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FEP Catalogue and Scenario Development

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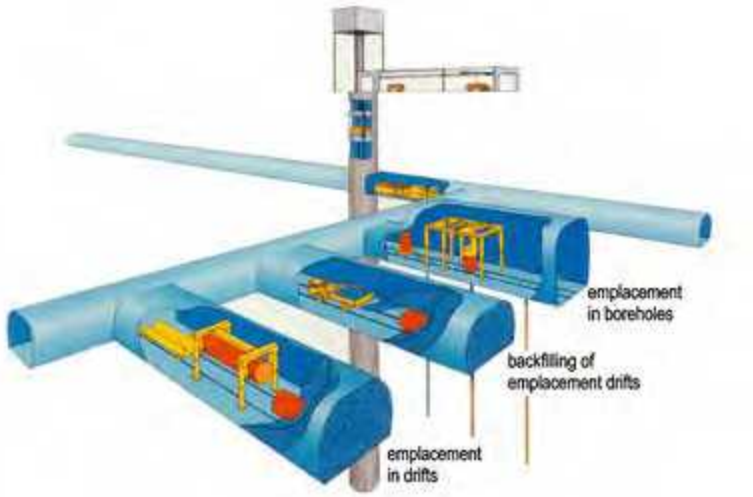
Outline

- Joint U.S.-German Objective
- U.S. FEP Analysis and Scenario Development Approach
  - SNL: Geoff Freeze, S. David Sevougian, Michael Gross, Christi Leigh
- German FEP Analysis and Scenario Development Approach
  - GRS: Jens Wolf, Jörg Mönig, Dieter Buhmann
- Collaborative Results to Date
  - FEP numbering scheme
  - FEP template
- Future Work

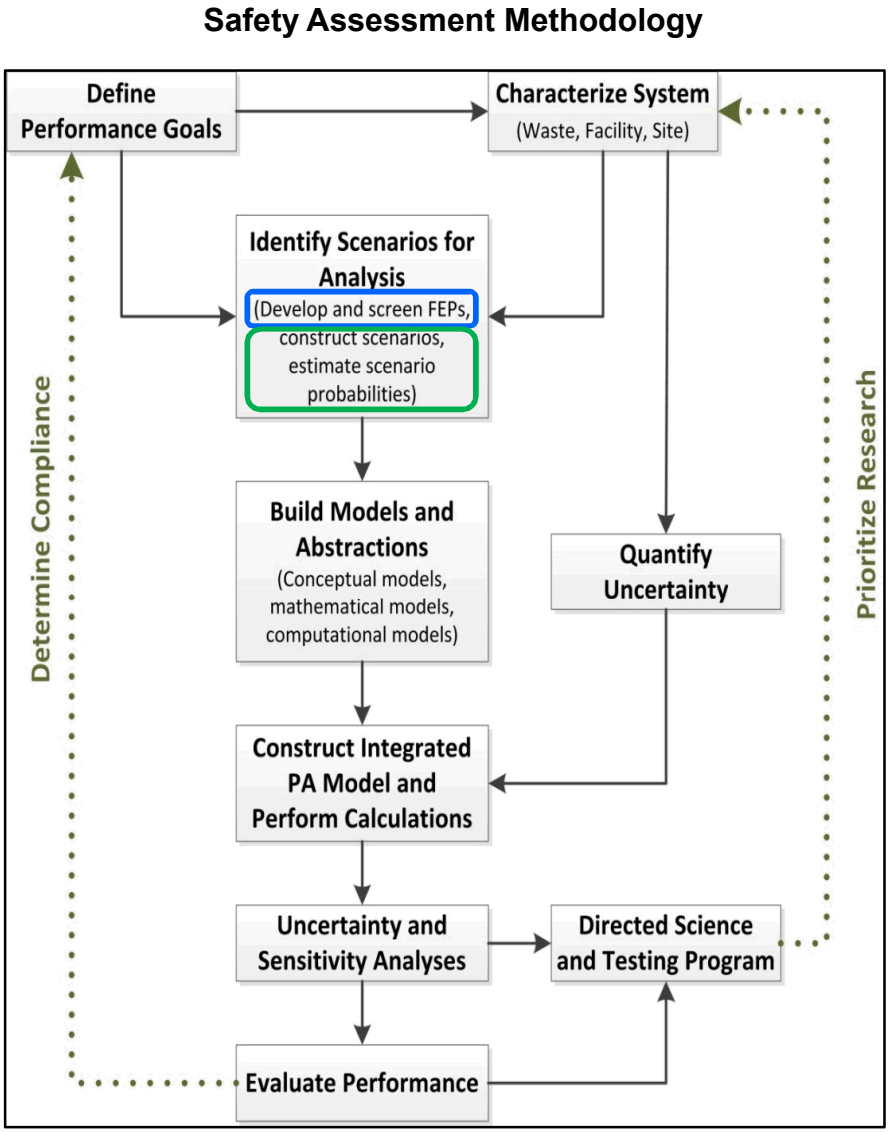
Objectives

- U.S. – German collaboration to produce a common FEP list
  - Identify relevant features, events, and processes (FEPs) for disposal of heat-generating waste (SNF and HLW) in salt
    - Applicable to all potential salt concepts and sites
  - Review FEP analysis approach
- Salt Club
  - FEP Catalogue for use by all Salt Club members
  - Inform new NEA FEP database



U.S. FEP Analysis

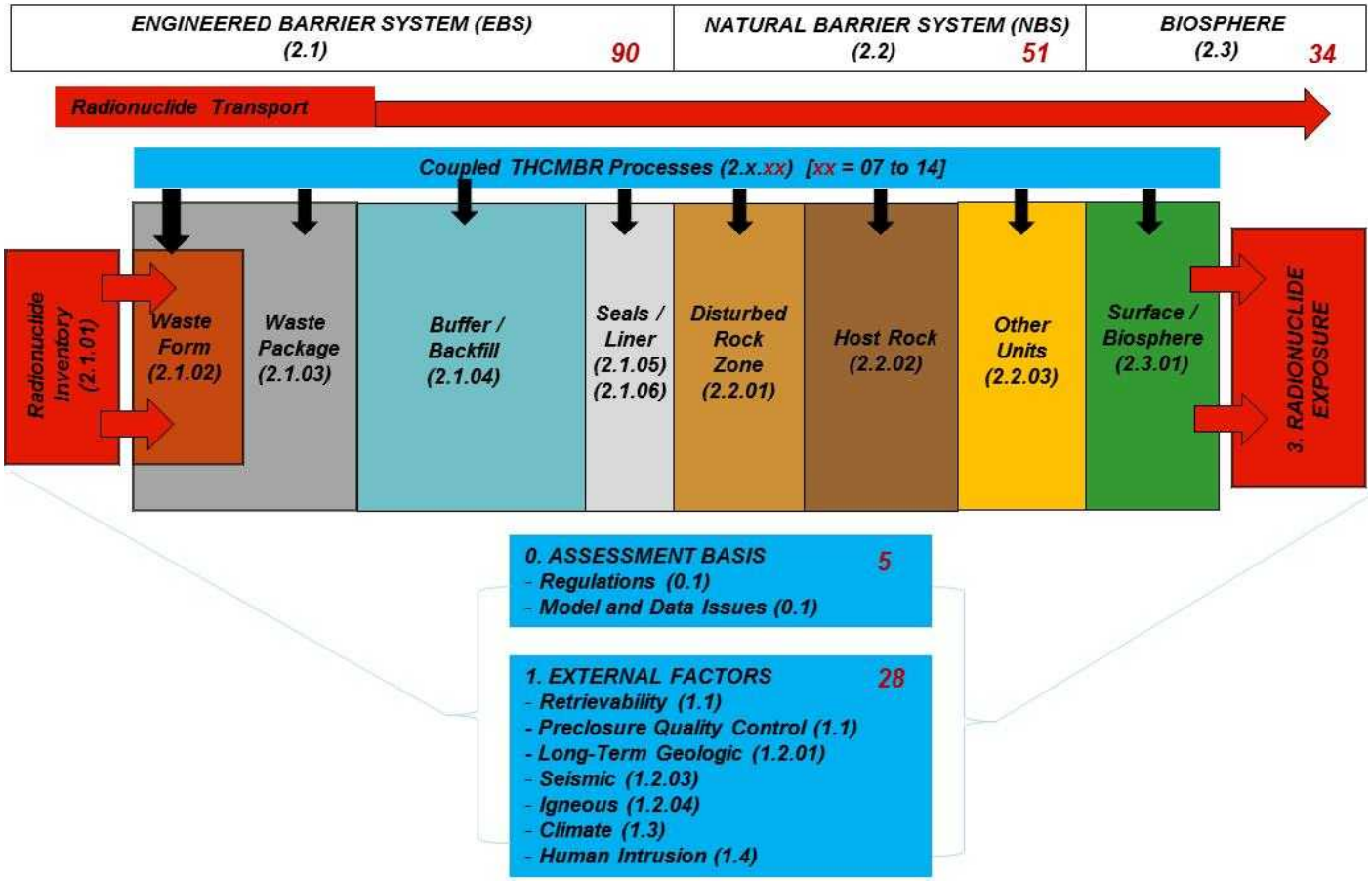
- FEP Identification
  - Generic DOE Used Fuel Disposition (UFD) FEPs
  - Generic bedded salt FEPs
  - US-German Salt FEPs
    - FEP Matrix
    - FEP Content
- FEP Screening
- Scenario Development



U.S. Generic UFD FEPs

- Freeze et al. (2010, 2011)

- 208 FEPs – derived from the NEA FEP Database (1999, 2006) to be broadly applicable to a range of SNF/HLW disposal concepts



U.S. Generic UFD FEPs

- Example of a single UFD FEP

Broad FEP description provided in the "Description" column

Additional detail provided in the "Associated Processes" column

"Screening Decision" is dependent on design and siting

UFD FEP Number	Description	Associated Processes	Related FEPs	Screening Decision
2.1.08.06	Alteration and Evolution of EBS Flow Pathways	- Drift collapse - Degradation/consolidation of EBS components - Plugging of flow pathways - Formation of corrosion products - Water ponding [see also Evolution of Flow Pathways in WPs in 2.1.03.08, Evolution of Backfill in 2.1.04.01, Drift Collapse in 2.1.07.02, and Mechanical Degradation of EBS in 2.1.07.10]	2.1.08.12.0A 2.1.08.15.0A 2.1.03.10.0A 2.1.03.11.0A 2.1.09.02.0A	

2.1 = EBS
08 = Hydrologic

2.1.03 = EBS Waste Package
2.1.04 = EBS Buffer/Backfill
2.1.07 = EBS Mechanical
2.1.08 = EBS Hydrologic
2.1.09 = EBS Chemical

U.S. Generic Bedded Salt FEPs

- Sevougian et al. (2012)

- Reviewed generic UFD FEP list
  - Broadly applicable to four different concepts
    - Granite/crystalline, Clay/argillite, Salt, Deep borehole
- Modified UFD FEPs to be more salt-specific, as necessary
  - Assumptions about design and geologic setting for bedded salt repository "generic reference case"
  - Cross-check against WIPP FEPs catalogue
  - Cross-check against German (Gorleben) FEP catalogue
- Further modified as part of "FEP Matrix" approach
  - Better identify related FEPs
  - Eliminate redundancies

U.S. Generic Bedded Salt FEPs

- Example of a single Bedded Salt FEP
  - Site and design-specific considerations:
    - crushed salt backfill
    - salt creep closure
    - disturbed scenario FEPs (e.g., seismic ground motion, fault displacement)

Salt-specific detail shown in red text

UFD FEP Number	Description	Associated Processes	Related FEP Number	Screening Decision
2.1.07.03	Mechanical Effects of Backfill	- Consolidation of crushed salt backfill during room closure process - Static and dynamic loading on other EBS components - Backfill restricts displacement of other EBS components during ground motion and fault displacement - Protection of other EBS components from rockfall / drift collapse caused by ground motion and fault displacement	2.1.04.04.0A	

2.1 = EBS
07 = Mechanical

2.1.04 = EBS Buffer/Backfill

FEP Matrix

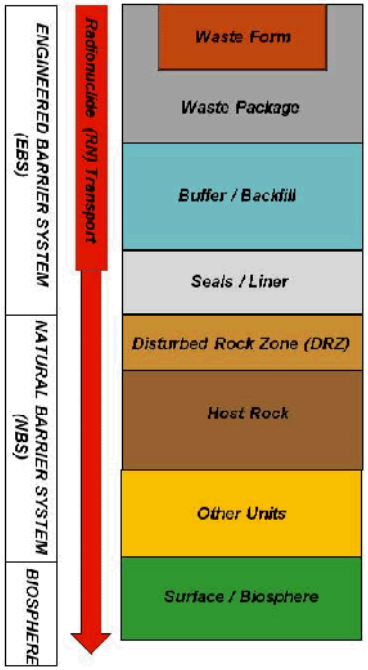
Freeze et al. (2013b)

- Two-dimensional FEP organizational structure
  - Matrix Rows = Feature Categories
  - Matrix Columns = Process and Event Categories
- Matrix Cell contains all FEPs related to the “Process/Event” acting upon or within the “Feature”
- Related FEPs are grouped by Matrix Cell (or by Row or Column)
  - Not distributed among various locations as in the NEA-based hierarchical list
- FEP Numbering
  - Developed a new numbering scheme consistent with FEP Matrix
    - Can still be mapped to NEA Database numbering for traceability

FEP Matrix

Coupled THCMBR Processes and Events

Features \ Characteristics, Processes, and Events	Characteristics	Processes											Events					
		Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Waste and Engineered Features																		
Waste Form and Cladding																		
Waste Package and Internals																		
Buffer/Backfill																		
Emplacement Tunnels/Drifts and Mine Workings																		
Seals/Plugs																		
Geosphere Features																		
Host Rock (Repository Horizon)																		
Other Geologic Units (non-Repository Horizon)																		
Surface Features																		
Biosphere																		
System Features																		
Repository System																		



FEP Matrix

- All FEPs relevant to Buffer and Backfill
  - Some are broadly applicable to both
  - Some are specific to Buffer or Backfill

Characteristics, Processes, and Events / Features		Processes										Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	2.1.04.00a 2.1.04.00b	2.1.04.01a 2.1.07.01a	2.1.04.01b 2.1.08.03 2.1.08.07b 2.1.08.08c	2.1.04.01c 2.1.09.06 2.1.09.13c 2.1.11.13c	2.1.09.13c 2.1.11.13d	2.1.09.51c 2.1.09.52c 2.1.09.53c 2.1.09.54c 2.1.09.55c 2.1.11.14b	2.1.04.01d	2.1.13.02c					2.1.14.02a	2.1.03.01b	1.2.03.01b	1.2.04.01b	1.4.02.01b 1.4.11.01b	
• Waste Package Buffer	2.1.04.00a	2.1.11.09a	2.1.04.01b	2.1.04.01c		2.1.09.51c 2.1.09.52c	2.1.04.01											
• Tunnel/Drift/Room Backfill	2.1.04.00b	2.1.07.03 2.1.11.09	2.1.04.01b	2.1.09.05		2.1.09.51c 2.1.09.52c	2.1.11.02c 2.1.11.05											
Emplacement Tunnels/Drifts and Mine Workings	2.1.04.00c	2.1.07.02 2.1.07.08a 2.1.11.09b 2.1.12.01d	2.1.08.08d 2.1.11.10b 2.1.12.01e 2.1.12.02	1.09.04 2.1.09.11b 2.1.11.13e 2.1.12.01f	2.1.10.01d 2.1.11.13f	2.1.09.53d 2.1.09.54d 2.1.09.55d 2.1.11.14c	2.1.11.02d 2.1.11.04 2.1.11.05	2.1.13.01b 2.1.11.04 2.1.11.05					2.1.14.02b	2.1.03.01c	1.2.03.01c	1.2.04.01c	1.4.02.01c 1.4.11.01c	
• Open Excavations			2.1.08.07c	2.1.05.10														
• Tunnel/Drift Support	2.1.04.00d 2.1.04.01		2.1.08.08	2.1.09.01a 2.1.09.07		2.1.09.52a												
• Liners	2.1.04.00d 2.1.04.01		2.1.08.08	2.1.09.01a 2.1.09.07		2.1.09.52a												
• Other	2.1.04.00d 2.1.05.01			2.1.09.07 2.1.09.09b														

FEP Matrix

- All FEPs relevant only to Backfill

Features \ Characteristics, Processes, and Events		Processes										Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	2.1.04.00a 2.1.04.00b	2.1.04.01a 2.1.07.01a	2.1.04.01b 2.1.08.03 2.1.08.07b 2.1.08.08c	2.1.04.01c 2.1.09.06 2.1.09.13c 2.1.11.13c	2.1.09.13c 2.1.11.13d	2.1.09.51c 2.1.09.52c 2.1.09.53c 2.1.09.54c 2.1.09.55c 2.1.11.14b	2.1.04.01d	2.1.13.02c					2.1.14.02a	2.1.03.01b	1.2.03.01b	1.2.04.01b	1.4.02.01b 1.4.11.01b	
• Waste Package Buffer	2.1.04.00a	2.1.11.09a	2.1.04.01b	2.1.04.01c		2.1.09.51c	2.1.04.01											
• Tunnel/Drift/Room Backfill	2.1.04.00b	2.1.07.03 2.1.11.09	2.1.04.01b	2.1.09.05		2.1.09.51c 2.1.09.52c	2.1.11.02c 2.1.11.05											
Emplacement Tunnels/Drifts and Mine Workings	2.1.04.00c	2.1.07.02 2.1.07.03a 2.1.11.09b 2.1.12.01d	2.1.08.08d 2.1.11.10b 2.1.12.01e 2.1.12.02	1.09.04 2.1.09.11b 2.1.11.13e 2.1.12.01f	2.1.10.01d 2.1.11.13f	2.1.09.53d 2.1.09.54d 2.1.09.55d 2.1.11.14c	2.1.11.02d 2.1.11.04 2.1.11.05	2.1.13.01b 2.1.11.04 2.1.11.05					2.1.14.02b	2.1.03.01c	1.2.03.01c	1.2.04.01c	1.4.02.01c 1.4.11.01c	
• Open Excavations			2.1.08.07c	2.1.05.10														
• Tunnel/Drift Support	2.1.04.00d 2.1.04.01		2.1.08.08	2.1.09.01a 2.1.09.07		2.1.09.52a												
• Liners	2.1.04.00d 2.1.04.01		2.1.08.08	2.1.09.01a 2.1.09.07		2.1.09.52a												
• Other	2.1.04.00d 2.1.05.01			2.1.09.07 2.1.09.08a														

FEP Matrix

- All Thermal-Mechanical FEPs relevant to Buffer/Backfill and Emplacement Tunnels/Drifts

Features \ Characteristics, Processes, and Events		Processes										Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	2.1.04.00a 2.1.04.00b	2.1.04.01a 2.1.07.01a	2.1.04.01b 2.1.08.03 2.1.08.07b 2.1.08.08c	2.1.04.01c 2.1.09.06 2.1.09.13c 2.1.11.13c	2.1.09.13c 2.1.11.13d	2.1.09.51c 2.1.09.52c 2.1.09.53c 2.1.09.54c 2.1.09.55c 2.1.11.14b	2.1.04.01d	2.1.13.02c					2.1.14.02a	2.1.03.01b	1.2.03.01b	1.2.04.01b	1.4.02.01b 1.4.11.01b	
• Waste Package Buffer	2.1.04.00a	2.1.11.09a	2.1.04.01b	2.1.04.01c		2.1.09.51c 2.1.09.52c	2.1.04.01f											
• Tunnel/Drift/Room Backfill	2.1.04.00b	2.1.07.03 2.1.11.09	2.1.04.01b	2.1.09.05		2.1.09.51c 2.1.09.52c	2.1.11.02c 2.1.11.05											
Emplacement Tunnels/Drifts and Mine Workings	2.1.04.00c	2.1.07.01b 2.1.07.02 2.1.07.08a 2.1.11.09b 2.1.12.01d	2.1.08.06 2.1.08.08d 2.1.11.10b 2.1.12.01e 2.1.12.02	2.1.09.012 1.09.04 2.1.09.11b 2.1.11.13e 2.1.12.01f	2.1.10.01d 2.1.11.13f	2.1.09.53d 2.1.09.54d 2.1.09.55d 2.1.11.14c	2.1.11.02d 2.1.11.04 2.1.11.05	2.1.13.01b 2.1.11.04 2.1.11.05					2.1.14.02b	2.1.03.01c	1.2.03.01c	1.2.04.01c	1.4.02.01c 1.4.11.01c	
• Open Excavations			2.1.08.07c	2.1.05.10														
• Tunnel/Drift Support	2.1.04.00d 2.1.04.01f		2.1.08.08b	2.1.06.01a 2.1.06.07		2.1.09.52a												
• Liners	2.1.04.00d 2.1.04.01f		2.1.08.08b	2.1.06.01a 2.1.06.07		2.1.09.52a												
• Other	2.1.04.00d 2.1.05.01f			2.1.06.07 2.1.06.08a														

FEP Matrix

- All Thermal-Mechanical FEPs relevant to Backfill only

Characteristics, Processes, and Events / Features		Processes										Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	2.1.04.00a 2.1.04.00b	2.1.04.01a 2.1.07.01a	2.1.04.01b 2.1.08.03 2.1.08.07b 2.1.08.08c	2.1.04.01c 2.1.09.06 2.1.09.13c 2.1.11.13c	2.1.09.13c 2.1.11.13d	2.1.09.51c 2.1.09.52c 2.1.09.53c 2.1.09.54c 2.1.09.55c 2.1.11.14b	2.1.04.01d	2.1.13.02c					2.1.14.02a	2.1.03.01b	1.2.03.01b	1.2.04.01b	1.4.02.01b 1.4.11.01b	
• Waste Package Buffer	2.1.04.00a	2.1.11.08a	2.1.04.01b	2.1.04.01c		2.1.09.51c 2.1.09.52c	2.1.04.01											
• Tunnel/Drift/Room Backfill	2.1.04.00b	2.1.07.03 2.1.11.08	2.1.04.01b	2.1.08.05		2.1.09.51c 2.1.09.52c	2.1.11.02c 2.1.11.03											
Emplacement Tunnels/Drifts and Mine Workings	2.1.04.00c	2.1.07.01b 2.1.07.02 2.1.07.08a 2.1.11.09b 2.1.12.01d	2.1.08.06 2.1.08.08d 2.1.11.10b 2.1.12.01e 2.1.12.02	2.1.09.01Z 1.09.04 2.1.09.11b 2.1.11.13e 2.1.12.01f	2.1.10.01d 2.1.11.13f	2.1.09.53d 2.1.09.54d 2.1.09.55d 2.1.11.14c	2.1.11.02d 2.1.11.04 2.1.11.05	2.1.13.01b 2.1.11.04 2.1.11.05					2.1.14.02b	2.1.03.01c	1.2.03.01c	1.2.04.01c	1.4.02.01c 1.4.11.01c	
• Open Excavations			2.1.08.07c	2.1.08.10														
• Tunnel/Drift Support	2.1.04.00d 2.1.04.01		2.1.08.08	2.1.06.01a 2.1.06.07		2.1.09.52a												
• Liners	2.1.04.00d 2.1.04.01		2.1.08.08	2.1.06.01a 2.1.06.07		2.1.09.52a												
• Other	2.1.04.00d 2.1.05.01			2.1.06.07 2.1.06.08a														

FEP Matrix

- Characteristic FEPs
  - FEPs containing properties and parameter values that describe a feature or group of features
  - No phenomena (i.e., process or event) to be screened

Characteristics, Processes, and Events / Features		Processes										Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
Buffer/Backfill	2.1.04.00a 2.1.04.00b	2.1.04.01a 2.1.07.01a	2.1.04.01b 2.1.08.03 2.1.08.07b 2.1.08.08c	2.1.04.01c 2.1.09.06 2.1.09.13c 2.1.11.13c	2.1.09.13c 2.1.11.13d	2.1.09.51c 2.1.09.52c 2.1.09.53c 2.1.09.54c 2.1.09.55c 2.1.11.14b	2.1.04.01d	2.1.13.02c					2.1.14.02a	2.1.03.01b	1.2.03.01b	1.2.04.01b	1.4.02.01b 1.4.11.01b	
• Waste Package Buffer	2.1.04.00a	2.1.11.09a	2.1.04.01b	2.1.04.01c		2.1.09.51c 2.1.09.52c	2.1.04.01f											
• Tunnel/Drift/Room Backfill	2.1.04.00b	2.1.07.03 2.1.11.09	2.1.04.01b	2.1.09.06		2.1.09.51c 2.1.09.52c	2.1.11.02c 2.1.11.05											
Emplacement Tunnels/Drifts and Mine Workings	2.1.04.00c	2.1.07.01b 2.1.07.02 2.1.07.08a 2.1.11.09b 2.1.12.01d	2.1.08.06 2.1.08.08d 2.1.11.10b 2.1.12.01e 2.1.12.02	2.1.09.01Z 1.09.04 2.1.09.11b 2.1.11.13e 2.1.12.01f	2.1.10.01d 2.1.11.13f	2.1.09.53d 2.1.09.54d 2.1.09.55d 2.1.11.14c	2.1.11.02d 2.1.11.04 2.1.11.05	2.1.13.01b 2.1.11.04 2.1.11.05					2.1.14.02b	2.1.03.01c	1.2.03.01c	1.2.04.01c	1.4.02.01c 1.4.11.01c	
• Open Excavations			2.1.08.07c	2.1.09.10														
• Tunnel/Drift Support	2.1.04.00d 2.1.09.01		2.1.08.08a	2.1.09.01a 2.1.09.07		2.1.09.52a												
• Liners	2.1.04.00d 2.1.09.01		2.1.08.08a	2.1.09.01a 2.1.09.07		2.1.09.52a												
• Other	2.1.04.00d 2.1.09.01			2.1.09.07 2.1.09.08a														

U.S. FEP Screening

Sevougian et al. (2012)

- FEP screening requires “generic” assumptions
  - Bedded salt
  - Waste package (UNF and HLW) barrier does not provide significant performance credit
  - Crushed salt backfill
  - 10,000 year screening period
- Assumptions captured in a salt reference case design
  - Sevougian et al. (2012)
- Preliminary FEP screening decisions based on generic reference case design
  - Included / Excluded: low probability, low consequence, by regulation
  - Site- or Design-Specific: requires detailed site or design information
  - Evaluate: further evaluation needed

U.S. Scenario Development

Freeze et al. (2013a)

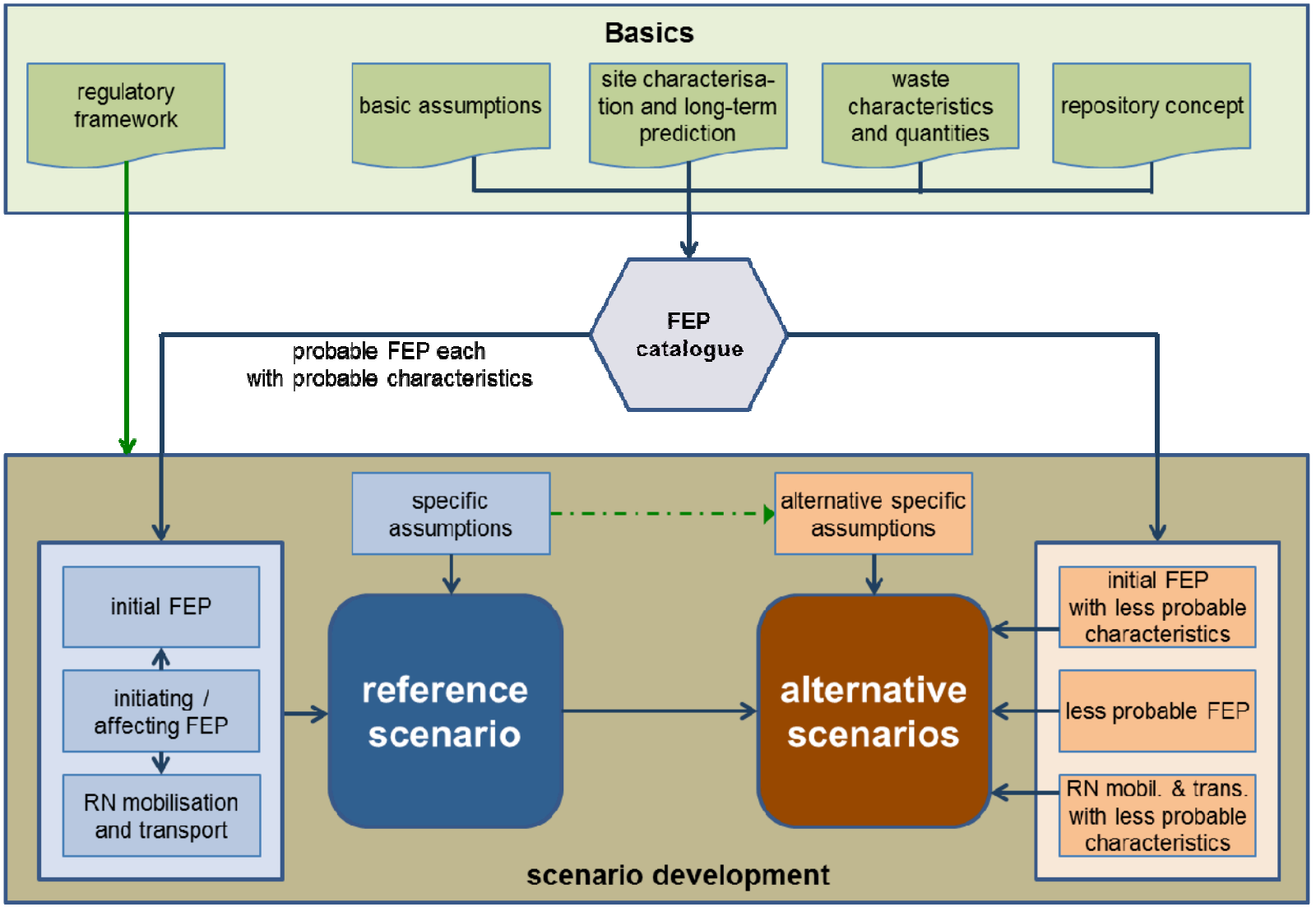
- Initial generic scenario development performed independent of FEP screening
  - Scenario "overview" based on qualitative description of salt repository initial state and evolution
  - Scenario details supported by FEP screening
- Generic scenario development focused on undisturbed scenarios
  - Disturbed scenarios require site-specific and design-specific knowledge
- Safety Assessment Model development focused on high-performance computing (HPC)-based numerical implementation to better represent coupled THCM processes
  - Multiple realization probabilistic analyses

German FEP Analysis

Wolf et al. (2012a, 2012b)

- 2008-2010:
  General FEP-Catalogue for domal salt (reference Gorleben)
  - based on NEA (1999)
  - Combination of top-down and bottom up approach
- 2010-2012: Gorleben FEP-Catalogue
  - status of knowledge on the Gorleben site
    $\rightarrow$ basis of system analysis
  - transparency and comprehensiveness
  - fundamental basis for Scenario Development

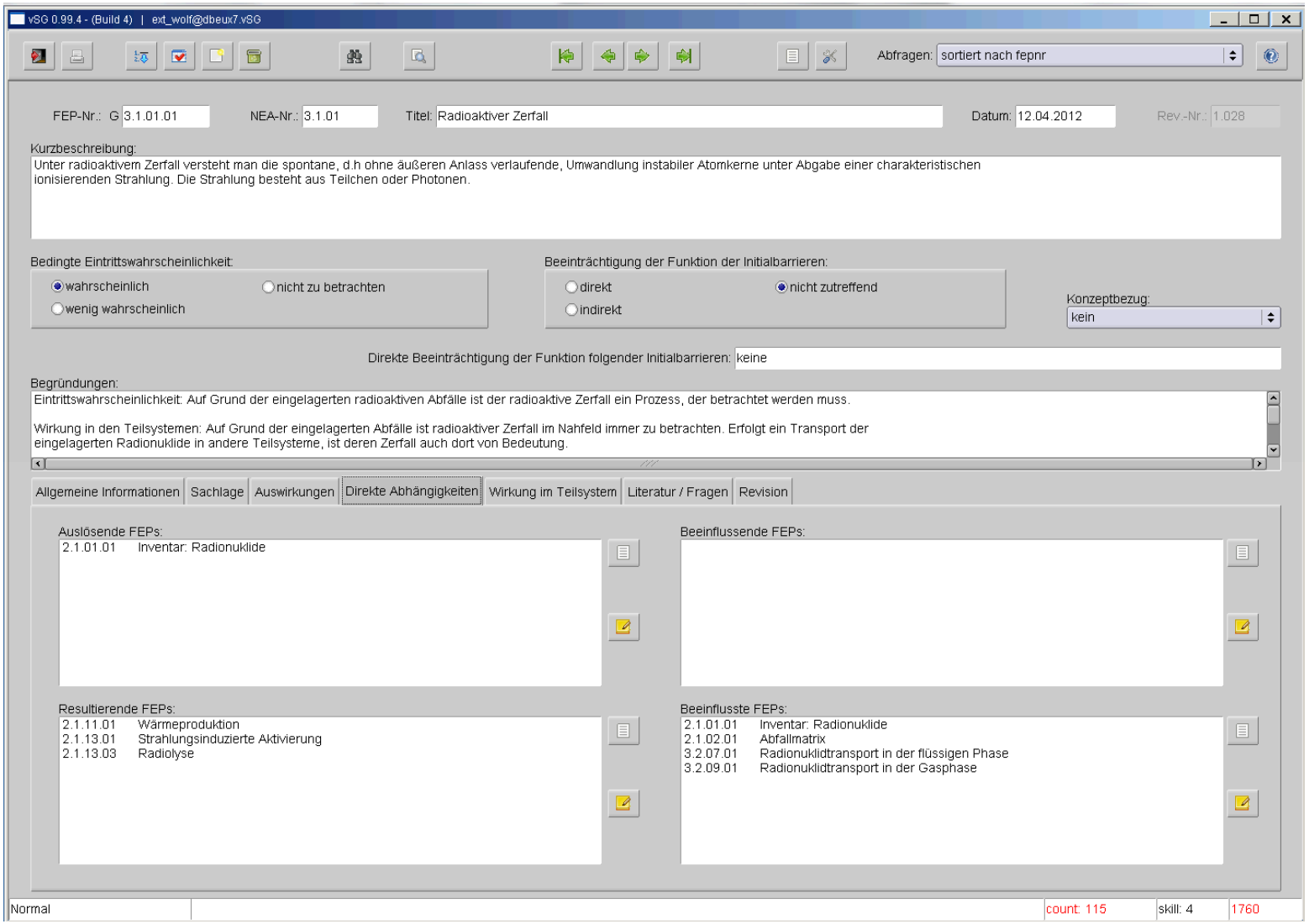
German Scenario Development



German FEP Description

- definition of FEP
- situation at site
- consequences at site
- temporal boundaries
- conditional probability
- interactions of FEP
- adverse effect on initial barriers
- open question
- literature

German FEP Data Base



Gorleben FEP Analysis

- 115 FEPs
- statement on probability:
  probable: 98, less probable: 4, not to consider: 13 (Screening I)
- FEP-Screening (II):
  6 probable FEP are classified as not relevant
- FEP list for scenario development:
  92 probable and 4 less probable FEP
- 17 alternative scenarios (all less probable)

Collaborative Results

- FEP numbering scheme: F.XX.EP.XX

F: Compartment (Features):

Waste Form:	WF
Waste Package:	WP
Buffer/Backfill:	BB
Mine Workings:	MW
Seals/Plugs:	SP
Host Rock:	HR
Other Geologic Units:	OU

Compartment Type XX:

Overall FEP: 00

Subcompartment (e.g. shaft seal, drift seal, borehole plug, …): 01, 02, 03, ….

Collaborative Results

- FEP numbering scheme: F.XX.EP.XX

FEP type EP:

Physical-chemical characteristics: CP

Mechanical and thermal-mechanical processes: TM

Hydrological and thermal-hydrological processes: TH

Chemical and thermal-chemical processes: TC

Biological and thermal-biological processes: TB

Transport and thermal-transport processes: TT

Thermal: TR

Radiological: RA

Long-Term Geologic: LG

Climatic: CL

Human Activities (Processes): HP

Other (Processes): OP

Nuclear Criticality: NC

Early Failure: EF

Seismic: SM

Igneous: IG

Human Activities (Events): HE

Other (Events): OE

Collaborative Results

- FEP Template

1. Definition
2. Description and Related FEPs
    - 2.1 General
    - 2.2 Concept specific (bedded salt vs. domal salt)
    - 2.3 Properties and parameter values
    - 2.4 Related FEPs
3. Processes and Screening Decision
4. Screening Justification
5. Open Issues
6. References

Future Work

- FEP descriptions
  - Applicability of presented FEP template
  - Schedule for FEP descriptions
- Preamble for FEP catalogue
  - Definitions
  - Explanations of Screening process etc.
- Information exchange on scenario development

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