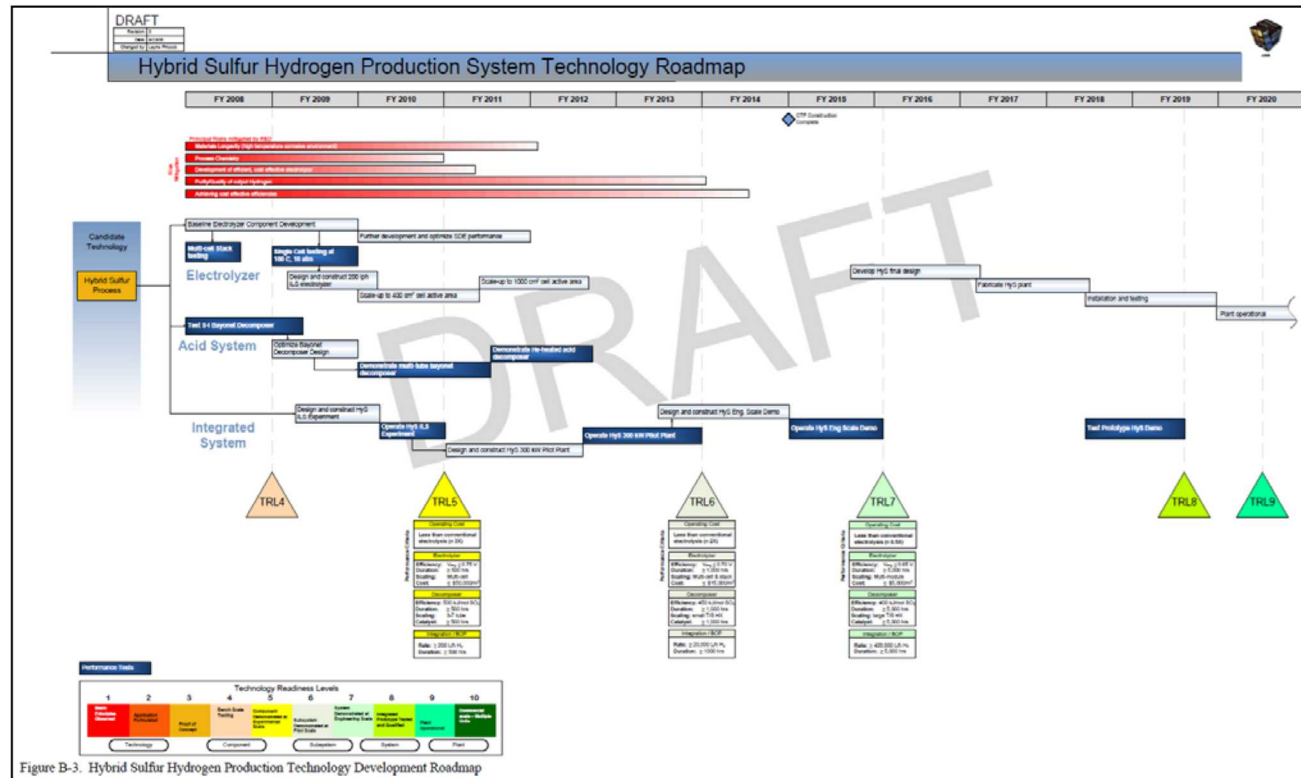
- As a simpler alternative to KRLs, one could possibly use the “state-of-the-art” knowledge scale (“SAL”)—from the 2019 SFWST Roadmap Update:



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):



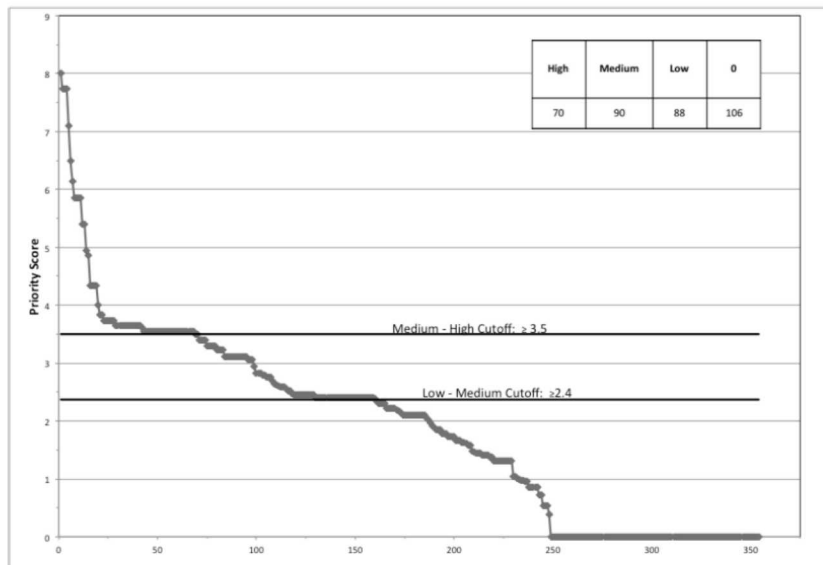
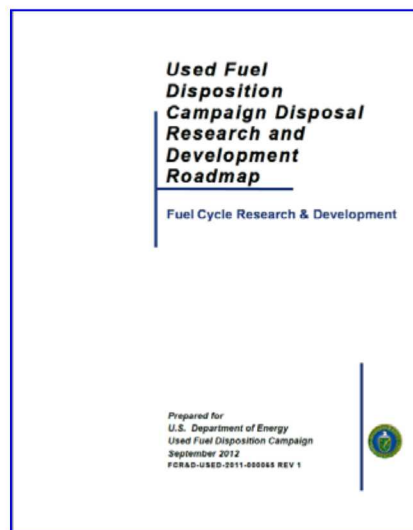
Collins, J. W., J. M. Beck, E. O. Opare, and L. F. Pincock 2008. NGNP – Creating Validated RRL and TRDMs for Critical Systems, Subsystems and Components, INL/EXT-08-14842, Idaho National Laboratory, Idaho Falls, Idaho 83415, September 2008

Repository KRA process – “Example of a Partial Maturation Plan”



2012 UFD R&D Roadmap

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



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

TRA or KRA Process – “Evaluate System TRL”



- **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).	The integration of technologies has been verified and validated with sufficient detail to be actionable.	System Development and Demonstration	0.60 to 0.79
		Pilot line capability demonstrated; ready to begin low-rate, initial production (MRL 8).			
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.	Production	0.80 to 0.89
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.	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.