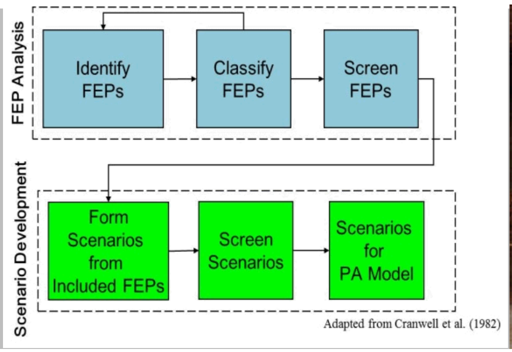
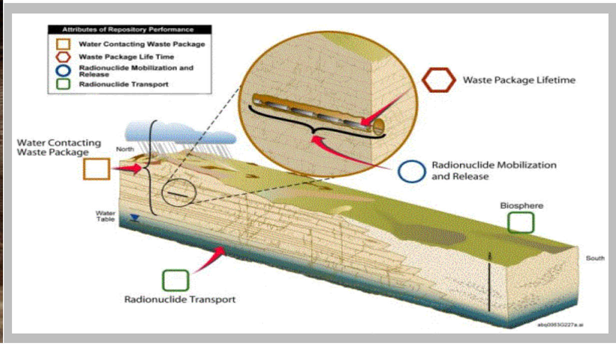
SAND2015-4106C

Exceptional service in the national interest

Sandia National Laboratories





Scenario Development in the U.S.

Geoff Freeze, Ross Kirkes, and Christi Leigh
Sandia National Laboratories

NEA IGSC Scenario Development Workshop
June 1-3, 2015
Paris, France

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

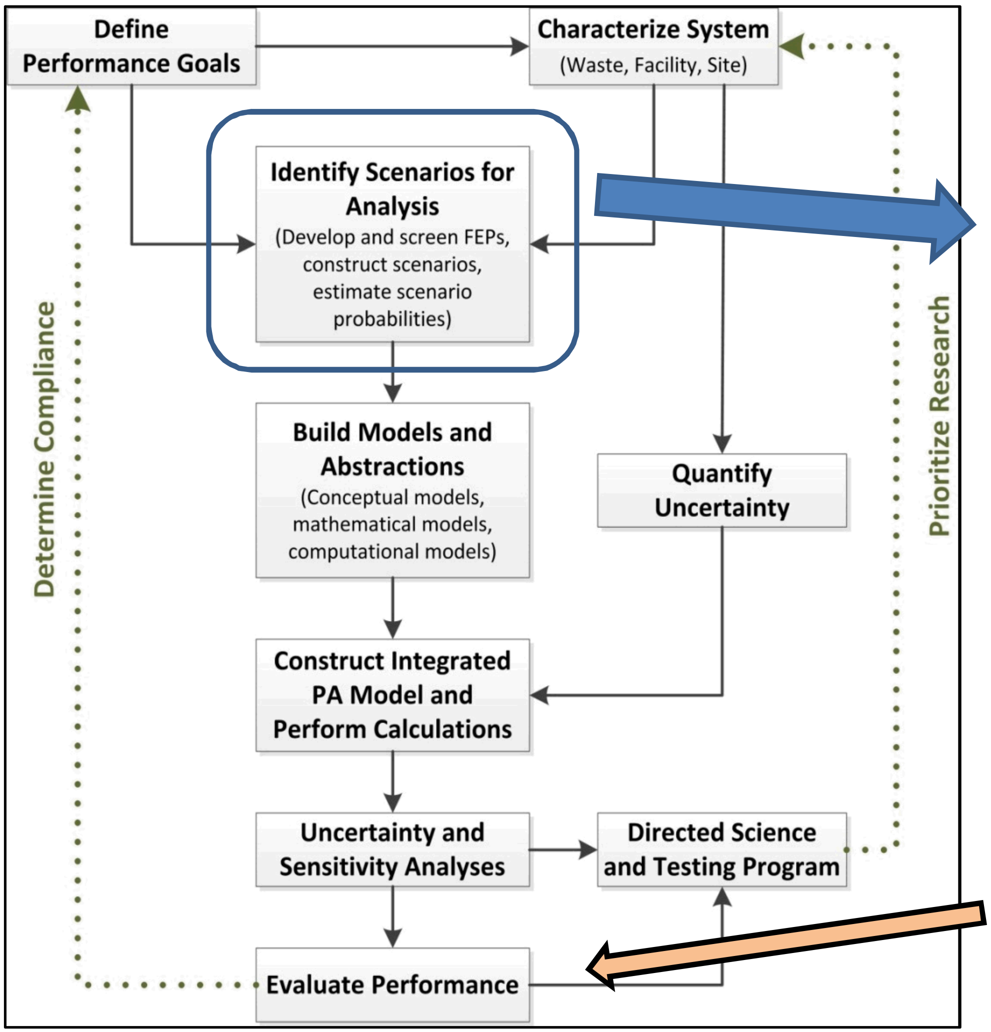
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2015-xxxxPE. Approved for Unclassified, Unlimited Release.

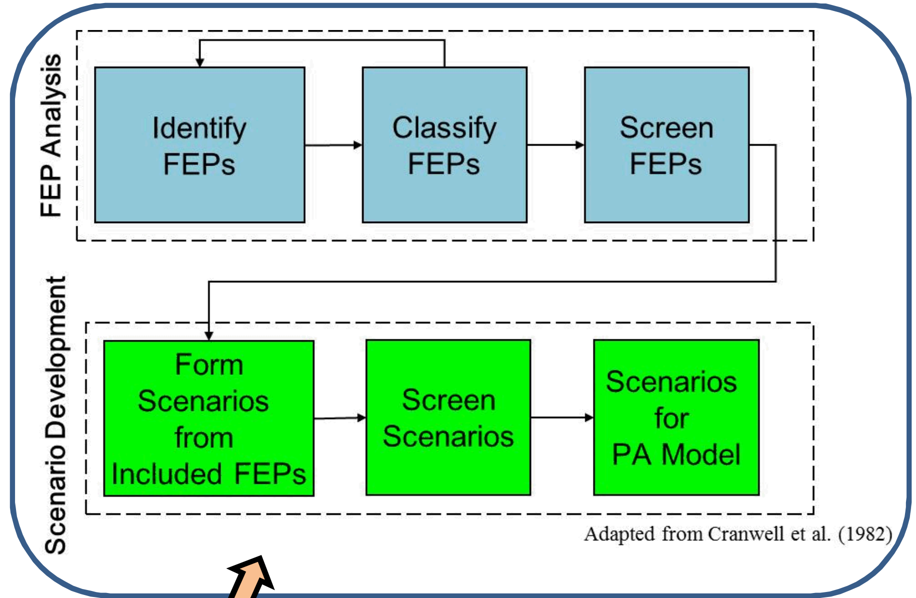
Overview of US Programs

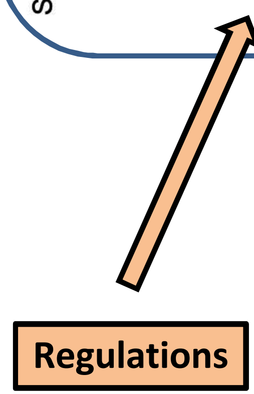
	SNF /HLW	SNF /HLW (Generic)	Transuranic (TRU)
Site	Yucca Mountain, Nevada (YM)	N/A	Waste Isolation Pilot Plant (WIPP)
Implementer	Office of Civilian Radioactive Waste Management (OCRWM)	Dept. of Energy, Office of Nuclear Energy (DOE-NE) Used Fuel Disposition Campaign (UFD)	Dept. of Energy, Office of Envir. Management (DOE-EM)
Regulator	Nuclear Regulatory Commission (NRC) 10 CFR 63 Envir. Protection Agency (EPA) 40 CFR 197	Nuclear Regulatory Commission (NRC) 10 CFR 60 ? Envir. Protection Agency (EPA) 40 CFR 191 ?	Envir. Protection Agency (EPA) 40 CFR 191, 40 CFR 194

Performance Assessment (PA) Methodology

Sandia National Laboratories





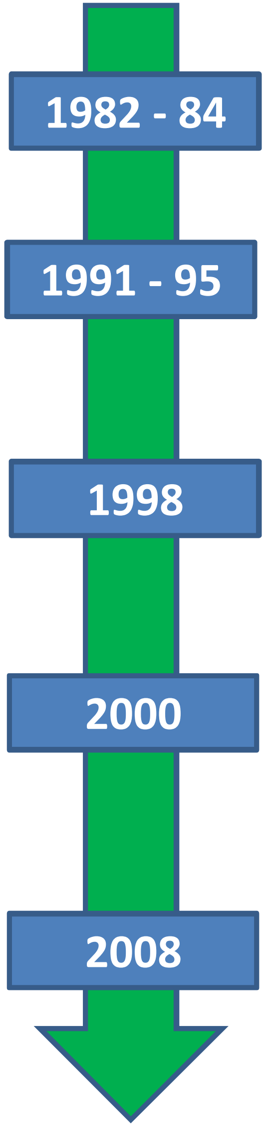


Scenario = a well-defined, connected sequence of FEPs that can be thought of as an outline of a possible future condition of the potential repository system (NEA 2003)

SNF/HLW Scenario Development

- Yucca Mountain (YM)
  - Repository in unsaturated tuff
  - YM FEPs
    - Required by 10 CFR 63 and 40 CFR 197
  - YM Scenario Classes / Modeling Cases
    - Scenario/event class = "all possible specific initiating events that are caused by a common natural process (e.g., the event class for seismicity includes the range of credible earthquakes)" [10 CFR 63.102(j)]
- Used Fuel Disposition Campaign (UFD)
  - Generic (non-site-specific) repositories in salt, clay, granite, deep borehole
  - Generic UFD FEPs
  - Undisturbed scenarios only
    - Disturbed scenarios are site specific

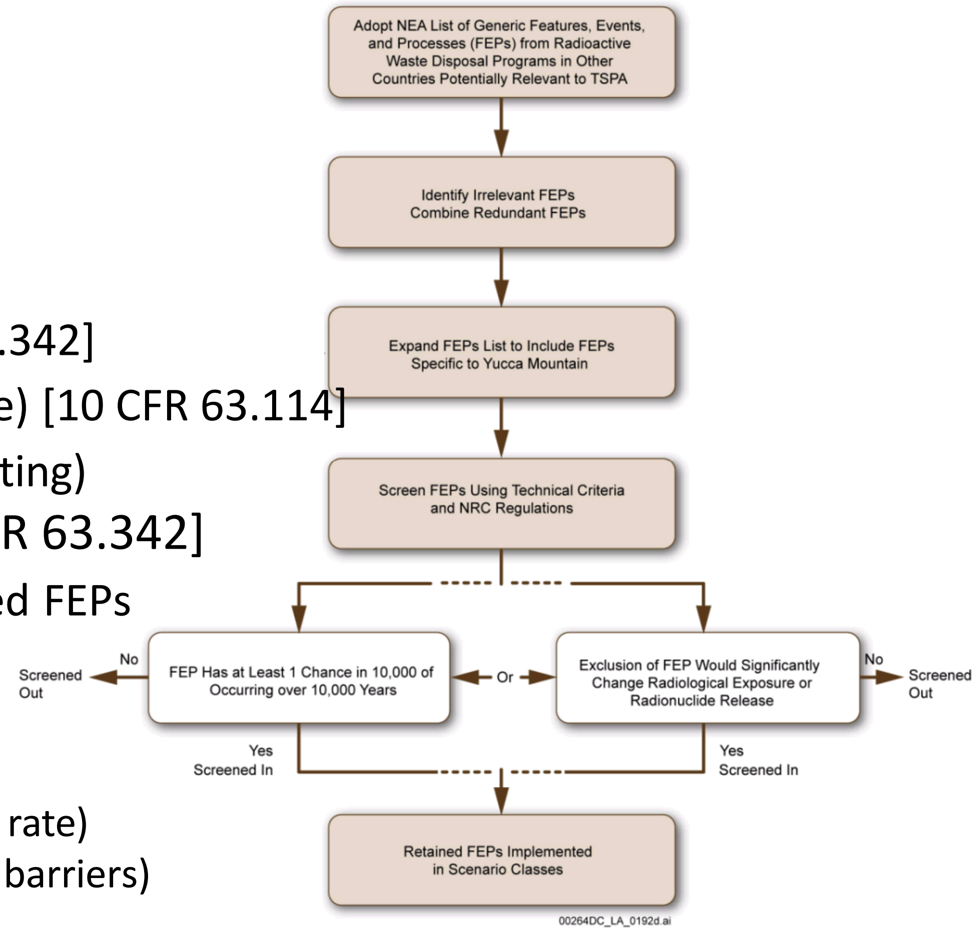
YM Scenario Development Timeline



	Scenario Classes	FEP Analysis
PA-EA	Nominal (undisturbed) Igneous (eruption)	Informal
PA-91 PA-93 PA-95	Nominal (with early WP failure) Igneous (intrusion) Human Intrusion	Informal
TSPA-VA	Nominal (with early WP failure and igneous and seismic WP damage) Igneous (eruption) Human Intrusion	Semi-formal (from 1261 NEA)
TSPA-SR	Nominal Igneous (intrusion, eruption) Human Intrusion	Formal 328 YM FEPs
TSPA-LA	Nominal (undisturbed) Early WP/DS failure Igneous (intrusion, eruption) Seismic (ground motion, fault displacement) Human Intrusion	Formal 374 YM FEPs

YM Total System Performance Assessment for License Application (TSPA-LA 2008) Iterative FEP Analysis

- Identify and Classify FEPs
  - from NEA FEP List
  - from YM-specific information
- Screen FEPs
  - 10,000-Year Screening Criteria
    - Probability (< 1×10^{-8}/yr) [10 CFR 63.342]
    - Consequence (no significant change) [10 CFR 63.114]
    - Regulation (biosphere, geologic setting)
  - > 10,000 yrs to 1,000,000 yrs [10 CFR 63.342]
    - Project continued effects of included FEPs
    - Assess post 10,000-yr effects of:
      - Seismic
      - Igneous
      - Climate Change (deep percolation rate)
      - General corrosion (on engineered barriers)



YM Total System Performance Assessment for License Application (TSPA-LA 2008) Iterative Scenario Development

Sandia National Laboratories

- Form and Screen Scenario Classes

  <u>Included</u>
  - Nominal
  - Igneous
  - Seismic
  - Early Failure

  <u>Included (Stylized Analysis)</u>
  - Human Intrusion
    - Specified drilling intrusion

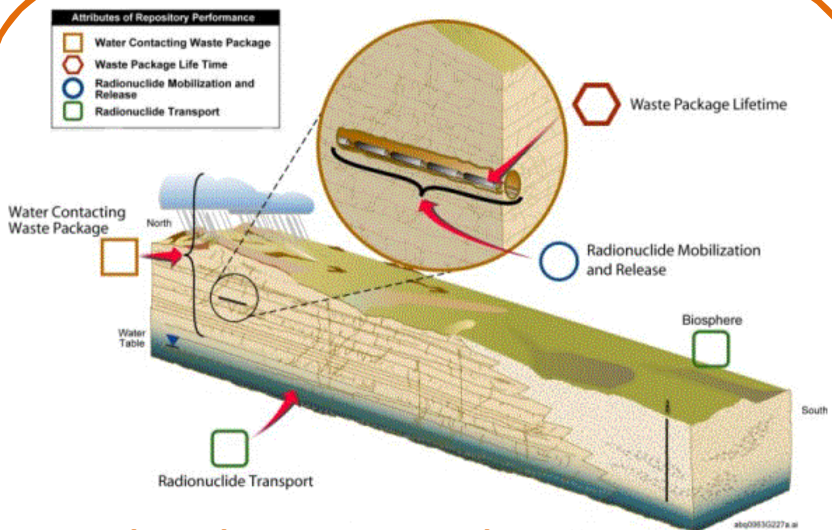
  <u>Excluded</u>
  - Criticality

Total FEPs: 152 Included, 222 Exclude

REPOSITORY SUBSYSTEM PHYSICAL ELEMENTS AND FEATURES	REPOSITORY PROCESSES AND EVENTS: Hydrologic and Thermal-Hydrologic	Chemical and Thermal-Chemical	Mechanical and Thermal-Mechanical	Microbiological	Radiological	Characteristics	Transport	Igneous	Seismic	Criticality	Early Failure	Human Intrusion
										X		
Topography and Surficial Soils	I=8 X=3	I=0 X=1	I=0 X=1			I=3 X=2		I=0 X=1	I=0 X=1			
Unsaturated Zone Above	I=30 X=29	I=3 X=7	I=1 X=5	I=0 X=2		I=7 X=9	I=0 X=6	I=2 X=4	I=2 X=5			
Emplacement Drifts	I=27 X=18	I=22 X=33	I=5 X=24	I=3 X=8	I=0 X=4	I=9 X=20	I=11 X=20	I=6 X=3	I=5 X=8	I=0 X=4		I=3 X=7
Backfill/Seals	I=0 X=4	I=0 X=4	I=1 X=6			I=0 X=6	I=0 X=3					
Drip Shield	I=1 X=3	I=2 X=10	I=6 X=15	I=0 X=2	I=0 X=1	I=3 X=0		I=1 X=0	I=3 X=1		I=1 X=0	I=1 X=0
Waste Package	I=0 X=3	I=11 X=14	I=7 X=17	I=1 X=1	I=0 X=1	I=3 X=2	I=2 X=0	I=1 X=2	I=3 X=3	I=0 X=8	I=1 X=0	I=1 X=0
Cladding	I=0 X=1	I=3 X=17	I=7 X=18	I=0 X=2	I=0 X=1	I=2 X=1	I=1 X=0	I=1 X=0	I=3 X=1			
Waste Form	I=0 X=2	I=17 X=16	I=8 X=13	I=1 X=3	I=0 X=1	I=16 X=6	I=14 X=4	I=1 X=0	I=3 X=1	I=0 X=8		I=1 X=0
Pallet	I=0 X=1	I=2 X=1	I=4 X=6	I=1 X=1	I=0 X=1	I=1 X=0		I=1 X=0	I=3 X=1			
Invert	I=4 X=4	I=11 X=4	I=4 X=10	I=0 X=4	I=0 X=1	I=3 X=3	I=12 X=10	I=1 X=1	I=3 X=2	I=0 X=4		
Unsaturated Zone Below	I=18 X=13	I=3 X=11	I=0 X=4	I=1 X=2		I=7 X=11	I=7 X=12	I=2 X=5	I=2 X=6	I=0 X=4		
Saturated Zone	I=13 X=10	I=4 X=5	I=0 X=3	I=1 X=2		I=10 X=7	I=10 X=11	I=2 X=5	I=2 X=5	I=0 X=4		
Biosphere	I=4 X=0	I=1 X=1			I=6 X=3	I=23 X=17	I=23 X=12	I=3 X=1				
System	I=2 X=0		I=0 X=3		I=1 X=0	I=18 X=31		I=3 X=3	I=3 X=6			I=3 X=10

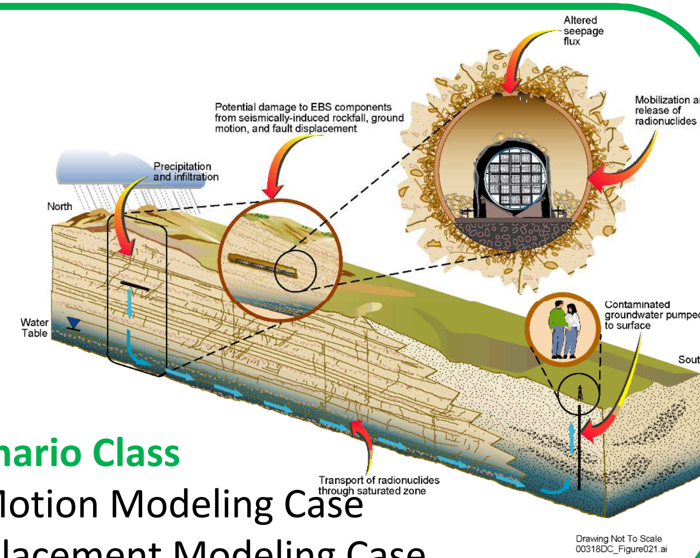
YMP Scenario Classes (TSPA-LA)

- **Nominal Scenario Class**
  - Nominal (Undisturbed) Modeling Case

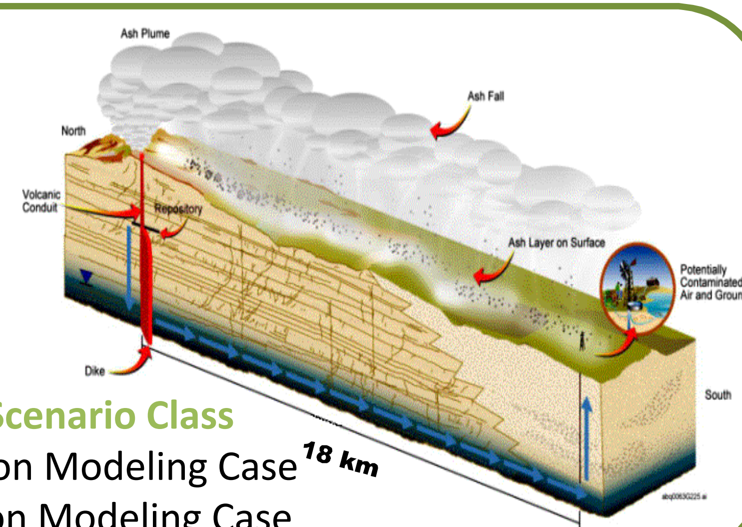


- **Early Failure Scenario Class**
  - Waste Package (WP) Modeling Case
  - Drip Shield (DS) Modeling Case

- **Human Intrusion**
  - Separate evaluation of a stylized drilling scenario
  - (per 10 CFR 63.322; 40 CFR 197.26)



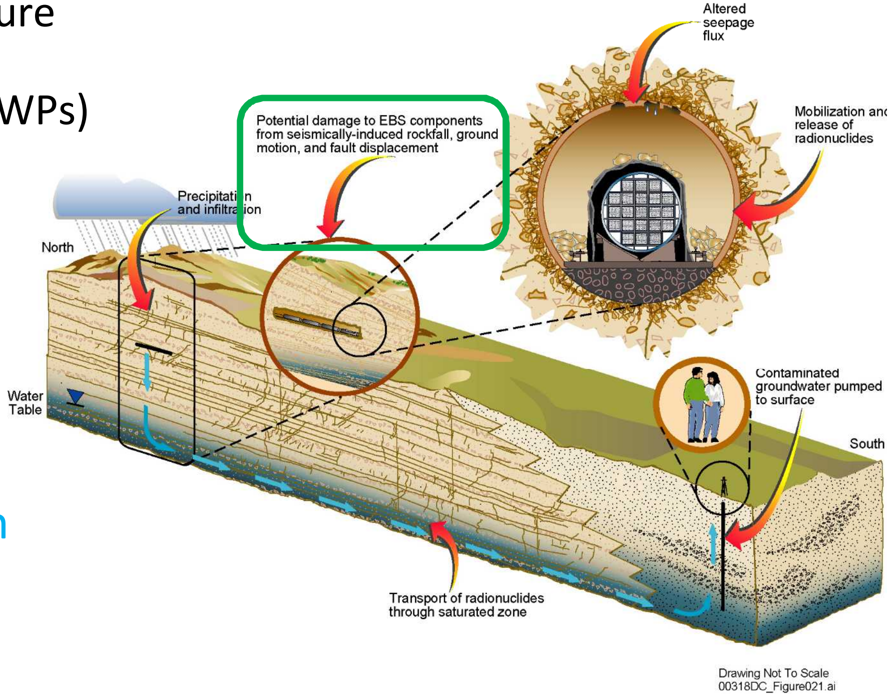
- **Seismic Scenario Class**
  - Ground Motion Modeling Case
  - Fault Displacement Modeling Case



- **Igneous Scenario Class**
  - Intrusion Modeling Case
  - Eruption Modeling Case

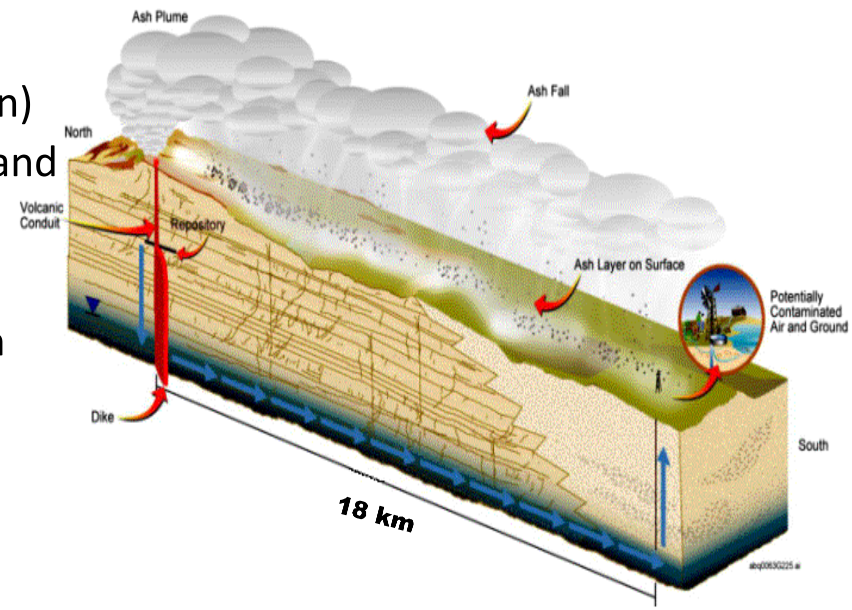
YMP Scenario Modeling Cases (TSPA-LA)

- Nominal
  - No releases until WP corrosion creates pathway
    - General corrosion of DSs between 270,000 and 340,000 yrs
    - Stress corrosion cracking (SCC) of WP closure welds common by 500,000 yrs
    - Minimal general corrosion failures (9% of WPs) between 500,000 and 1M yrs
- Seismic Ground Motion
  - Event frequency ≤ 10^{-5}/yr
  - Produces SCC failures of WP and DS (also rockfall on thinned DS)
  - Modeling case includes nominal corrosion processes
- Seismic Fault Displacement
  - Event frequency ≈ 2 x 10^{-7}/yr
  - Ruptures WPs and DSs (mean of ~47 WPs and DSs damaged)

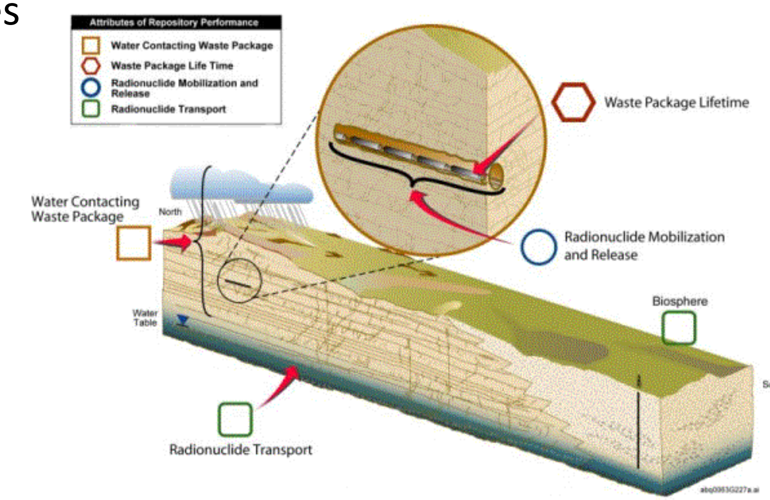


YMP Scenario Modeling Cases (TSPA-LA)

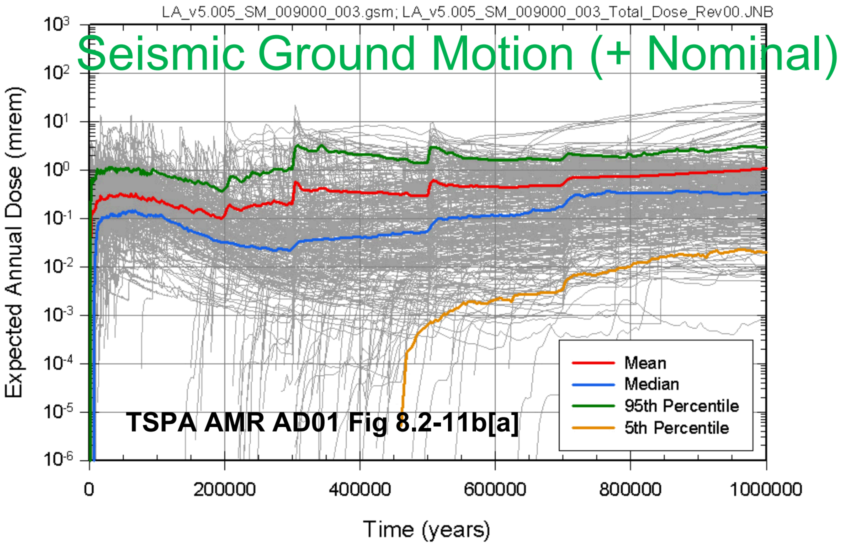
- Igneous Intrusion
  - Mean event frequency = 1.7 x 10^{-8}/yr (uncertain)
  - All WPs and DSs damaged – no barrier to flow and transport
- Volcanic Eruption
  - Probability of waste intersection conditional on igneous event = 0.08
  - Mean number of WPs intersected = 3.8



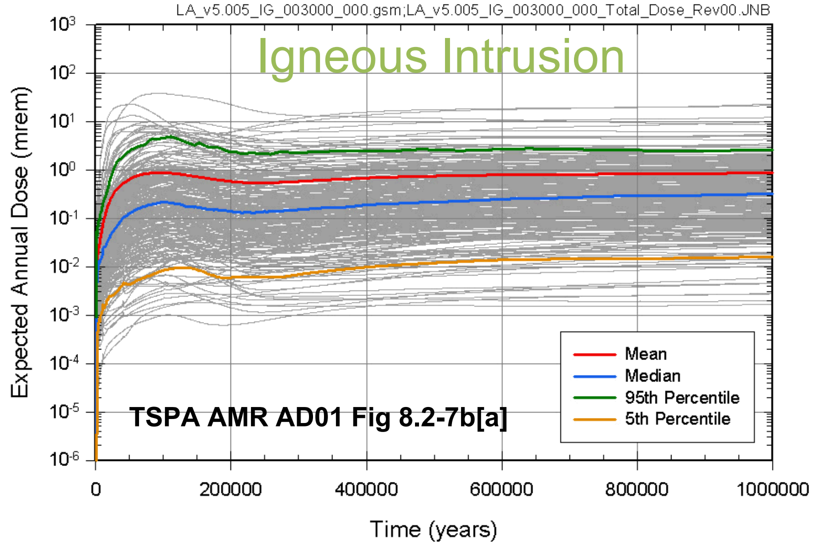
- Waste Package (WP) Early Failure
  - Probability of 1 or more early failure waste packages = 0.44
  - Expected number of early failure WPs (given early failures occur) = 2.5
- Drip Shield (DS) Early Failure
  - Probability of 1 or more early failure drip shields = 0.017
  - Expected number of early failure DSs (given early failures occur) = 1.1



YMP Total Expected Dose (TSPA-LA)



+

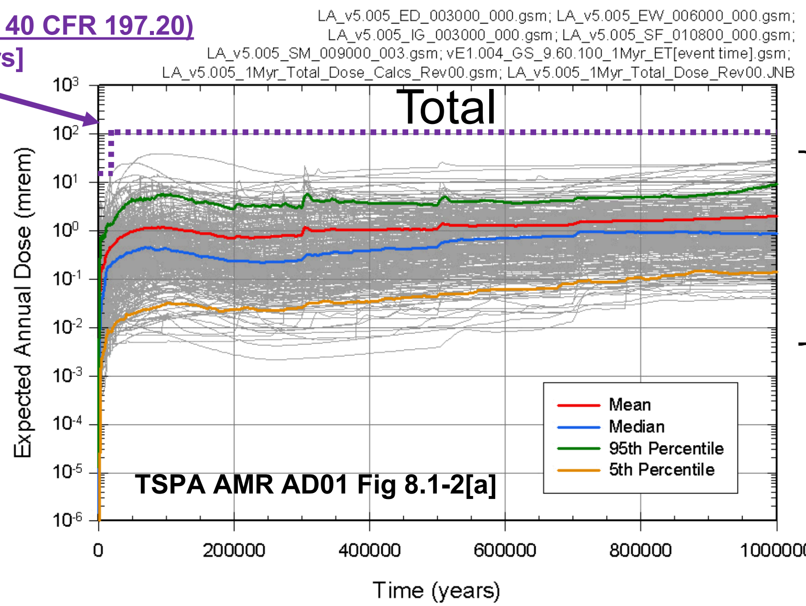


+ ... =

Individual Protection Standard (10 CFR 63.311; 40 CFR 197.20)

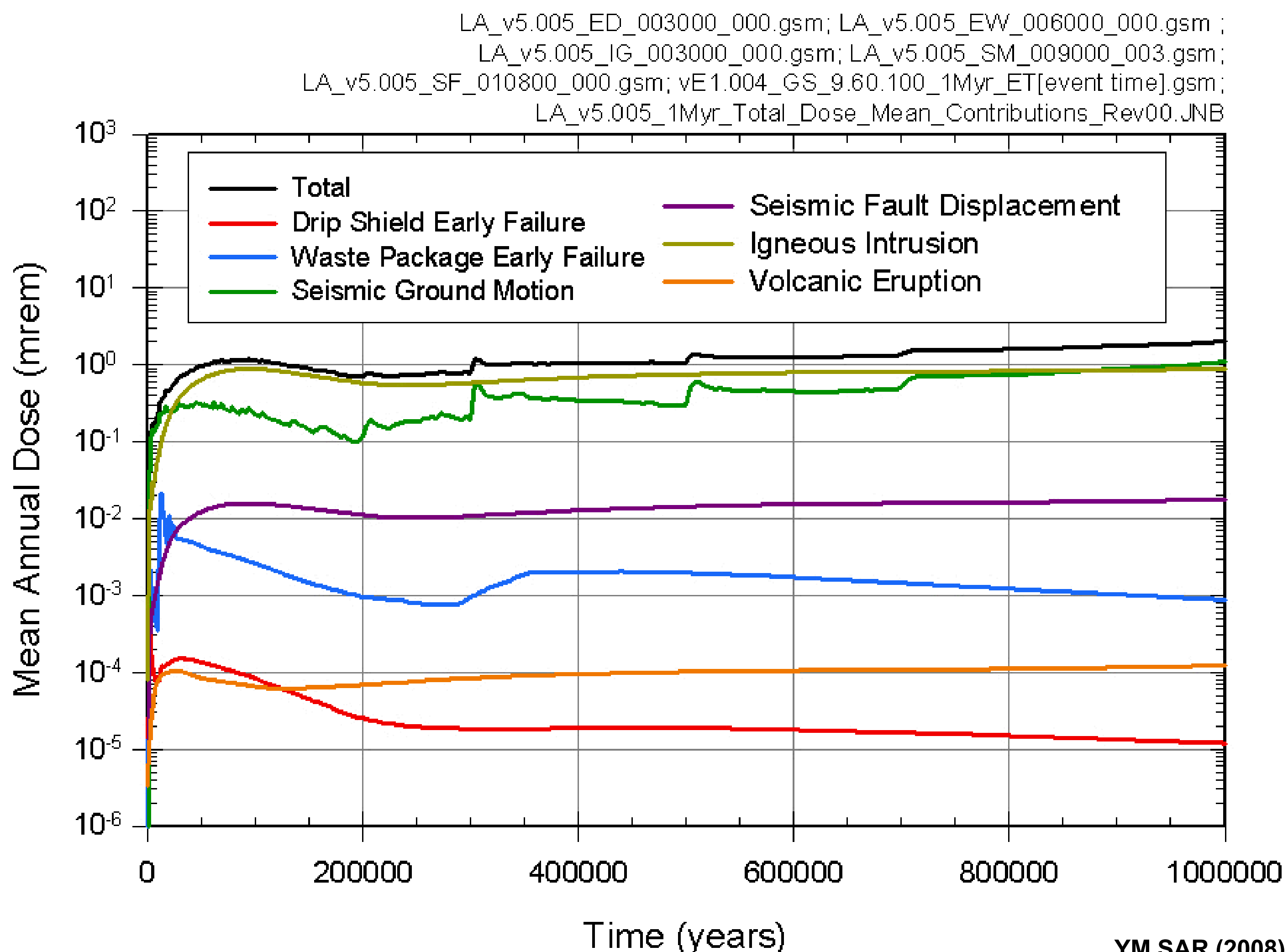
100 mrem/yr (1 mSv/yr) [>10,000 to 1,000,000 yrs]

15 mrem/yr (150 μSv/yr) [≤10,000 yrs]



Uncertainty over 300 realizations

YMP Total Mean Dose (TSPA-LA) Contribution by Modeling Case



YM SAR (2008)

UFD FEP Analysis Process

- FEP Identification and Categorization
  - Started with YMP FEP list (374 FEPs) which was derived from NEA international FEP list (2000+ FEPs)
    - Considerable redundancy across the 2000+ FEPs
  - Consolidated and generalized YMP FEPs
  - Developed preliminary UFD FEP list (208 FEPs)
    - UFD FEPs categorized in accordance with NEA international FEP categories
    - Applicable to generic repositories in salt, clay, granite, (and deep borehole)

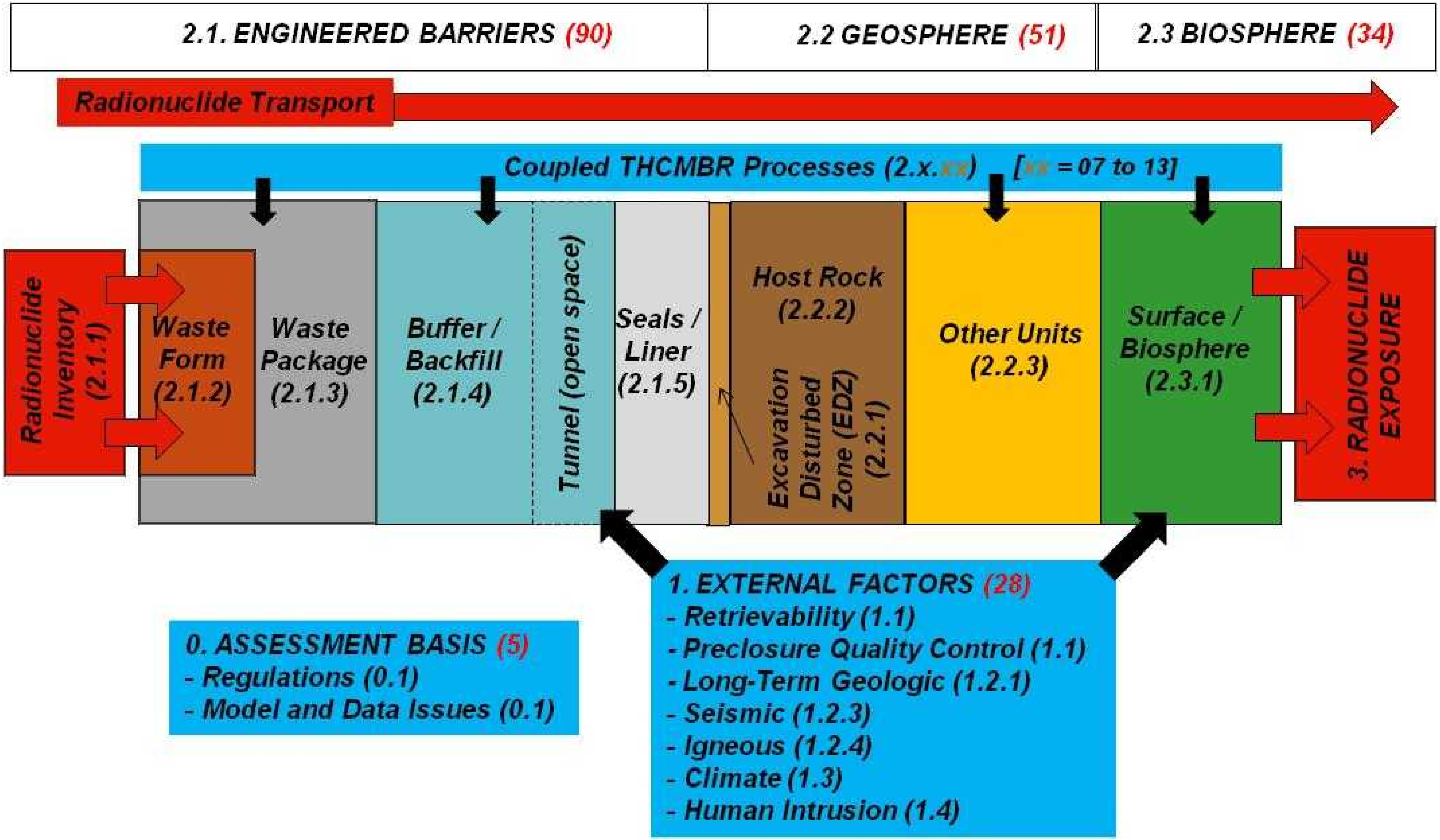
Small number of "lumped" FEPs capture all YMP and international FEPs (from several different programs and disposal concepts) at a broad level of detail

Additional detail provided by "Associated Processes"

UFD FEP Number	Phenomena	Associated Processes	Domain	Disposal Options
2.1.09.51	Advection of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Saturation [see also Gas Phase Transport in 2.1.12.03]	EBS (TRAN)	

UFD FEP Analysis Process

- 208 generic UFD FEPs



Current UFD FEP Analysis and Scenario Development

Sandia National Laboratories

- FEP Screening and Scenario Formation
  - Preliminary FEP screening for generic repository concepts
  - Preliminary scenarios and High-Performance Computing (HPC)-based PA Models for generic repository concepts
    - Undisturbed scenarios only (disturbed scenarios are site specific)
- US/German Salt FEP Catalogue
  - Evaluating salt FEPs based on UFD, WIPP, and Gorleben FEP lists
  - Using FEP Matrix organizational structure

Characteristics, Processes, and Events / Features and Components		Processes											Events					
	(CP) Characteristics	(TM) Mechanical and Thermal-Mechanical	(TH) Hydrologic and Thermal-Hydrologic	(TC) Chemical and Thermal-Chemical	(TB) Biological and Thermal-Biological	(TT) Transport and Thermal-Transport	(TR) Thermal	(RA) Radiological	(LG) Long-Term Geologic	(CL) Climatic	(HP) Human Activities (long timescale)	(OP) Other	(NC) Nuclear Criticality	(EF) Early Failure	(SM) Seismic	(IG) Igneous	(HE) Human Activities (short timescale)	(OE) Other
Waste and Engineered Barriers Region																		
(WF) Waste Form and Cladding																		
• Commercial SNF & Cladding																		
• Commercial HLW Glass																		
• Naval SNF & Cladding																		
• Defense SNF & Cladding																		
• Defense HLW																		
• Other																		
(WP)Waste Package and Internals				1														
• Commercial SNF																		
• Commercial HLW																		
• Naval																		
• Defense SNF																		
• Defense HLW																		
• Other Packages																		
(BB) Buffer/Backfill																		
• Waste Package Buffer																		
• Tunnel/Drift/Room Backfill	1	2				2												
(MW) Emplacement Tunnels/ Drifts and Mine Workings																		
• Open Excavations			1														1	
• Drift Support																		
• Liners																		
• Other																		
(SP) Seals/Plugs																		
• Drift/Panel Seals/Closures																		
• Shaft Seals		1		1														
• Plugged Boreholes																		
Geosphere and Natural Barriers Region																		
(HR) Host Rock (Repos. Horizon)																		
• Bedded or Domal Salt	1	1				2						1						
• Disturbed Rock Zone	1	1	1			2												
• Interbeds and Seams	1					2												
(OU) Other Geologic Units																		
• Aquifer(s)																		
• Unsaturated Zone																		
• Pressurized Brine Reservoir(s)																		
Surface Region																		
(BP) Biosphere																		
• Natural Surface and Near-Surface Environment																		
• Flora and Fauna																		
• Humans																		
• Food and Drinking Water																		
• Dwellings and Man-Made Surface Features/Materials																		
System Region																		
(RS) Repository System																		
• Assessment Basis																		
• Pre-closure and Operational																		
• Other Global	1																	

WIPP Scenario Development History

- Early scenario development process preceded regulatory guidance
- SAND80-1429 (Cranwell et al., 1982) documented a formal process for developing scenarios and the "Performance Assessment Methodology"
- Scenarios for WIPP PA "refined" from 1989 to 1996 based on input from scientific program, stakeholders, and regulator (EPA).

WIPP Scenario Development

- Step 1: Identify disruptive FEPs
  - Disruptive FEPs are defined as those FEPs that result in the creation of new pathways, or significant alteration of existing pathways, for fluid flow and, potentially, radionuclide transport within the disposal system.
- Step 2: Classify FEPs
  - Natural FEPs
  - Waste and Repository Induced FEPs
  - Human-induced FEPs
- Step 3: Screen FEPs
  - Retained FEPs are included in one or more performance scenarios
  - Excluded FEPs are screened out based on screening criteria

WIPP Scenario Development

- Step 4: Combine FEPs to form performance scenarios
  - Undisturbed Performance (UP) scenario
    - Considered the "base case"; represents the starting point for DP scenarios
      - Includes the Natural System FEPs that are retained
      - Includes the Waste related FEPs that are retained
      - May include certain Human FEPs if such activities are already underway (e.g., mining), at least for the near term
  - Disturbed Performance (DP) scenarios
    - Include disruptive events
      - Drilling (Human Intrusion)
      - Mining
      - WIPP has no natural disruptive events (e.g., earthquakes, tsunamis, tornados)
  - Scenario formation should err on the side of inclusion
    - Use unrestricted brainstorming at first - don't discount scenarios initially, this comes in Step 5 (scenario screening)

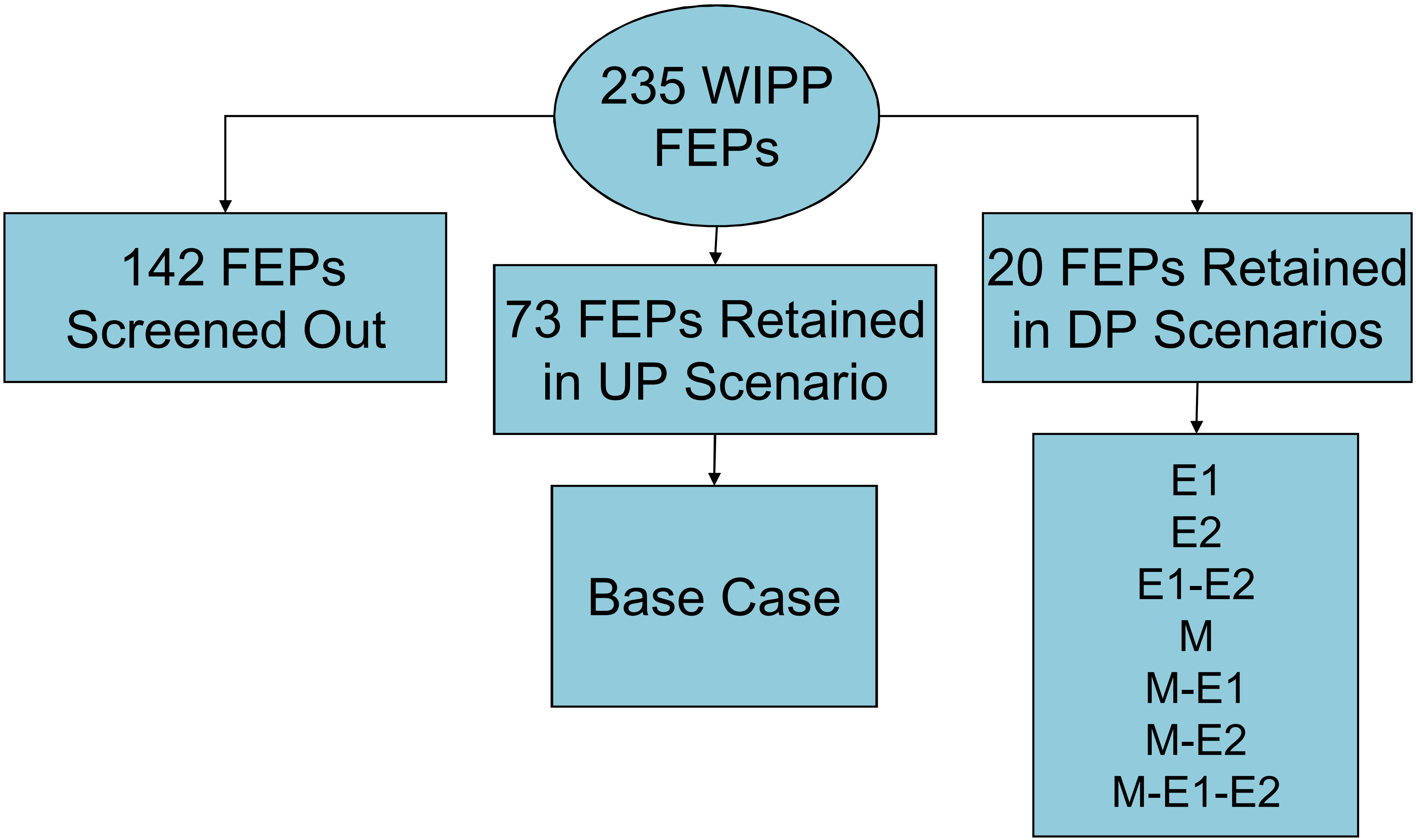
WIPP Scenario Development

- Step 5: Screen Scenarios
  - Ask, “Is this a credible and realistic scenario?”
  - Make adjustments as necessary
  - Use peer groups, other repository programs to gauge applicability
- Step 6: Finalize Set of Scenarios
  - Refine scenarios and decide the proper manner to represent in PA
    - Some scenarios are single events
      - E1 (drilling intrusion with brine pocket intercepted)
      - E2 (drilling intrusion with no brine pocket intercepted)
    - Some scenarios are combined
      - E1E2
  - All components of PA benefit from an iterative process

WIPP Scenario Refinement

- Initial FEPs list development occurred before scenario development, but;
- Preliminary PAs were used to refine, and make FEPs list more appropriate and meaningful
- Evolving regulations and input from stakeholders and peers led to further refinement and development of appropriate scenarios
  - Regulatory-mandated human intrusion affected disturbed and undisturbed scenarios, specific screening criteria, etc.
  - Mining scenario not included until EPA required it with the promulgation of 40 CFR 194
  - Stakeholder concerns that a brine pocket intrusion (E1) could be followed by a non-brine pocket intrusion into the same panel thereby producing more harmful effects, hence E1E2 Scenario.

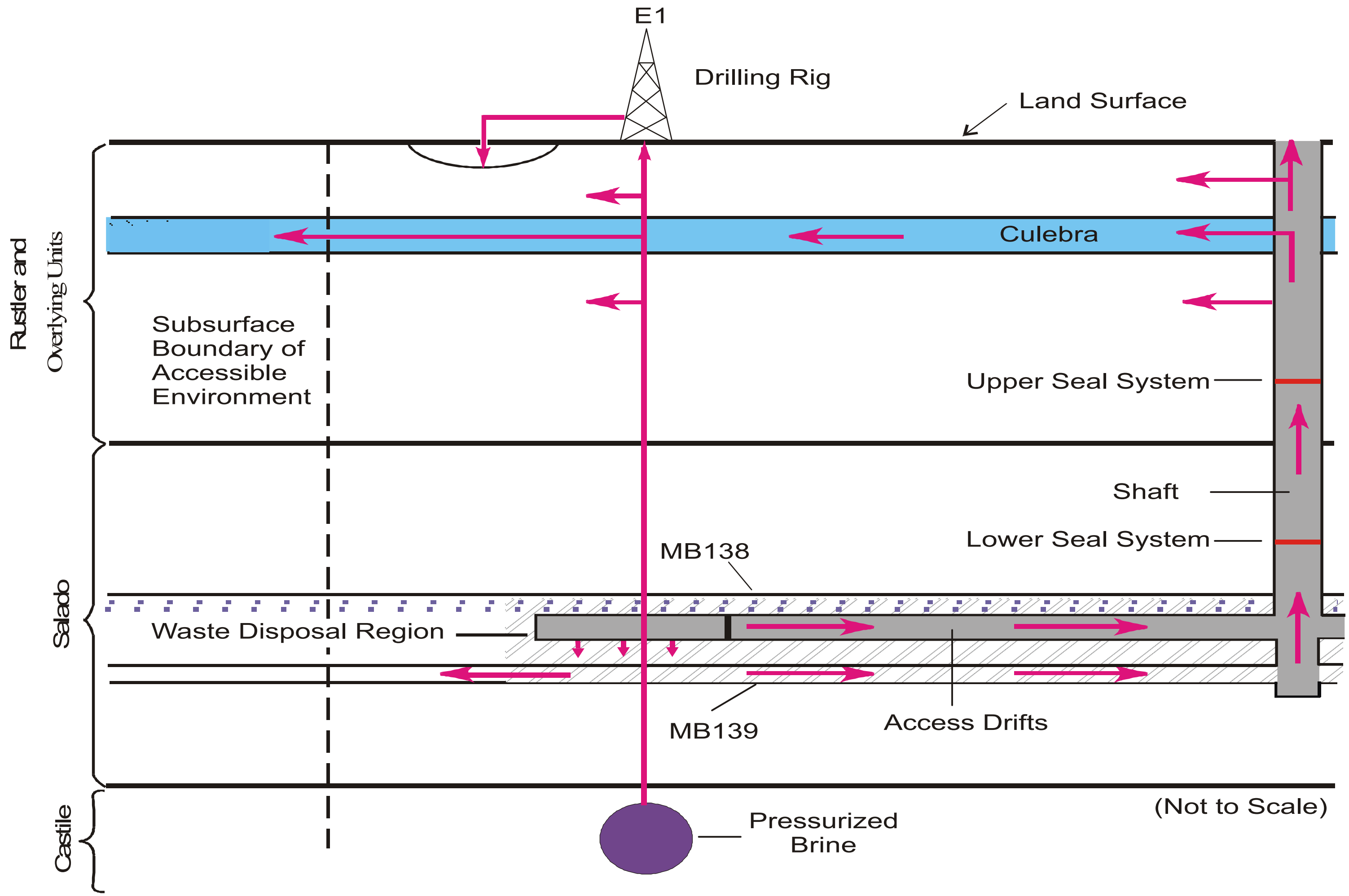
WIPP Scenarios



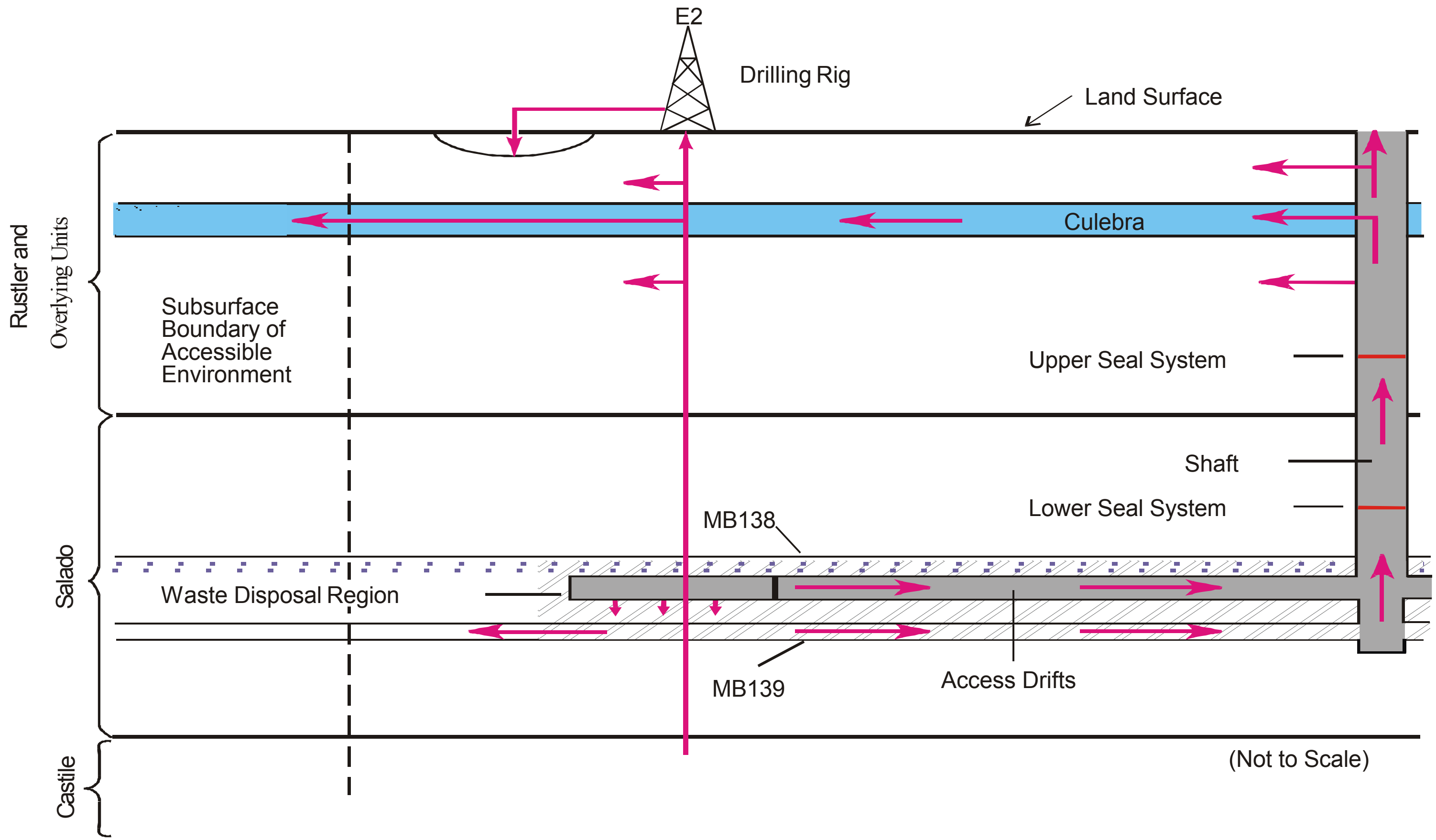
WIPP DP Scenarios

- E1 – drilling intrusion into pressurized brine pocket
- E2 – drilling intrusion that does not hit brine
- E1-E2 – drilling intrusion into the repository that was previously hit by an intrusion that intercepted a brine pocket
- M – mining
- M-E1 – mining in combination with E1
- M-E2 – mining in combination with E2
- M-E1-E2 – mining in combination with E1-E2

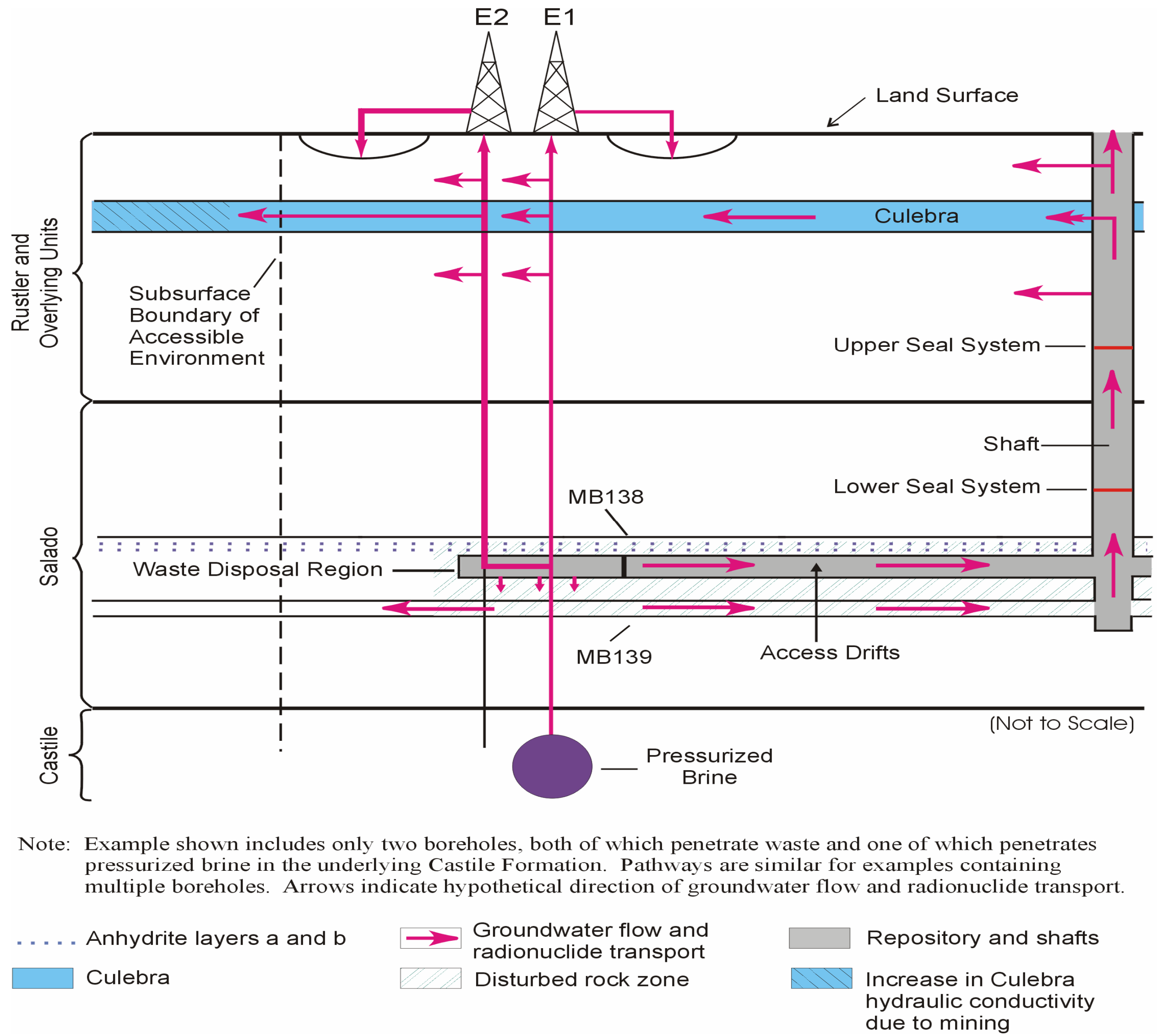
WIPP E1 Scenario



WIPP E2 Scenario



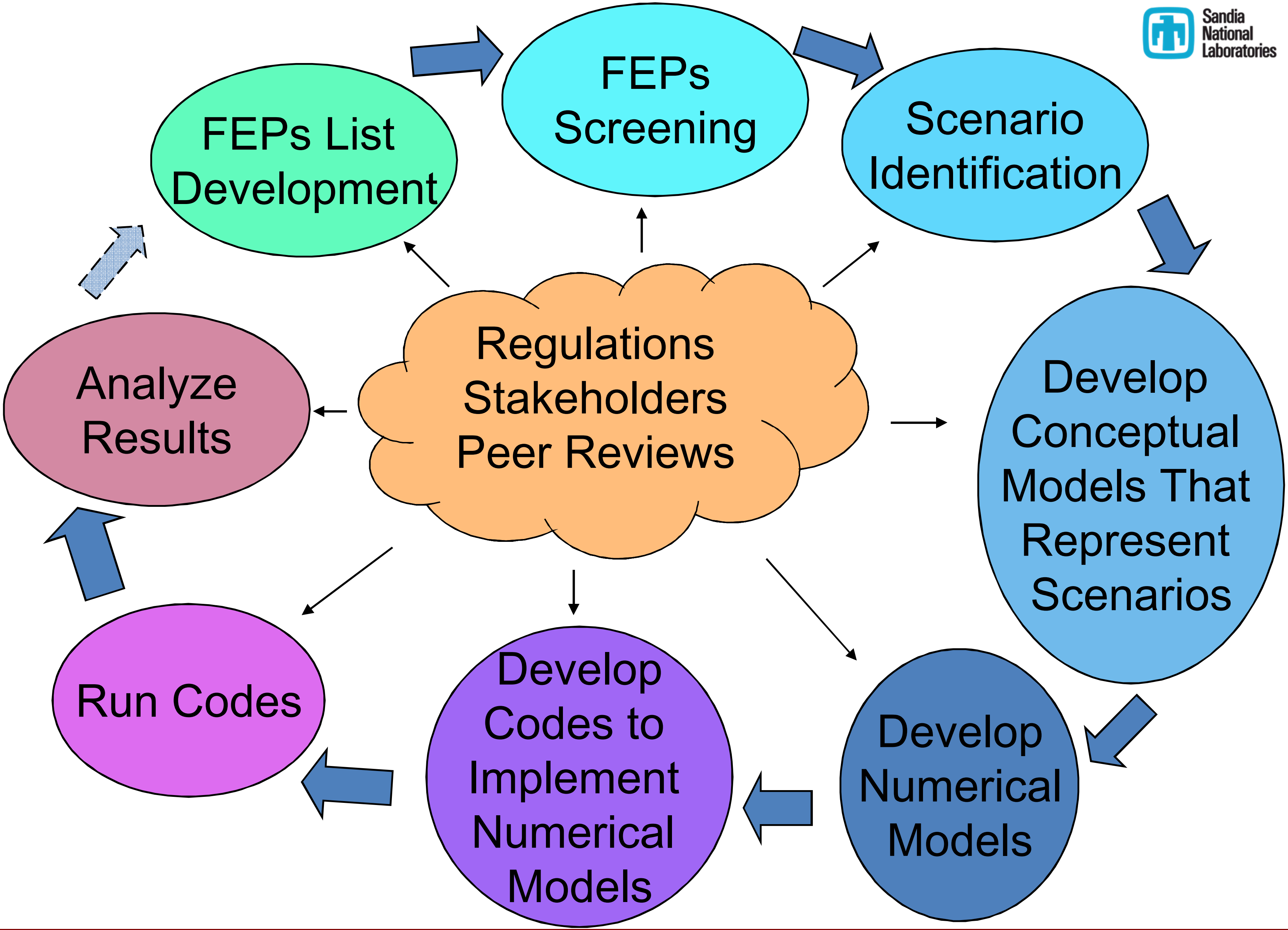
WIPP E1E2 Scenario



WIPP Mining Scenario

- Specified by 40 CFR 194.32 (b)
  - *Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame.*
- Supplemental Information, 40 CFR 194 Subpart C
  - *…DOE may use the location-specific values of hydraulic conductivity, established for the different spatial locations within the Culebra dolomite, and treat them as sampled parameters with each having a range of values varying between unchanged and increased 1,000-fold relative to the value that would exist in the absence of mining.*

Backup Slides


FEPs List Development
FEPs Screening
Scenario Identification
Develop Conceptual Models That Represent Scenarios
Develop Numerical Models
Develop Codes to Implement Numerical Models
Run Codes
Analyze Results
Regulations Stakeholders Peer Reviews

Nominal Scenario Class (TSPA-LA) (1 modeling case)

- Nominal Modeling Case
  - No releases until waste package (WP) corrosion creates pathway
  - WP failures rare before 100,000 years
  - WP failures due to stress corrosion cracking (SCC) of closure welds occur as general corrosion removes annealed layer
    - SCC common by 500,000 years
    - Releases through SCC occur by diffusion only
  - Drip shield (DS) failures due to general corrosion occur between 270,000 and 340,000 years
  - WP "patch" failures due to general corrosion rarely occur before 500,000 years
    - Mean of 9% of WPs show patch failures at 1 million years
    - Patch failures allow advective releases

Early Failure Scenario Class (TSPA-LA) (2 modeling cases)

- Waste Package (WP) Early Failure Modeling Case
  - Failures occur at time of repository closure
  - Median probability of early failure = 4.4×10^{-5} per WP
  - Probability of 1 or more early failure waste packages = 0.44
  - Expected number of early failure waste packages (given early failures occur) = 2.5
  - Diffusion until DS failure by corrosion
- Drip Shield (DS) Early Failure Modeling Case
  - Failures occur at time of repository closure
  - Median probability of early failure = 4.3×10^{-7} per DS
  - Probability of 1 or more early failure drip shields = 0.017
  - Expected number of early failure drip shields (given early failures occur) = 1.1
  - Simplifying assumption: WP under early failed DS is also failed in seeping conditions
  - Transport by both advection and diffusion

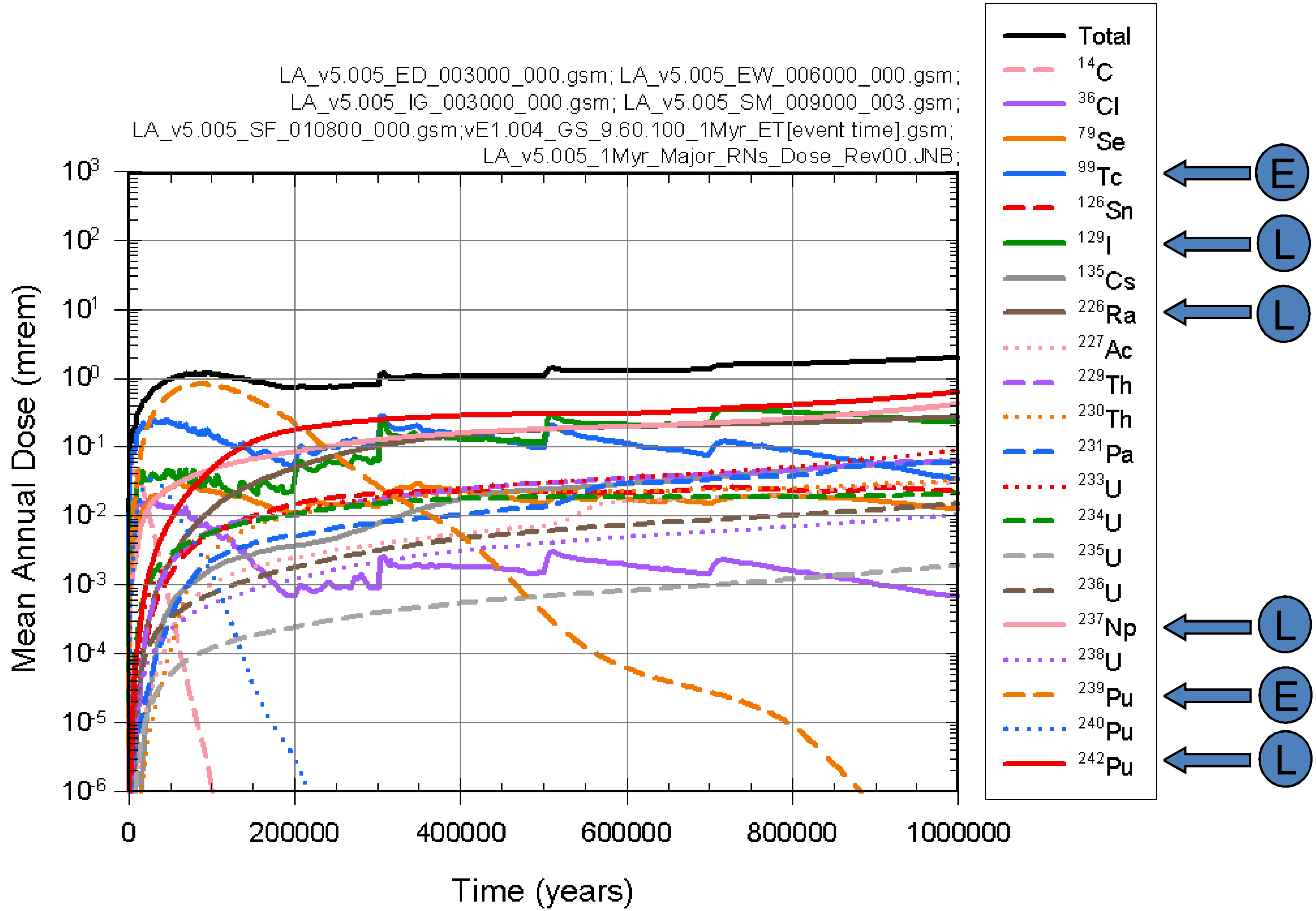
Igneous Scenario Class (TSPA-LA) (2 modeling cases)

- Intrusion Modeling Case
  - Mean frequency 1.7 x 10^{-8}/yr (uncertain event frequency)
  - All waste packages and drip shields sufficiently damaged to provide no barrier to flow and transport
  - Seepage equal to percolation flux (no capillary barrier)
- Eruption Modeling Case
  - Probability of waste intersection by eruption conditional on igneous event is 0.08
  - Mean number of waste packages intersected = 3.8
  - Mean fraction of waste package content ejected = 0.3
  - Ash redistribution by fluvial processes after deposition

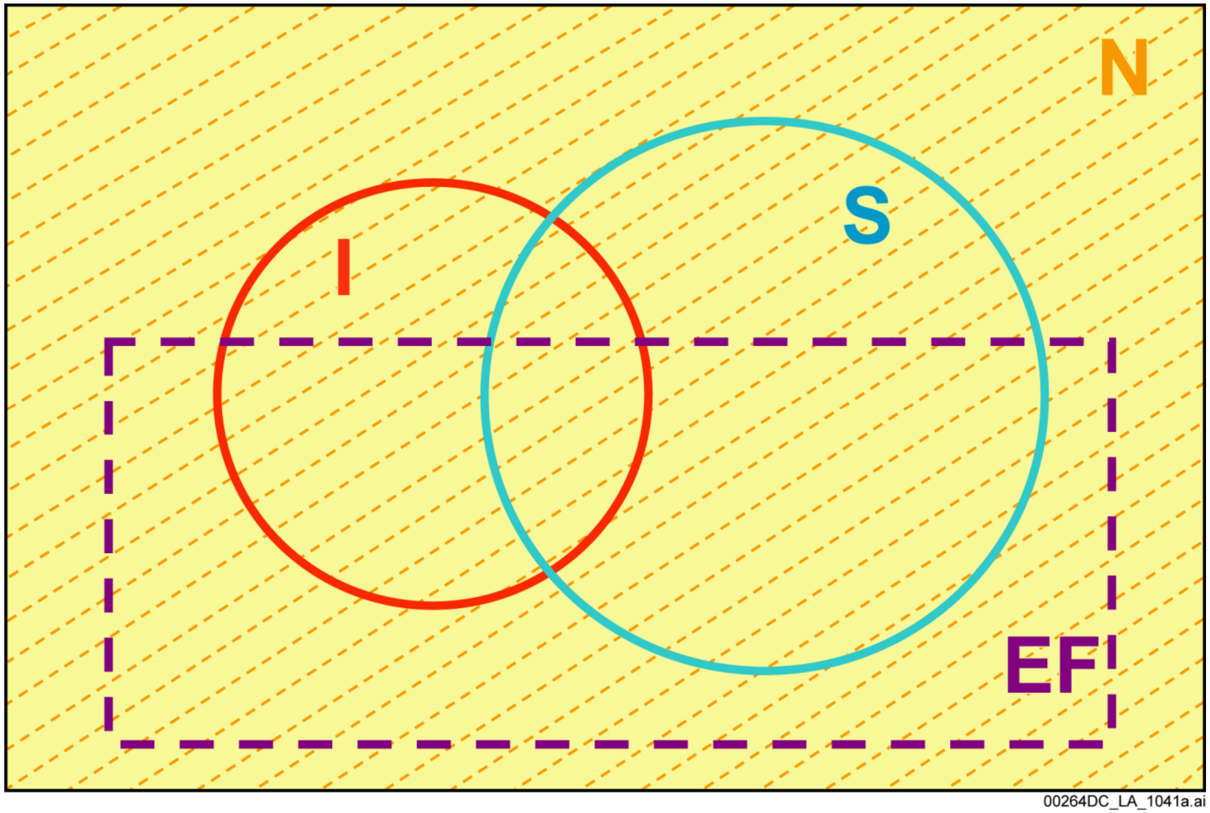
Seismic Scenario Class (TSPA-LA) (2 modeling cases)

- Ground Motion (GM) Modeling Case
  - Ground motions result in SCC that allow diffusive releases
    - Frequency of events that damage codisposal (CDSP) packages: ~ 10-5 / yr
    - Frequency of events that damage transportation, aging, and disposal (TAD) packages for commercial spent nuclear fuel (CSNF): ~ 10-8 / yr
  - Cracked area accumulates with additional seismic events
  - Repeated damage may cause WP rupture (<10-8/ yr)
  - Drip shield thins by general corrosion and fails due to dynamic loading of accumulated rockfall
  - Nominal corrosion processes included for million-year analyses
    - Corrosion affects EBS response to ground motion
- Fault Displacement Modeling Case
  - Annual frequency approximately 2 x 10^{-7}/ yr
  - Fault displacements rupture waste packages and drip shields, allowing advection and diffusion
    - Size of rupture uncertain, 0 to cross-sectional area of WP
  - Mean of ~ 47 waste packages and drip shields damaged

Radionuclides Important to Mean Dose Early (E) and Late (L)



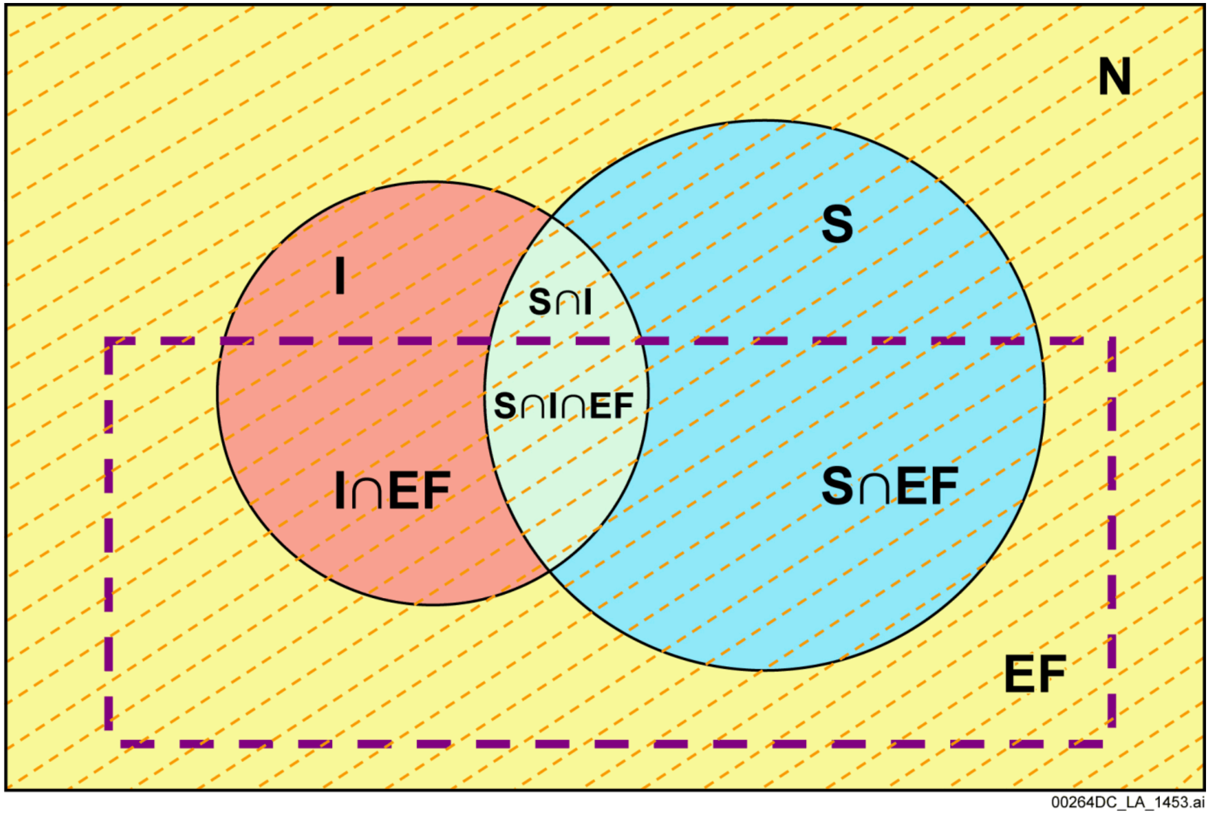
YM Venn Diagram Representing Sets of Futures Associated with Events



N = nominal; I = igneous; S = seismic; EF = early failure

The overlap of areas indicates that these futures are independent and not mutually exclusive. [Source: SNL 2008, Figure 6-2; YM SAR Figure 2.2-2].

YM Venn Diagram Representing Sets of Futures Associated with Events



N = nominal; I = igneous; S = seismic; EF = early failure; S∩I = seismic/igneous; I∩EF = igneous/early failure; S∩EF = seismic/early failure; S∩I∩EF = seismic/igneous/early failure;

These futures are independent and mutually exclusive.
[Source: SNL 2008, Figure 6-3; YM SAR Figure 2.2-3].