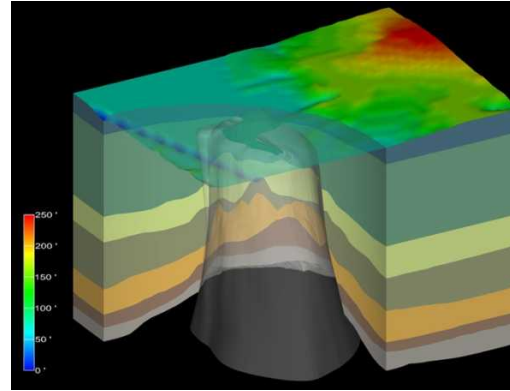


Exceptional service in the national interest

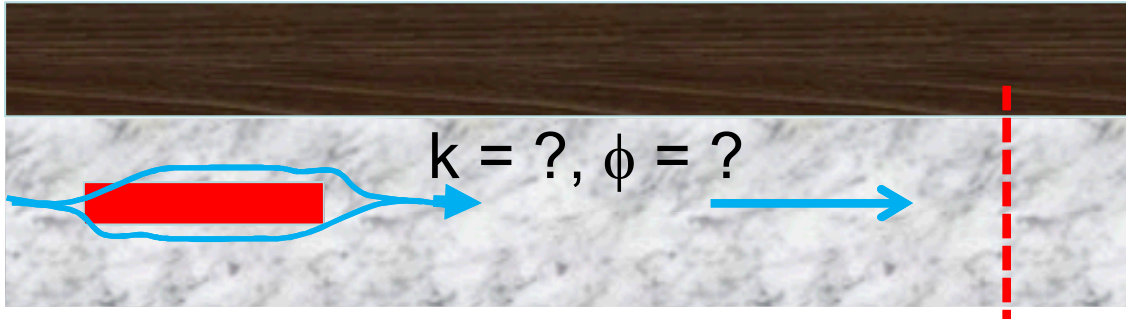


Radioactive Waste Repository Development, Safety Assessment, and Site Characterization

IAEA Training Course – July 1-5, 2013

Robert J. MacKinnon

Problem Statement



Effective properties of the medium



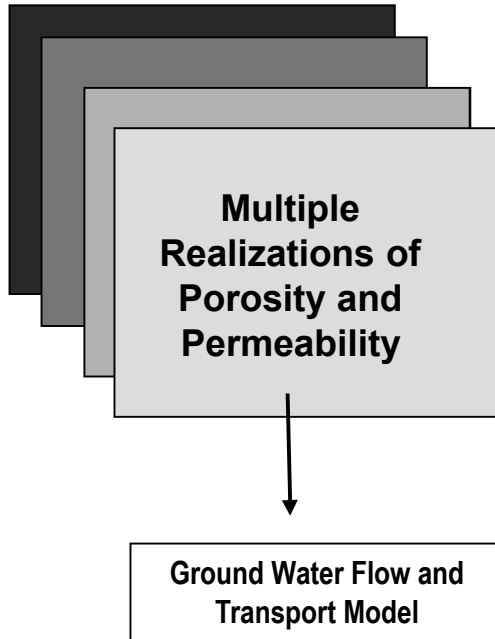
Effective properties of discrete zones within the unit

Radionuclides are being released from a repository. What will the concentration of a given radionuclide be at a downgradient location in 10,000 years?

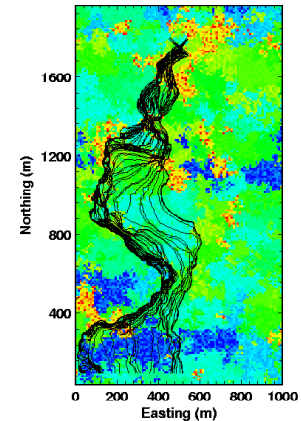
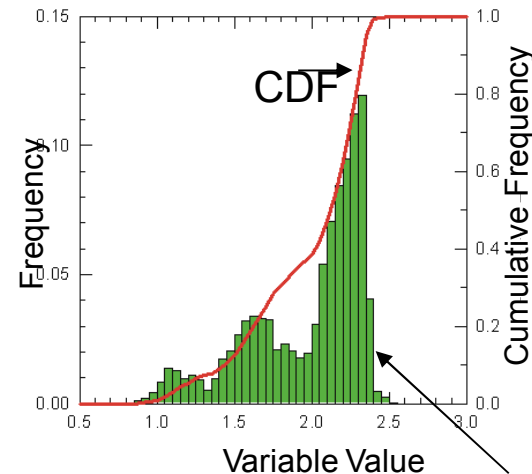


Continuously varying properties at the model cell resolution

Problem Statement



Radionuclides are being released from a repository. What will the concentration of a given radionuclide be at a downgradient location in 10,000 years?

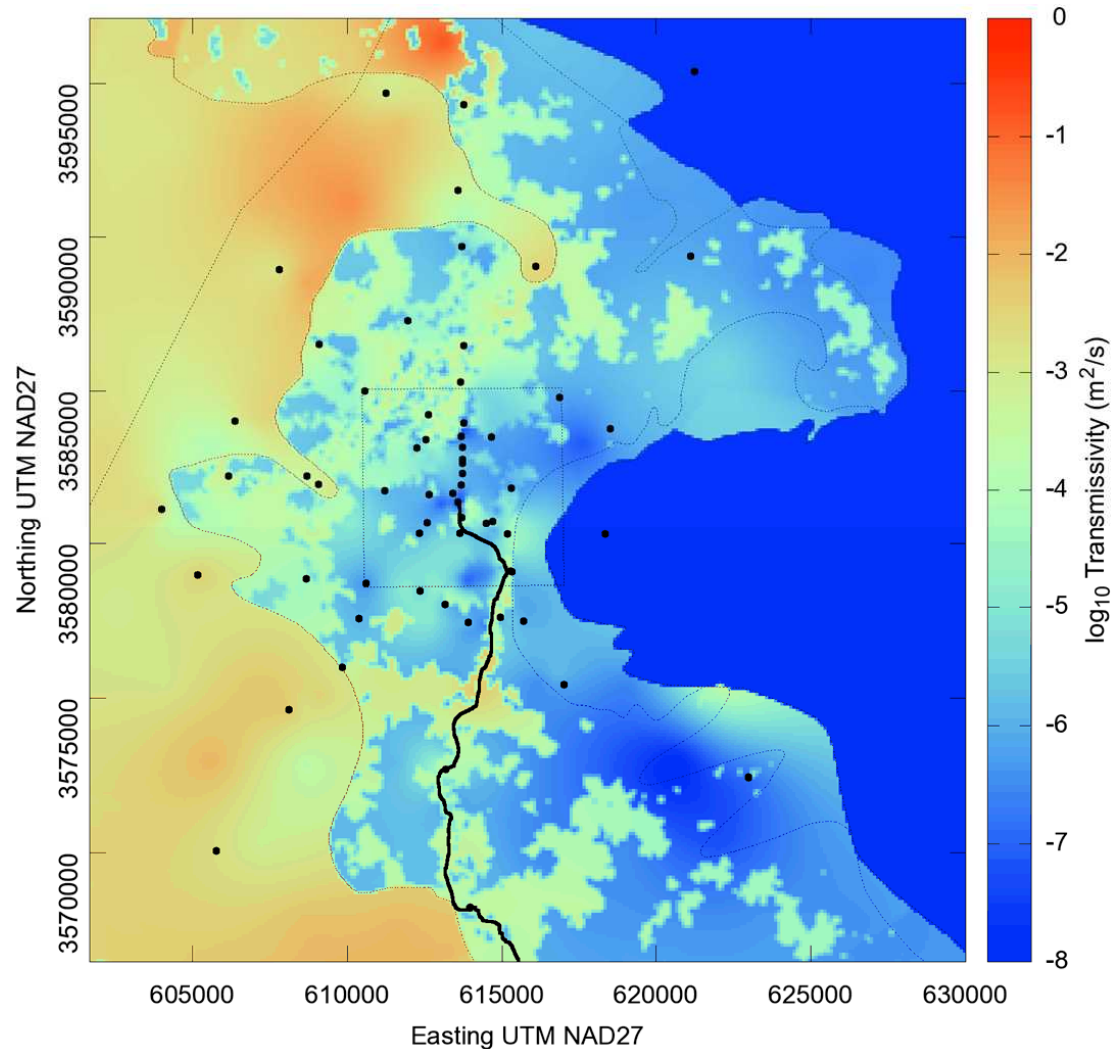


How do we define the input parameter distributions?

How do we sample input distributions?

Output defines the joint probability of the inputs

Spatial Variability of Transmissivity



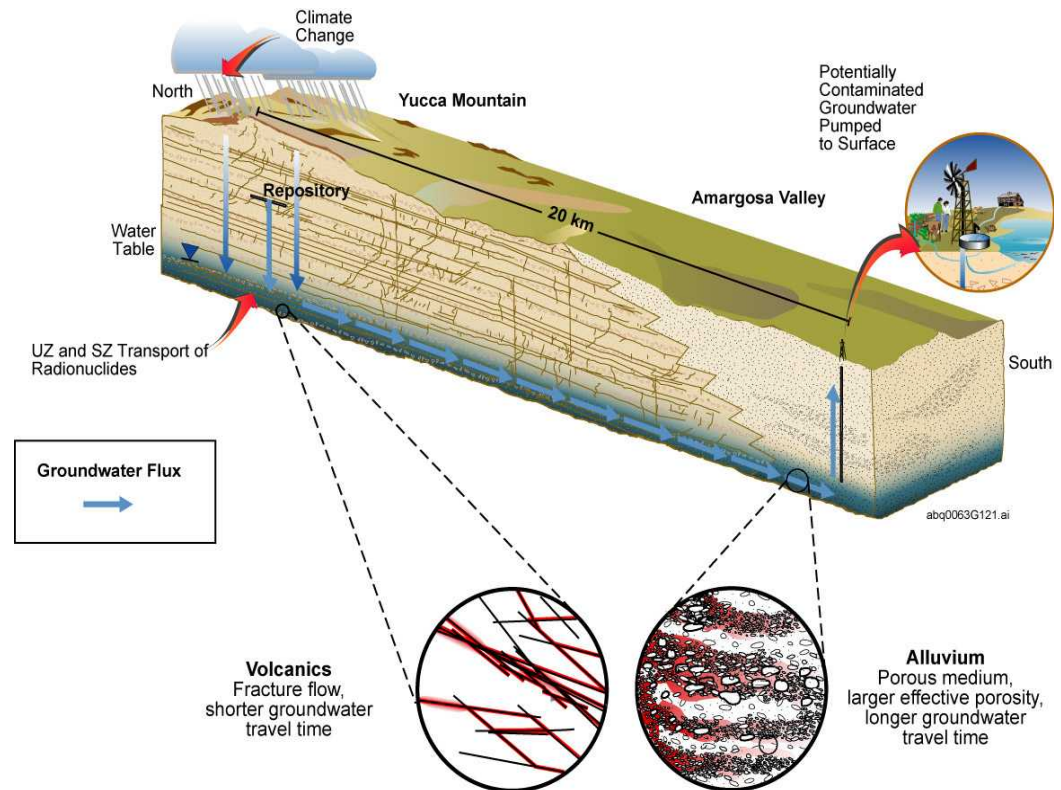
Example Culebra T field used in flow and particle tracking model, with illustrative particle track from the center of the WIPP to the edge of the domain. Black dots are observation well locations.

Variability in Saturated Zone Transport

The conceptual model for radionuclide transport varies with location in the saturated zone.

A dual porosity conceptual model of transport is used in the fractured volcanic units.

A porous medium conceptual model is used in the alluvium.



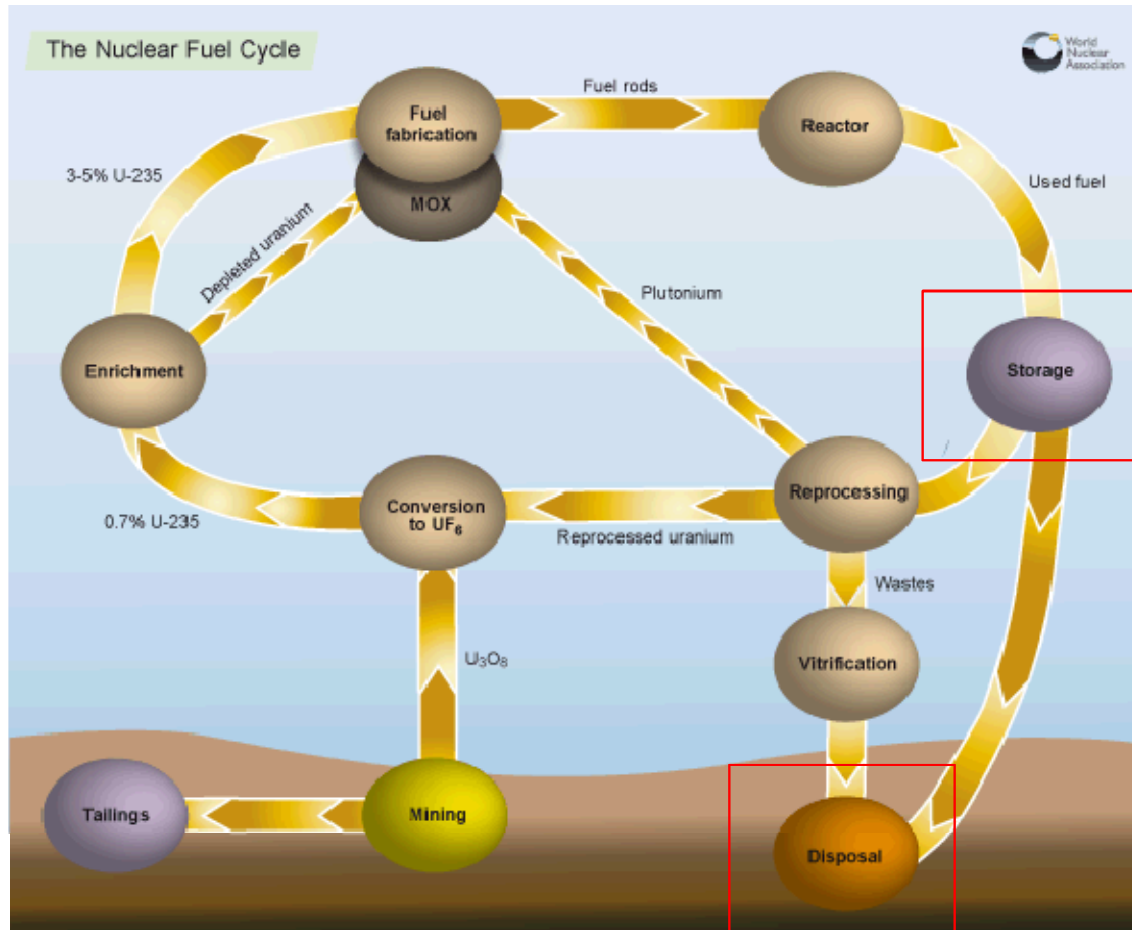
Identification, Analysis and Presentation of Spatial Variability in Site Investigations

1. Key elements of a radioactive waste repository development programme
2. An introduction to uncertainty and spatial variability
3. Site Investigations
4. Introduction to geostatistics for site characterization and safety assessment
5. An overview of safety assessment approaches and methodologies
6. Spatial variability
7. Spatial estimation and simulation methods
8. Spatial upscaling for modelling
9. Propagating the heterogeneity and uncertainty evaluations through from site investigation measurements to a safety assessment
10. Uncertainty analysis in site characterization and safety assessment
11. Parameter sensitivity and uncertainty analysis
12. Examples of how uncertainty and spatial variability evaluations have been treated in the YMP, WIPP, and international programmes

Sources of Information

- **IAEA Safety Standards: No. SSR-5 “Disposal of Radioactive Waste”**
- **OECD Radioactive Waste Management Document: “Post-Closure Safety**
- **Case For Geological Repositories: Nature And Purpose”**
- **National Academy of Sciences: “One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste”**
- **Nuclear Energy Agency: “Confidence in the Long-term Safety of Deep**
- **Geological Repositories: Its Development and Communication”**
- **Yucca Mountain Repository Safety Analysis Report**
- **WIPP Certification and Recertification Reports**
- **And other examples and perspectives from various institutional and personal experience**
- **Geological Disposal: An overview of the generic Disposal System Safety Case, UK, NDA**
- **International Atomic Energy Agency (IAEA), IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection, Vienna. Publication STI/PUB/1290, 2007**

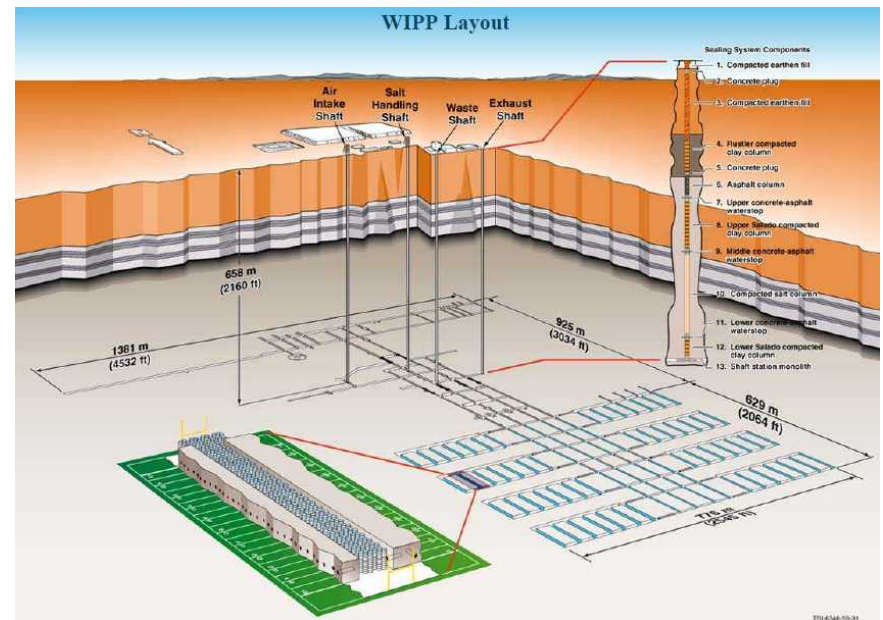
Nuclear Fuel Cycle



- US does not recycle
- France, Russia, UK, Japan* have a policy to recycle

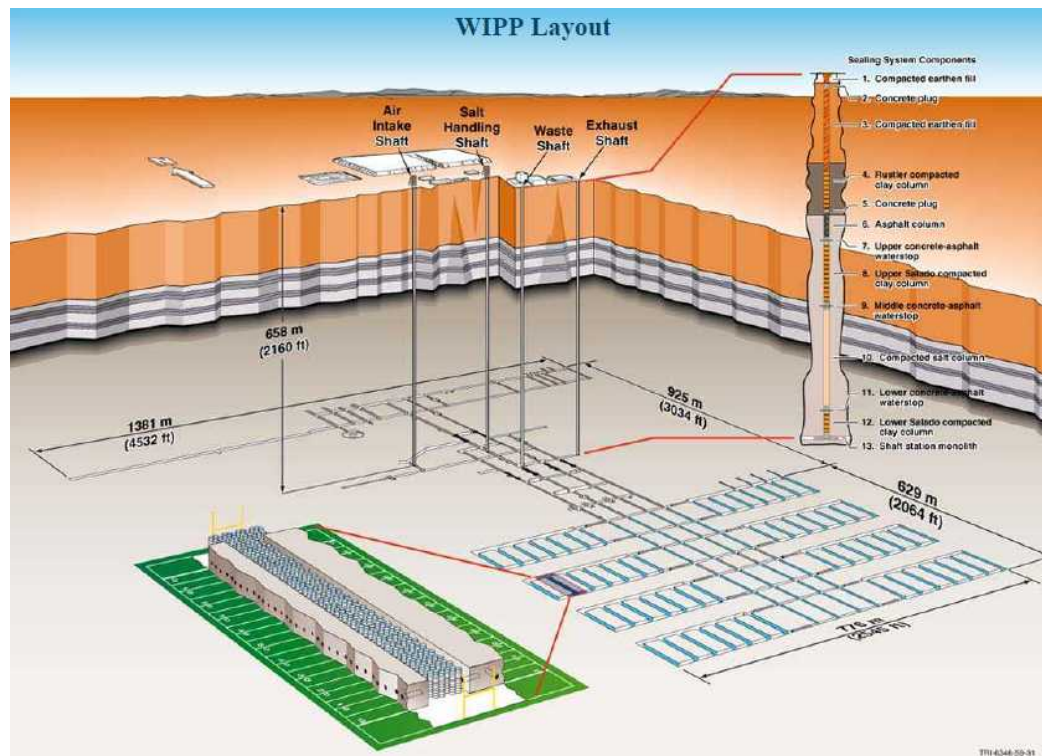
Terminology

- **Storage - Retention of waste (or material) with the intention of retrieval pending some future action (e.g., reprocessing)**
- **Disposal - Emplacement of radioactive waste with no intention of retrieval, i.e., permanent disposal**



What is a deep geological repository? Sandia National Laboratories

*A **deep geological repository** is a nuclear waste repository excavated deep within a stable geologic environment (typically below 300 m or 1000 feet). It entails a combination of waste form, waste package, engineered seals and geology that is suited to provide a high level of long-term isolation and containment without future maintenance (Wikipedia).*



Fundamental Safety Premise

- To manage the waste burden through permanent disposal in a manner that protects the accessible biosphere (groundwater and other resources used by or accessed by people.
 - Disposal facilities are to be developed in such a way that people and the environment are protected both now and in the future
 - To leave future risks no greater than one would accept at present.
- The fundamental safety objective is to protect people and the environment from the potential for harmful effects of radioactive waste.
- The strategy to achieve this fundamental safety objective is to *contain and isolate* the waste from the accessible biosphere, to the extent that is necessary.

Repository Program Life-Cycle

- Typically characterized by long timeframes
 - International experience *should* lessen the technical challenges
 - Workforce planning, information management, institutional performance, etc., become issues with career-long development cycles
- All programs characterized by stages of development that build upon prior effort
 - Staged, adaptive management approaches with stakeholder engagement is broadly recommended
 - Step-wise (and adaptive) development enables the accumulation of technical data, evaluation of alternative disposal concepts, iterative safety and design assessments with progressive improvement (*confidence and defensibility*), public consultations, political decision-making, etc.
 - Adaptive Staging is a management process characterized both by specific objectives and by a formal and deliberate decision-making process

Waste Isolation Pilot Plant

Geologic Disposal of Transuranic Waste



- Initially sited – 1975
- Certified by the EPA – 1998
- First Waste Receipt – March 26, 1999
- Recertification – Every 5 years
- More than 11,262 shipments to date
 - 86,440 m³ emplaced
 - allowable capacity 175,000 m³
- Disposal operations continue

Repository Program Life-Cycle

- **Pre-Operational Phase**
 - Selection of Geologic Disposal Concepts and Options
 - Site Selection & Characterization
 - Conceptual Planning
 - Area Survey, Site Characterization & Site Confirmation
 - Licensing and Construction
- **Operational Phase**
 - Pilot and Full-Scale Operations with Transportation
 - Closure
- **Post-Closure Phase**
 - Performance Confirmation, Monitoring, Institutional Controls, Permanent Markers

Fundamental Needs

- **Government Responsibilities**
 - *Establishes the need, objectives, timeline and decision points, allocates responsibilities (including independent functions), financing*
- **Regulatory Body Responsibilities**
 - *Establishes regulatory requirements (i.e., the safety objectives, compliance metrics, etc.) & procedures for demonstrating compliance and other licensing conditions*
- **Operator / Implementer Responsibilities**
 - *Responsible for the disposal facility safety*
 - *Implements site selection, characterization, facility design, etc.*
 - *Assembles the safety assessments and safety case, license application*
 - *Works in accordance with national strategy, in compliance with regulatory requirements and within the legal regulatory framework*
 - *Maintains management systems for quality assurance, quality control, information management, workforce training, etc.*

Major Repository Elements

- A repository concept consists of a waste inventory for disposal, a rock type to be excavated, and an engineered barrier system that recognizes contributions from natural and engineered barriers
- Drifts for waste emplacement, tunnels for access and ventilation, and shafts and ramps that provide access from the surface, are collectively referred to as the repository layout
- The layout must accommodate the geologic structure, which is simple for extensive horizontal strata (e.g., bedded clay/shale or salt) and more complex for geologic structures
 - The N72W orientation of emplacement drifts in the Yucca Mountain repository layout was selected to maximize opening stability
 - Layout orientation in bedded salt could be selected for convenience, with no significant fracturing in the host rock
 - Ground support measures are also considered in selecting layout orientation
- Ventilation systems are engineered to ensure separation of active work areas from radiological controlled areas, for example, using negative ventilation pressure in emplacement drifts
- Repositories will have a drain plan whereby any groundwater inflow can be collected for removal from the facility
- Layouts are also designed for eventual plugging and sealing at repository closure

Key Attributes for Describing Disposal Concepts Sandia National Laboratories

- Plastic vs. competent host rock (persistence of fracture permeability, and stability of underground openings in heated rock on time scales of years to tens of years)
- Low-permeability vs. higher permeability host rock (the importance of host rock performance vs. engineered material performance, to the isolation performance of the disposal system)
- Saturated vs. unsaturated (concerning the types of barriers needed to isolate waste from groundwater, and the potential for saturated flow paths within the repository, particularly after permanent closure)
- Open after closure vs. installation of low-permeability backfill at closure (whether low-permeability

Primary Safety Functions of Engineered Barrier Components for Various Disposal Concepts

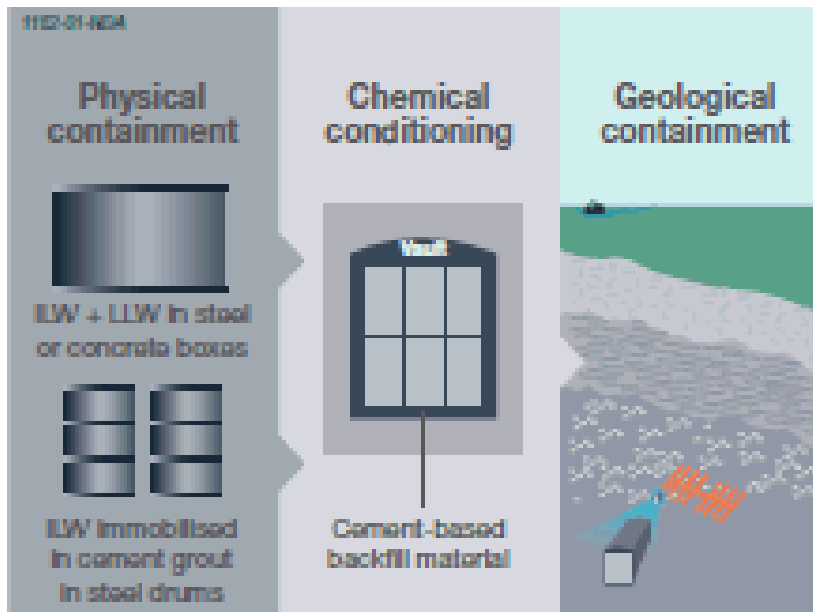
Country / Concept	Waste Form	Container / Overpack	Buffer / Backfill	Others (seals, liner, etc.)
France; Clay ^a	Expected to provide resistance to leaching for 100,000 years in all scenarios	Expected to facilitate waste emplacement and retrieval, protect the waste from water and limit releases over the long-term in all scenarios	Expected to control the THM environment and limit releases	The tunnel lining supports the host rock during the operational phase. The tunnel backfill and seals prevent access to the repository, prevent radionuclide transport along tunnels and hold the buffer in place
Sweden/KBS-3; Crystalline / Granite ^a	Expected to slow the rate of radionuclide release	Expected to provide radionuclide isolation for ~1,000,000 years in all scenarios	Expected to provide mechanical protection and act as a diffusional barrier for ~1,000,000 years in all scenarios	The tunnel backfill is expected to provide mechanical support for the buffer and the host rock for ~1,000,000 years in all scenarios
U.S.; Generic Salt ^b	Expected to be stable in a salt environment and provide containment/ slow release of radionuclides for tens of thousands of years	Primarily a preclosure safety function for handling and shielding (but a temperature limit is imposed to ensure the containers remain intact until after closure	Expected to prevent water contact with the waste (and therefore limit releases) after crushed salt reconsolidation; also for preclosure radiation shielding;	Shaft and drift seals prevent intrusion of brine from overlying, water-bearing strata
U.S.; Deep Borehole ^c	No credit taken as a flow or transport barrier	No credit taken as a flow or transport barrier after closure; serves only for handling and emplacement	Expected to limit migration of contaminants through the borehole via low permeability and high sorption capacity of bentonite	Seal system expected to limit entry of water and migration of contaminants through the borehole via low permeability and high sorption capacity of bentonite

NOTE: ^aOrganisation for Economic Co-operation and Development 2003a.

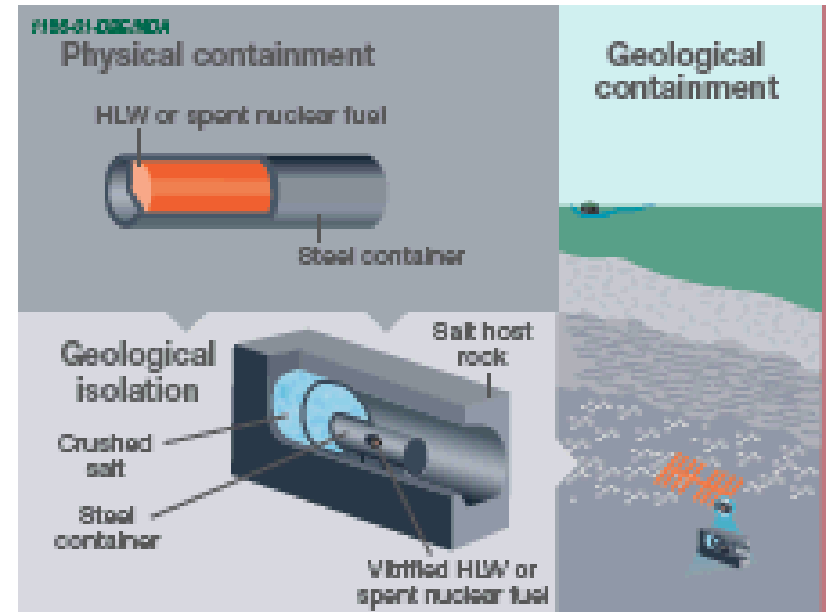
^bCarter et al. 2011a.

^cBrady et al. 2009.

Disposal Concepts (drawings from UK NDA)



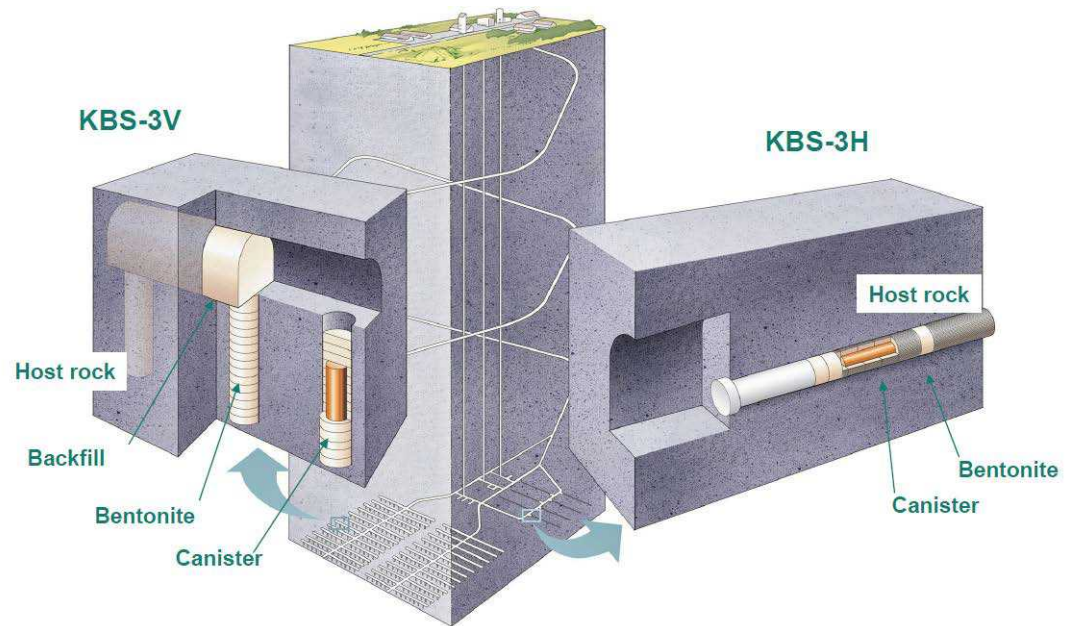
Disposal concept for ILW developed in the UK for higher strength rock.



Disposal concept for HLW and spent nuclear fuel developed in Germany for evaporite rock (salt)

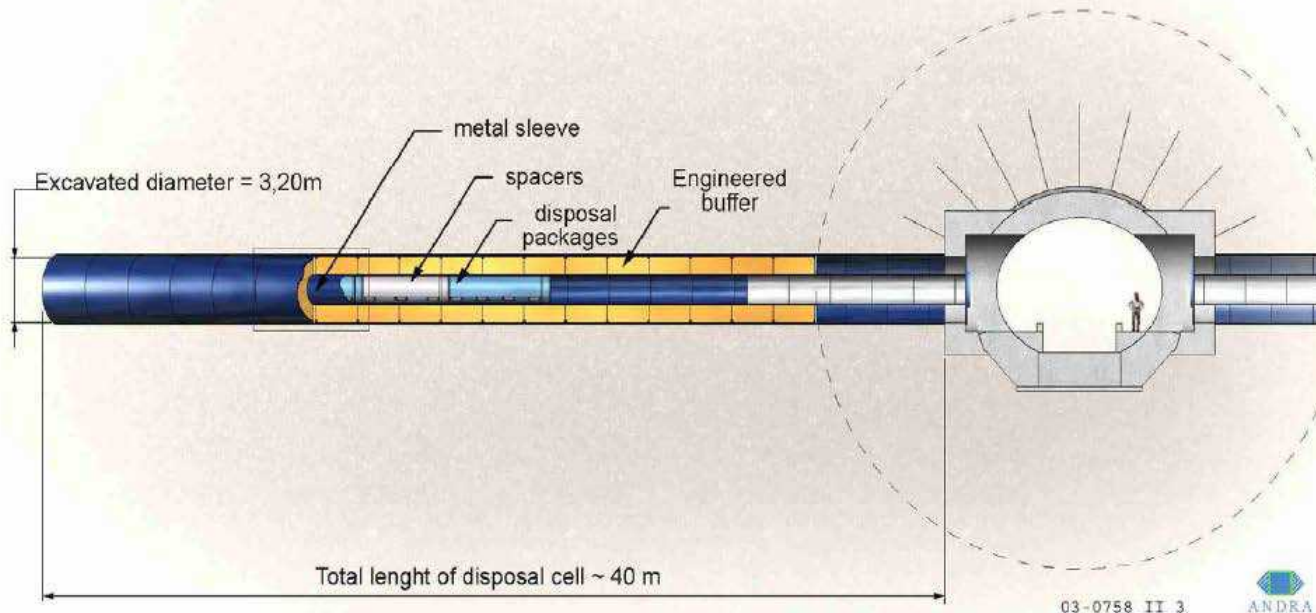
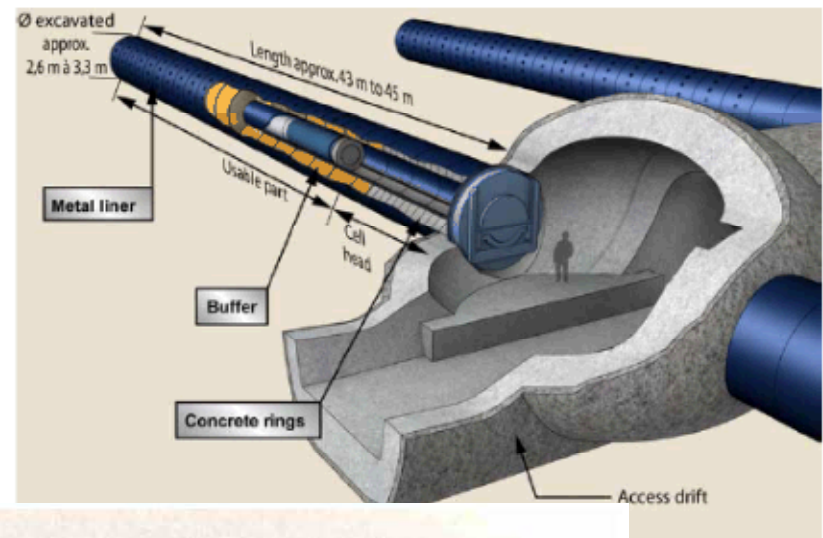
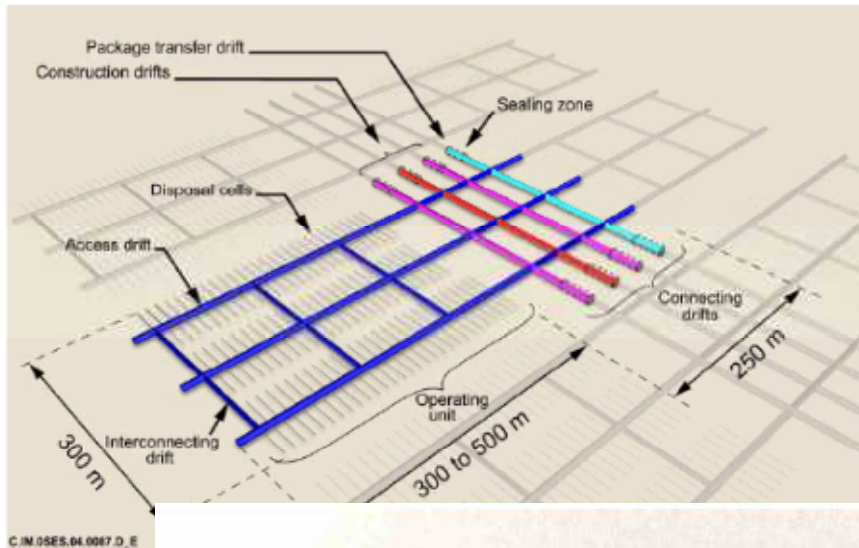
Representative Disposal Concept for Mined Granite Repository

- Sweden, Finland, Spain, Switzerland, China
- Spent fuel or HLW
- Reducing conditions
- Vertical & horizontal emplacement modes
- Well studied concept

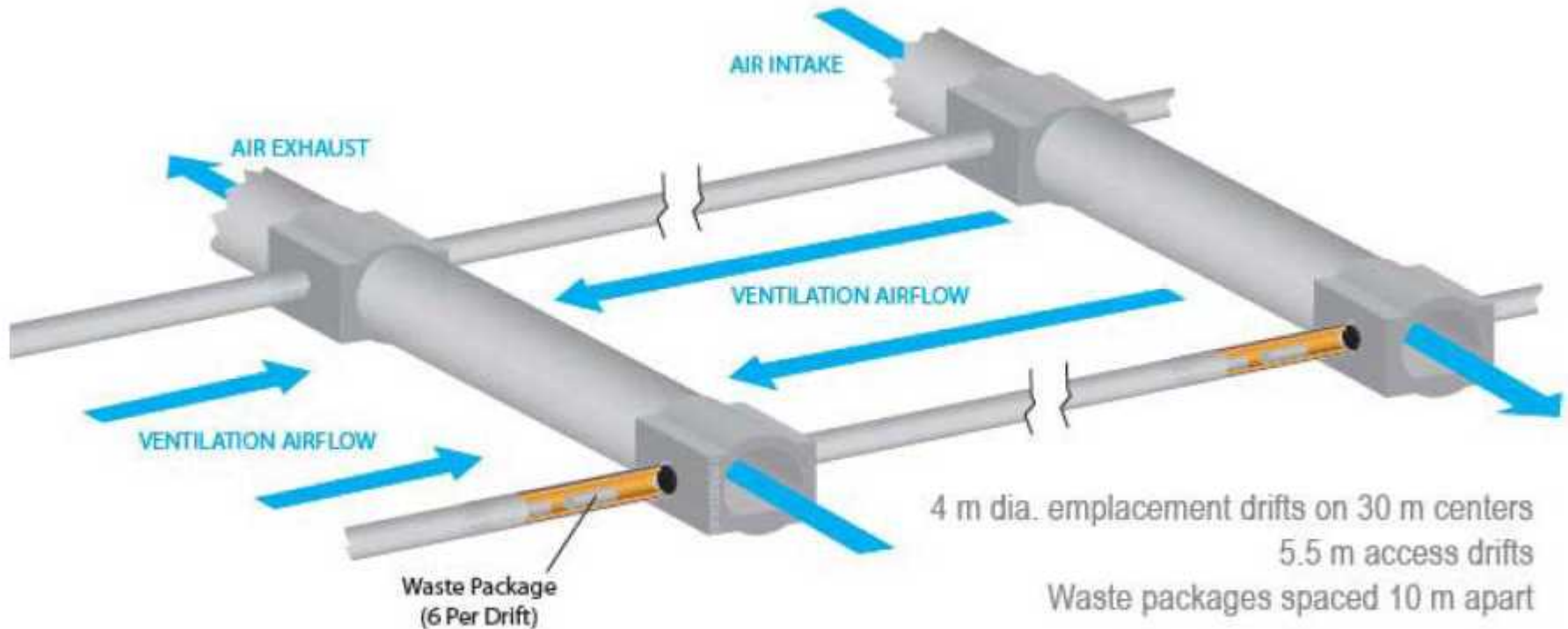


Schematic of the KBS-3 Vertical and Horizontal Disposal Concepts (SKB 2010).
Schematic of the Two KBS-3 Variants Being Investigated
by Posiva: KBS-3V (left) and KBS-3H (right)

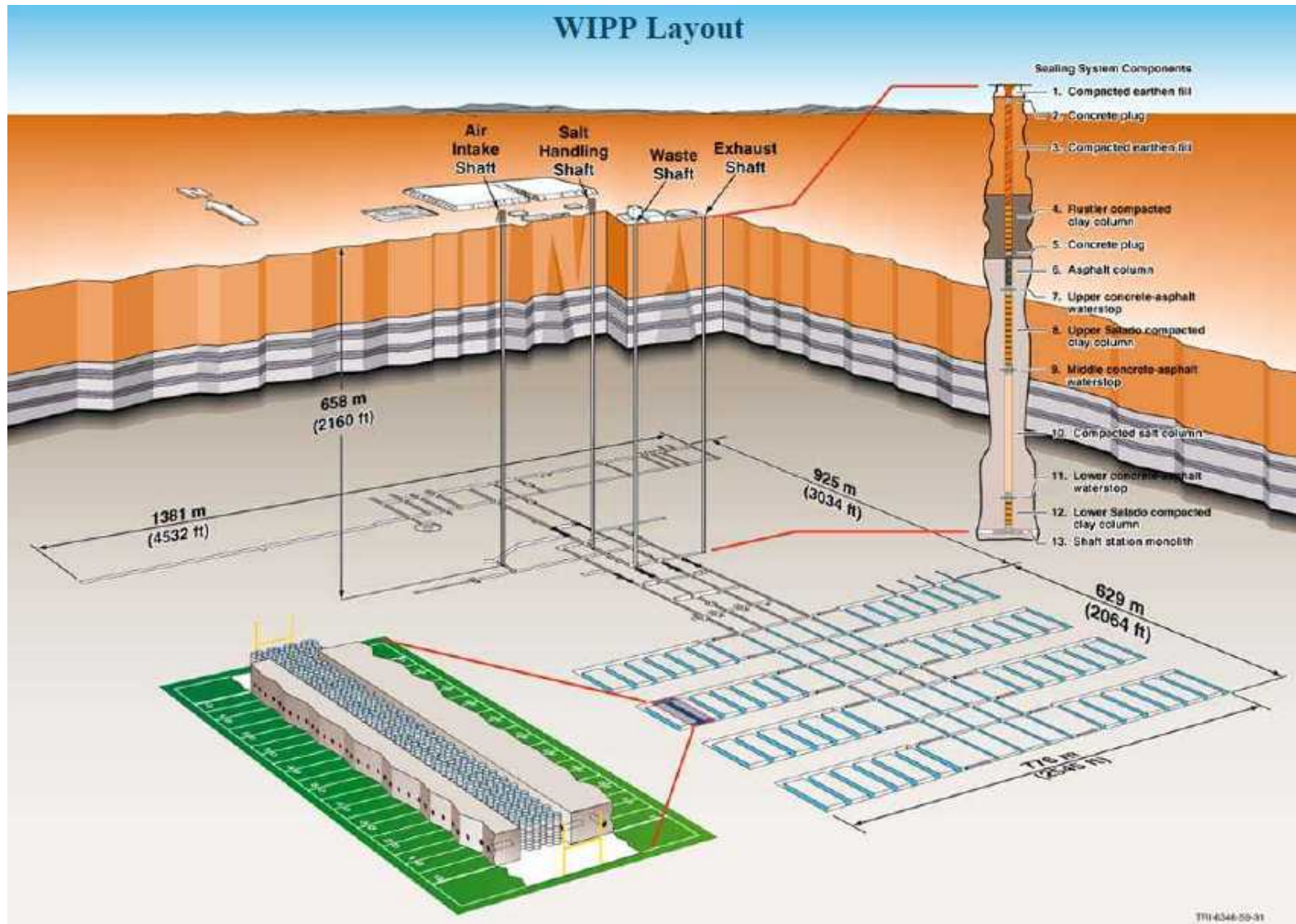
Conceptual Illustration of a Repository Design Concept for Clay, and Details of the Emplacement Borehole



Conceptual Illustration of an Open-Mode Geologic Disposal Facility Concept for Clay



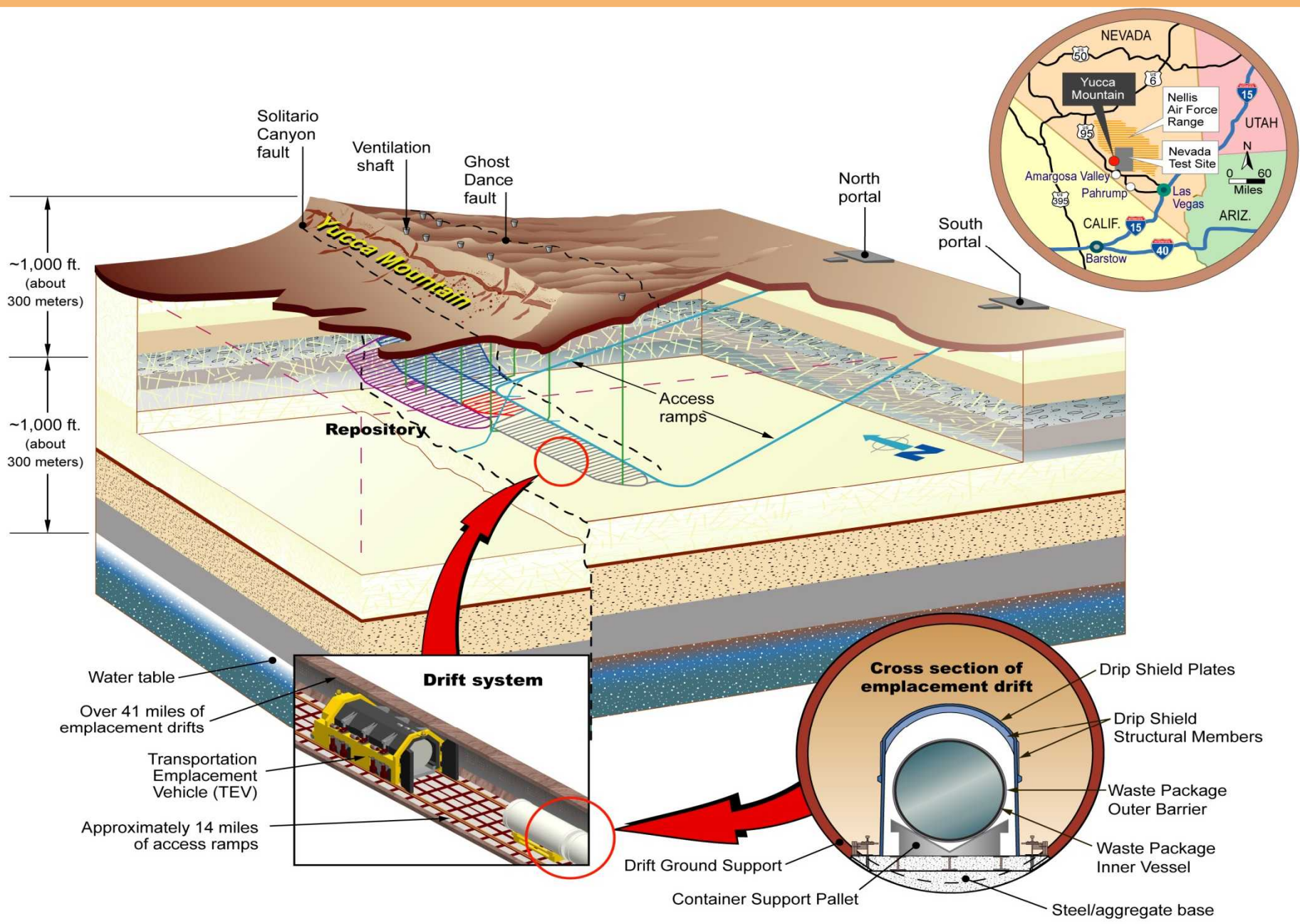
Deep Geologic Repository in Salt



Disposal Configuration for Transuranic Waste at the WIPP



SAND2010-7975C Geologic Disposal Options in the USA

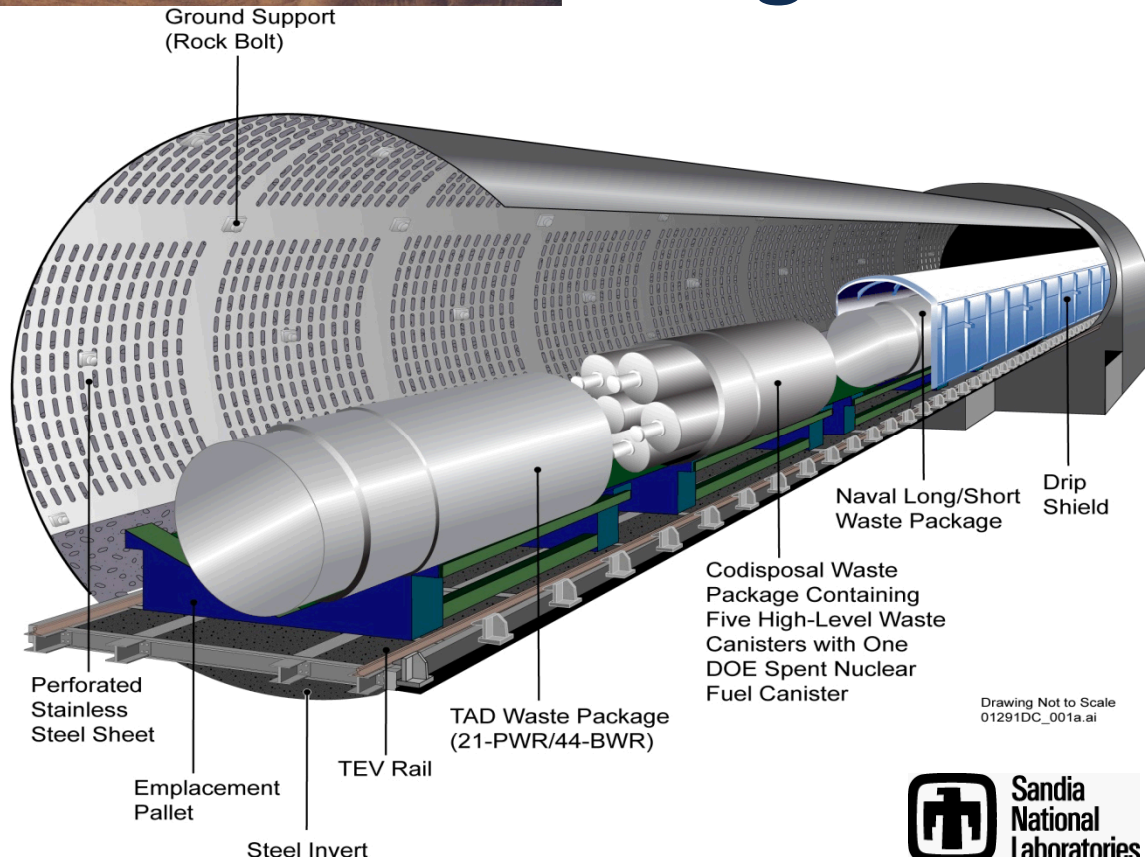


Yucca Mountain Subsurface Design

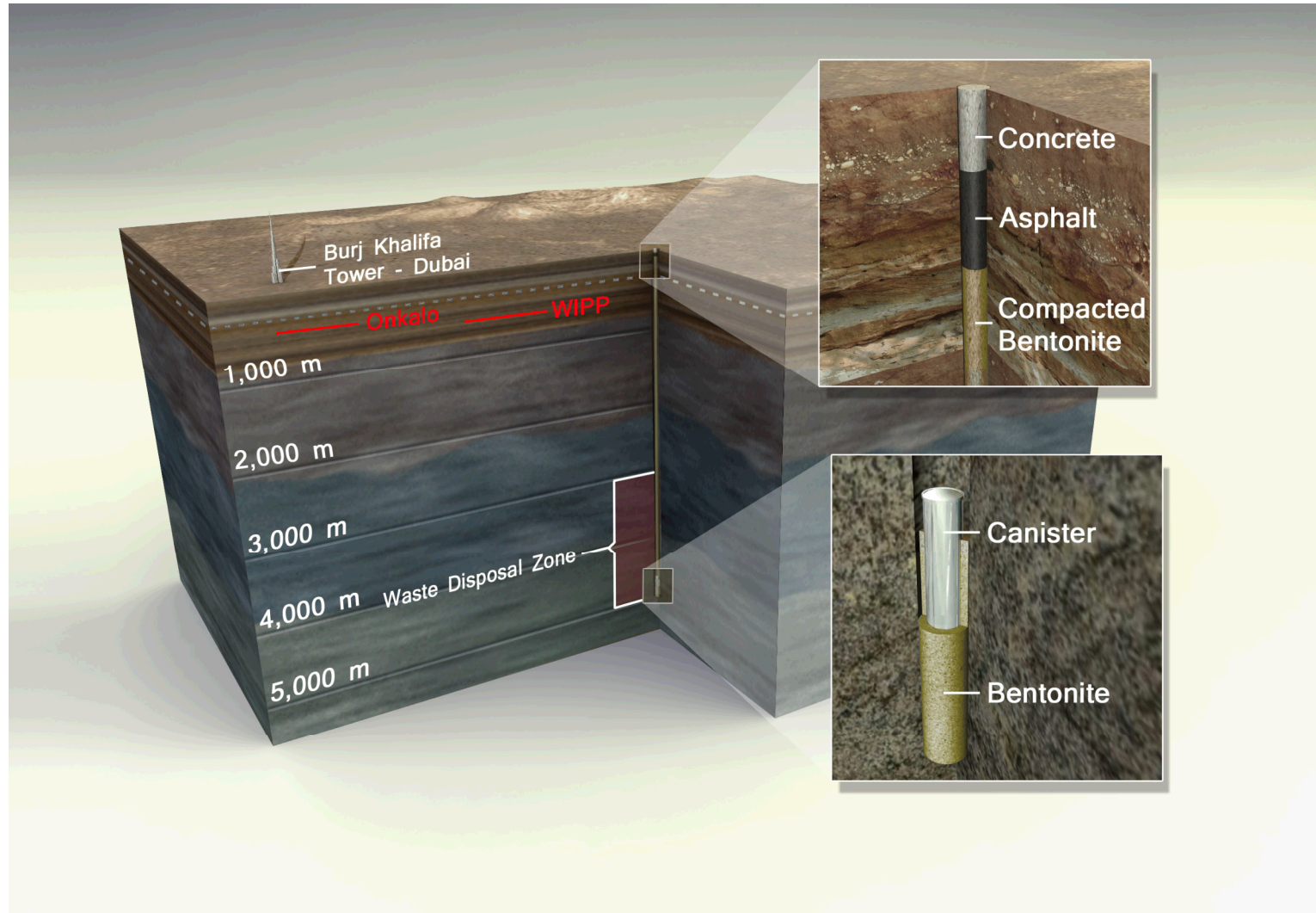
Existing exploratory drifts shown in yellow.
Approximate area for proposed emplacement
drifts shown in blue.

Actual location of drifts is several hundred
meters below the land surface.

- Emplacement drifts
 - 5.5 m diameter
 - approx. 100 drifts, 600-800 m long
- Waste packages
 - ~11,000 packages
 - ~ 5 m long, 2 m diameter
 - outer layer 2.5 cm Alloy 22 (Ni-Cr-Mo-V)
 - inner layer 5 cm stainless steel
- Drip shields
 - free-standing 1.5 cm Ti shell



Deep Borehole Disposal Concept



Relative Attributes of Disposal Options

Property	Salt	Shale	Granite	Deep boreholes
Thermal conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on decade scale	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemical	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology*	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

 Favorable property
  Average
  Unfavorable property

* See figures in text.

SAND2010-7975C Geologic Disposal Options in the USA

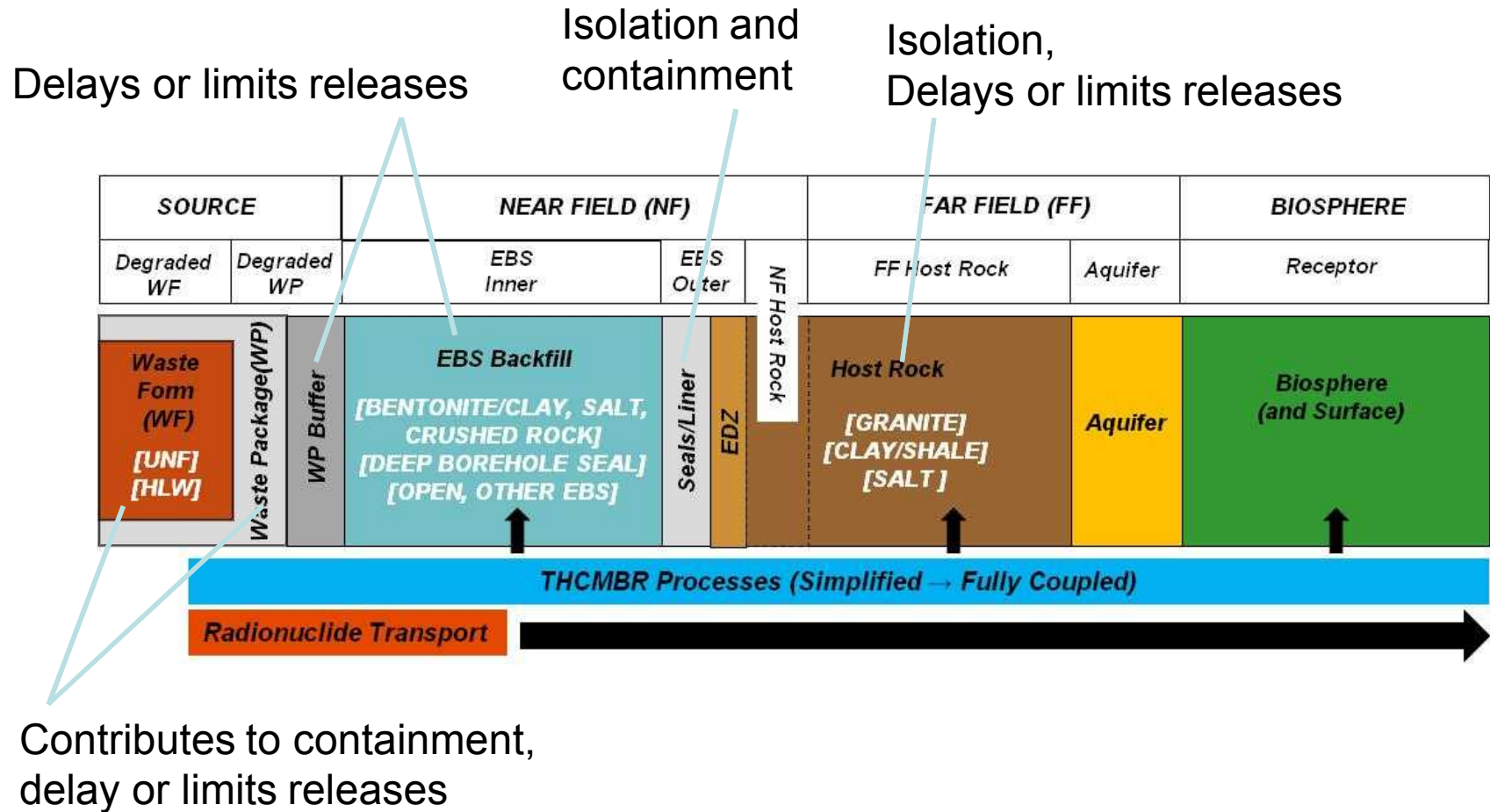
Safety Functions

- The following definitions are used by different agencies:
 - ONDRAF/NIRAS [2007], Belgium: "function that the disposal system should fulfill to achieve long-term safety".
 - SKB [2006], Sweden: "role through which a component contributes to safety".
 - Andra [2005], France: "consists of meeting the safety objectives by implementing different types of actions that all contribute to the safety of the repository during the different phases of the repository".
 - Nagra [2002], Switzerland: "a function relevant to long-term security and safety".

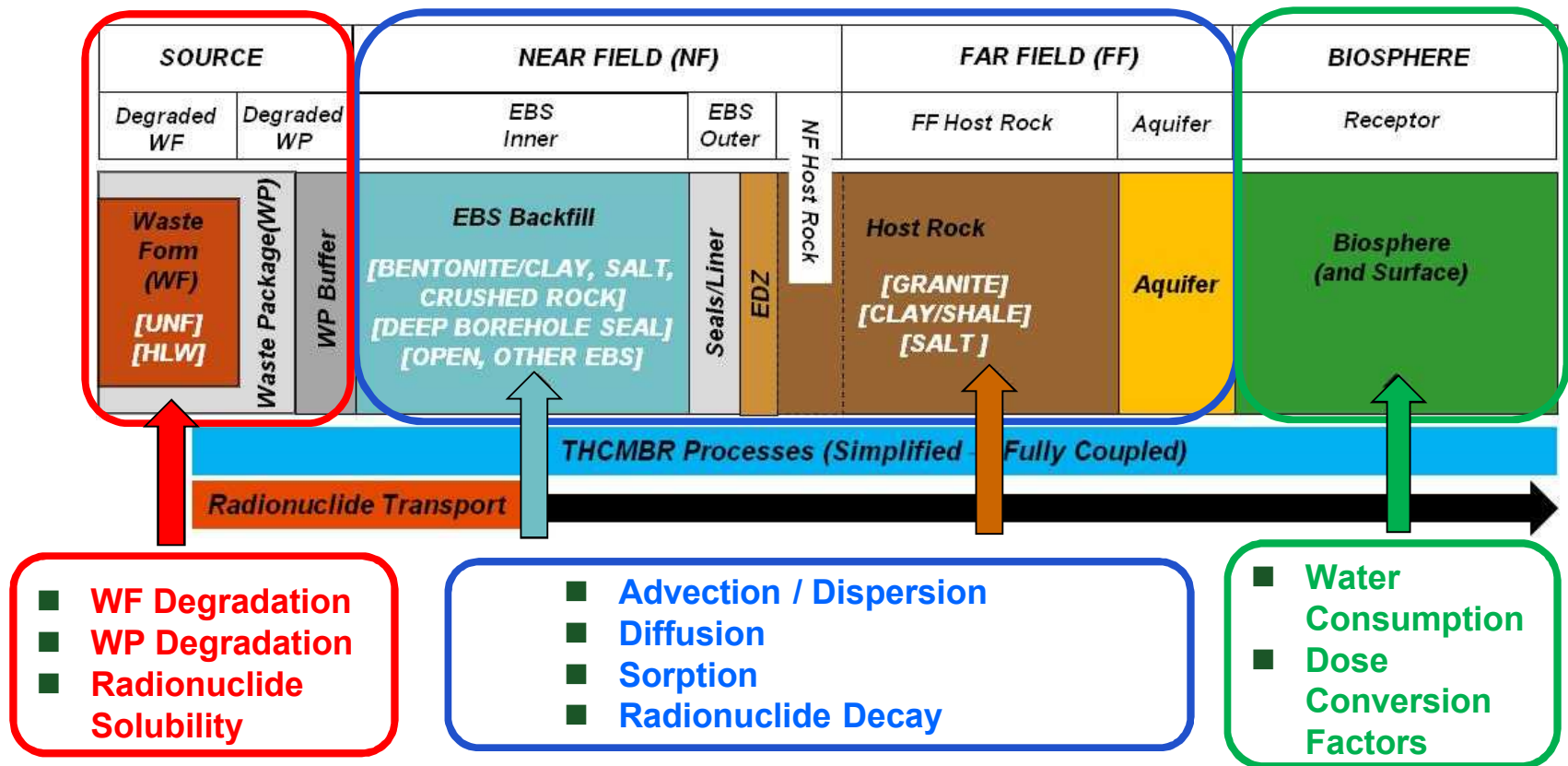
Safety Functions

- Isolation - isolate the waste and EBS from people, surface events, and climate change
 - Thick geological formations
 - Stability of region facility is located
- Containment - retain radionuclides within the waste package and EBS for as long as required
- Limit and delay releases after complete containment is lost – reduce water flow, retardation, solubility

Schematic Representation of a Multiple Barrier System



Processes in a Multiple Barrier System



Safety and Performance Indicators

- A safety indicator is typically established by provides a measure of the overall performance of a geological disposal system with respect to a specific safety aspect, in comparison with a reference value that can be shown to be safe or is considered to be safe
 - Radiological dose rate and risk are examples
- Performance indicators are quantities that provide a measure for the performance of a system component, several components or the whole system in comparison with each other
 - Activity over time in components of the disposal system
 - Transport time through components

Major Types of Radioactive Waste

■ Low Level Waste (LLW)

- Low-level wastes are usually defined in terms of what they are not. They are not spent fuel, milling tailings, reprocessed materials, or transuranic materials. Low-level radioactive waste includes items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. Majority of LLW rises from nuclear fuel production, spent nuclear fuel processing, and operation of nuclear power plants. This waste is typically contaminated protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment and tools, luminous dials, medical tubes, swabs, injection needles, syringes, and laboratory animal carcasses and tissues.

■ Intermediate Level Waste (ILW)

- Intermediate-level waste (ILW) contains higher amounts of radioactivity and in some cases requires shielding. Intermediate-level wastes includes resins, chemical sludge and metal reactor nuclear fuel cladding, as well as contaminated materials from reactor decommissioning. It may be solidified in concrete or bitumen for disposal. U.S. regulations do not define this category of waste; the term is used in Europe and elsewhere.

■ Transuranic Waste (TRU)

- Transuranic waste (TRUW) as defined by U.S. regulations is, without regard to form or origin, waste that is contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and concentrations greater than 100 nCi/g (3.7 MBq/kg), excluding high-level waste. Elements that have an atomic number greater than uranium are called transuranic ("beyond uranium").

Major Types of Radioactive Waste

- High Level Waste (HLW)

- Created by the reprocessing of spent nuclear fuel. HLW contains many of the [fission products](#) and transuranic elements generated in the reactor core and is the type of nuclear waste with the highest activity. In the US, HLW from reprocessing of spent fuel from electrical power stations amounts to less than 1% of the total volume of US HLW; the rest is defense related. Typically stabilized by vitrification.

- Spent Nuclear Fuel

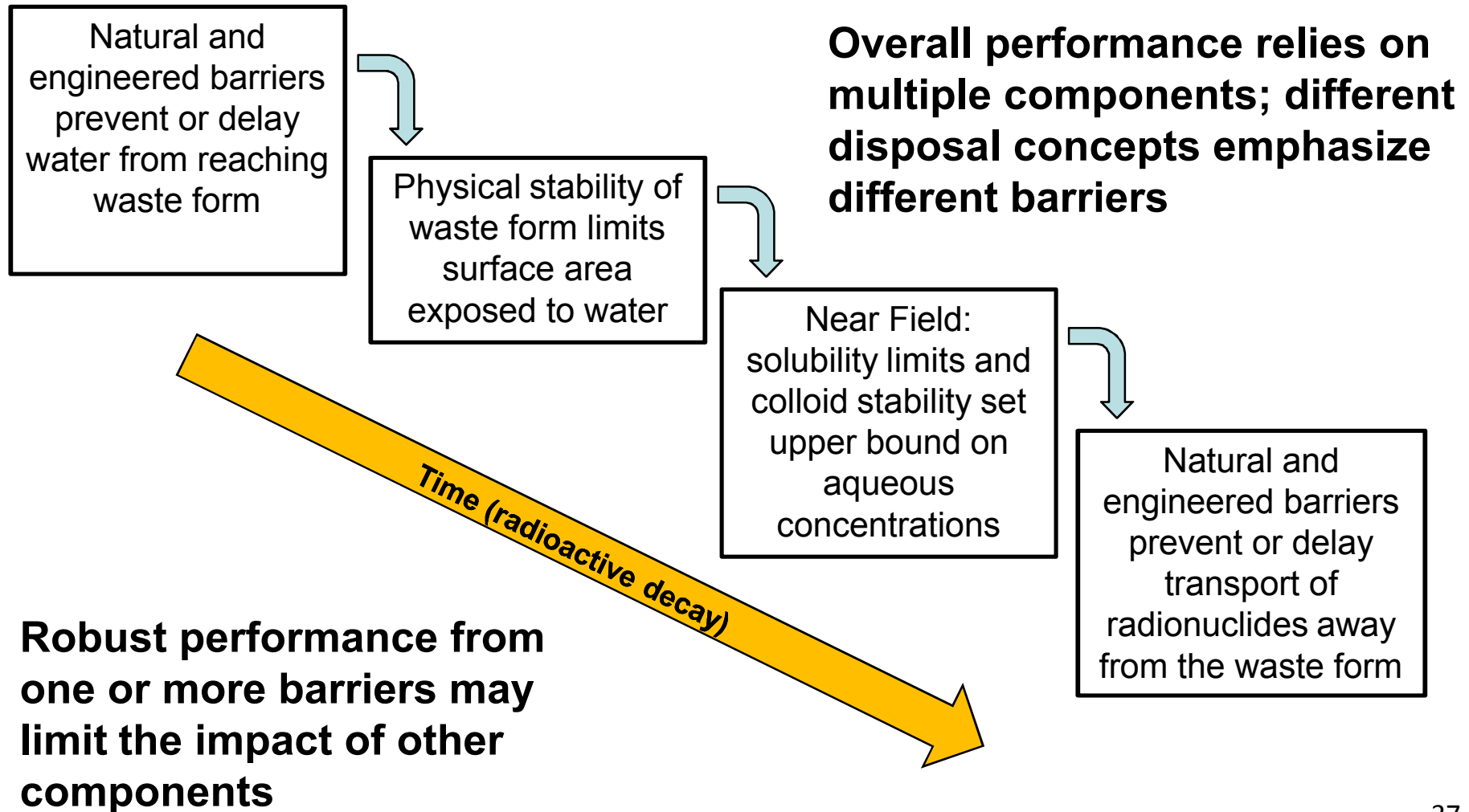
- High-level radioactive waste consists of “irradiated” or used nuclear reactor fuel (i.e., fuel that has been used in a reactor to produce electricity).

High-level waste is very radioactive and, therefore, requires special shielding during handling and transport. It also needs cooling, because it generates a great deal of heat. Most of the heat, for the first several hundred years, is from the medium-lived fission products cesium-137 and strontium-90.

Major Types of Waste Forms

- Spent Nuclear Fuel is in a solid form consisting of small fuel pellets of uranium dioxide in long corrosion-resistant metal alloy tubes
- Treatment and conditioning processes are used to convert radioactive waste materials into a form that is suitable for transportation, storage and final disposal
 - Cementation through the use of specially formulated grouts provides the means to immobilize radioactive material that is on solids and in various forms of sludges and precipitates/gels (flocks) or activated materials.
 - Vitrification is the transformation of a liquid into a glass. In general borosilicate glass has been chosen as the medium for dealing with liquid HLW and converting it into a solid waste form that will remain stable for many thousands of years.

How Does the Waste Form Impact Estimates of Disposal System Dose?



Inventory

- Radionuclides to be disposed include fission products from reactor operations, actinides from neutron capture in uranium and plutonium, and activation products from neutron irradiation of structural materials and trace elements
- Altogether, these fission products, actinides, and activation products constitute more than 100 radionuclides that may be collectively present in the waste packages at the time of repository closure
- Many of the radionuclides have short half-life, low solubility and/or strongly sorbing characteristics, or are present in small quantities
- As a result, only a small subset of radionuclides needs to be considered in the evaluation of repository postclosure performance, and calculation of risk from that subset of radionuclides will result in essentially the same risk as would a calculation that includes all radionuclides

- Determining the radionuclide inventory for use in the Post Closure Safety Assessment is a multistep process
 - Determine those radionuclides that can exist in the SNF and HLW
 - Screen to determine those radionuclides that can potentially contribute to dose in the biosphere
 - Radionuclides that contribute only a small percentage to dose (e.g., 1% or 5% cutoffs) are eliminated from further consideration
 - Finally, the average initial inventory of radionuclides is estimated for each waste form and waste package
 - Three sources of uncertainty in radionuclide inventory
 - Computational method and nuclear data used to predict radionuclide inventories (e.g., isotopic neutron cross section or decay half-life)
 - Existence or condition of records (e.g., burnup of batch compositions)
 - Future decisions about creation, packaging, and shipping (typically largest uncertainty)

Inventory

Table 2.3.7-2. Results of the Screening Analysis

Radionuclide	Scenario Classes with Groundwater Transport		Igneous Eruptive Modeling Case	
	10 ² years to 10 ⁴ years	10 ⁴ years to 10 ⁸ years	10 ² years to 10 ⁴ years	10 ⁴ years to 10 ⁸ years
²²⁷ Ac	—	²²⁷ Ac	—	²²⁷ Ac
²⁴¹ Am	²⁴¹ Am	—	²⁴¹ Am	—
²⁴³ Am	²⁴³ Am	²⁴³ Am	²⁴³ Am	²⁴³ Am
¹⁴ C	¹⁴ C	¹⁴ C	—	—
³⁶ Cl	³⁶ Cl	³⁶ Cl	—	—
²⁴⁵ Cm	Added to ensure that the effect of its decay on the inventory of ²⁴¹ Am are included			
¹³⁵ Cs	¹³⁵ Cs	¹³⁵ Cs	—	—
¹³⁷ Cs	¹³⁷ Cs	—	¹³⁷ Cs	—
¹²⁹ I	¹²⁹ I	¹²⁹ I	—	¹²⁹ I
²³⁷ Np	²³⁷ Np	²³⁷ Np	—	²³⁷ Np
²³¹ Pa	²³¹ Pa	²³¹ Pa	—	²³¹ Pa
²¹⁰ Pb	—	²¹⁰ Pb	—	²¹⁰ Pb
²³⁸ Pu	²³⁸ Pu	—	²³⁸ Pu	—
²³⁹ Pu	²³⁹ Pu	²³⁹ Pu	²³⁹ Pu	²³⁹ Pu
²⁴⁰ Pu	²⁴⁰ Pu	²⁴⁰ Pu	²⁴⁰ Pu	²⁴⁰ Pu
²⁴¹ Pu	Added to ensure that the effect of its decay on the inventory of ²⁴¹ Am and ²³⁷ Np are included			
²⁴² Pu	—	²⁴² Pu	—	²⁴² Pu
²²⁶ Ra	—	²²⁶ Ra	—	²²⁶ Ra
²²⁸ Ra	—	²²⁸ Ra	—	²²⁸ Ra

YMP 2008

Totals

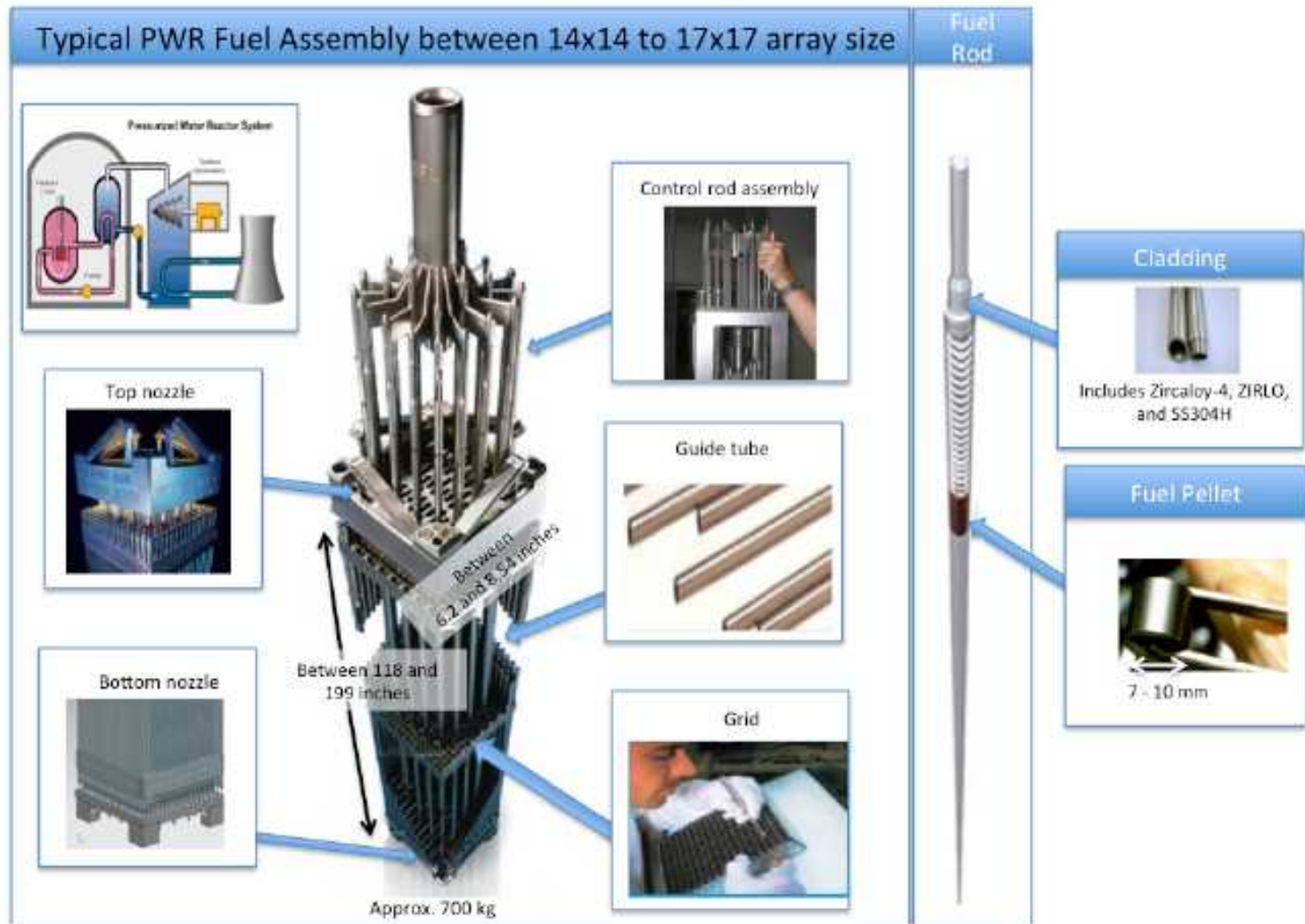
Isotopes	32	25
Elements	18	15

Inventory

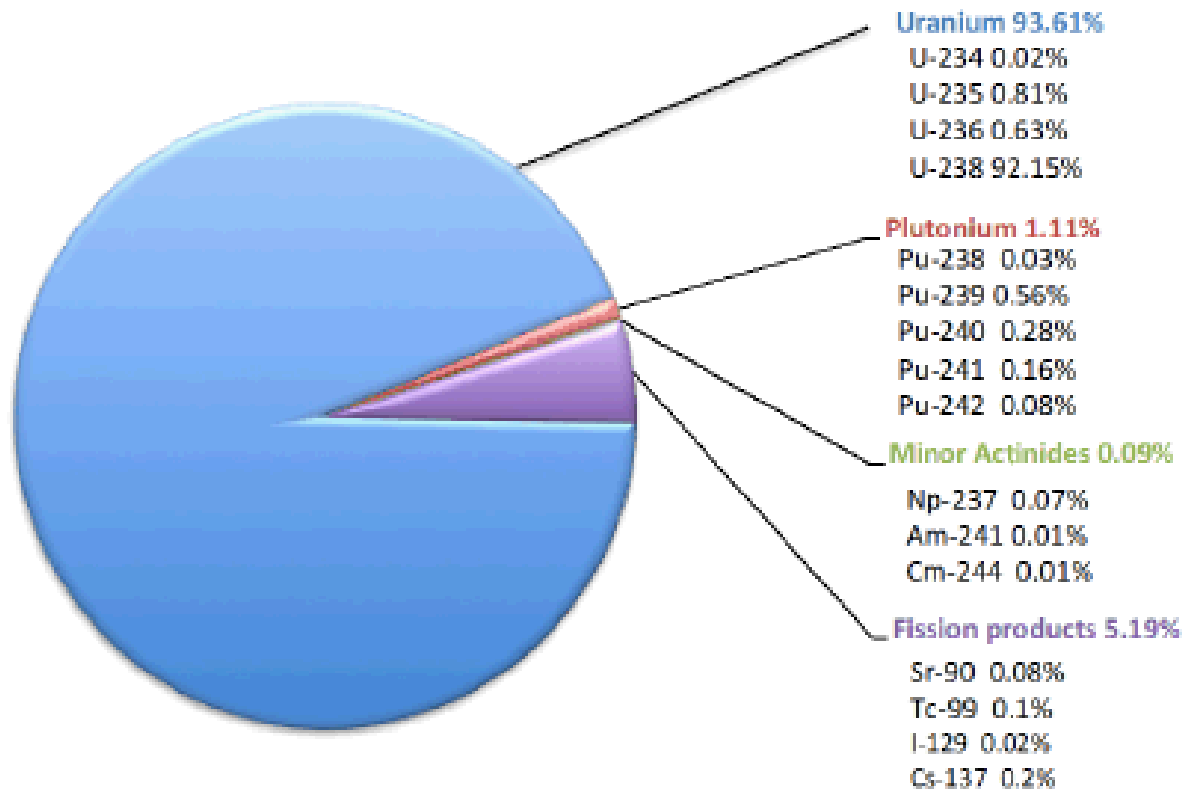
Table 2.3.7-3. Nominal Initial Radionuclide Inventory for Each Waste Form

Radionuclide	Grams per Waste Package		
	Commercial SNF	DOE SNF	HLW
²²⁷ Ac	2.47×10^{-6}	1.22×10^{-3}	1.91×10^{-4}
²⁴¹ Am	8.18×10^3	2.18×10^2	3.75×10^1
²⁴³ Am	1.24×10^3	6.73×10^0	5.75×10^{-1}
¹⁴ C	1.35×10^0	1.81×10^0	0
³⁶ Cl	3.23×10^0	4.23×10^0	0
²⁴⁵ Cm	1.75×10^1	9.25×10^{-2}	5.43×10^{-2}
¹³⁵ Cs	4.38×10^3	9.74×10^1	1.27×10^2
¹³⁷ Cs	5.90×10^3	9.72×10^1	3.02×10^2
¹²⁹ I	1.73×10^3	3.56×10^1	7.27×10^1
²³⁷ Np	4.57×10^3	8.14×10^1	9.95×10^1
²³¹ Pa	9.17×10^{-3}	2.14×10^0	1.53×10^0
²¹⁰ Pb	0	3.35×10^{-7}	3.40×10^{-10}
²³⁸ Pu	1.52×10^3	1.25×10^1	3.91×10^1
²³⁹ Pu	4.32×10^4	2.21×10^3	5.58×10^2
²⁴⁰ Pu	2.05×10^4	4.35×10^2	4.61×10^1
²⁴¹ Pu	2.68×10^3	2.92×10^1	1.22×10^0
²⁴² Pu	5.28×10^3	3.02×10^1	3.89×10^0
²²⁶ Ra	0	4.57×10^{-5}	2.42×10^{-5}
²²⁸ Ra	0	1.51×10^{-5}	6.00×10^{-6}

Typical PWR fuel assembly.

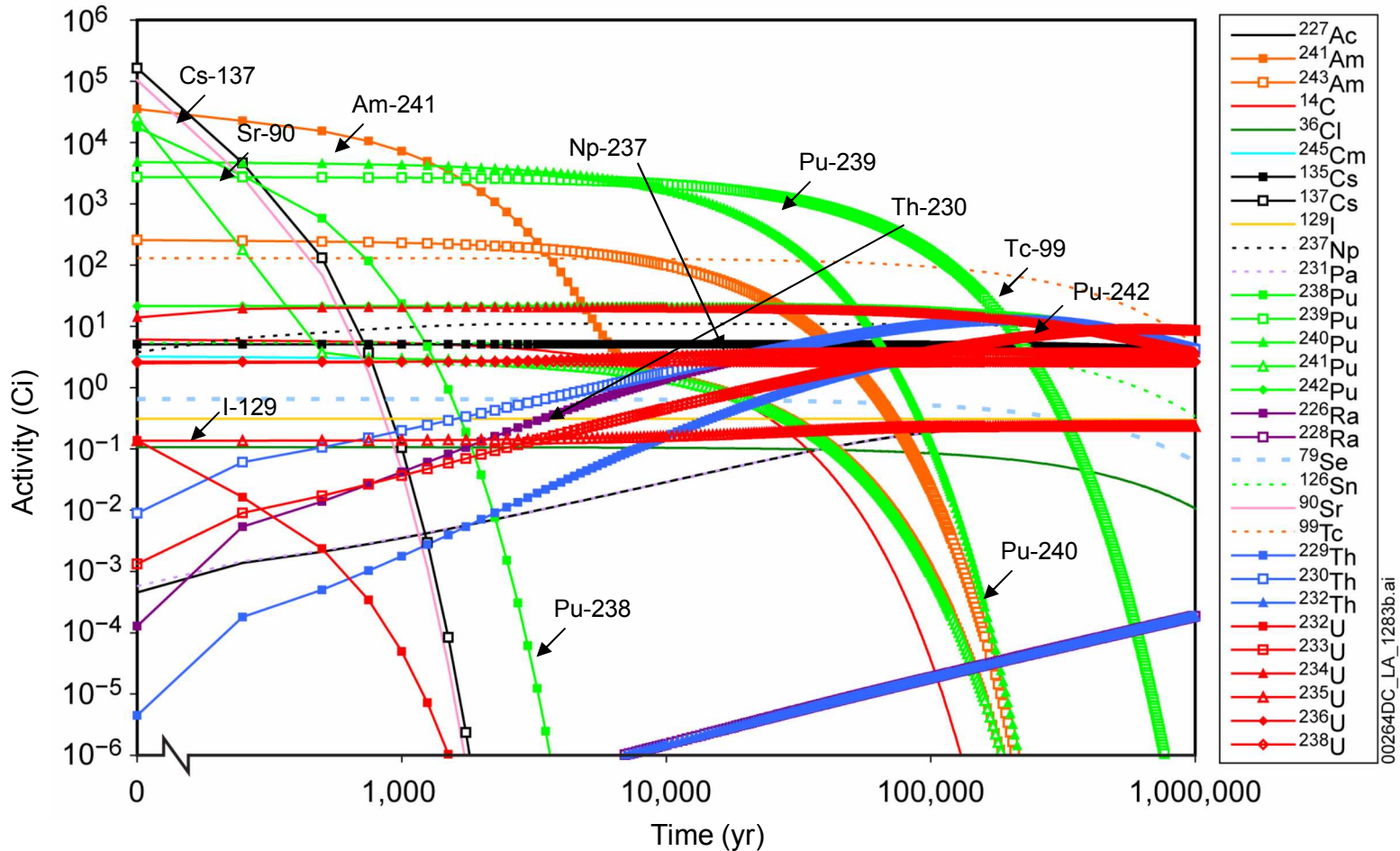


Isotopic Composition



Discharge isotopic composition of a WE 17×17 assembly with initial enrichment of 4.5 wt % that has accumulated 45 GWd/MTU burnup

Radionuclide Inventory Decay for the Waste in a Commercial SNF Waste Package (21 PWR)

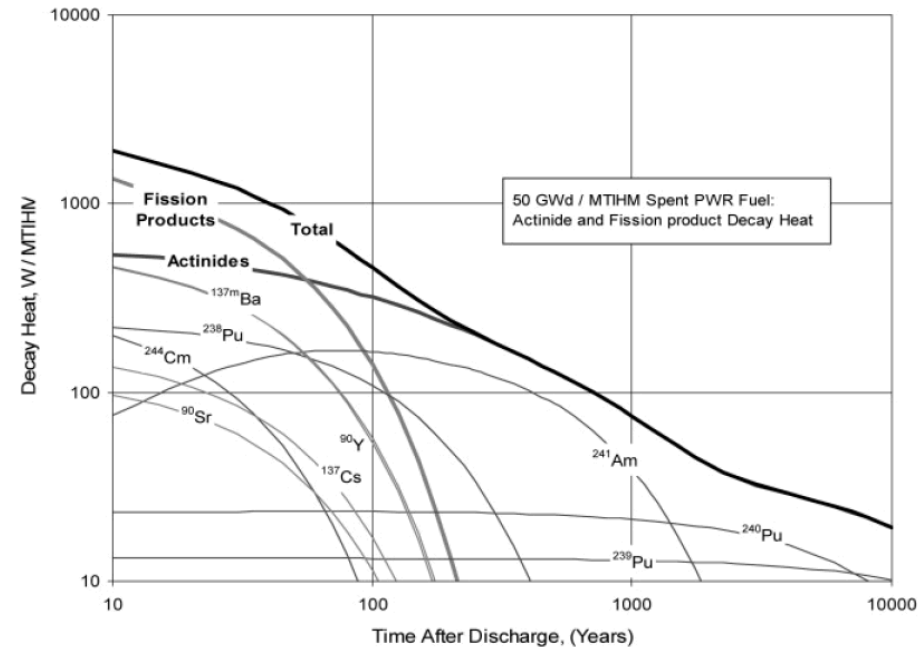
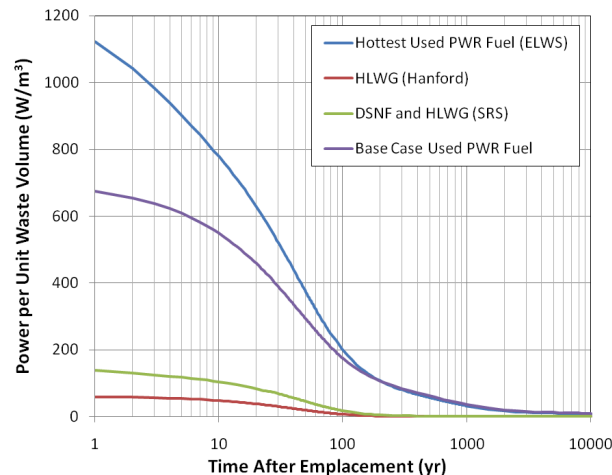


DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for an single representative Yucca Mountain used fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Thermal Objectives for Repositories

Temperature constraints are design-specific and may have considerable flexibility

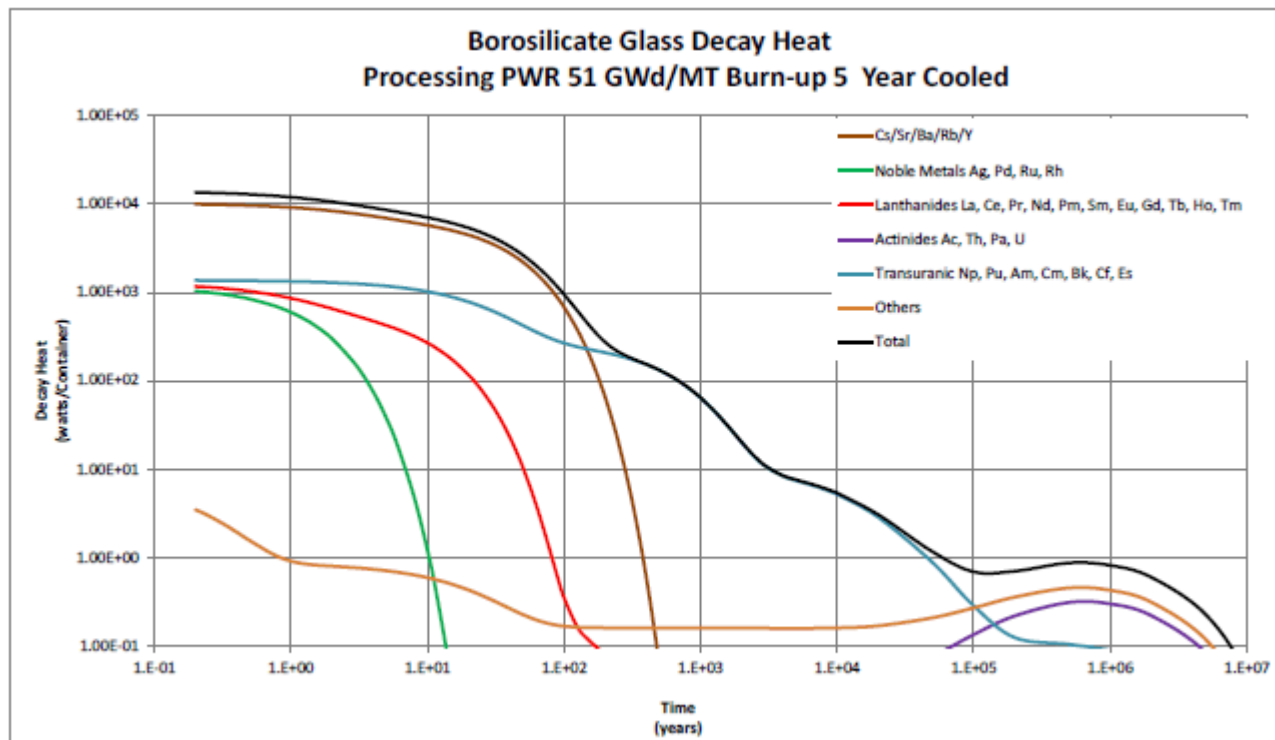
- For disposal concepts that rely on clay backfill/buffer
 - Peak temperatures below boiling at the waste package surface
- For salt disposal concepts
 - Peak temperatures in salt below 200° C
- For ventilated disposal concepts without backfill
 - Peak temperatures may be dictated by material properties of host rock or engineered barriers



Wigeland, R.A., T.H. Fanning, and E.E. Morris, 2006, "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," *Nuclear Technology* v. 154, Figure 1

Calculated thermal power for representative Yucca Mountain waste forms

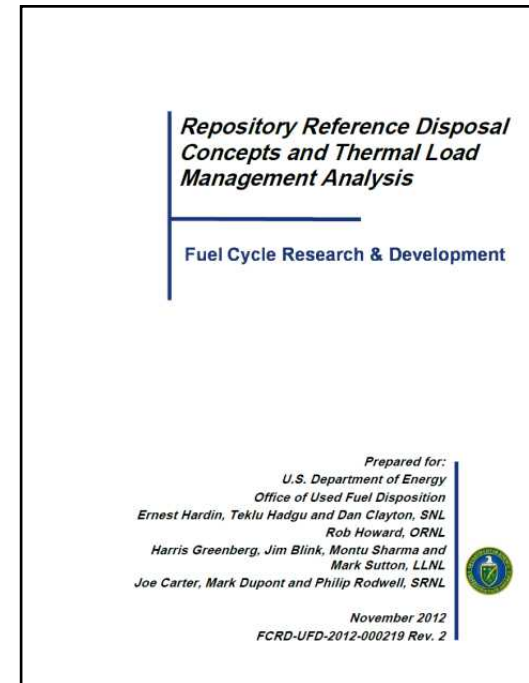
Borosilicate Glass Decay Heat



Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GW-d/MT 5-year Cooled PWR Fuel

Options for Achieving Thermal Objectives

- Repository Design
 - Size of waste packages
 - Spacing between packages
 - Thermal properties of engineered materials
- Operational Options
 - Aging
 - Ventilation
 - Load management
- Modifications to Waste Forms
 - Decreasing density of fission-product and actinide loading
 - Separation of heat-generating isotopes



Example Thermal Modeling Results:

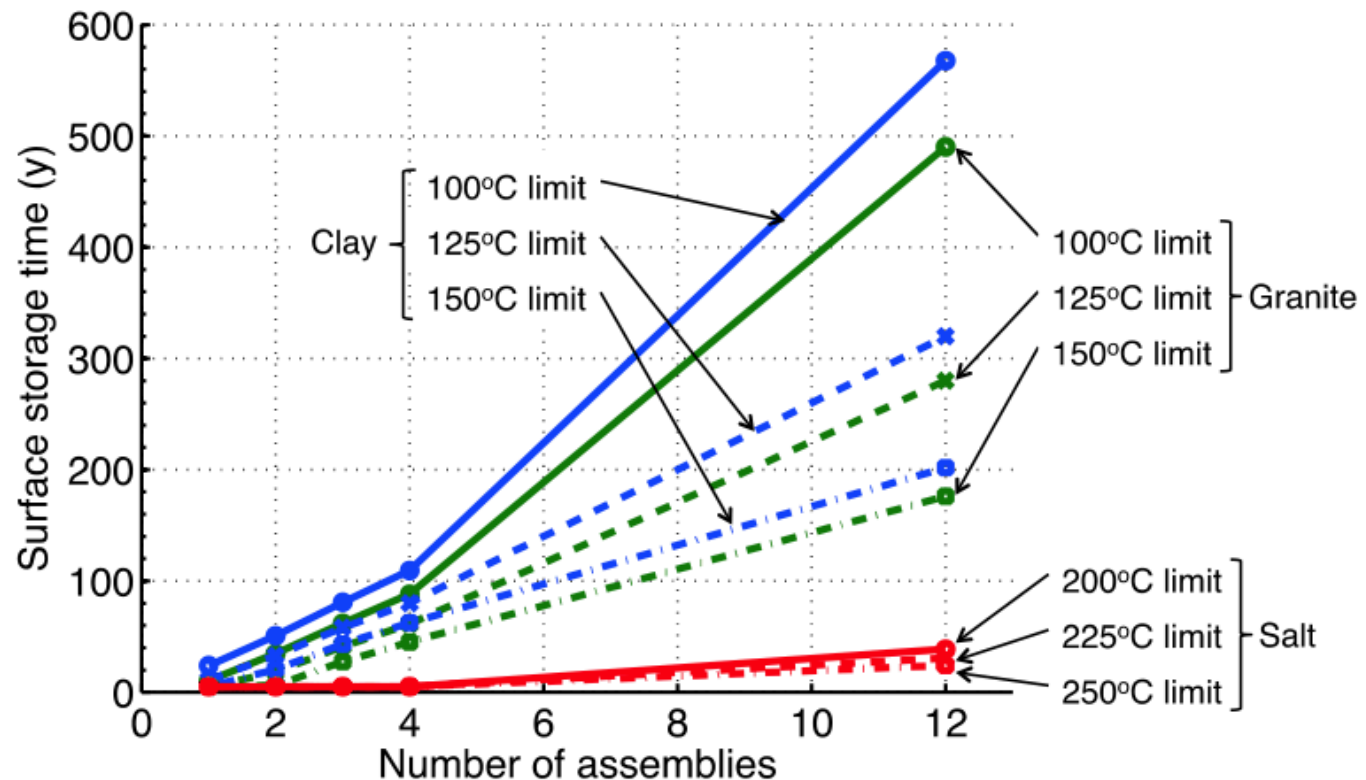
Managing Peak Temperature in Enclosed Emplacement Concepts through Canister Size and Decay Storage

Decay Storage Needed to Meet WP Surface Temperature Limits vs. WP Size or Capacity (PWR Assemblies; 60 GWd/MT Burnup)

Temperature limits based on current international and previous U.S. concepts:

- 100°C for clay buffers and clay/shale media (e.g., SKB 2006)
- 200°C for salt (e.g., Salt Repository Project, Fluor 1986)

Final temperature constraints will be site- and design-specific



Thermal conductivity for all media selected at 100°C.

Waste Packages

■ Pre-Closure

- Waste Packages must be designed to protect both worker and public health and safety after being laden with waste forms and closed.
- Protection must take place in the surface facility, during transport to the subsurface, and after placement but before final closure.

■ Post-Closure Safety

- Depending on the disposal concept, the waste package may be designed to last for hundreds of years and possibly many tens of thousands of years, and are made of materials whose properties and thicknesses are chosen to provide appropriate containment times

■ The following criteria are considered for material selection:

- Mechanical performance (strength)
- Chemical performance (resistance to corrosion)
- Predictability of performance
- Ease of fabrication
- Thermal performance
- Cost

Waste Packages

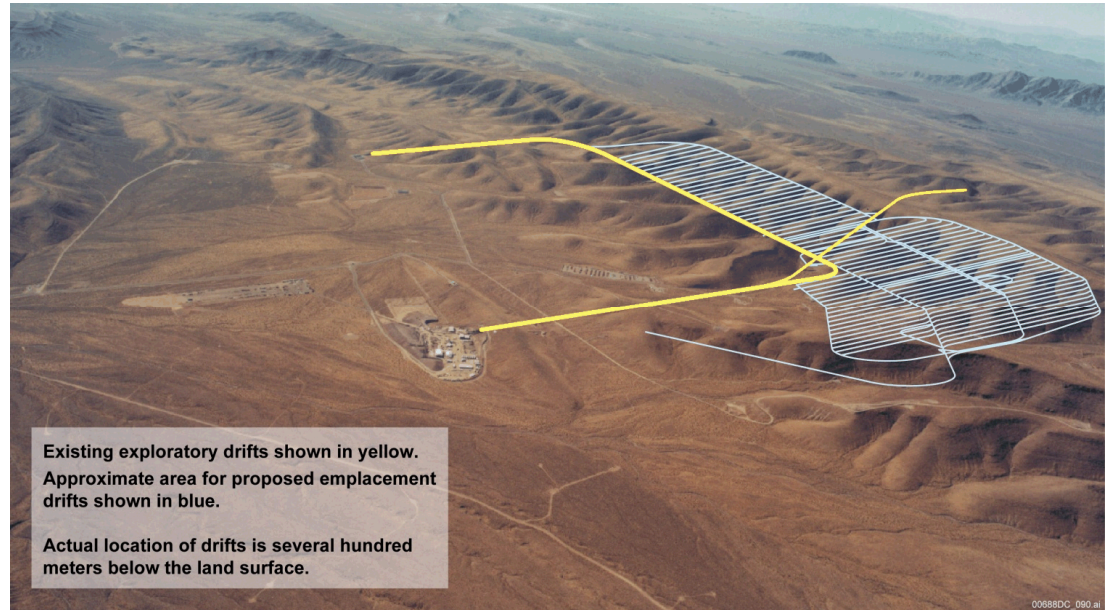
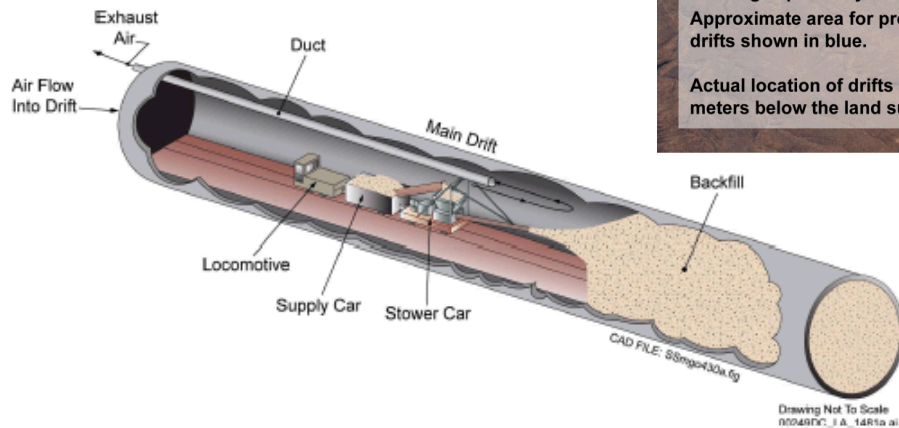
- Materials considered in different programs
 - Alloy 22 – Unsaturated hard rock (US-YMP) – hundreds of thousands of years containment
 - Carbon Steel Drums – Rock Salt (US-WIPP)
 - Copper – Crystalline rock – Sweden and Finland – thousands of years of containment
 - Carbon steel – Clay rock – Swiss
 - Carbon steel – Salt rock – Germans

Buffer/Backfill

- A material used to fill voids in a geological disposal facility. Three types of backfill are recognized:
 - Buffer or backfill, which is emplaced to fill around waste packages;
 - drift backfill, which is emplaced in disposal excavated volume
 - mass backfill, which is the bulk material used to backfill the excavated volume apart from the disposal areas
- Buffer adjacent to the waste package
 - Provides physical protection for the waste packages, limits the movement of water to and around the waste package, and in some concepts provides a chemical function. For example, in WIPP Magnesium oxide MgO absorbs carbon dioxide produced from organic components in the waste
 - Bentonite clay used in Swedish, Finnish, and Swiss concepts, Germans use crushed salt

Engineered Backfill/Seals

Maintain isolation and prevent Inflow of water and migration of radionuclides out of facility



Conceptual Arrangement for Placement of Backfill in Ramps

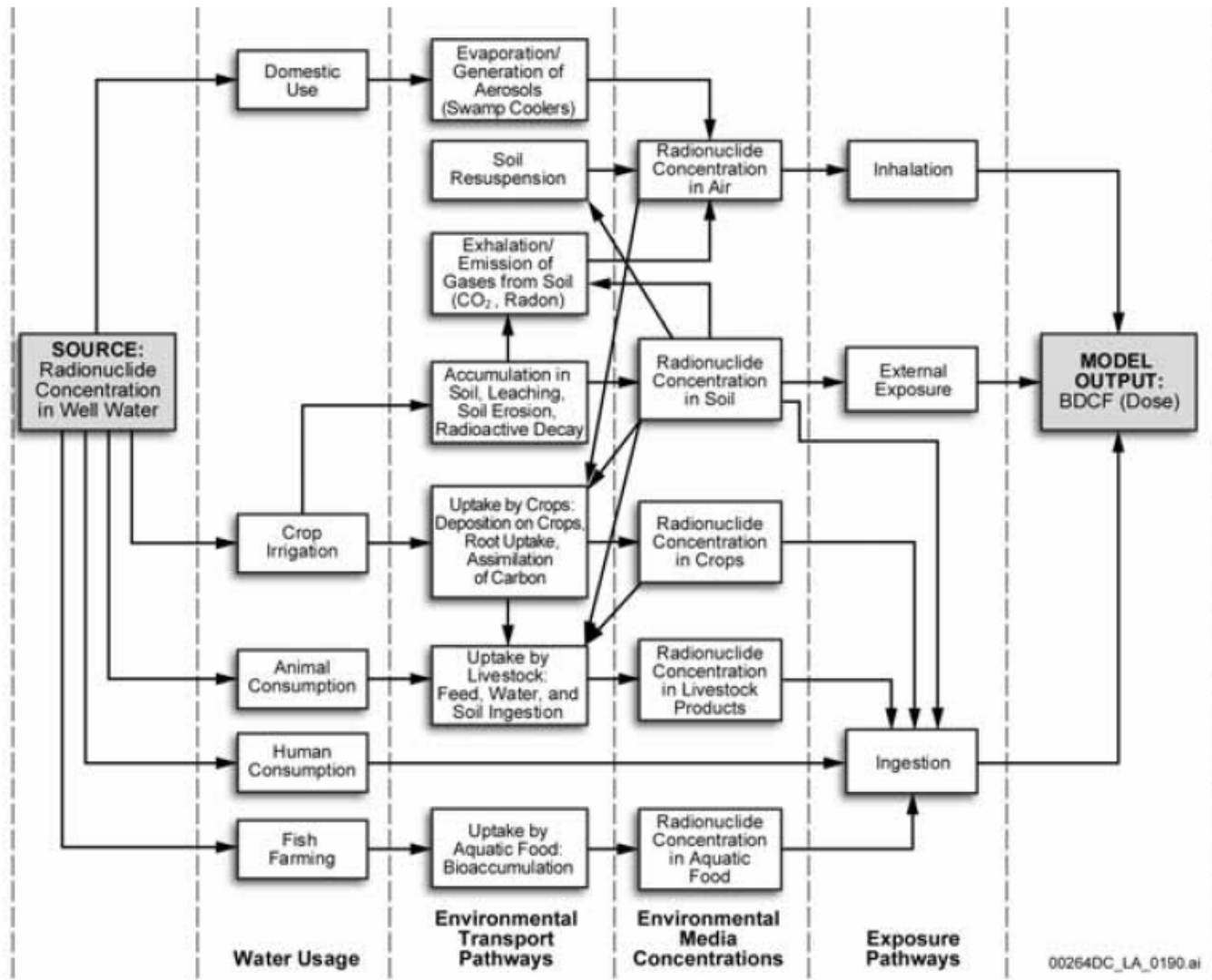
Role of the Geosphere

- Isolates the waste from humans
- Protects the EBS from human and natural processes occurring at the surface
- Provides a stable and predictable mechanical and chemical environment for the EBS
- Conducts heat generated by the waste away from the EBS to reduce peak temperatures
- Delays and limits the release and transport of radionuclides to the biosphere through the processes of sorption, dispersion, and dilution

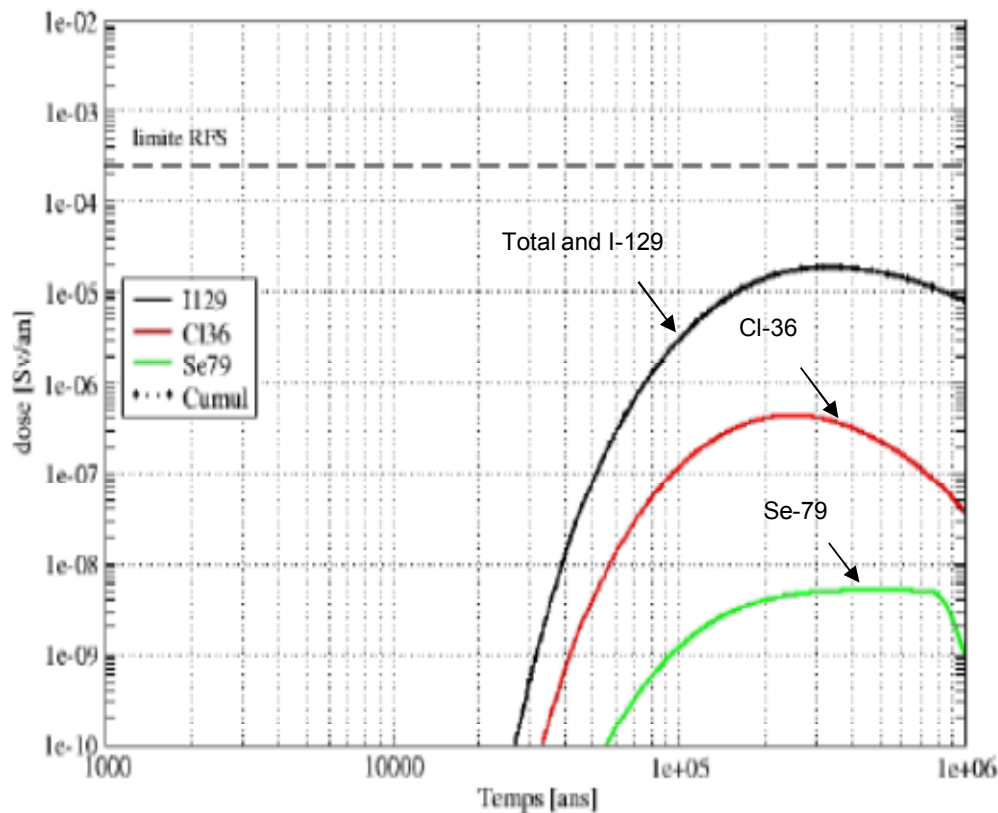
Role of the Biosphere

- [IAEA, 2007] defines the biosphere as *“that part of the environment normally inhabited by living organisms”*.
 - ----- it is *the accessible environment where radiation exposures can occur*
- The evaluation of how well the natural and engineered barrier systems of a repository are projected to retain or retard the migration of radionuclides from the repository to the accessible environment is the focus of EBS and geosphere modeling
- The evaluation of doses to the defined receptor, when the radionuclide release to the accessible environment occurs, is the focus of biosphere modeling
 - Typically a representative individual is defined for whom the dose is calculated, where the individual is from a local community with representative diet and patterns of behavior
 - Biosphere dose conversion factors are used to convert geosphere modeling output into a dose value

Biosphere (YMP)

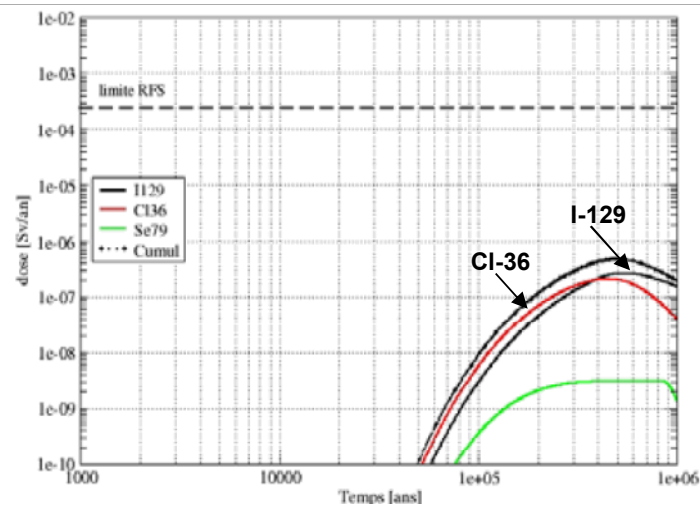


Contributors to Total Dose: Meuse / Haute Marne Site (France)



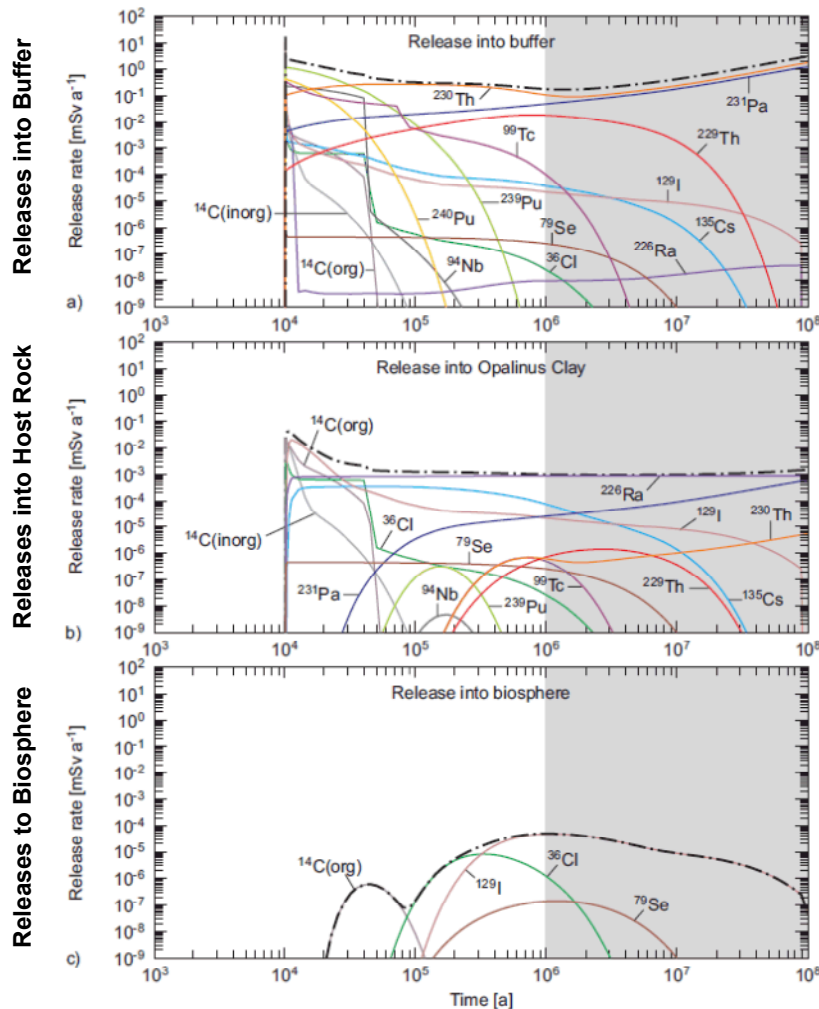
I-129 is the dominant contributor at peak dose

Examples shown for direct disposal of used fuel (left) and vitrified waste (below)



ANDRA 2005, Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation, Figure 5.5-18, SEN million year model, CU1 spent nuclear fuel and Figure 5.5-22, SEN million year model, C1+C2 vitrified waste

Contributors to total dose: Opalinus Clay (Switzerland)



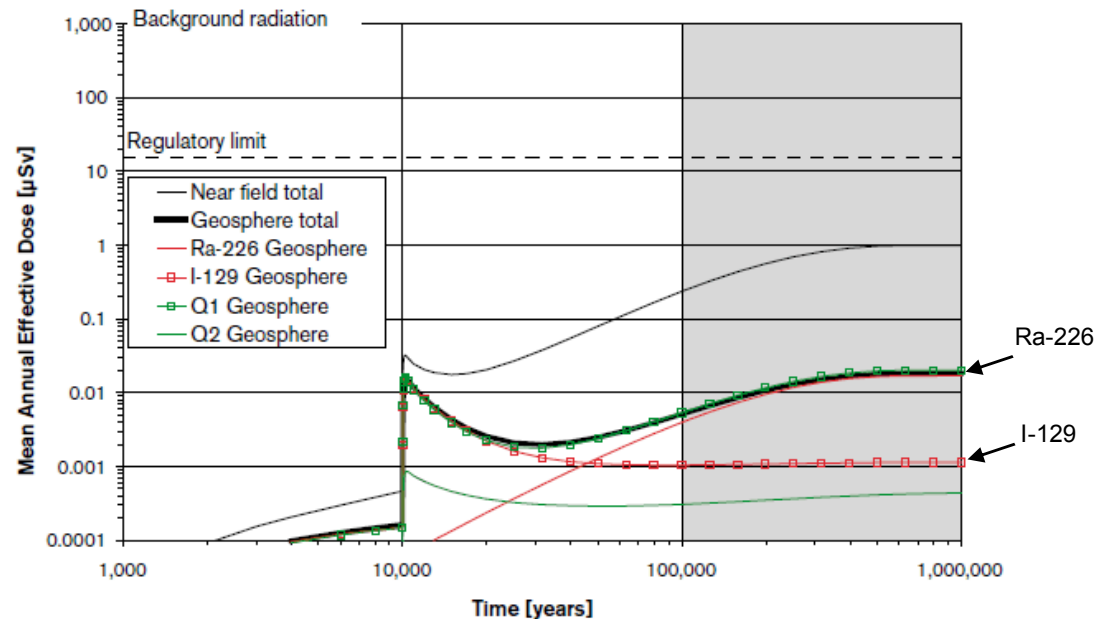
Releases from spent fuel dominated by early spike of I-129 and long-lived actinides (Th-230, Pa-231)

Releases from clay buffer dominated by relatively more mobile Ra-226 and I-129

Releases to biosphere dominated by I-129, Cl-36, C-14, and Se-79

NAGRA 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, Figure 6.5-1

Contributors to total dose: Forsmark site (Sweden)



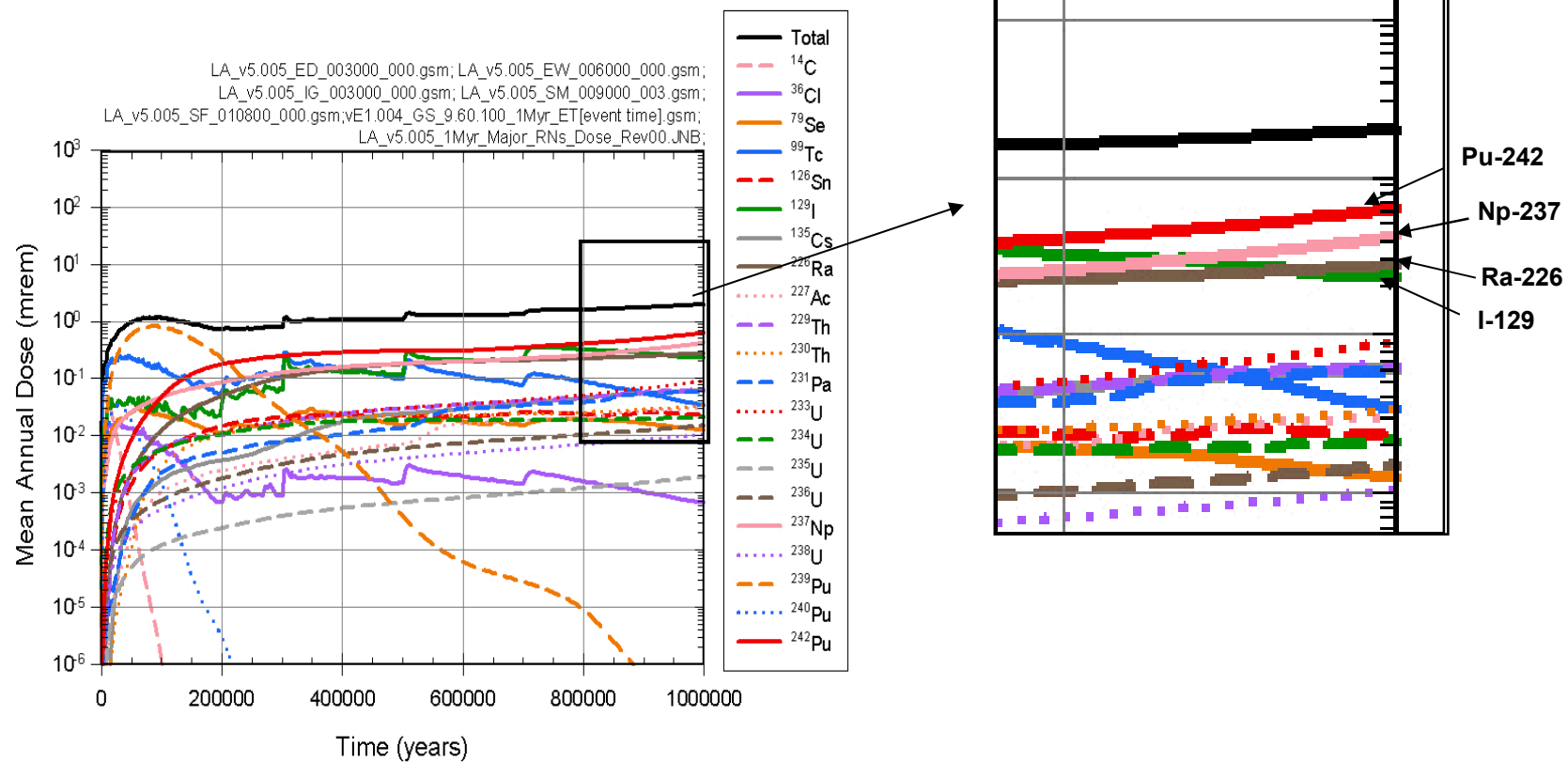
Early peak from rapid release of I-129 when package fails (assumed at 10,000 yr for this case)

Long-term peak from Ra-226 controlled by fuel dissolution and diffusion through buffer

Figure 10-18. The Forsmark pinhole failure base case (geosphere total, i.e. LDF values applied to releases from the far-field model) decomposed with respect to dominant nuclides (Ra-226 and I-129) and release paths (Q1 and Q2). The effect of discarding geosphere retention is also shown (near field total, i.e. LDF applied to releases from the near field model). 10,000 realisations analytic model.

Contributors to total dose: Yucca Mountain

DOE/RW-0573 Rev 0 Figure 2.4-20b



Summary of Radionuclides Contributing to Dose

- Major contributors to total dose differ for different disposal concepts
 - For all disposal concepts, I-129 is likely to be a major contributor at 1 million years
 - For oxidizing sites with advective release pathways, actinides may dominate
 - For reducing sites with advective release pathways, relatively mobile Ra-226 may be important in addition to fission products
 - For disposal concepts dominated by diffusive releases, long-lived mobile fission and activation products are likely to dominate

Site Characterization

- Provides basis for understanding how the geosphere evolved to its current state and how it will evolve in the future
- Provides identification and confirmation of relevant features, processes, and events (FEPs) and the basis for development of conceptual models
- Provides the basis for establishing parameter values and uncertainty in those values for use in performance assessment

Conceptual Geosphere and Property Models

- Geology Conceptual Model
 - Describes the stratigraphy, lithology, geological features, and evolution of the system to its current state and how it will evolve in the future
- Hydrogeology Conceptual Model
 - Describes the hydrogeological units and features, conceptual understanding of flow in the different units and features, hydrological properties, recharge and discharge areas, and spatial and temporal changes in flow conditions
- Geochemistry Conceptual
 - Describes the chemistry of the host rock and groundwater system
- Transport
 - Describes the conceptual understanding of transport processes through the different units and transport properties

Conceptual Geosphere and Property Models

- Geomechanical Properties
 - Provides host rock geomechanical properties for design and predicting long-term response of the EBS
- Thermal Properties
 - Provides thermal properties for design and calculation of heat transfer into the host rock

Phases of Repository Planning and Development

Site Selection,
Characterization,
Repository
Design

Licensing

Construction

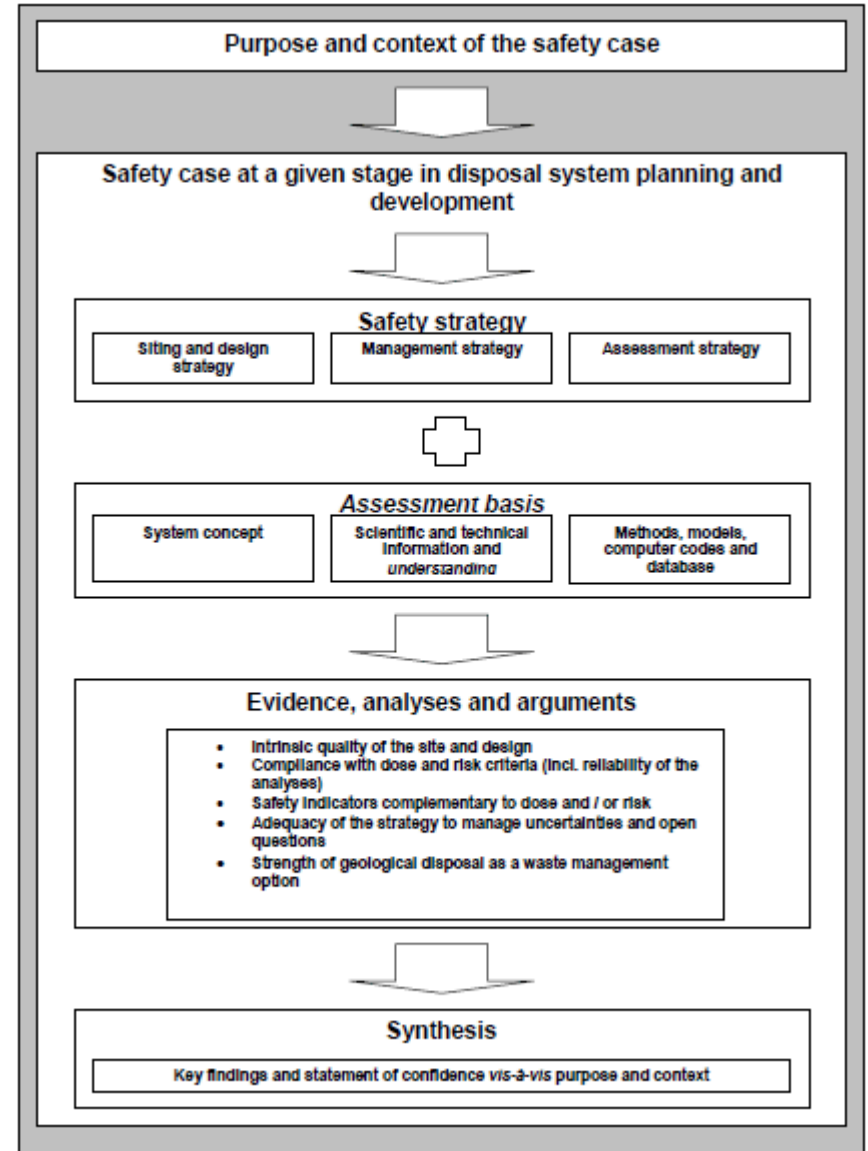
Operation

Closure

Post-
closure

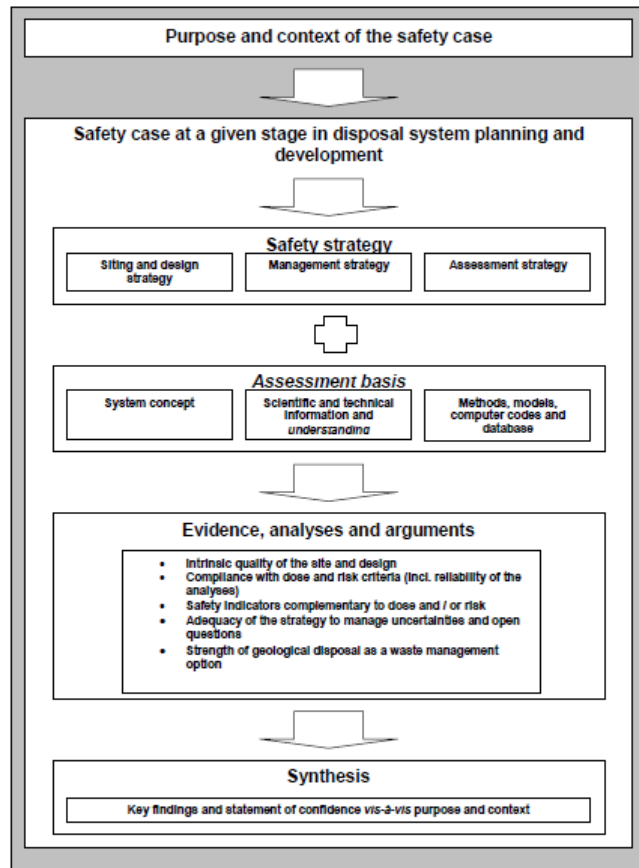
Safety Case Context for PA Model

- “The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility.” (NEA 2004)
 - Quantitative information – calculated values for safety standards and indicators, including uncertainty (e.g., a safety or performance assessment)
 - Qualitative information – supporting evidence that builds confidence in the quality of the underlying science and conclusions (e.g, natural analogs)
- Two major roles:
 - Management: a tool to guide the activities of the implementer (e.g., DOE) through the various phases of repository development
 - Communication: transparently explain the current understanding of safety to a broad range of stakeholders, decision makers, and the general public

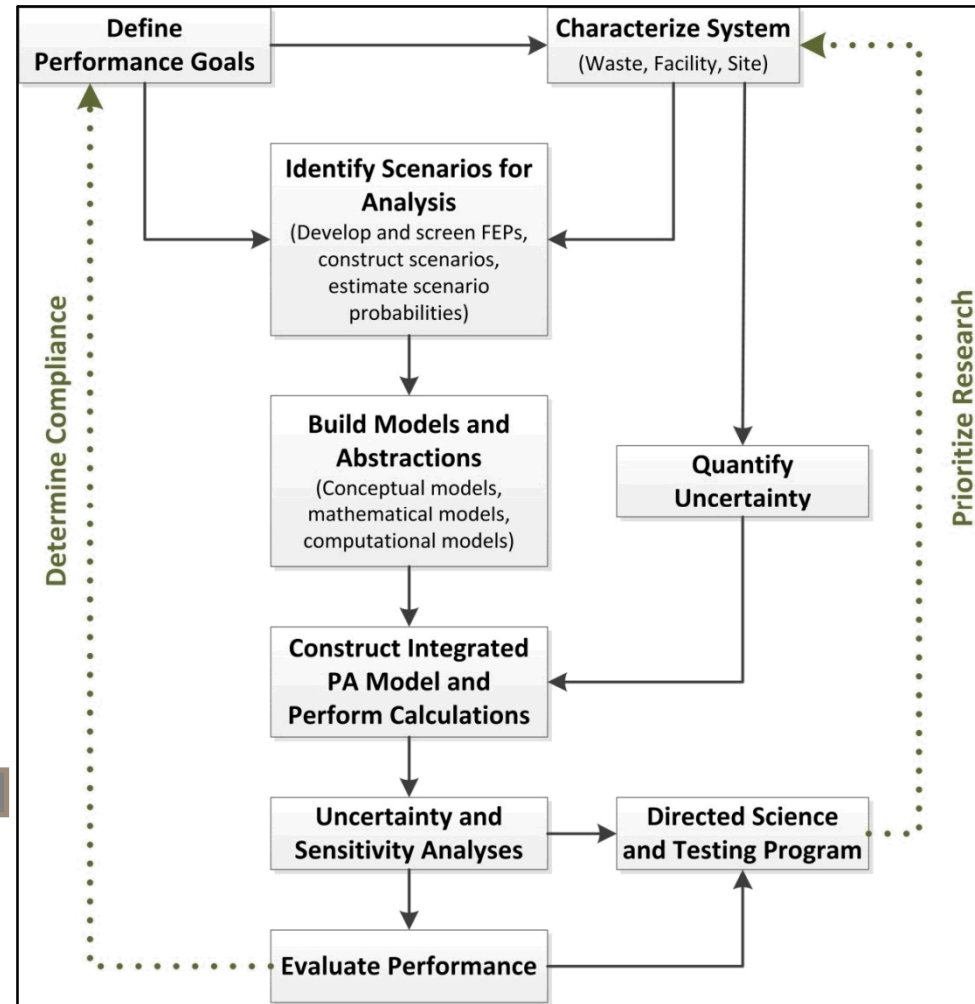


Role of Postclosure Safety (Performance) Assessment

- “Performance assessment is arguably the most important part of the safety case...” (NWTRB 2011)
- Iterative



Iterative PA Methodology



Role of PA in the Case for Safety

- Performance assessment is performed iteratively throughout the development of a repository:
 - Evaluate and synthesize the current scientific understanding and data for the given design concept or possible repository at a site
 - Understand and forecast long-term performance of the repository and identify factors that are most important to that performance
 - Identify factors and processes for which improved understanding or data are needed
 - Identify possible repository design modifications to improve performance or to reduce uncertainties
 - Demonstrate that the repository concept meets attendant regulatory requirements and will remain safe over the required timescale

Role of PA in the Case for Safety

- In early stages, characterization program is broad-based and focused on gaining an adequate understanding of the system (waste, facility, and site) and identifying greatest sources of uncertainty
- As knowledge and understanding of the system improve, features, events and processes (FEPs) can be developed/ screened and scenarios can be developed/analyzed
- Conceptual and mathematical models are developed based on relevant (included) FEPs
- Probabilistic modeling is conducted, taking into account both parameter uncertainties and scenario uncertainties, to generate estimates of performance
- Sensitivity analysis is conducted and scenario assumptions and parameters with greatest impact on performance measures are identified and prioritized
- R&D activities that produce reasonable reductions in uncertainty are funded while other activities are terminated or scaled back
- Iterative— new information used to refine requirements, performance measures, alternatives, and models

Phases of Repository Planning and Development

Key Elements & Sub- elements of Safety Case

Site Selection,
Characterization,
Repository Design

Licensing

Construction

Operation

Closure

Post-closure

Statement
of Purpose

Safety
Strategy

Site
Characterization

Repository
Design

Pre-closure
Safety

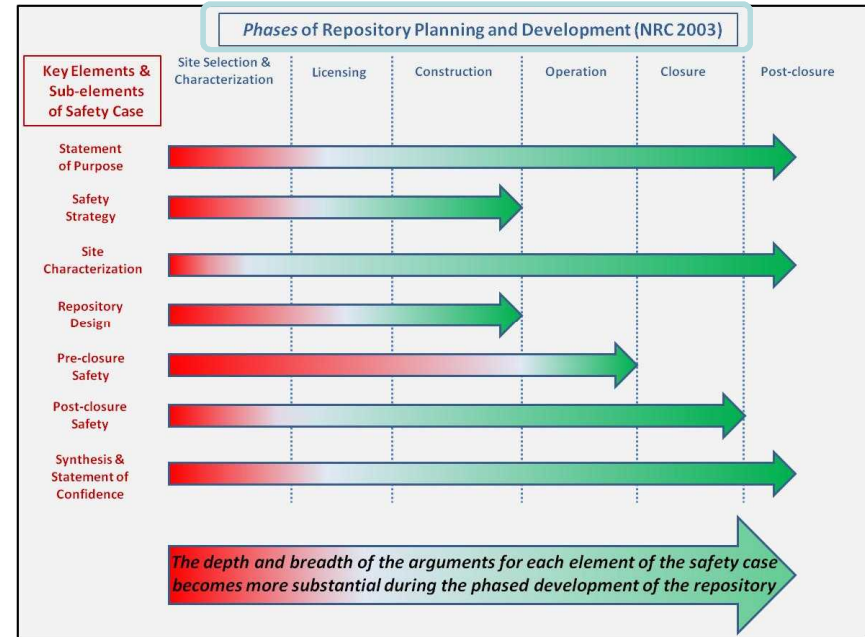
Post-closure
Safety

Synthesis &
Statement of
Confidence

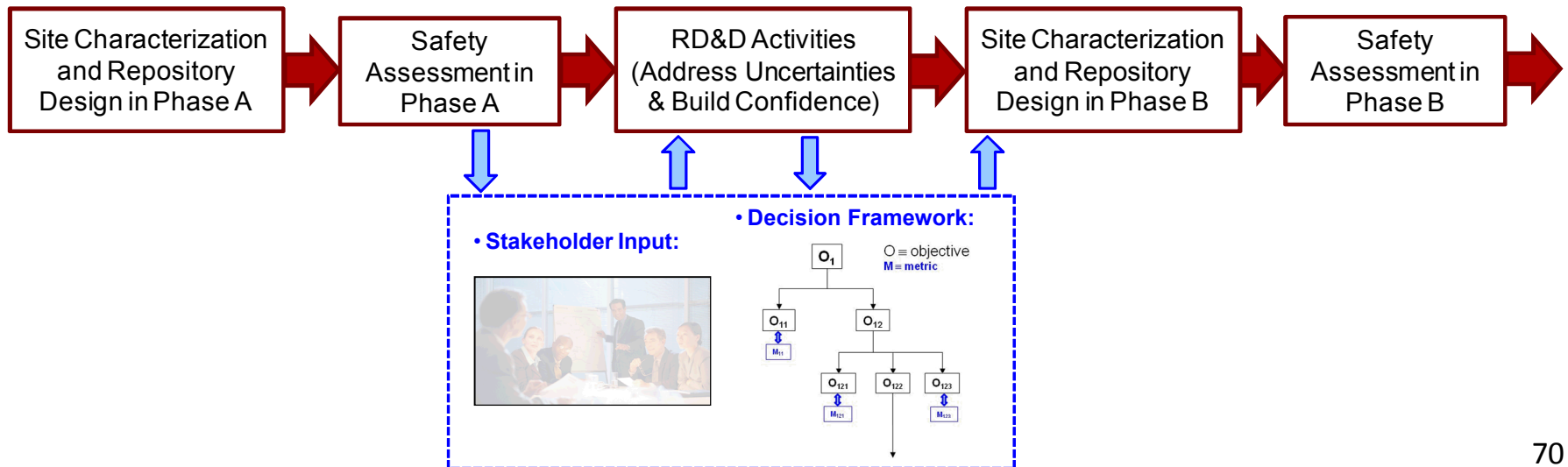
The depth and breadth of the arguments for each element of the safety case becomes more substantial during the phased development of the repository

Evolution of the Safety Case

- Safety understanding and the associated technical bases evolve with phases of repository development:

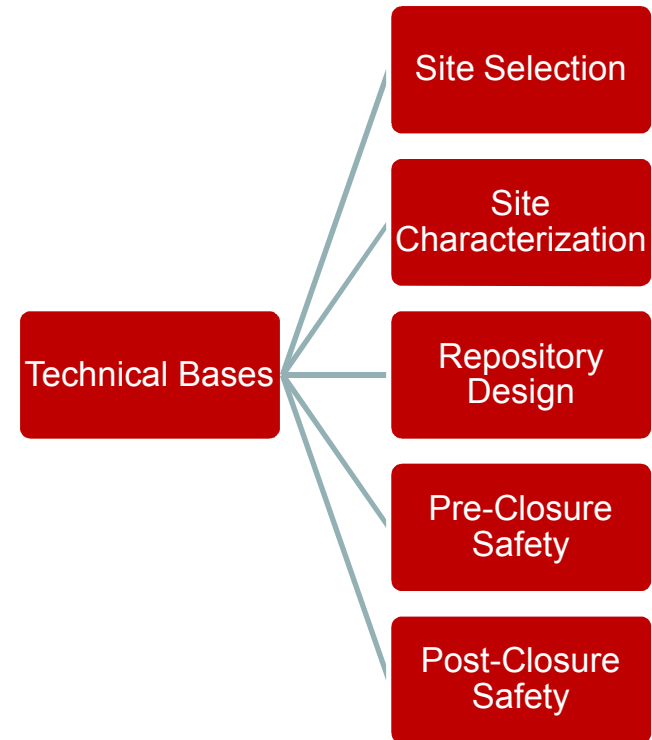


- Iteration of Safety Assessment and Site Characterization/Design:

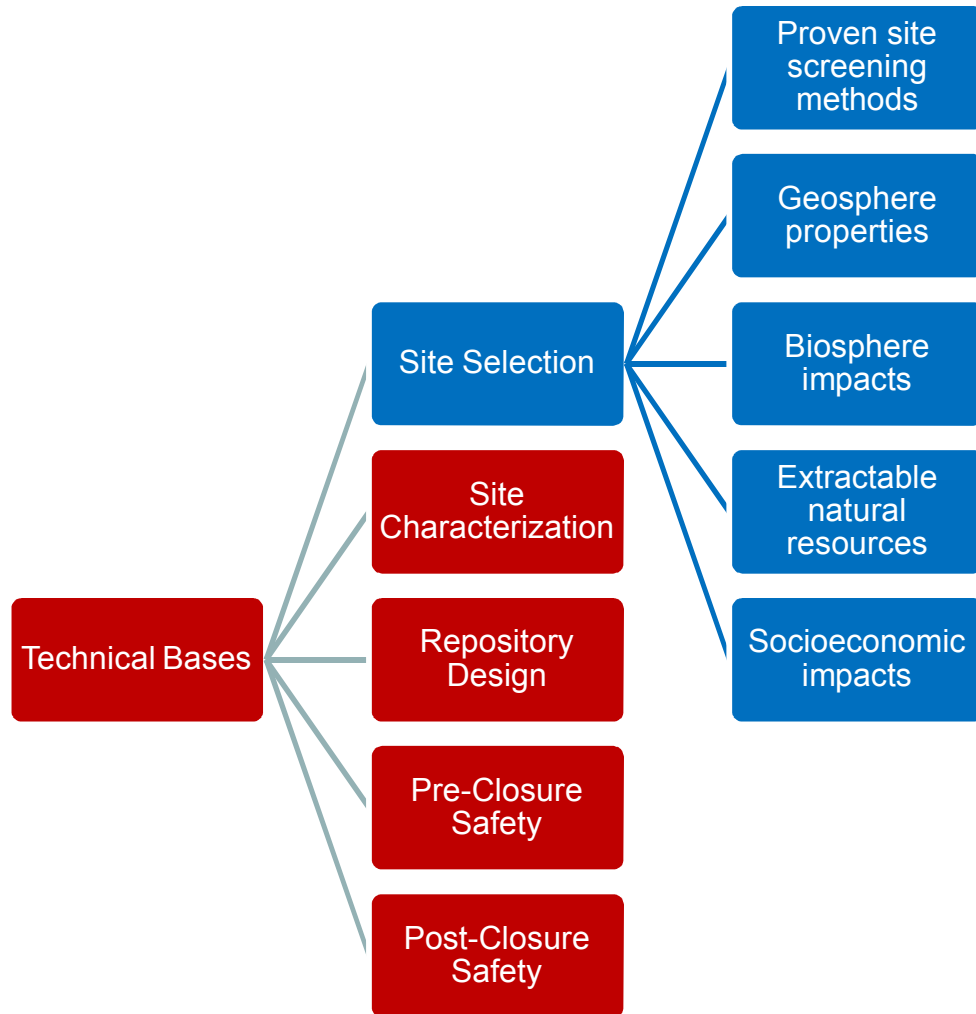


Technical Bases for a Geologic Repository

- Technical bases
 - Data and arguments that build confidence that technical objectives are achieved
- Technical objectives
 - Functional objectives
 - Capacity, timing, specific wastes to be disposed, operational, retrievability(?), etc.
 - Safety criteria
 - Pre-closure
 - Post-closure

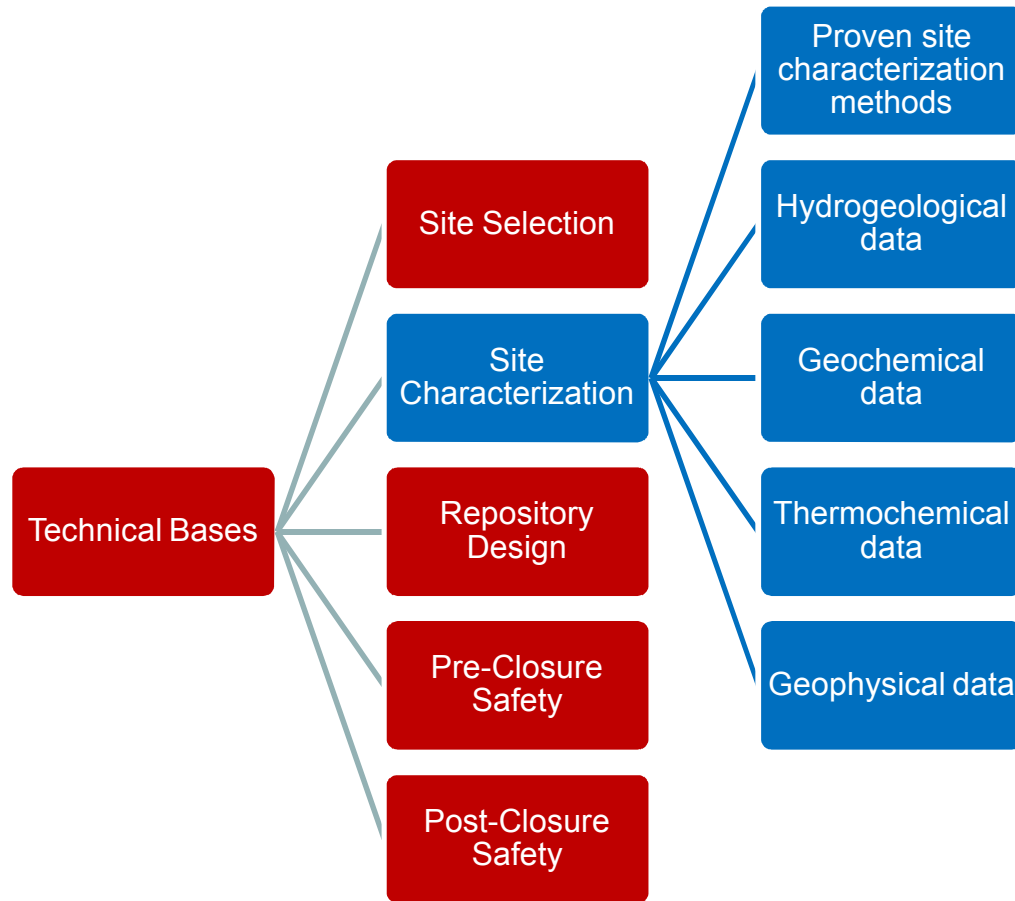


Site Selection Bases



- Objective
 - Build confidence in
 - site selection process
 - site(s) selected
- Inputs from
 - Site characterization activities
 - Knowledge of important FEPs
 - Historical resource drilling data
 - Community involvement
 - Lessons learned from previous site selection experiences
- Meet objective by sufficiently demonstrating/documenting
 - Knowledge of the subject areas
 - Sufficiently low risk of an unacceptable outcome

Site Characterization Bases



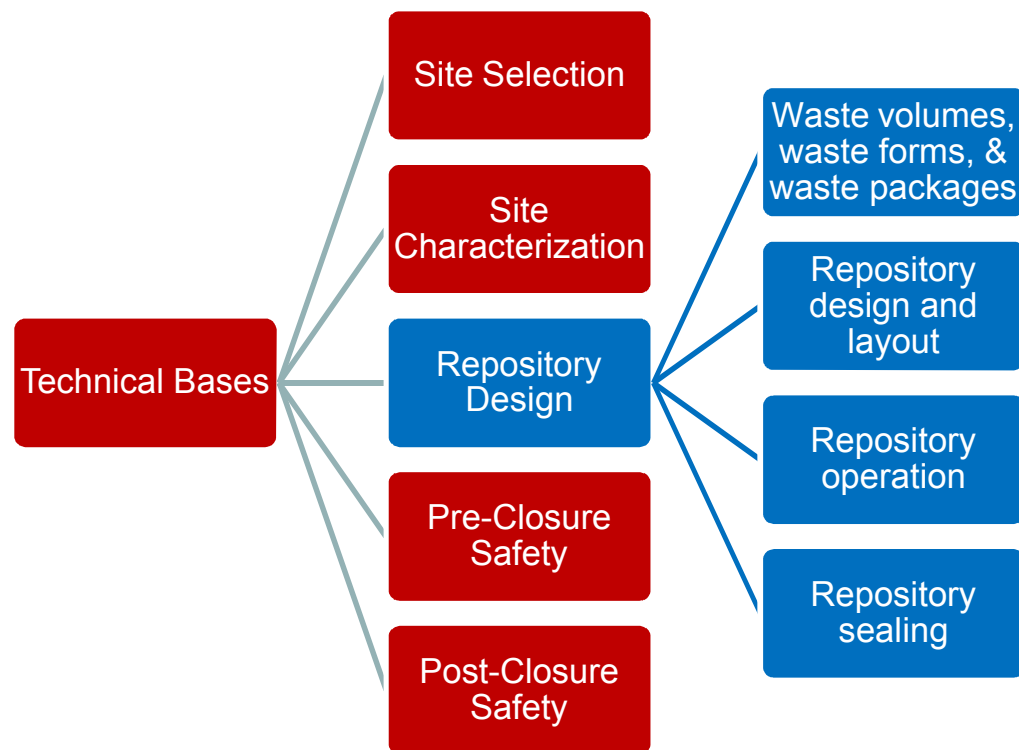
- Objective

- Obtain sufficient site characterization data to assess the long-term safety of a repository at the site
- Reduce parameter uncertainty

- Inputs from

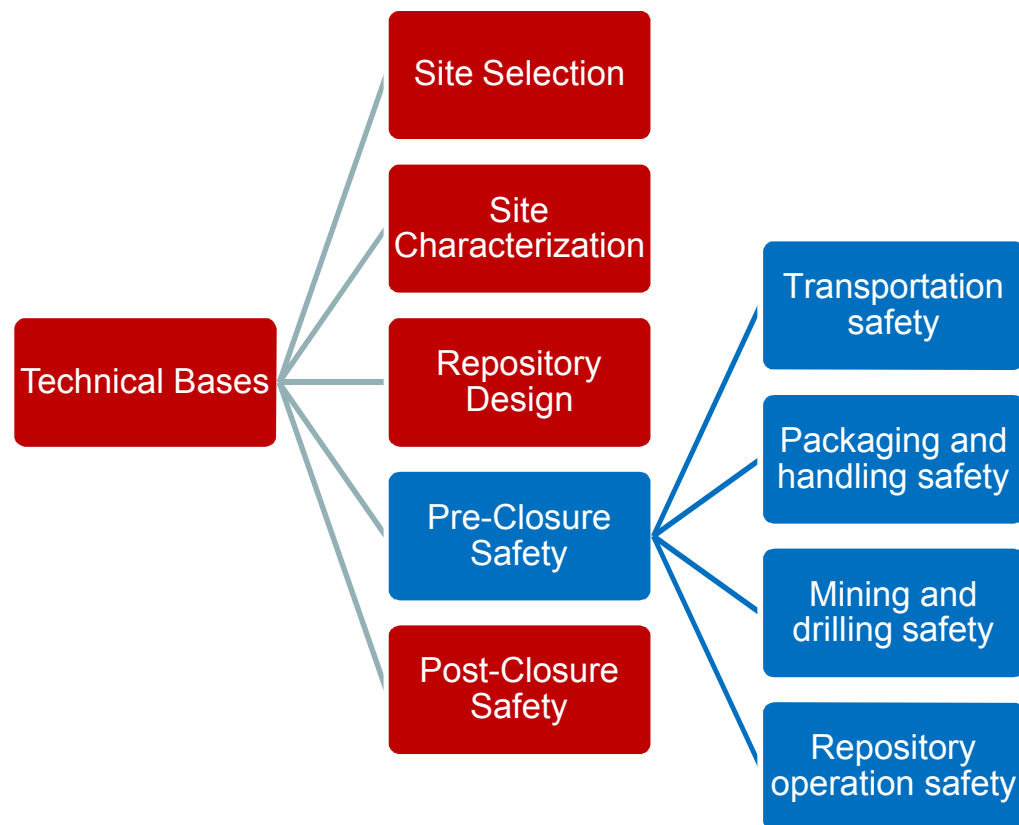
- Surface based characterization
 - 3D seismic imaging
 - Gravity survey
 - Magnetic survey
 - Electrical resistivity profile
- Borehole-based characterization
 - Geophysical logging
 - Geological and hydrological sampling and analyses

Repository Design Bases



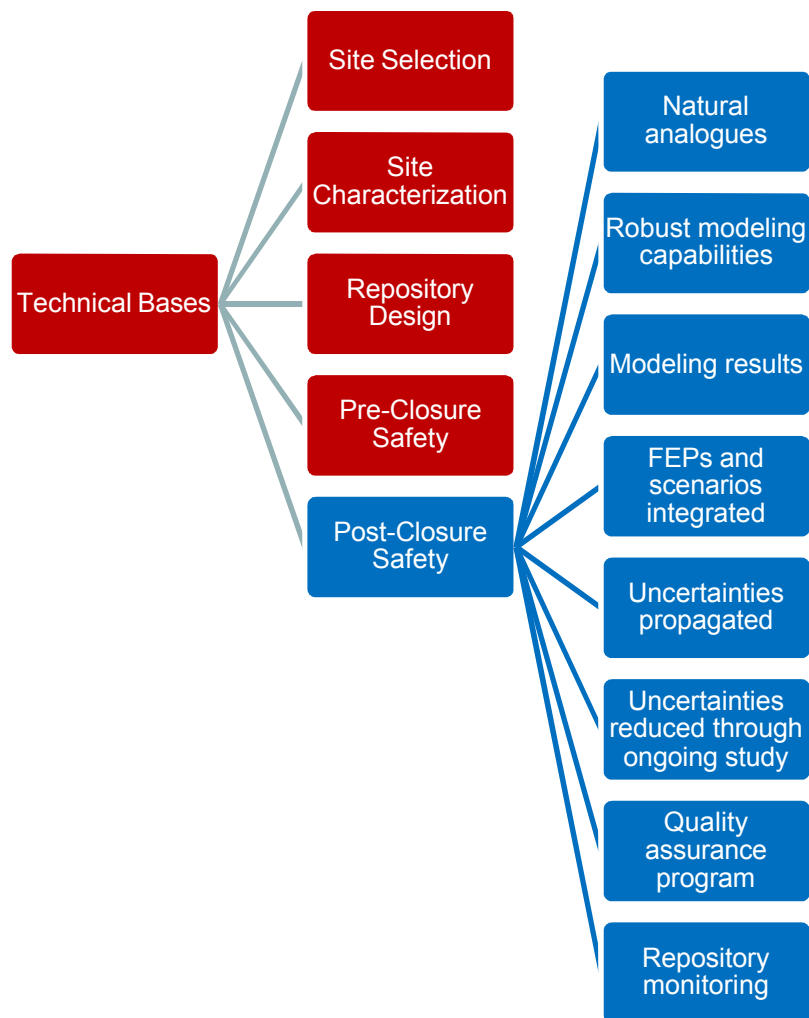
- Objective
 - Demonstrate a feasible repository design for the site
- Inputs from
 - Projected inventory, waste forms, and waste packages
 - Repository design needed to accommodate
 - Waste volumes and number of waste packages
 - Thermal load
 - Design specifications
 - E.g., thermal limits for engineered barriers
 - International programs

Pre-Closure Safety Bases



- Objective
 - Demonstrate pre-closure safety for the proposed repository
- Inputs from
 - Repository design
 - E.g., shielding
 - Standard operating procedures
 - Safety data from drilling, mining, handling, and transportation
 - Radioactive waste disposal programs
 - Underground research laboratories
 - Waste containers can be analyzed for failure potential due to potential event sequences

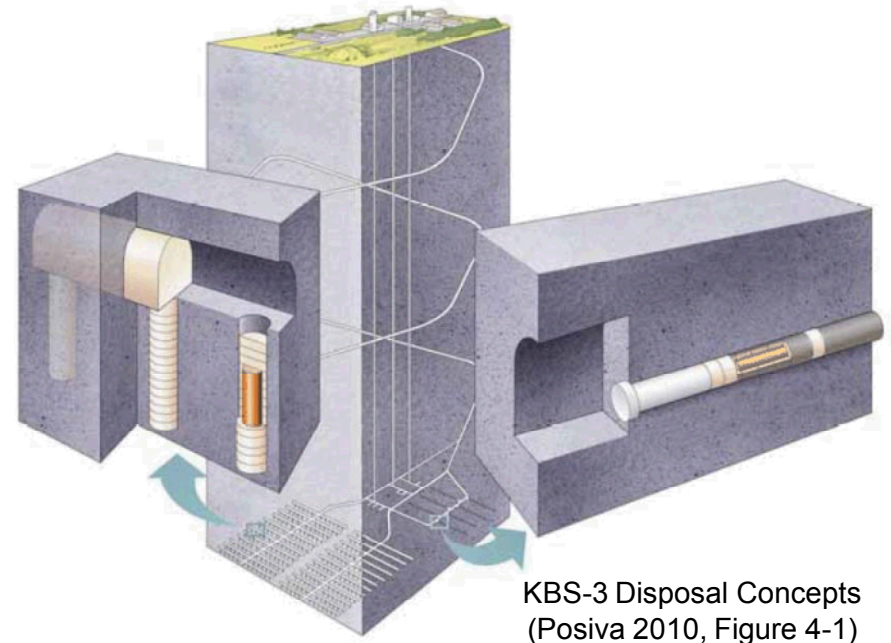
Post-Closure Safety Bases



- Objective
 - Demonstrate long-term safety for disposal concept
- Bases
 - Natural analogs (long-term stability of bentonite, copper deposits; UO₂ ore bodies)
 - Models used are adequate and robust
 - Long-term performance evaluations indicate long-term safety
 - FEPs screening and scenario development are well developed, demonstrated, and integrated with performance evaluations (IAEA 2004)
 - Uncertainties in parameter values and processes are propagated
 - Reductions in uncertainty are actively pursued via studies and collaboration as part of the post-closure safety assessment program
 - A well established quality assurance program
 - A repository monitoring program to confirm repository performance

Post-Closure Safety Attributes for Disposal in Mined Crystalline Rock

- Far from biosphere
- Minimal rock pressures
 - Long-lasting excavations reduce stresses on canisters
 - Retrievability
- Low permeability at depth (300 – 500 m)
 - $\sim 10^{-13}$ to $\sim 10^{-10}$ m s⁻¹
 - Age dating indicates old water, little movement
- Favorable chemical environment
 - Reducing conditions
 - low degradation rates, low radionuclide solubilities, increased sorption, UO₂ stable
 - Salinity at depth reduces colloid stability
- Low probability of accidental human intrusion
- Long-term stability of bentonite, UO₂ ore, and copper based on natural analogues
- Much supporting data from studies and programs around the world



Post-Closure Safety FEPs Important to Siting, Site Characterization, and Repository Design

- **Geology**
 - Stratigraphy, properties of host rock (permeability, porosity, mechanical stability, fracture networks, variations with depth)
 - Sorption in geosphere (mineralogy in flow and matrix porosity)
- **Hydrogeology**
 - Fracture flow, matrix diffusion, hydraulic gradients, potential for buffer erosion
 - Evidence of deep groundwater circulation (age dating)
- **Chemical conditions**
 - Oxygen, redox potential, pH, salinity, and other chemical parameters relevant to degradation rates (e.g., sulfide), radionuclide solubility, sorption, colloid stability, buffer performance
 - Colloids (stability, composition, abundance)
- **Biosphere**
 - Population, agriculture, aquaculture, etc.
- **Potential disruptive events**
 - See next slide

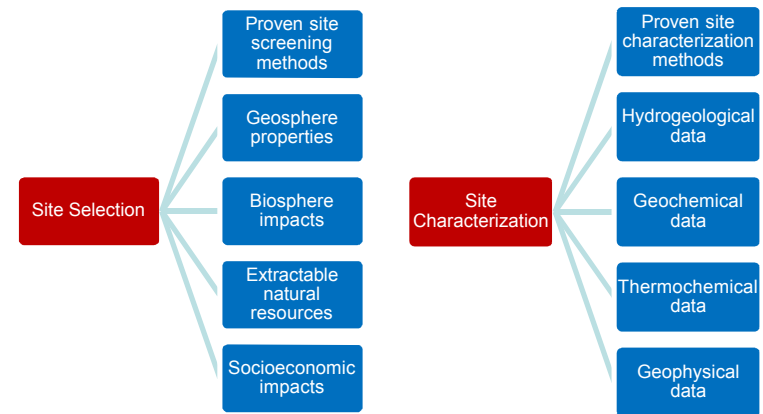
Disturbed Scenario FEPs Important to Siting, Site Characterization, and Repository Design

- Disruptive events include
 - Earthquakes
 - Probability of size and frequency
 - Glaciation, ice sheets, climate change, and periglacial effects
 - Potential effects on earthquakes, deep groundwater circulation, chemical conditions
 - Igneous or volcanic intrusion
 - Probability based on evidence of Quaternary-age volcanic rocks or igneous intrusions in the vicinity
 - Human intrusion
 - Probability of
 - Drilling/mining for resources, disposal of wastes, building a bunker, etc.
 - Potential consequences
- Disturbed scenarios are important for their potential to
 - Damage the repository and engineered barriers
 - Alter flow pathways and properties in the geosphere

Prioritizing Site Characterization Activities

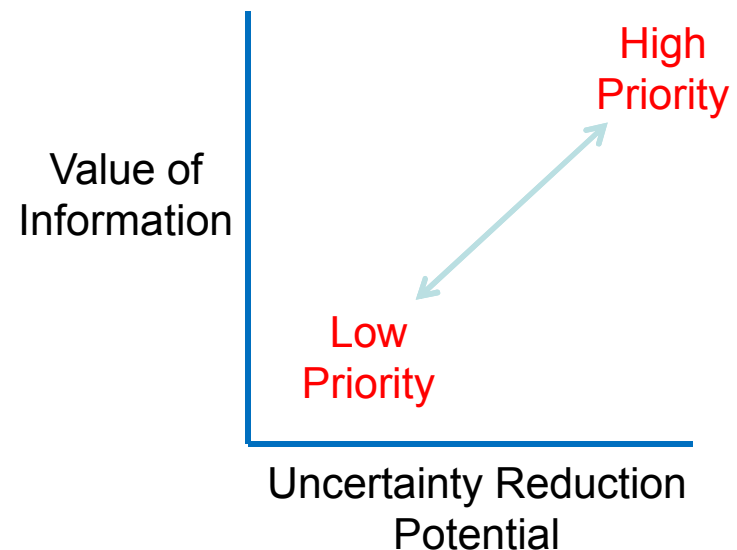
- Site characterization activities prioritized by

- Importance in demonstrating technical bases
- Importance in post-closure dose rate calculations
- Potential to reduce uncertainty in dose rate calculations
- Other factors (e.g., cost, maturity of activity, redundancy)



- Prioritization process can be formalized

1. Identify a set of metrics
 - Value of information, uncertainty, cost, maturity, etc.
2. Define an objective function to weight the metrics and the metric scores
3. Have experts evaluate each activity using the metrics
4. Tally the objective function results



Integrated Technical Roles

There are three key technical roles in the development of a nuclear waste repository:

- *Site Characterization*
- *Repository Design*
- *Performance Assessment*

Technical and programmatic integration among these groups is vitally important to successfully select and investigate a site, and license and operate a repository.

Integrated Technical Roles

There are numerous obstacles to successful integration between these groups.

- Lack of consensus regarding the overall framework for completing the tasks of repository development*
- Contrasting cultures among the three groups (e.g., engineering perspective vs. scientific research perspective)*
- Organizational separation of the three groups*
- Physical separation of the three groups*
- Competing budgetary goals*

Integrated Technical Roles

Potential solutions to these obstacles can be both formal and informal in nature.

- *Interaction between managers from the three groups is necessary to negotiate goals, strategy, schedules, etc.*
- *Formalized interactions between technical staff from the groups in the form of technical exchanges and workshops should be arranged*
- *Collaborative work between groups should be encouraged wherever possible*
- *Each group should have some expertise in other areas (e.g., uncertainty analysis in site characterization)*

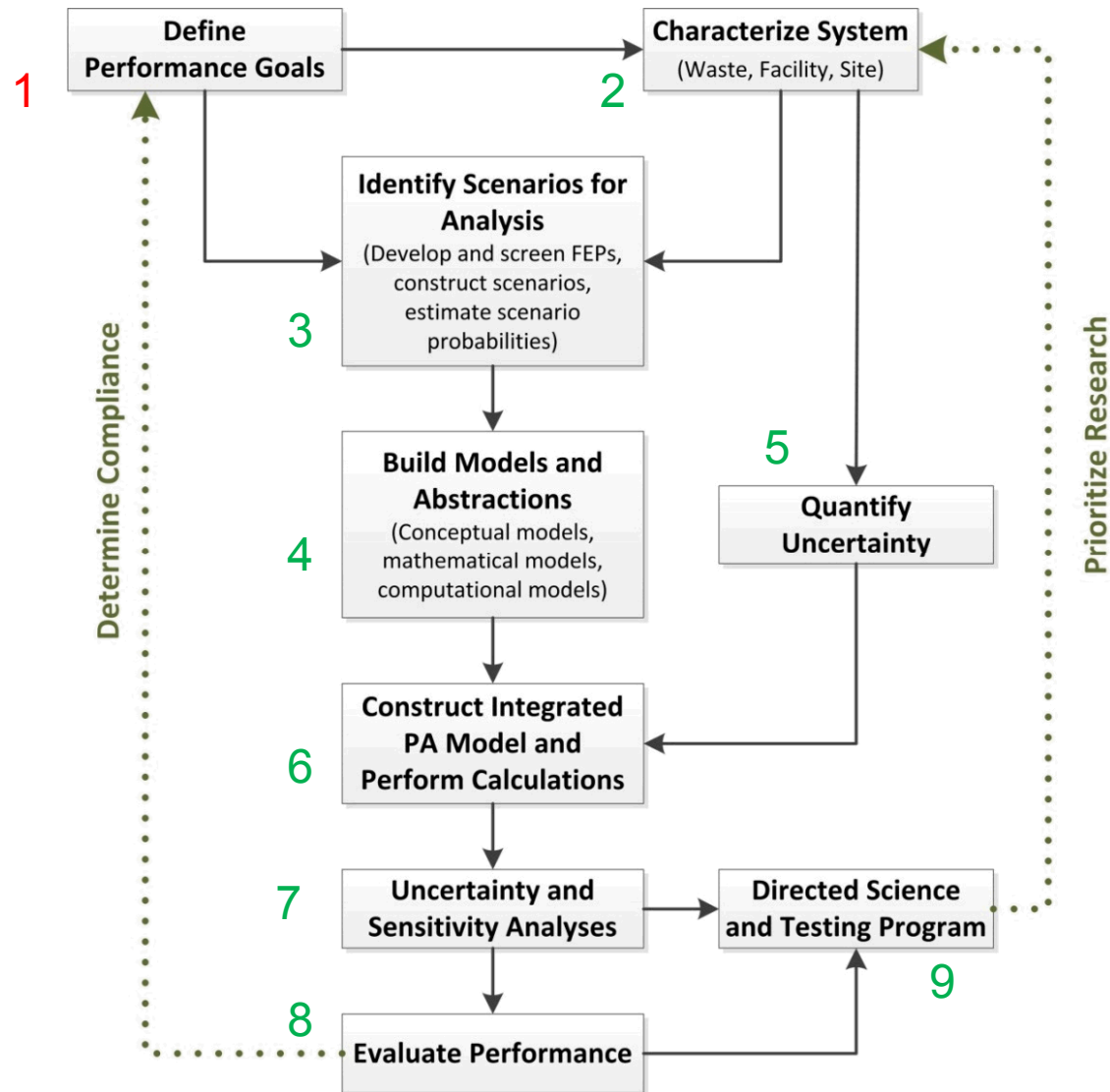
PA Methodology

Performance assessment (PA) methodology can form the framework around which integration among repository design, site characterization, and PA groups can be organized.

The iterative nature of the PA process provides an opportunity for collaboration and updating of information exchanged among the groups.

The roles, responsibilities, and authorities for each of the three groups can be defined for each step in the PA process.

Performance Assessment Methodology



Performance Goals

Performance goals are typically defined up front because they determine the design of the performance assessment and have considerable influence on scenario construction, model development, and research programs.

Ideally, performance goals are taken directly from legal regulations governing the repository.

For early iterations of the performance assessment methodology, final regulatory performance measures may not yet be promulgated, and assumptions about possible standards need to be made.

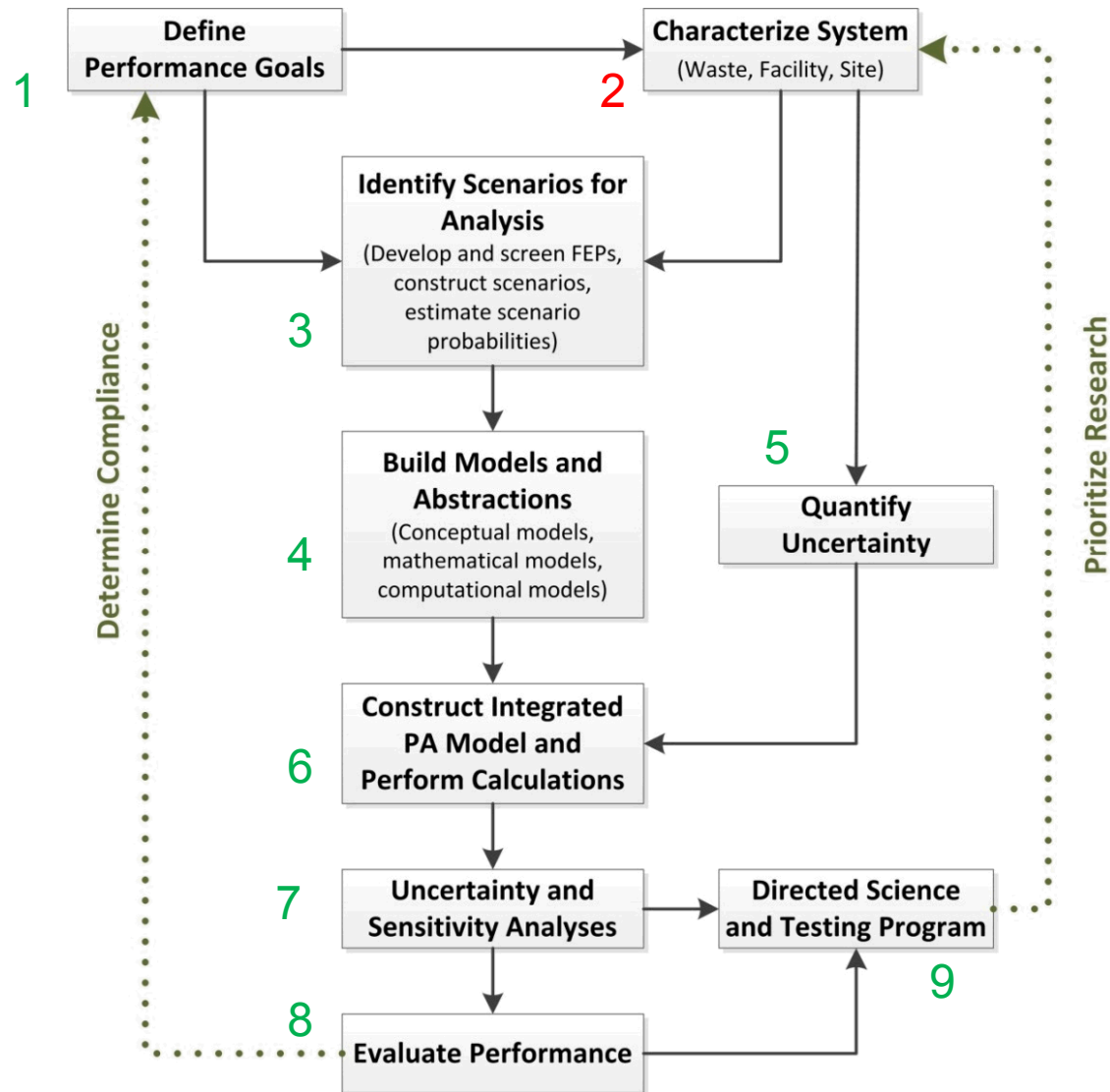
Performance Goals

The performance assessment group designs the analyses to simulate the quantities specified in the regulations (e.g., radiological dose to the receptor group or maximum groundwater concentrations).

The performance assessment, site characterization, and design groups should translate system performance goals into intermediate performance indicators at the sub-system level (e.g., temperature in backfill, transport time in the saturated zone).

All participants must know the performance goals and indicators and understand the relevance of their research or analyses to these performance measures

PA Methodology



Characterize System

A system description includes the characteristics of the waste (e.g., radionuclide inventory, decay chains, half-lives), the facility (e.g., layout, thermal loading from emplaced waste, design and properties of engineered barriers), and the site (e.g., geology, hydrology, geochemistry).

System information is derived from laboratory and field tests, published literature, natural analogues, and/or expert judgment.

In the early stages of a nuclear waste disposal program, the characterization program is broad-based and focused on gaining an adequate understanding of the system, identifying the greatest sources of uncertainty, and identifying the FEPs most likely to affect the system's long-term performance.

Preliminary Characterization

The repository design group produces a design that is consistent with preliminary site-characterization data and regulatory guidance.

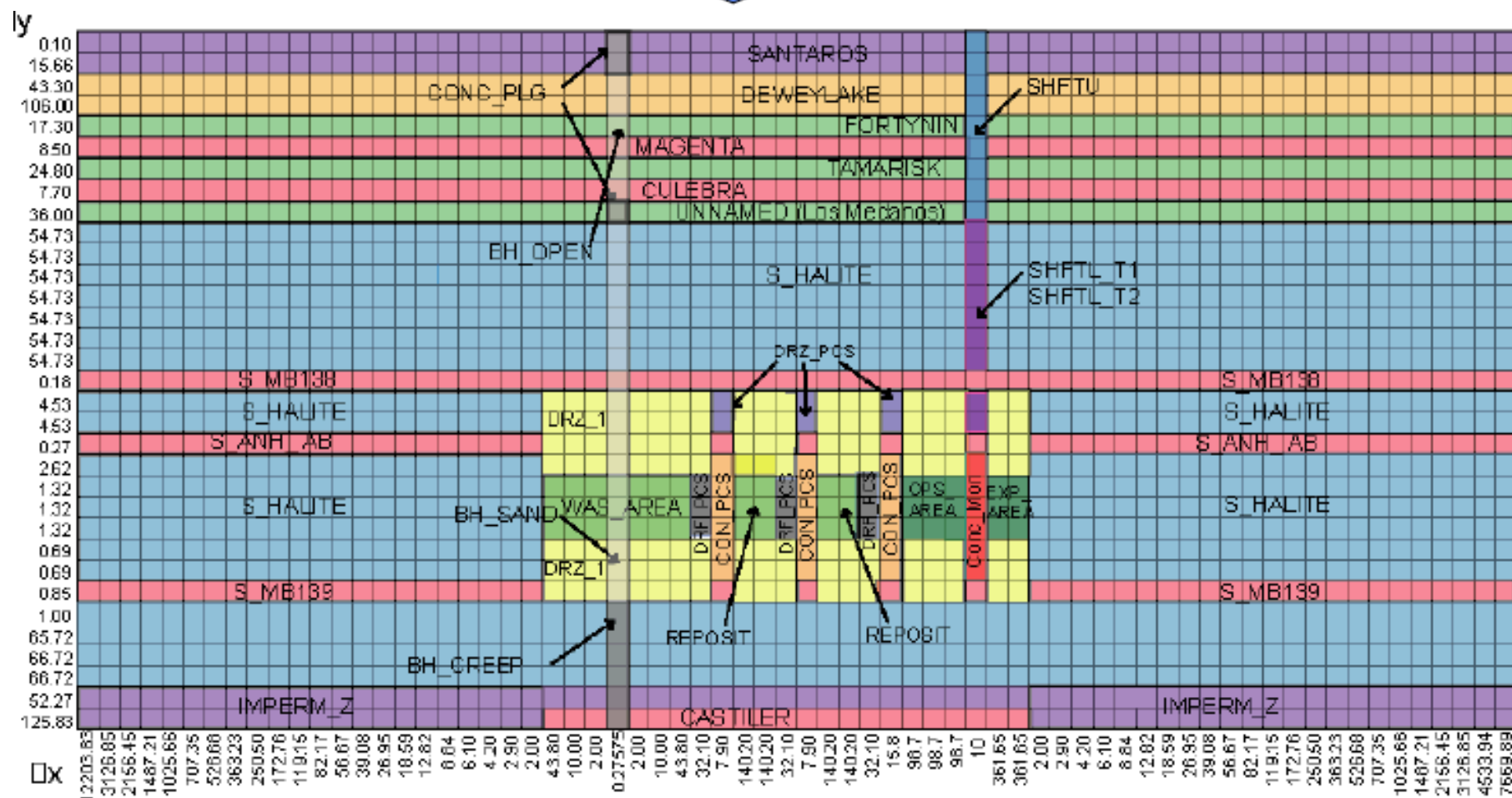
The site characterization group collects a set of basic geological and hydrological data from the site for use by the repository design and performance assessment groups.

Some preliminary prioritization of site-characterization work can be made on the basis of the intermediate performance indicators identified in Step 1.

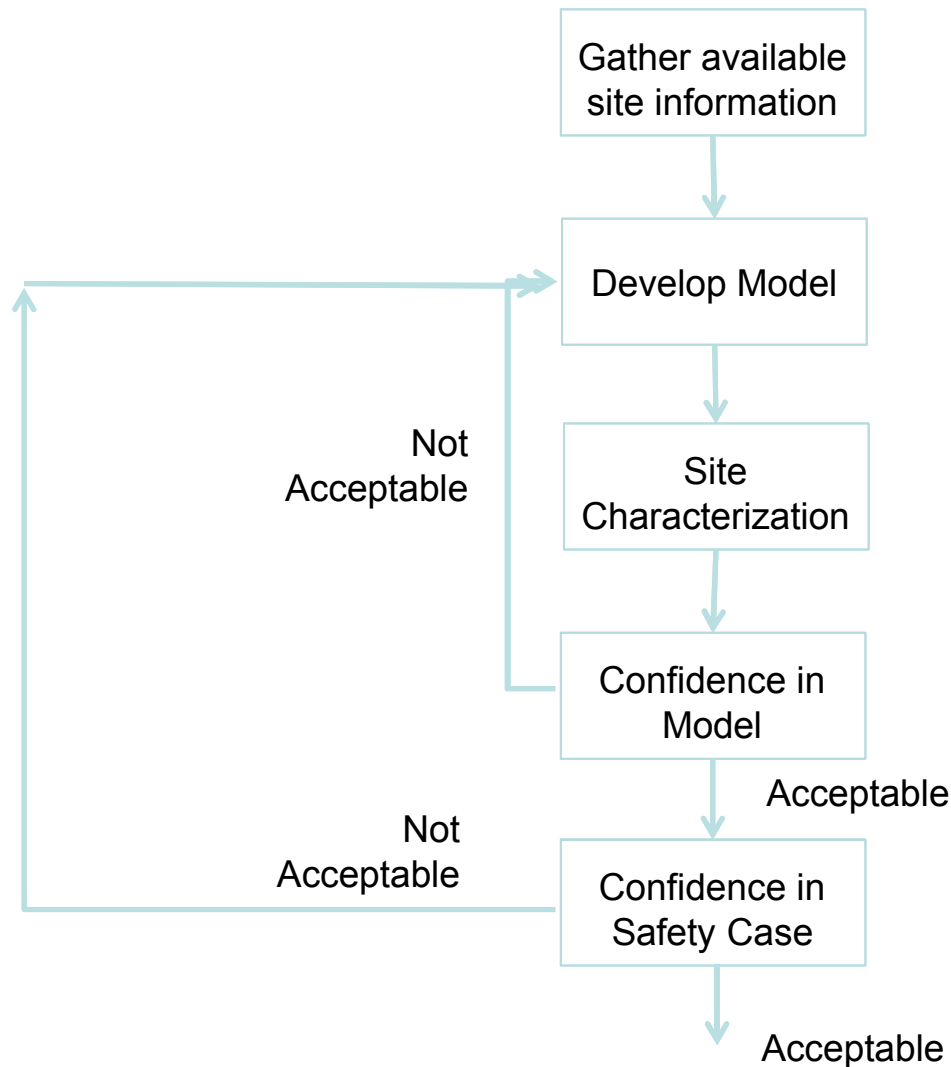
The image consists of two parts. On the left is a large, multi-axle drilling rig mounted on a truck, positioned in an open, arid landscape under a clear blue sky. The rig's mast is extended vertically. On the right is a close-up photograph of a rock core sample. The sample is a cylindrical section of rock, showing a light-colored, crystalline material with some darker, possibly mineralized, veins or fractures. A white label with the number '753.0' is attached to the top of the core. A yellow measuring tape is visible along the bottom edge of the core sample.



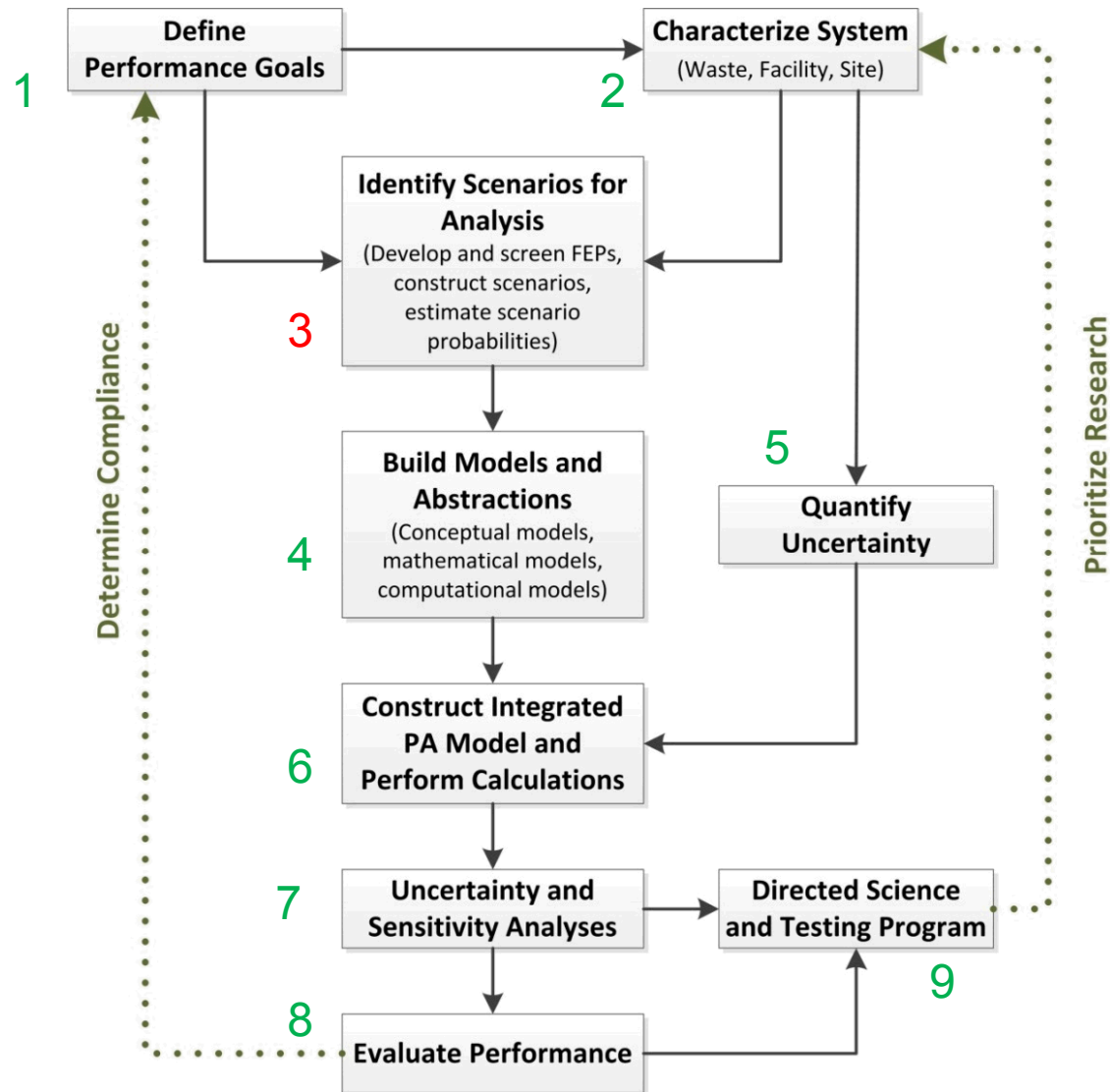
Integration of Site Characterization Data



Site Geological Model



PA Methodology



Scenario Analysis

Processes and events, and sequences of processes and events, which may be relevant over the time frame of interest, need to be identified and included in the quantitative performance assessment.

This step, generally referred to as scenario analysis, consists of two activities: FEP analysis and scenario development.

An important goal in identifying the FEPs potentially relevant to long-term performance is the demonstration of completeness (i.e., nothing is too insignificant or improbable to be considered as potentially relevant).

Features, Events & Processes

The analysis of features, events, and processes (FEPs) systematically examines those aspects of the repository system that could affect performance.

The FEPs methodology was originally developed for the analysis of nuclear reactor safety to provide assurance that all possible reactor failure modes were considered.

FEPs may be naturally occurring, induced by the disposal system, or related to human activity.

Features, Events & Processes

The first step of the FEPs analysis is to compile a comprehensive list of FEPs for the repository system.

FEPs are screened on the basis of several factors:

- *Physical reasonableness*
- *Probability of occurrence*
- *Consequence*

A comprehensive set of “scenarios” are developed by combining FEPs that remain after screening.

A typical approach to scenario development is to create an “expected” or nominal scenario and one or more “disturbed” scenarios.

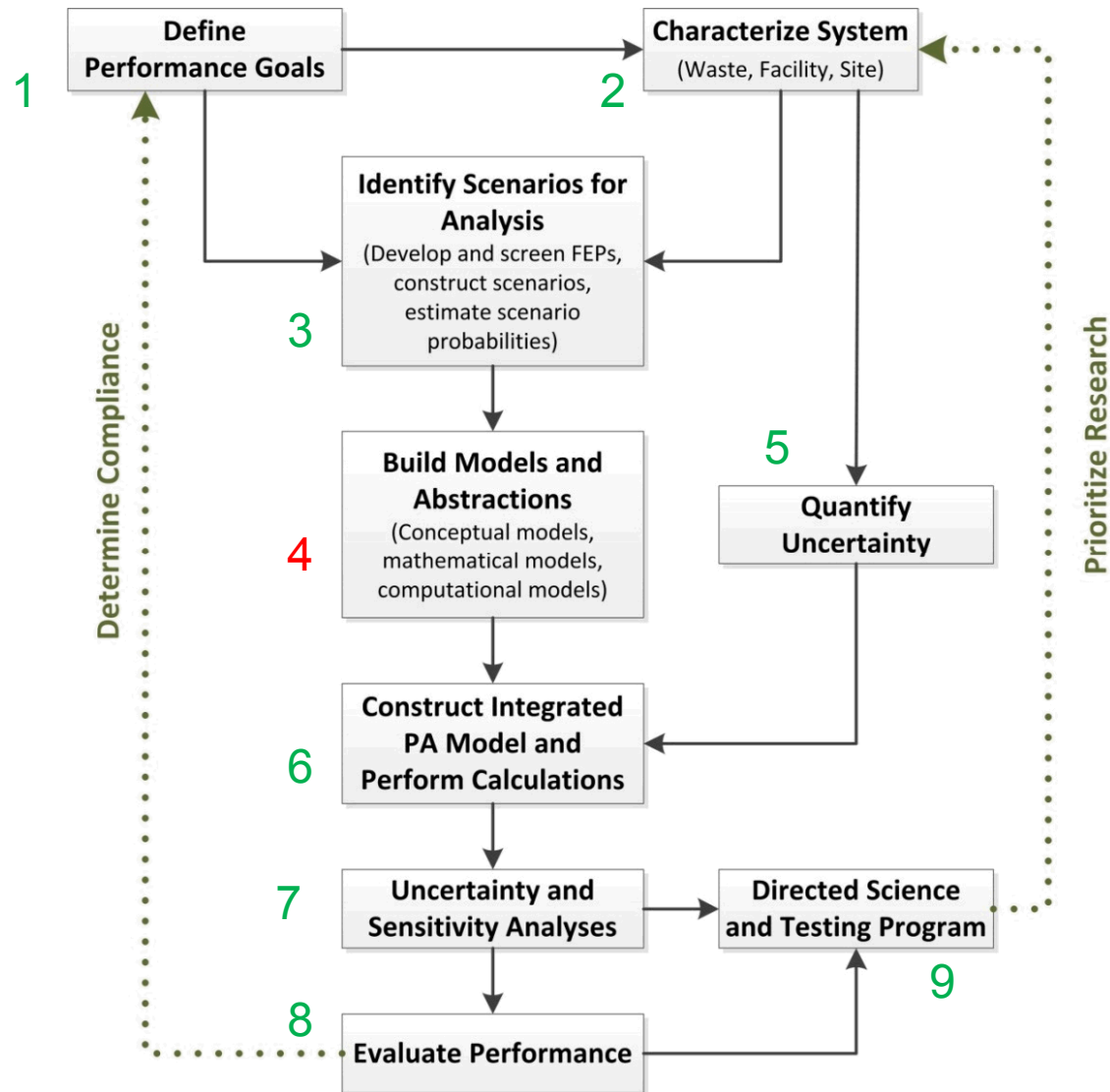
Features, Events & Processes

The FEPs analysis is an important component of the performance assessment methodology, but may not be fully appreciated by the site characterization and repository design groups.

The FEPs analysis is a way of formalizing the contents of the conceptual model of the repository system.

The site characterization and repository design groups have a responsibility to verify that the list of FEPs is complete and that the screening process is valid.

PA Methodology



Build Models and Abstractions

- FEPs and scenarios retained after the screening process are represented in the PA through conceptual models, mathematical models, and computational (numerical) models
- A conceptual model is a description of the physical and chemical processes, dimensionality, and assumptions, consistent with available information, that formalizes the understanding of how a system behaves
- A mathematical model translates the conceptual model into a set of governing mathematical equations or expressions and initial and boundary conditions
- A computational model provides numerical (or analytical) solutions to the mathematical models

Model Construction

Development of computational models may occur at different levels:

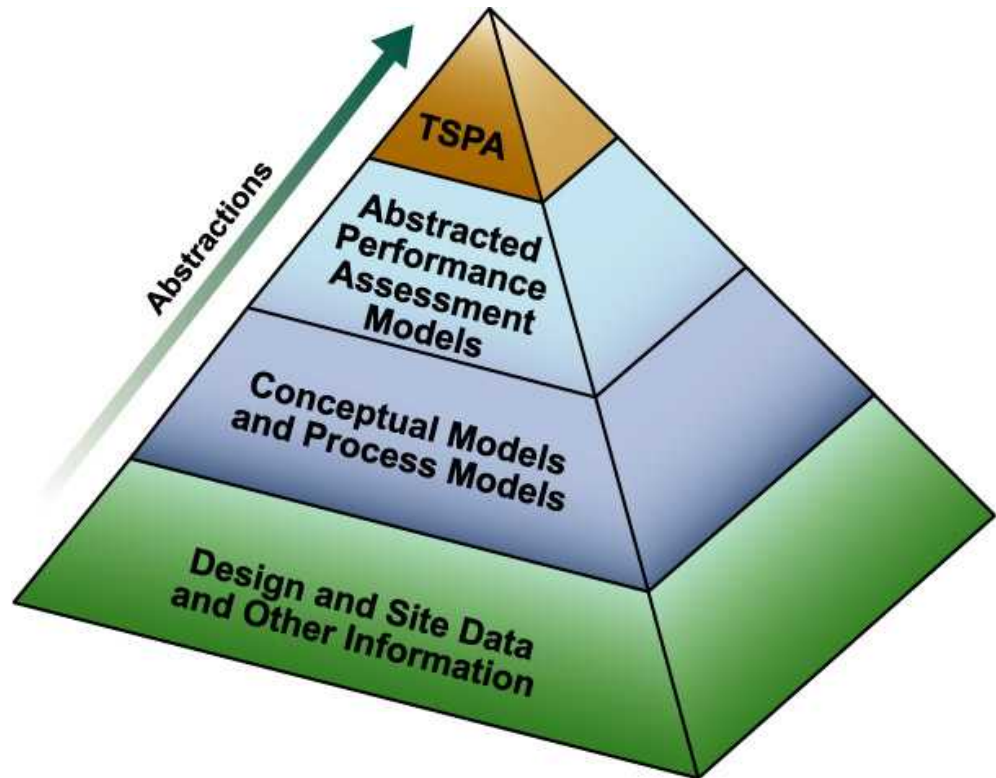
- *Testing interpretation models (site characterization)*
- *Sub-system models (site characterization and/or PA)*
- *Total system performance assessment models (PA)*

Abstraction of sub-system models may be necessary for incorporation into the TSPA model.

Abstractions may include reduction in dimensionality, simplified processes, look-up tables, etc.

Model Construction

The total system performance assessment model consists of sets of data and information, assumptions, and computational models that together describe the essential processes of the repository system and its long-term performance



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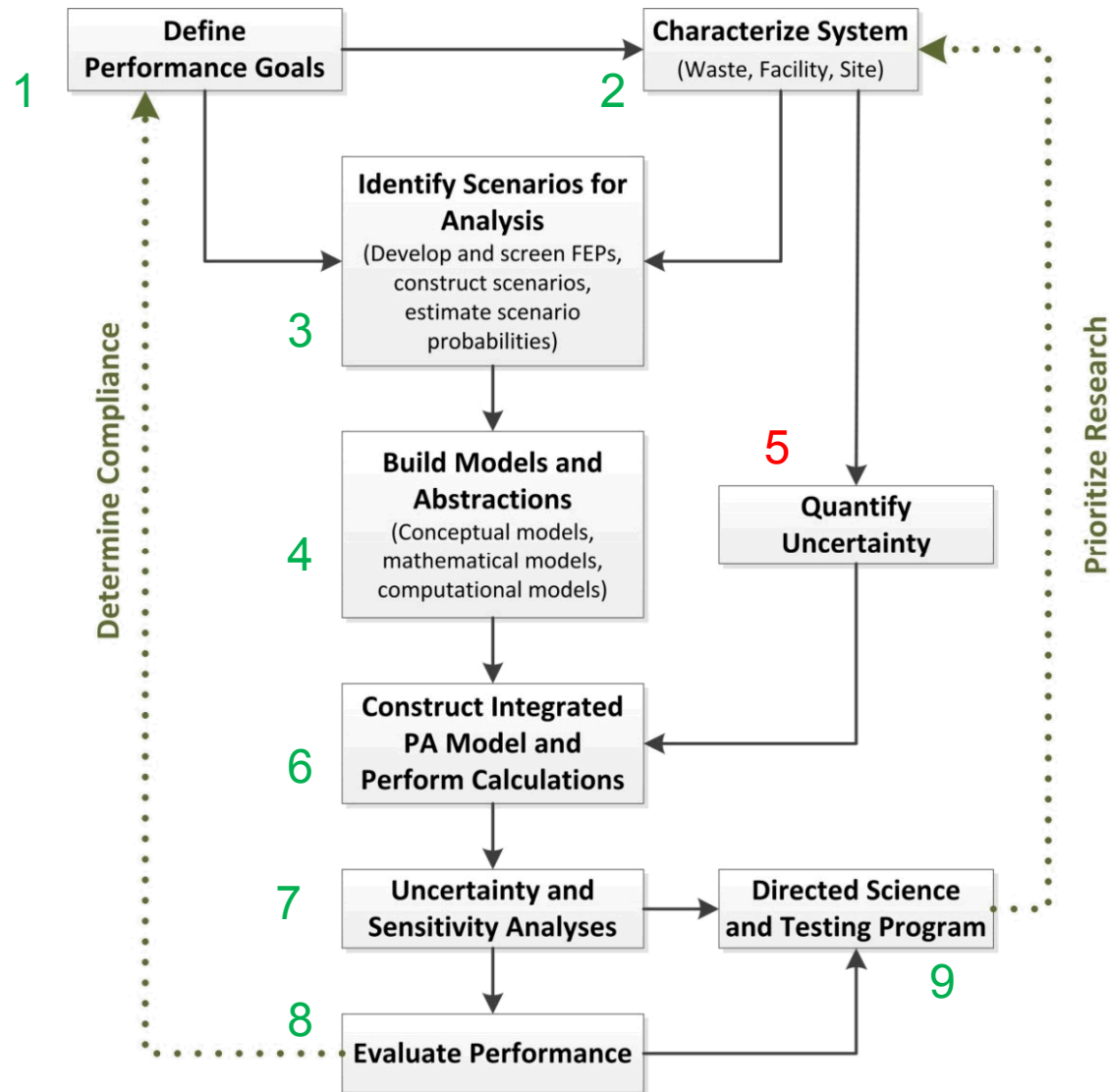
Model Construction

If site characterization model is to be used directly in the TSPA model, a high degree of integration between site characterization and PA groups is required

If an abstraction of the sub-system model is to be used in the TSPA model, coordination between site characterization and PA groups is needed to assure that the essential behavior of the detailed modeling is captured in the TSPA model

The repository design group should verify that important aspects of the repository system are incorporated into the TSPA model

PA Methodology



Build Models and Abstractions

- The total system performance assessment model consists of sets of data, assumptions, and computational models that together describe the essential processes of the repository system and its long-term performance
- Because the safety assessment methodology deals with future outcomes and includes uncertainty in both descriptions of FEPs and parameter values, an essential element of the safety assessment is to capture uncertainty in probabilistic analyses that represent likely outcomes, based on the best available values of process model parameters and the processes involved.

Quantify Uncertainty

- Three major sources of uncertainty must be considered in a performance assessment:
 - Uncertainty in the future state of the system
 - Model uncertainty
 - Data and parameter uncertainty

Quantify Uncertainty

- Uncertainty in the future state of the system
 - Arises because it may be difficult to forecast exactly how the disposal system will evolve over tens to hundreds of thousands to millions of years.
 - The system's evolution can be affected by natural events (e.g., seismicity) as well as human-induced events (e.g., drilling).
 - This form of uncertainty is referred to as aleatory uncertainty and is also known as stochastic, type A, or irreducible uncertainty.
 - Aleatory uncertainty is typically addressed in a performance assessment model through scenario construction and screening, where each retained scenario represents a possible future state of the disposal system.
 - Scenario probabilities are used to weight the consequences of each scenario according to its probability of occurrence.

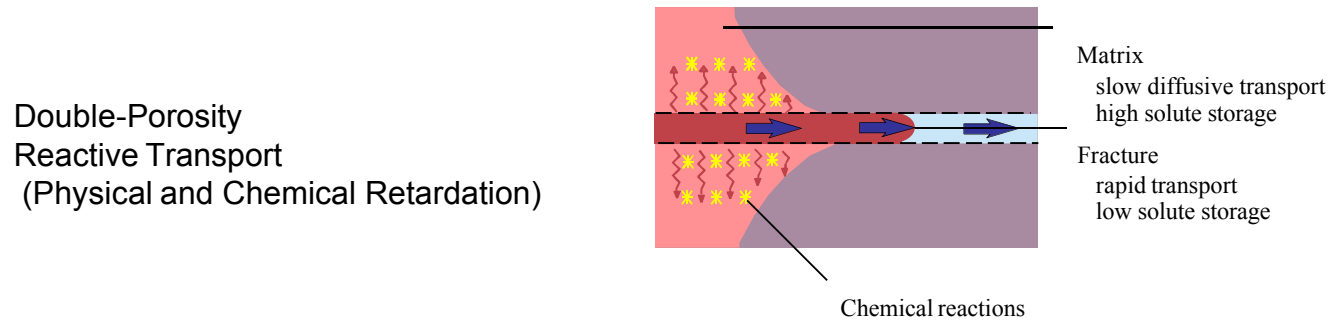
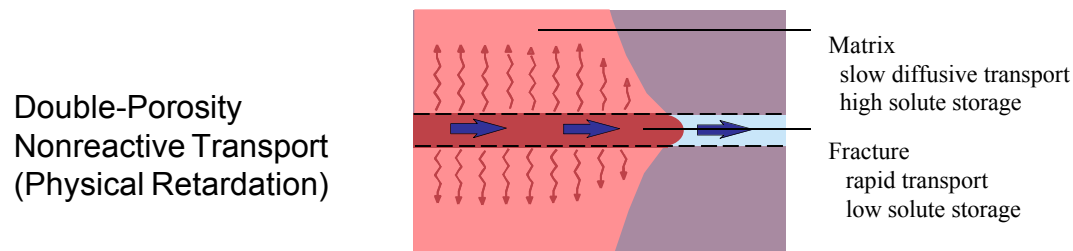
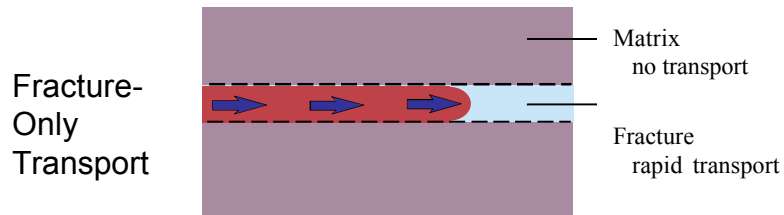
Quantify Uncertainty

- Conceptual model uncertainty is introduced due to the
 - accuracy and appropriateness of the assumptions
 - Lack of understanding or completeness of the processes included
 - complexity of interactions between the processes
- Alternative conceptual models must be considered when more than one valid interpretation of system behavior is possible from the existing data.
- If resolution between alternative conceptual models cannot be obtained within site characterization activities, then the alternative models can be evaluated in the TSPA model.
- Alternatively, the more conservative of the competing alternative conceptual models can be used in the TSPA model.

Quantify Uncertainty

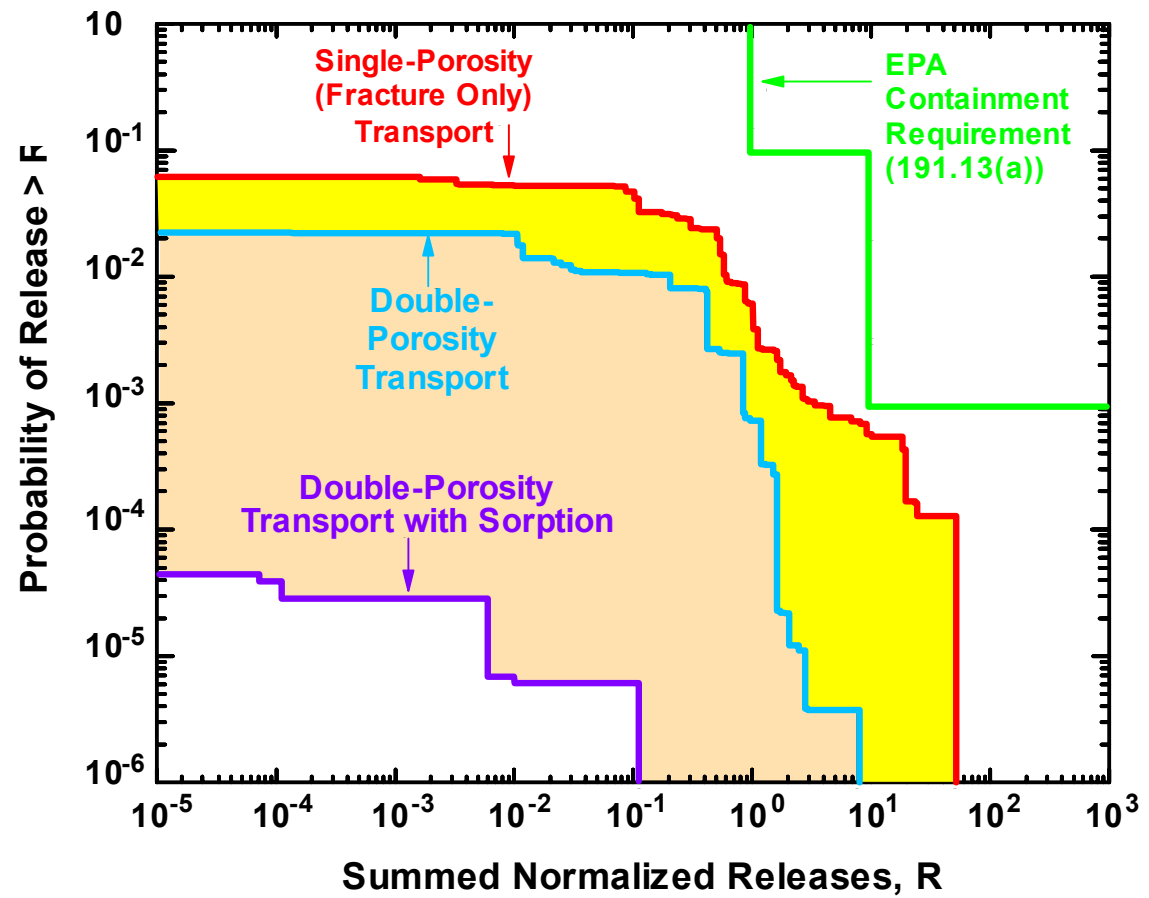
- Conceptual model uncertainty is introduced due to the
 - accuracy and appropriateness of the assumptions
 - lack of understanding or completeness of the processes included
 - complexity of interactions between the processes
- Alternative conceptual models must be consistent with the available data.
- Alternative conceptual models can be used in analyses of repository performance as sensitivity studies.
- If multiple alternative conceptual models are included, assigning probabilities may be difficult.

Alternative Conceptual Models



WIPP Alternative Conceptual Models Sandia National Laboratories

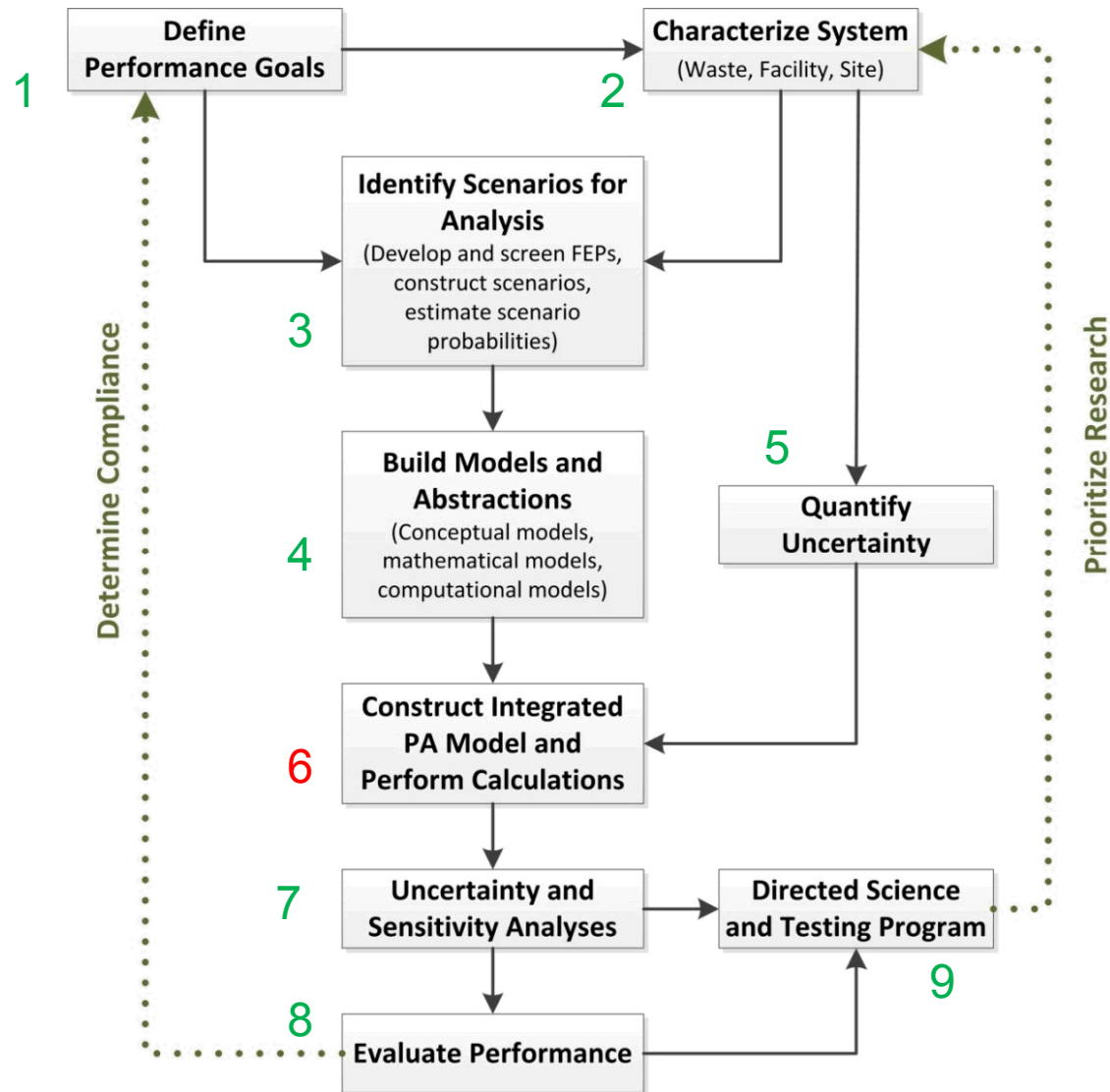
Conceptual model of fracture transport within the Culebra Dolomite has a strong influence on WIPP PA results.



Quantify Uncertainty

- Data and parameter uncertainty
 - Arises from incomplete knowledge of the present system and the inherent complexity and variability of natural systems.
 - Often, parameter values are not measured directly but rather are inferred from measured data that require interpretation.
 - Uncertainty in measured data can be introduced from limitations in measuring instruments, inability to fully characterize spatial and other variabilities, or human error.
- This form of uncertainty is referred to as epistemic uncertainty and is also known as subjective, state-of-knowledge, type B, or reducible uncertainty
- Accounted for by developing a distributions of values for each uncertain parameter, each distribution describes a range of values within which the true value is believed to fall, with an expected value that corresponds to the best estimate of the true value

PA Methodology



Construct Integrated PA Model and Perform Calculations

This step in the process is primarily the responsibility of the performance assessment group.

However, effective communication of TSPA modeling methods and results to the site characterization and repository design groups allows feedback to the performance assessment group and facilitates integration.

Construct Integrated PA Model and Perform Calculations

- An integrated PA model is required to estimate the consequence(s) of the retained scenarios and the overall probability-weighted consequence(s) of the disposal system considering all possible scenarios.
- The integrated PA model is constructed by
 - (1) coupling the sets of FEP and scenario sub-models together to calculate overall system performance
 - (2) identifying values and/or uncertainty distributions for system model input parameters

Construct Integrated PA Model and Perform Calculations

- Uncertainty in the input parameters can be treated using deterministic or probabilistic methods.
- In a deterministic simulation of a specific scenario, each input parameter is assigned a single value, typically representative of best estimate or conservative conditions.
- The PA model is then used to calculate a corresponding value(s) for the system performance measure(s).
- Bounding analyses involve parameter values selected such that the performance of the system is “worst case”. While defining what the worst case is can be a challenge, it is typically easy to defend if all agree that the performance could not be worse than that calculated.

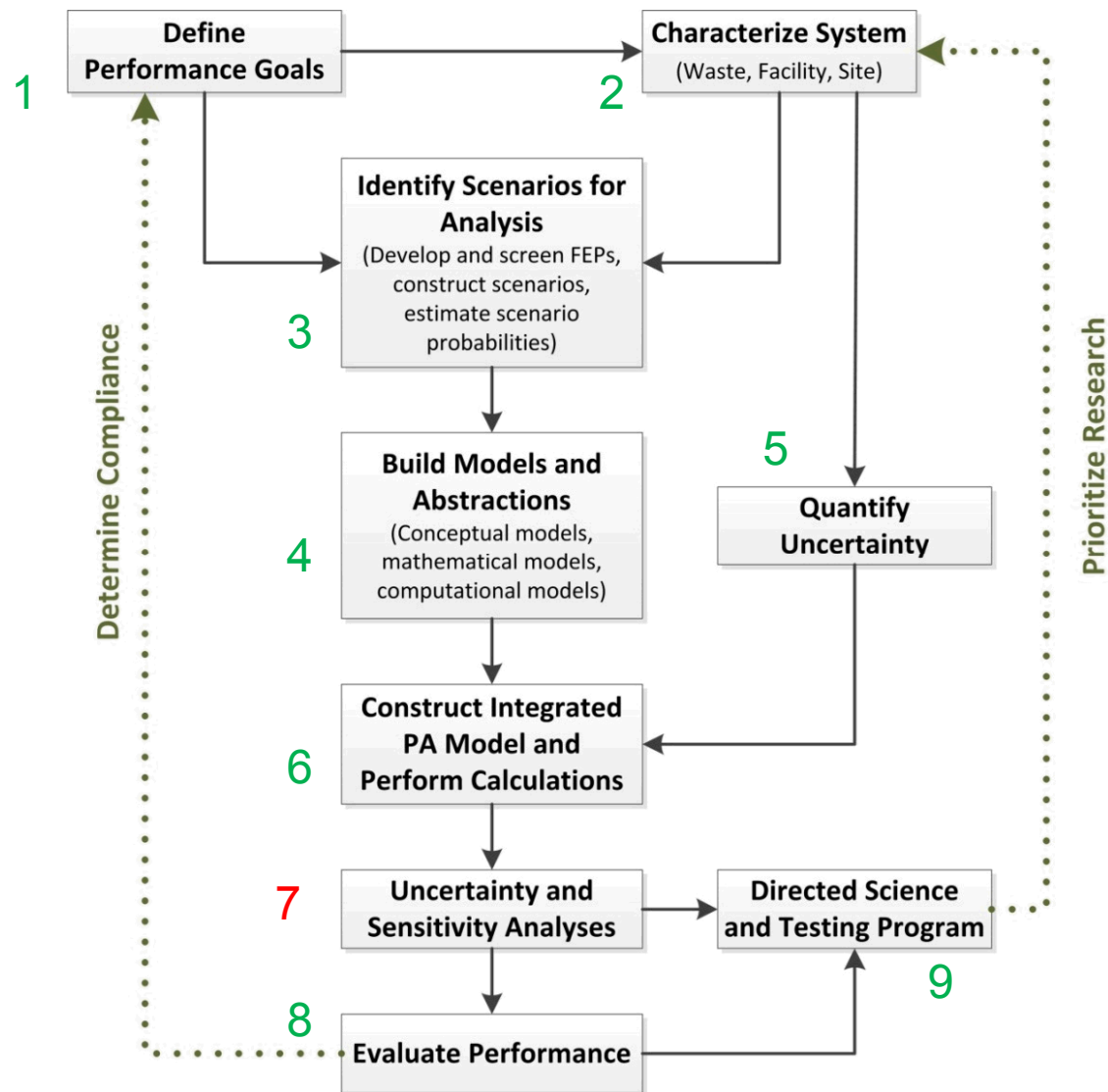
Construct Integrated PA Model and Perform Calculations

- In a probabilistic simulation, parameter values are sampled and propagated through the coupled set of models to generate a distribution of potential outcomes.
- Parameter uncertainty is propagated into the PA by conducting multiple calculations for each scenario using values sampled from the distributions of possible values (e.g., Monte Carlo simulation).
- Each individual calculation uses a different set of sampled input values and produces a different value(s) for the system performance measure(s).

Construct Integrated PA Model and Perform Calculations

- The result of each individual calculation represents a different possible realization of the future overall performance of the system, consistent with the uncertainty in the input parameters.
- Overall system performance for a specific scenario is then quantified by some measure of the distribution of results from all realizations, such as the mean or median of the system performance measure(s).
- Uncertainty associated with the probability of occurrence of each scenario is included in the PA by conducting separate analyses for each scenario and then probability weighting the results to estimate an overall system consequence.

PA Methodology



Perform Uncertainty and Sensitivity Analyses

Those factors that are identified as important to repository performance are evaluated in this step.

Studies to reduce uncertainty or modify the repository design related to important factors are identified in cooperation among the site characterization, repository design, and performance assessment groups.

The relative costs and benefits of additional data collection must be evaluated to prioritize future work.

Perform Uncertainty and Sensitivity Analyses

Sensitivity analyses are an integral part of the probabilistic modeling in the performance assessment to identify those factors that “drive” the analysis.

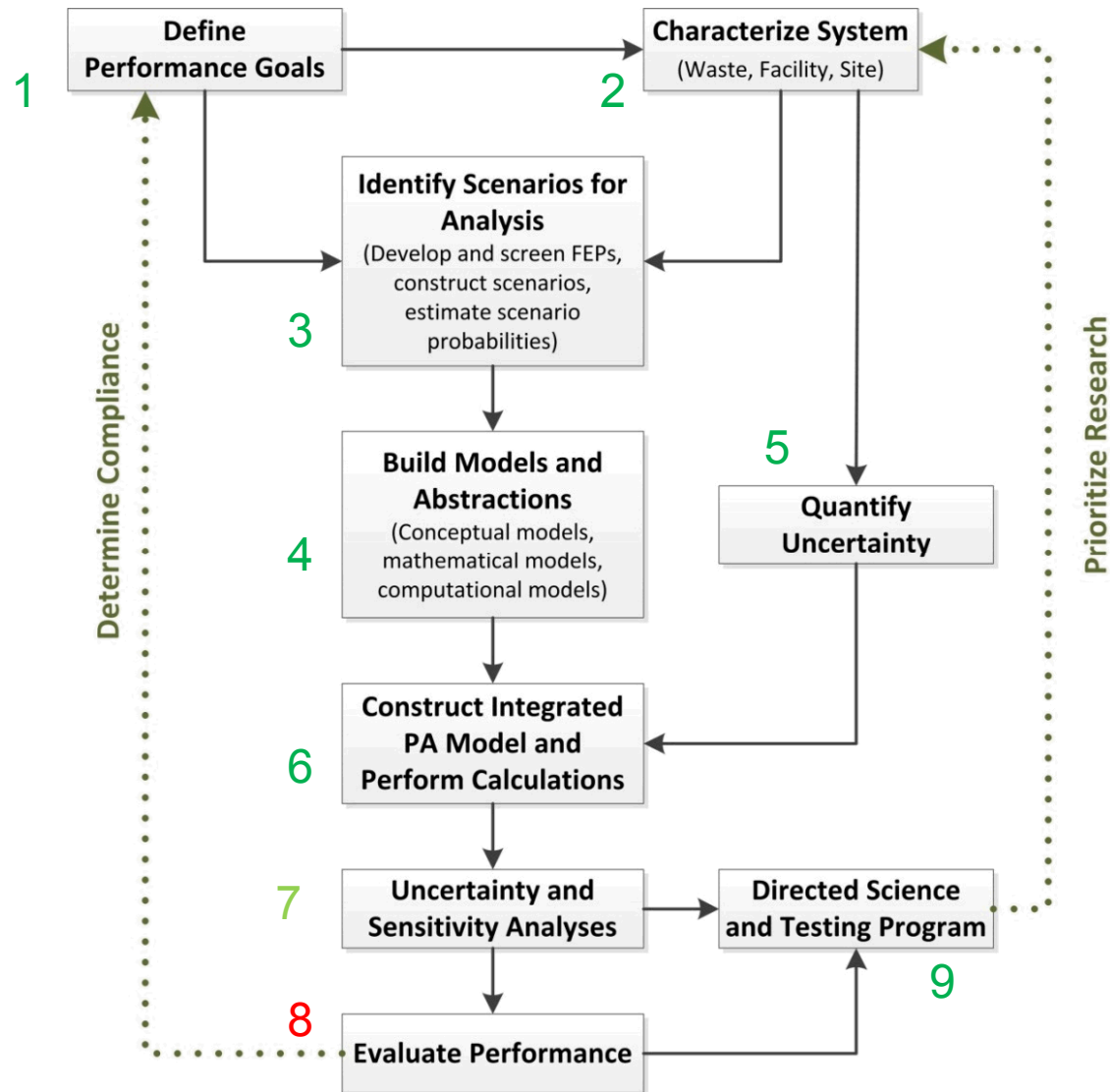
Information from sensitivity analyses is valuable for general understanding of the repository system and for improving analyses in the next iterative cycle.

Integration between site characterization, repository design, and performance assessment can be enhanced through greater involvement of the different groups in the conduct and interpretation of sensitivity studies.

Perform Uncertainty and Sensitivity Analyses

- The results of uncertainty analyses can be analyzed further using statistical techniques, such as step-wise linear regression, to identify and rank the importance of uncertain parameters.
- Caution must be used in interpreting the results of the sensitivity analysis because the rankings are conditional on the modeling assumptions and parameter distributions, because the processes not included in the models cannot be evaluated, and because the sensitivity of fixed-value parameters cannot be evaluated.
- Sensitivity analyses are included in the PA to enable the process to be iterative, providing feedback to R&D activities to efficiently and effectively reduce important sources of uncertainty.

PA Methodology



Evaluate Performance

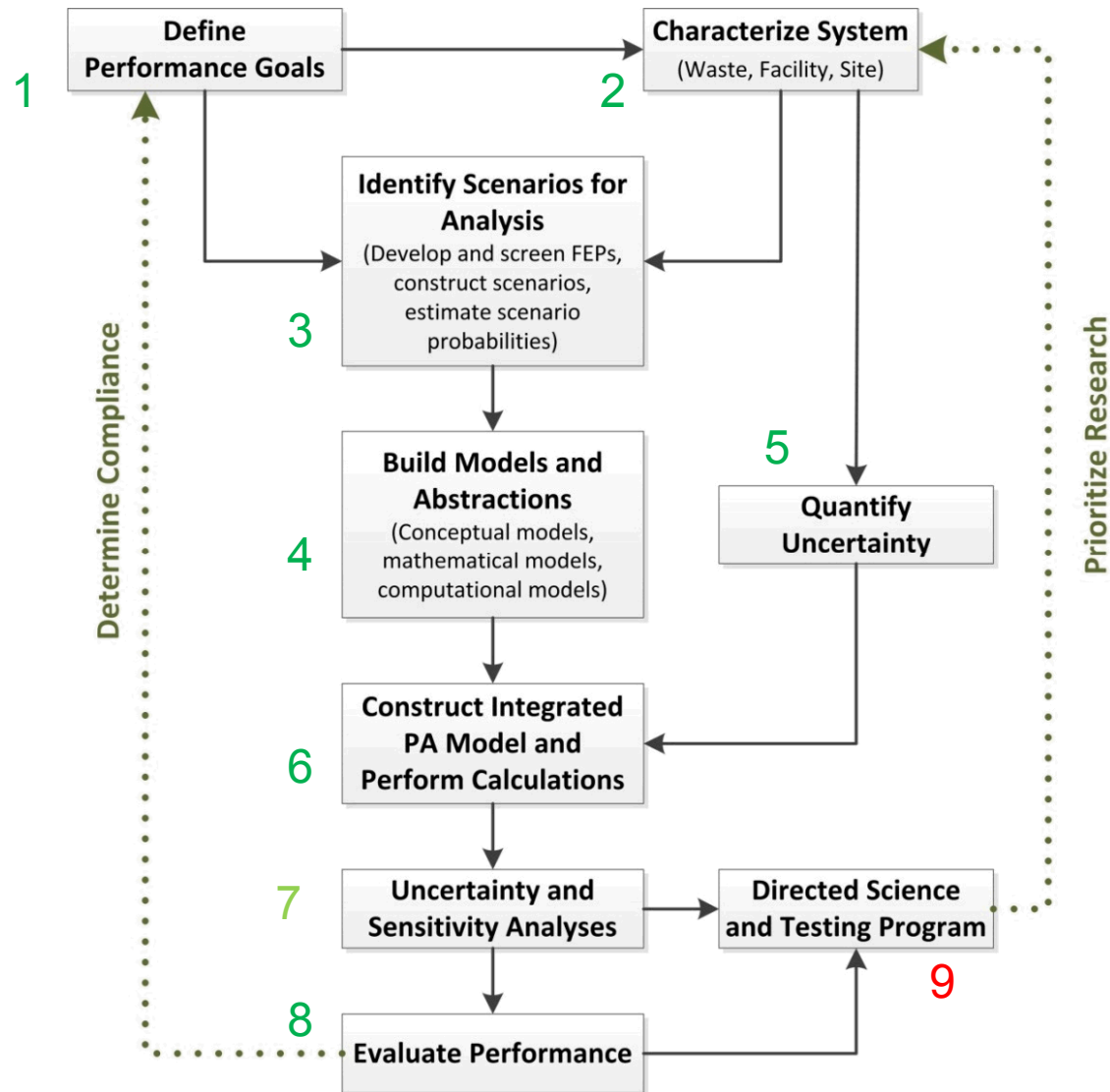
- Quantitative PA results provide indications of subsystem and overall system performance.
- When combined with sensitivity analyses, PA results can be used to identify the models and parameters that have the greatest effect on the behavior of the system.
- Identification of the uncertainties that are most important in preliminary PAs can help guide site characterization, repository design, and model development through a directed science and testing program.
- The steps in the PA process are repeated, as needed, until a final decision is reached.

Evaluate Performance

A decision in favor of regulatory acceptability of the repository would only be made at a mature stage of a repository program when PA models are sufficiently well developed and documented to support regulatory decisions.

A favorable decision of acceptability requires not only quantitative determination from the TSPA model, but also requires support and consensus from the site characterization and repository design groups.

PA Methodology



Directed Science and Testing Program

- Information from the overall performance evaluation and uncertainty and sensitivity analyses serves to identify important parameters and systems for further investigation.
- This may include identifying systems whose performance can be improved by modifications to the design, or parameters with uncertainties that, if reduced through further site or laboratory investigations, would significantly increase confidence in the overall safety assessment results.
- The safety assessment process thereby helps inform programmatic decision-making toward the testing and scientific investigations that will most effectively and efficiently improve the accuracy and confidence in safety assessment results and toward design decisions most likely to improve real system performance.

Additional Site Characterization

The primary objective of this step is the reduction of uncertainty.

The site characterization and repository design groups are responsible for these tasks.

Communication and integration should be maintained with the performance assessment group to assure that goals for uncertainty reduction are obtainable.

Summary

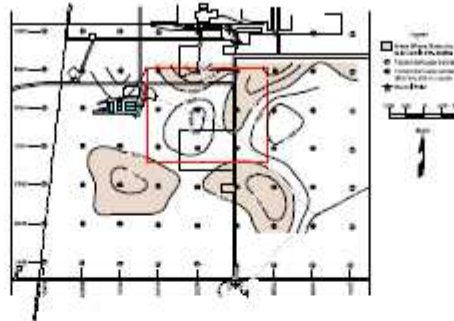
The iterative application of the safety assessment methodology through the lifetime of a deep geologic disposal project supports a robust and defensible:

- Evaluation of subsystem and total system performance with respect to specific criteria or requirements
- Consideration of expected and disturbed scenarios
- Evaluation of design options/alternatives
- Development of the models used to simulate the important FEPs and scenarios
- Determination and representation of significant sources of aleatory, epistemic, and model uncertainty
- Incorporation of information from laboratory and field tests, published literature, natural analogues, and expert judgment
- Prioritization of research and testing needs

Site Characterization



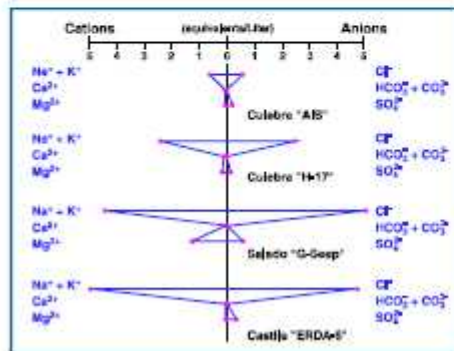
Geologic studies



Geophysical surveys



Hydrologic testing



Geochemical sampling
and analysis



Geomechanical testing



Surface-based geologic drilling,
coring, & geophysical logging

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- The potential site must provide adequate safety functions
 - Can the geosphere provide isolation of the waste for the required period of performance?
 - Can the geosphere protect the engineered barrier system for the required period of performance, taking into account low probability natural events?
 - Does the geosphere provide sufficient containment for the period of performance?

Site Characterization and Performance Assessment

- Projects begin with a broad-based approach to site characterization (SC) to identify site features and data relevant to confirming adequate safety functions
- Once initial site characterization has been completed, a FEPs (Features, Events, and Processes) analysis can be initiated
- FEPs analysis can focus future site characterization work on the features of the repository environment and the physical/chemical processes of greatest importance to PA

Decision Analysis

Prioritization of site characterization activities should be based primarily on quantitative information obtained through assessment of uncertainties, FEPS analysis, modeling and sensitivity analysis.

Actual decisions regarding additional data collection and analyses must also consider the costs associated with obtaining those data.

Highest priority is placed on activities that would result in large reductions in uncertainty in an important aspect of the system at a relatively low cost.

Decision Analysis

Intermediate priority is placed on activities that would result in large reductions in uncertainty in an important aspect of the system at a relatively high cost and activities that would result in modest reductions in uncertainty at a low cost.

Formal quantitative methods of decision analysis exist for calculating the value of information associated with additional site characterization.

Decisions on project priorities may be complicated by qualitative considerations.

Other Factors

Factors other than the quantitative sensitivity of the TSPA model may be important to consider in the prioritization of data collection and analyses.

Public and political confidence in the repository system may require a minimum level of understanding for certain aspects of the system, irregardless of the expected quantitative impact on performance.

Some data collection tasks that have a high technical priority may also require long time frames, placing them in conflict with project schedule goals.

Uncertainty and Control

There may be important trade-offs between reduction in uncertainty and control of the system through repository design modifications.

Alternative repository design features may be able to compensate for uncertainty in the system (e.g., YMP drip shields and uncertainty in drift seepage).

Some alternative repository design features included to improve performance may actually increase uncertainty in the system (e.g., YMP high-temperature waste loading and coupled hydrothermal processes).

Integration and Prioritization

Involvement of site characterization, design, and performance assessment staff in decision-making processes may prevent disputes in prioritization.

Additional modeling and sensitivity analyses may resolve disputes over prioritization in some cases.

Additional experimentation may be warranted to help resolve internal disputes over prioritization, if necessary.

Management action is the final recourse in the resolution of disputes over prioritization of work.