Summary of Disposal Research R&D Roadmap Update

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SFWD

Spent Fuel & Waste Disposition

Annual Working Group Meeting
UNLV-SEB – *Las Vegas, Nevada*
May 21-23, 2019

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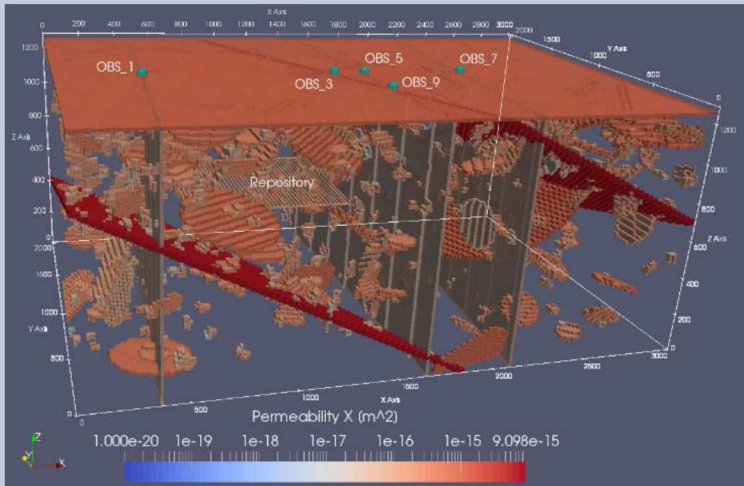


Acknowledgements

- **<u>Co-authors</u>: Paul Mariner, Ralph Rogers, Dave Dobson, Bob MacKinnon, Jeralyn Prouty, Laura Connolly**
- **<u>Workshop session chairs and rapporteurs</u>, as well as the <u>Technical Leads</u> for the SFWST Campaign work packages:**

  Dave Dobson, Argillite Session Chair;
  Carlos Jove-Colon, Argillite Session Rapporteur and Argillite Technical Lead;
  Paul Mariner, Crystalline Session Chair;
  Emily Stein, Crystalline Session Rapporteur;
  Yifeng Wang, Crystalline Technical Lead;
  Mark Rigali, Salt Session Chair;
  Kris Kuhlman, Salt Session Co-Rapporteur and Salt Technical Lead;
  Melissa Mills, Salt Session Co-Rapporteur;
  Dave Sassani, EBS Session Chair;
  Ed Matteo, EBS Session Rapporteur and EBS Technical Lead;
  Jens Birkholzer, International Session Chair and International Technical Lead;
  Frank Perry, International Session Rapporteur;
  Ernie Hardin, DPC Session Chair and DPC Technical Lead; and
  Laura Price, DPC Session Rapporteur.
- **Many SFWST and IWM Campaign experts, national lab staff, and DOE staff who took the time to participate in this Roadmap Update Workshop**

Roadmap Update Goals

Consensus of Project experts regarding:

1. **What *<u>has been accomplished</u>* on generic repository R&D in the U.S.**

   ← Work completed since the 2012 UFD R&D Roadmap

2. **What still *<u>needs to be accomplished</u>* on generic repository R&D**

   → updated 2019 R&D Roadmap or Plan

→ **<u>Current Status</u>: snapshot of state-of-the-art in 2019**

Granularity of R&D "Quanta" or "Items"

In 2019 Update, we prioritized the <u>R&D Activities</u>, which were formulated by the Technical Leads:

- Although there is no "right" or "wrong" way to quantize R&D activities, the target level is somewhere *between the fine level of FEPs and the broader level of WBS scope (annual scope descriptions for the Project's WBS elements)*
- The R&D Activities (which generally address multiple FEPs) were formulated over a series of several years

Generic R&D "Completion" State

Two criteria for advancing to the next "phase" of the R&D Program:

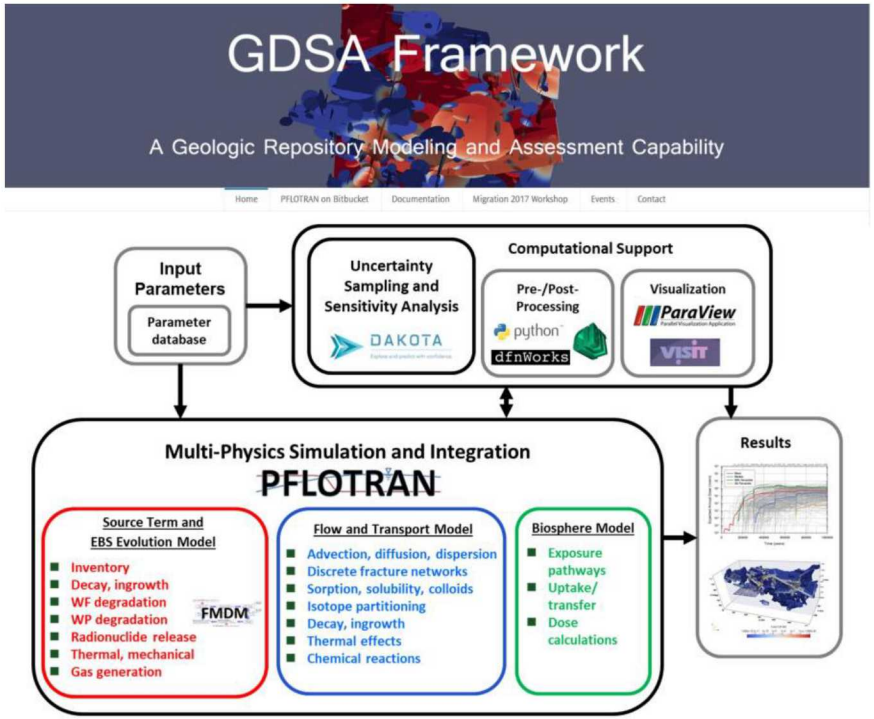
1. Change in State-of-the-Art Level (SAL):

→ R&D necessary to move the state-of-the-art knowledge to the next level (defined in the SAL metric table) for the given R&D Activity

2. Time/schedule criterion:

→ 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 (2022 for the purposes of the Update workshop)



3-Day 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

Roadmap Update Workshop Agenda

DAY 1, TUESDAY, 1/15/2019	
10:15 am - 5:00 pm	**Three Host-Rock Breakout Groups:*** **[Argillite; Crystalline; Salt]** 1) Decide upon SAL rating and rationale and determine generic R&D still needed 2) Brainstorm and add "Gap" Activities, as appropriate **also consider EBS, DPC, and International Activities, as assigned*
DAY 2, WEDNESDAY, 1/16/2019	
8:30 am – 5:00 pm	**Host-Rock Breakout Groups (continued):** **[Argillite; Crystalline; Salt]** 1) Decide upon ISC rating and justification 2) Discuss/document "unresolved" integration issues, particularly with PA-GDSA
1:00 pm – 5:00 pm	**Cross-cutting Breakout Groups:** **[EBS; DPC; International]** • Resolve differing SAL and ISC ratings among host rock groups
DAY 3, THURSDAY, 1/17/2019	
8:30 am – 2:30 pm	**Full Group: Summary Reports and Integration (30 minutes per breakout)**

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)

R&D Activity Group	Total Number of R&D Activities
Argillite	8
Crystalline	17
DPC	6
EBS	20
International	21
Salt	13
Other	7
PA	17
Total	**109**

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

Breakout Session	Total Number of R&D Activities Evaluated
Argillite	31
Crystalline	40
Salt	29
Total	**100**

- **EBS and International cross-cutting breakout sessions (Day 2 afternoon) resolved different ISC and SAL values for their R&D Activities, given in the three host-rock sessions, if any**

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**
  - → Theirs 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	*Fundamental Gaps in Method or Fundamental Data Needs, or Both*
4	*Improved Representation*
3	*Improved Defensibility*
2	*Improved Confidence*
1	*Well Understood*

- **Importance to the Safety Case (ISC):**

ISC Numerical Value	ISC Descriptive Value
5	***High*** *Importance to SC*
3	***Medium*** *Importance to SC*
1	***Low*** *Importance to SC*

R&D Activity Priority Score
(using ISC × SAL product)

ISC (importance to safety case) value:

ISC Numerical Value	ISC Descriptive Value
5	***High*** *Importance to SC*
3	***Medium*** *Importance to SC*
1	***Low*** *Importance to SC*

×

SAL (state of the art) value

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

=

Final R&D Priority Score for an Activity

SAL: / ISC:	1	2	3	4	5
High (5)	L	M	M	M-H	H
Medium (3)	L	M	M	M	M
Low (1)	L	L	L	L	L

Some Workshop Results – Expert Consensus on SAL and ISC Values

ID (*gap)	Activity	2019 Score
E-03	*THC processes in EBS*	M-H

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 a 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.

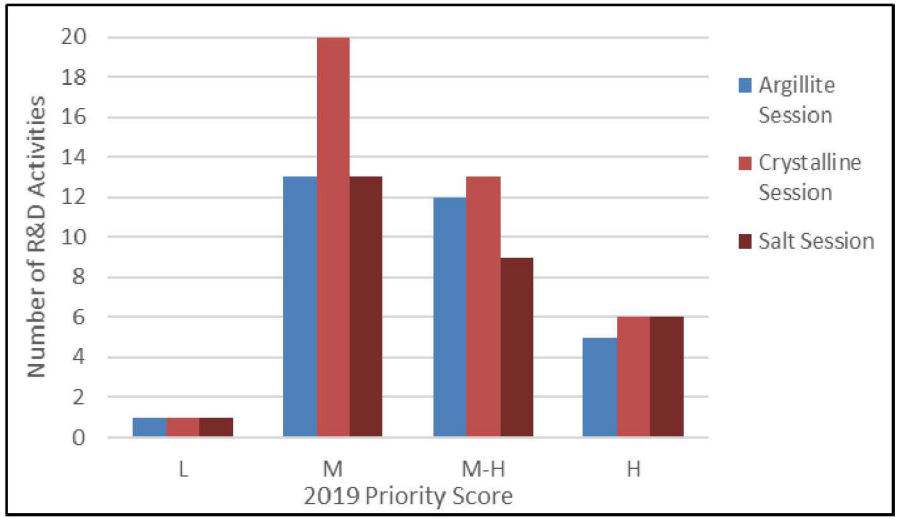
Evolution of State-of-the-Art Knowledge (App. J)

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

R&D Activity #	R&D Activity Name	Primary FEP	2012 Roadmap "State of the Art" (for the Primary FEP)	2019 Roadmap Update "State of the Art" Level (SAL)
A-2	Simplified Representation of THMC processes in EBS and host rock, e.g., clay illitization	2.1.04.01 Evolution and Degradation of Backfill/buffer	Fundamental Gaps in Method, Fundamental Data Needs	Improved Representation
A-7	Analysis of clay hydration/dehydration and alteration under various environmental conditions	2.2.08.06 Flow through EDZ (clay/shale)	Fundamental Gaps in Method, Fundamental Data Needs	Fundamental Gaps in Method or Fundamental Data Needs, or Both
C-1	Discrete Fracture Network (DFN) Model	2.2.09.51 Advection of Dissolved Radionuclides in Host Rock (crystalline)	Fundamental Gaps in Method, Fundamental Data Needs	Improved Representation
C-15	Design improved backfill and seal materials **(GAP)**	2.1.04.01 Evolution/Degradation of Backfill/buffer	Fundamental Gaps in Method, Fundamental Data Needs	Fundamental Gaps in Method or Fundamental Data Needs, or Both
E-1	SNF Degradation (& FMDM)	2.1.02.01 SNF Degradation	Fundamental Gaps in Method, Fundamental Data Needs	Improved Defensibility
E-2	SNF Degradation testing activities	2.1.02.01 SNF Degradation	Fundamental Gaps in Method, Fundamental Data Needs	Improved Representation
E-5	Corrosion Products - incorporation of radionuclides	2.1.09.02 Chemical Characteristics of Water in Waste Packages	Fundamental Gaps in Method, Fundamental Data Needs	Fundamental Gaps in Method or Fundamental Data Needs, or Both/
I-1	Radionuclide transport as pseudo-colloids, Grimsel	2.2.09.64 Radionuclide Release from Host Rock (crystalline or clay/shale/salt)	Fundamental Gaps in Method, Fundamental Data Needs	Improved Defensibility
I-2	FEBEX-DP Modeling: Dismantling phase of the long-term FEBEX heater test - Modeling	2.1.04.01 Evolution and Degradation of Backfill/buffer	Fundamental Gaps in Method, Fundamental Data Needs	Improved Representation
P-1	CSNF repository argillite reference case	FEP (0.1.10.01 Model Issues) not explicitly scored, but "Disposal System Modeling" rated as a "High" priority "Cross-Cutting" issue in 2012	Not Evaluated	Improved Representation
P-6	(Pseudo) Colloid-Facilitated Transport Model	2.2.09.61 Radionuclide Transport thru EDZ	Fundamental Gaps in Method, Fundamental Data Needs	Improved Defensibility
S-2	Salt Coupled THM processes, creep closure of excavations	2.2.07.01 Mechanical Effects on Host Rock (Salt)	Fundamental Gaps in Method Fundamental Data Needs	Improved Representation
S-13	Acid gas generation, fate, and transport **(GAP)**	2.2.12.02 Effects of Gas on Flow Through the Geosphere (Salt)	Fundamental Gaps in Method, Fundamental Data Needs	Fundamental Gaps in Method or Fundamental Data Needs, or Both

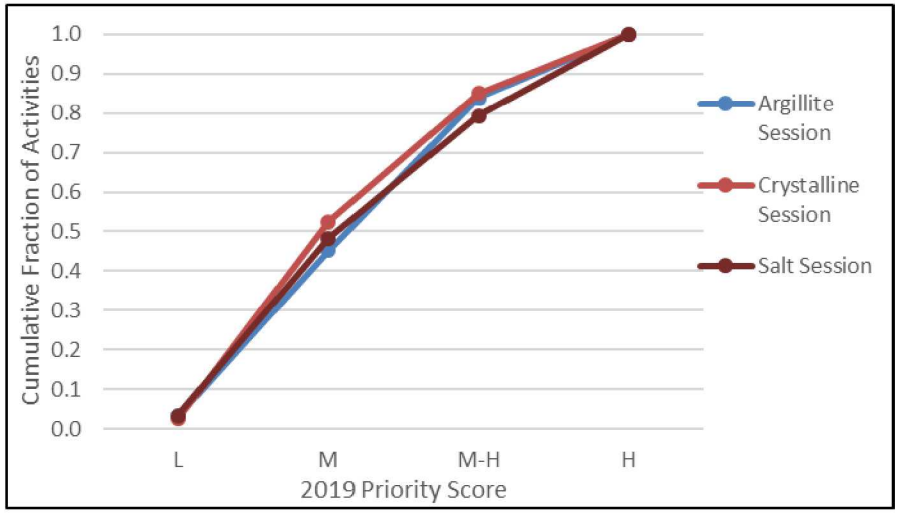
R&D Activity Priority Scores by Host-Rock Sessions

Histogram of R&D Activity Scores



Breakout Session	Total Number of R&D Activities Evaluated
Argillite	31
Crystalline	40
Salt	29

Cumulative Fraction of R&D Activity Scores

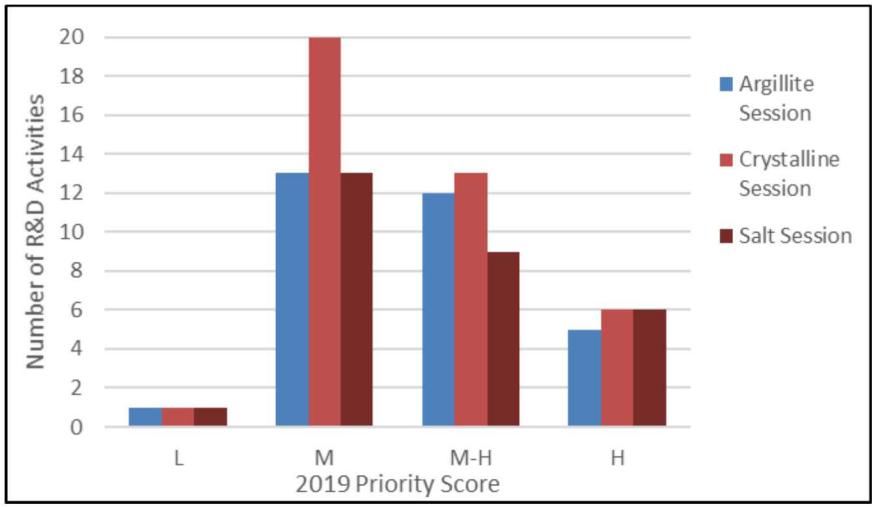


- Apparent uniformity of scoring among host-rock breakout groups
- Good "calibration"?

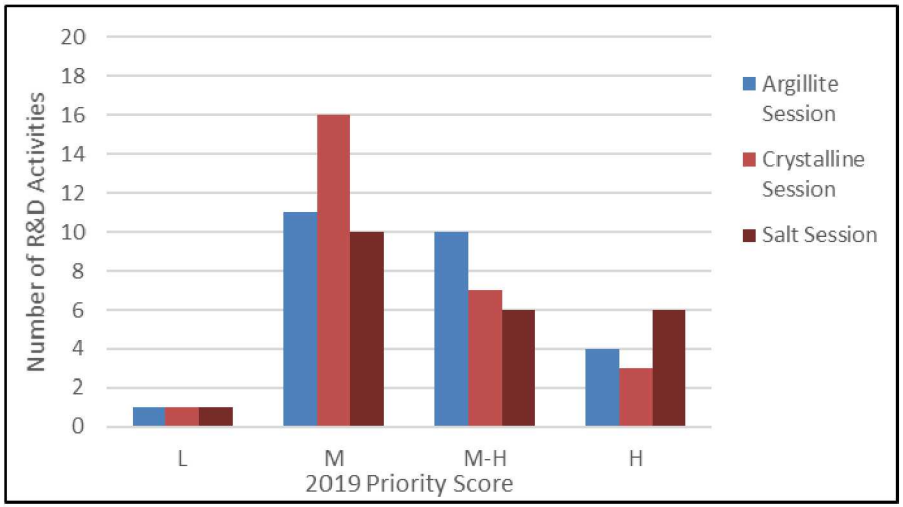
"Gap" Activities

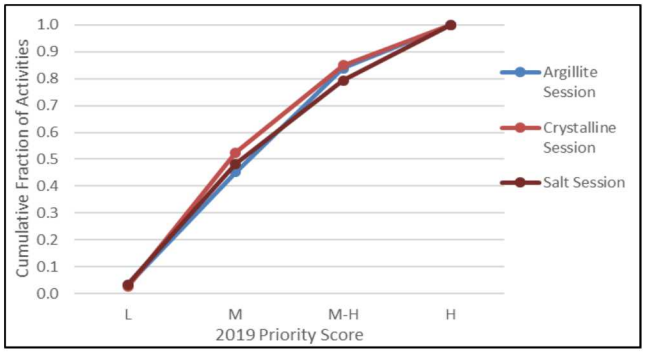
- Gap or long-term activities altered the results somewhat when removed from the charts:

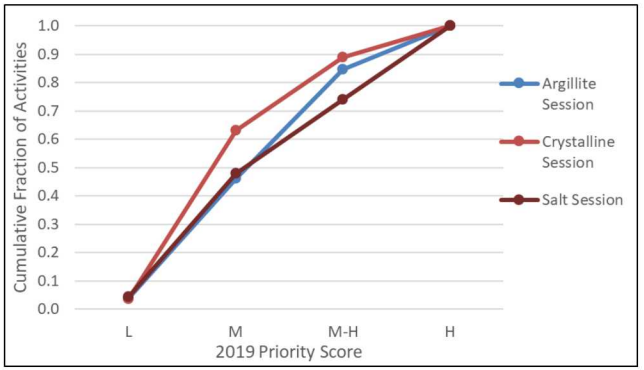
Histogram of all R&D Activity Scores



Histogram of "current" Activities (no "gaps")







High-Priority R&D Activities

High Priority R&D Activities	
A-08	Evaluation of ordinary Portland cement (OPC)
C-15	Design improved backfill and seal materials
C-16	Development of new waste package concepts and models for evaluation of waste package performance for long-term disposal
D-01	Probabilistic post-closure DPC criticality consequence analyses Task 1 - Scoping Phase Task 2 - Preliminary Analysis Phase Task 3 - Development Phase
D-03	DPC filler and neutron absorber degradation testing and analysis
D-04	Coupled multi-physics simulation of DPC postclosure (chemical, mechanical, thermal-hydraulic) including processes external to the waste package.
D-05	Source term development with and without criticality
E-09	Cement plug/liner degradation
E-11	EBS High Temp experimental data collection- To evaluate high temperature mineralogy /geochemistry changes.
E-14	In-Package Chemistry
E-17	Buffer Material by Design

High Priority R&D Activities	
I-04	Experiment of bentonite EBS under high temperature, HotBENT
I-06	Mont Terri FS Fault Slip Experiment
I-08	DECOVALEX-2019 Task A: Advective gas flow in bentonite
I-12	TH and THM Processes in Salt: German-US Collaborations (WEIMOS)
I-13	TH and THM Processes in Salt: German-US Collaborations (BENVASIM)
I-16	New Activity: DECOVALEX Task on Salt Heater Test and Coupled Modeling
I-18	New Activity: Other potential DECOVALEX Tasks of Interest: Large-Scale Gas Transport
P-12	WP Degradation Model Framework
S-01	Salt Coupled THM processes, hydraulic properties from mechanical behavior (geomechanical)
S-03	Coupled THC advection and diffusion processes in Salt, multi-phase flow processes and material properties in Salt
S-04	Coupled THC processes in Salt, Dissolution and precipitation of salt near heat sources (heat pipes)
S-05	Borehole-based Field Testing in Salt

Medium-High-Priority R&D Activities

Medium-High Priority R&D Activities	
A-04	Argillite Coupled THM processes modeling including host rock, EBS, and EDZ (TOUGH-FLAC)
C-01	Discrete Fracture Network (DFN) Model
C-06	Buffer Erosion (is this a gap in our program?) is it too site specific for generic R&D
C-08	Interaction of Buffer w/ Crystalline Rock
C-11	Investigation of fluid flow and transport in low permeability media (clay materials).
C-13	Evaluation and upscaling of the effects of spatial heterogeneity on radionuclide transport
C-14	Radionuclide sorption and incorporation by natural and engineered materials: Beyond a simple Kd approach
C-17	Model DFN evolution due to changes in stress field
E-02	SNF Degradation testing activities
E-03	THC processes in EBS
E-04	Waste Package Degradation Model (mechanistic)
E-06	Waste Package Degradation Testing
E-10	High-Temperature Behavior
E-20	Colloid source terms
I-02	FEBEX-DP Modeling: Dismantling phase of the long-term FEBEX heater test - Modeling
I-03	FEBEX-DP Experimental Work: Dismantling phase of the long-term FEBEX heater test
I-07	DECOVALEX-2019 Task E: Upscaling of modeling results from small scale to one-to-one scale based in heater test data in Callovo-Oxfordian claystone (COx) at MHM underground research laboratory in France.

Medium-High Priority R&D Activities	
I-09	DECOVALEX-2019 Task C: GREET (Groundwater REcovery Experiment in Tunnel) at Mizunami URL, Japan
I-14	TH and THM Processes in Reconsolidating Salt: German-US Collaborations (KOMPASS)
I-21	New Activity: SKB Task 10 Validation of DFN Modeling
O-02	GDSA Geologic Modeling
O-03	Web Visualization of Geologic Conceptual Framework for GDSA Geologic Modeling
P-01	CSNF repository argillite reference case
P-02	CSNF repository crystalline reference case
P-04	CSNF repository unsaturated zone (alluvium) reference case
P-11	Pitzer model
P-13	Full Representation of Chemical processes in PA
P-14	Generic Capability Development for PFLOTRAN
P-15	Species and element properties
P-16	Solid solution model
P-17	Multi-Component Gas Transport
S-02	Salt Coupled THM processes, creep closure of excavations
S-07	Brine Origin, Chemistry, and Composition in Salt (in support of field test S-5)
S-08	Evolution of run-of-mine salt backfill
S-11	THMC effects of anhydrites, clays, and other non-salt components

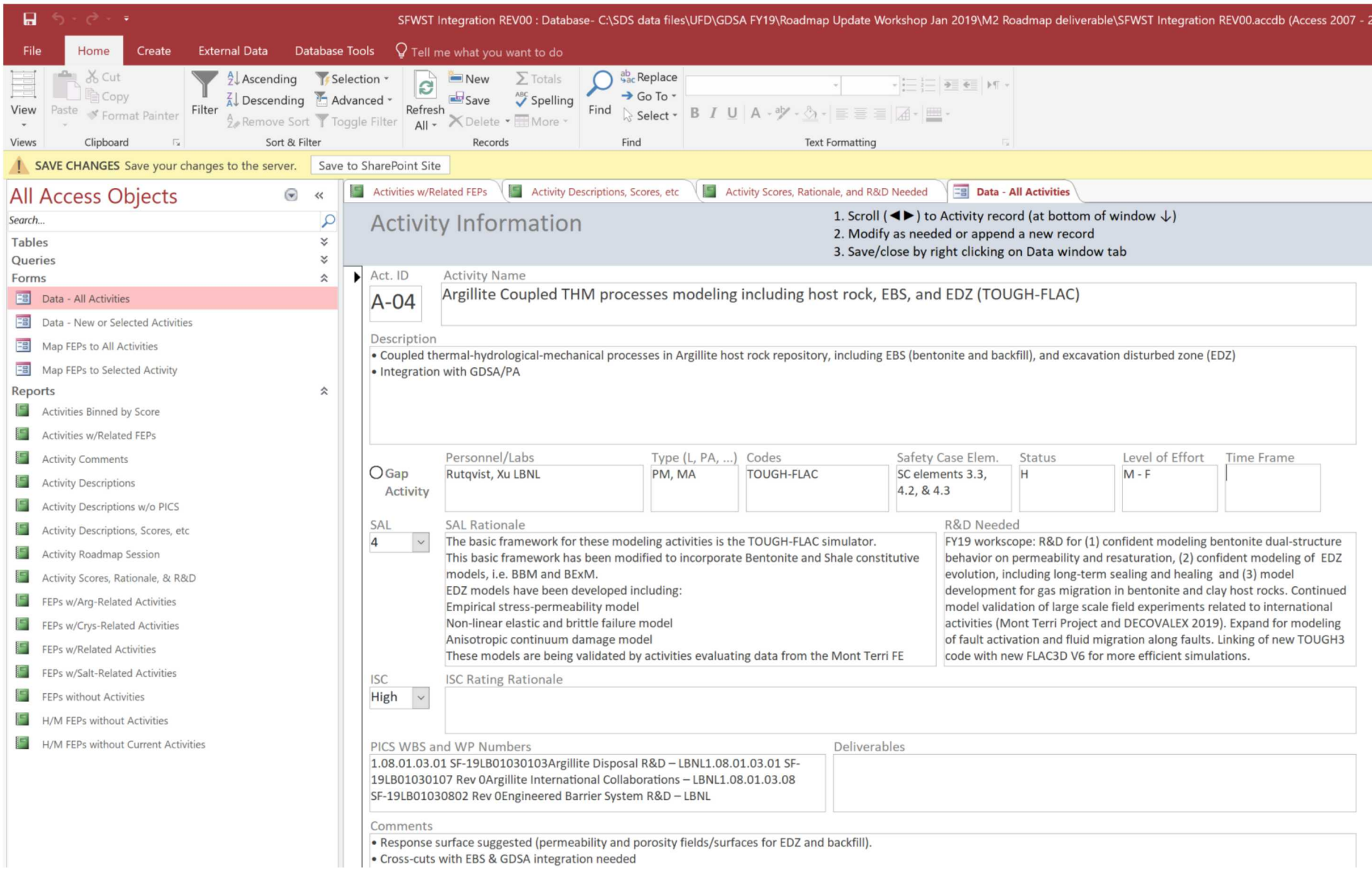
"High Impact R&D Topics"

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

High Impact R&D Topics	High-Priority R&D Activities	Medium-High-Priority R&D Activities
High Temperature Impacts	D-1, D-4, I-4, I-6, I-16, E-11, S-5	I-2, I-3, I-7, E-10
Buffer and Seal Studies	I-4, E-9, E-17, A-8, C-15	I-2, I-3, I-7, A-4, C-6, C-8, C-11
Coupled Processes (Salt)	S-1, S-3, S-4, I-12, I-13	I-14, S-2, S-7, S-8, S-11
Gas Flow in the EBS	I-6, I-8, I-18	I-9, P-17
Criticality	D-1, D-3, D-4, D-5	
Waste Package Degradation	C-16, P-12	E-4, E-6
In-Package Chemistry	E-14	E-2, E-20, P-15, P-16
Generic PA Models		P-1, P-2, P-4, P-11, P-13, P-14
Radionuclide Transport		C-11, C-13, C-14. P-15, P-16
DFN Issues		I-21, C-1, C-17
GDSA Geologic Modeling		O-2, O-3
THC Processes in EBS		E-3

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

R&D Activity Access® Database – Brief Demo



Some Insights

- **Much generic R&D accomplished since 2012 Roadmap:**
  - → Through R&D both in the U.S. and through many nicely leveraged International collaborations (most in URLs)
  - → State-of-the-Art knowledge level (SAL) has improved for many Activities/FEPs
- **Need for continuing generic R&D for identified "High Impact" Topical Areas, and for various individual R&D Activities:**
  - → Generic R&D needed was identified by consensus – also to discuss this week
- **Some obvious new priorities in the intervening seven years:**
  - → Possible direct disposal of dual-purpose canisters (DPCs) implies that criticality FEPs should be re-examined, and mitigation methods considered if necessary
- **PA-GDSA modeling provides insights for the ISC value of various 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

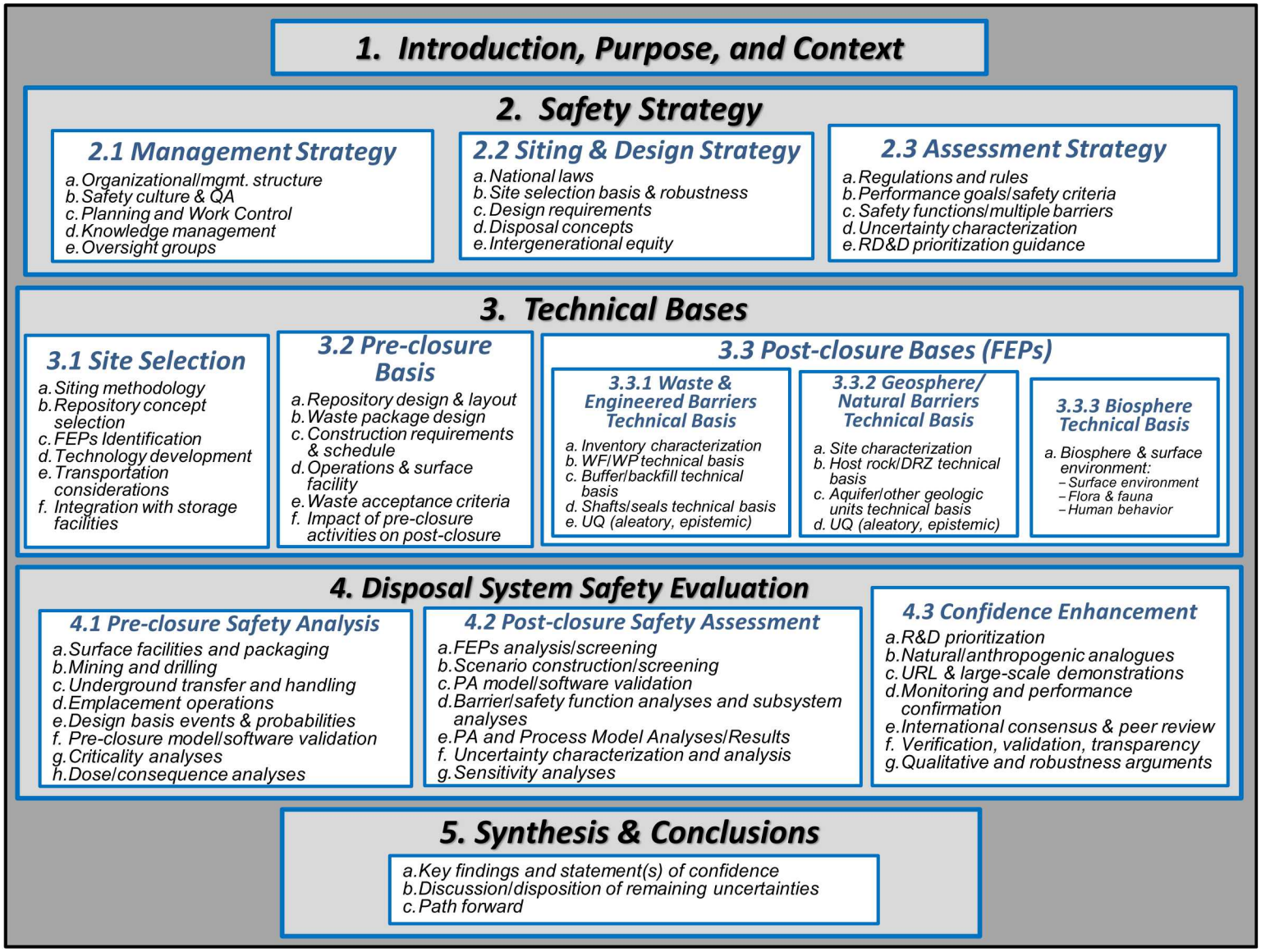
Further Roadmap-Related Discussion – at the end of each session

- **Discussion (20 minutes):**

  For each High or Medium-High R&D Activity:

  - → Do we agree with the "R&D Needed" text in our database? If not, how should we change it?
  - → How can we translate the Activity into an input to GDSA? If we cannot, then which component of the safety case does the activity support?
  - → Are the Activity and the GDSA reference case consistent with each other? If not, how can we make them consistent?
  - → Tentatively schedule sit-down meeting among the project staff who need to integrate on a particular Activity and identify the primary topics for discussion

Safety Case Components



Thanks for your Attention!

Back-Up Slides

ISC Metric Table

ISC Numerical Value	ISC Descriptive Value	ISC Definition (see Safety Case Elements figure)
5	***High*** *Importance to Safety Case*	Knowledge gained by proposed R&D strongly affects one of the three elements of "Disposal System Safety Evaluation" in the Safety Case (pre-closure safety analysis, post-closure safety assessment*, confidence enhancement*)
3	***Medium*** *Importance to Safety Case*	Knowledge gained strongly affects one of the Technical Bases* elements of the Safety Case but the Technical Basis element itself only weakly or moderately influences a safety assessment metric
1	***Low*** *Importance to Safety Case*	Knowledge gained is only of a supporting nature and does not strongly affect the associated process model or model inputs

*These three SC elements are the most relevant ones for the generic repository phase (see next slide)

SAL Metric Table

SAL Numeric Value	SAL Descriptive Value	SAL Definition	Questions to be answered for: (1) Rationale for current SAL (Column M) (2) R&D to move to next SAL (Column N)
5	*Fundamental Gaps in Method or Fundamental Data Needs, or Both*	The representation of an issue (conceptual and/or mathematical, experimental) is under development, and/or the data or parameters in the representation of an issue (process) is being gathered	Rationale for being at Level 5: • What is under development and what data is being gathered? • What are the fundamental gaps? R&D necessary to get to Level 4?
4	*Improved Representation*	Methods and data exist, and the representation may be reasonable but there is not widely-agreed upon confidence in the representation (scientific community and other stakeholders).	Rationale for being at Level 4: • What methods and data currently exist? • Why is the representation reasonable? • Why is there not widely agreed upon confidence? R&D necessary to get to Level 3? • e.g., what is needed to build agreement and confidence in the representation? and what additional data need to be gathered?
3	*Improved Defensibility*	Focuses on improving the technical basis and defensibility of how an issue (process) is represented by data and/or models	Rationale for being at Level 3: • Why and what needs to be (and can be) improved for defensibility for a generic repository? R&D necessary to get to Level 2? • e.g., What level of effort on data and models would lead to the issue being technically defensible
2	*Improved Confidence*	The representation of an issue is technically defensible, but improved confidence would be beneficial (i.e., lead to more realistic representation).	Rationale for being at Level 2: • Why is it technically defensible? R&D necessary to get to Level 1? • e.g., What R&D would lead to improved confidence?
1	*Well Understood*	The representation of an issue (process) is well developed, has a strong technical basis, and is defensible. Additional R&D would add little to the current understanding	

Examples of Activity Quantization

- ***Reasonable*** **:**

C-1	Discrete Fracture Network (DFN) Model	• Generation and representation of realistic fracture networks • Fluid flow& transport in fracture networks • Mapping tools (dfnWorks to PFLOTRAN) • Dual continuum; matrix diffusion

- ***Too broad*** **:**

C-13	Reactive transport modeling of groundwater chemistry evolution and radionuclide transport	This task will focus on the following improvements to the existing reactive transport modeling capability: • Incorporation of interfacial reactions (e.g., surface complexation), microbially mediated reactions, colloid-facilitated transport, and radionuclide decay and ingrowth; • Improved representation of spatial heterogeneity of chemical and transport properties • Coupling of radionuclide transport with evolving water chemistry along a transport pathway (e.g. alkaline plumes) • Robustness of numerical algorithms for coupling chemical reactions with solute transport • Explicit consideration of structural complexity of the media in the solute transport (e.g. the fracture-matrix system in DRZ or the micro, macro-pores system for host clay rock).

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