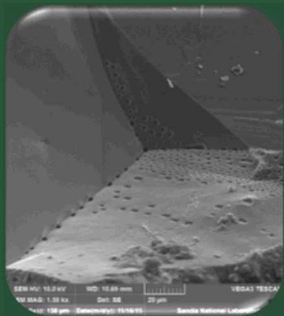

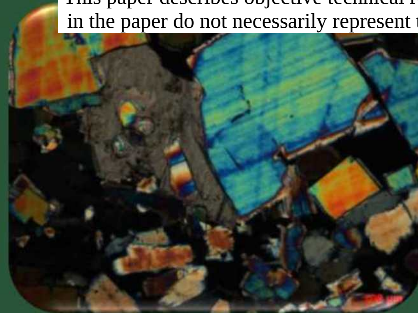

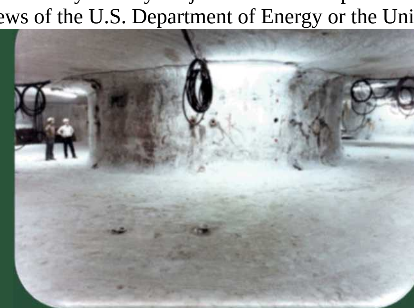

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Waste Package Requirements and Design Approaches in the US

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Oak Ridge National Laboratory

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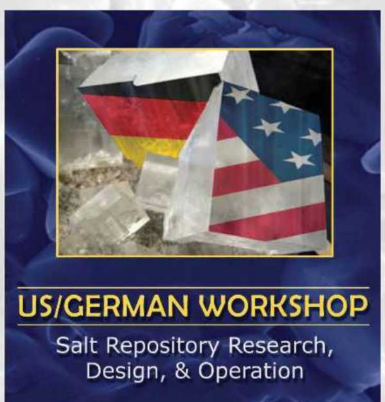
Itasca Consulting Group

Rapid City, SD, United States
May 28-30, 2019



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NOTICES

This is a technical presentation that does not take into account the contractual limitations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). Under the provisions of the Standard Contract, DOE does not consider spent nuclear fuel in canisters to be an acceptable waste form, absent a mutually agreed-to contract amendment. To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract provisions prevail.

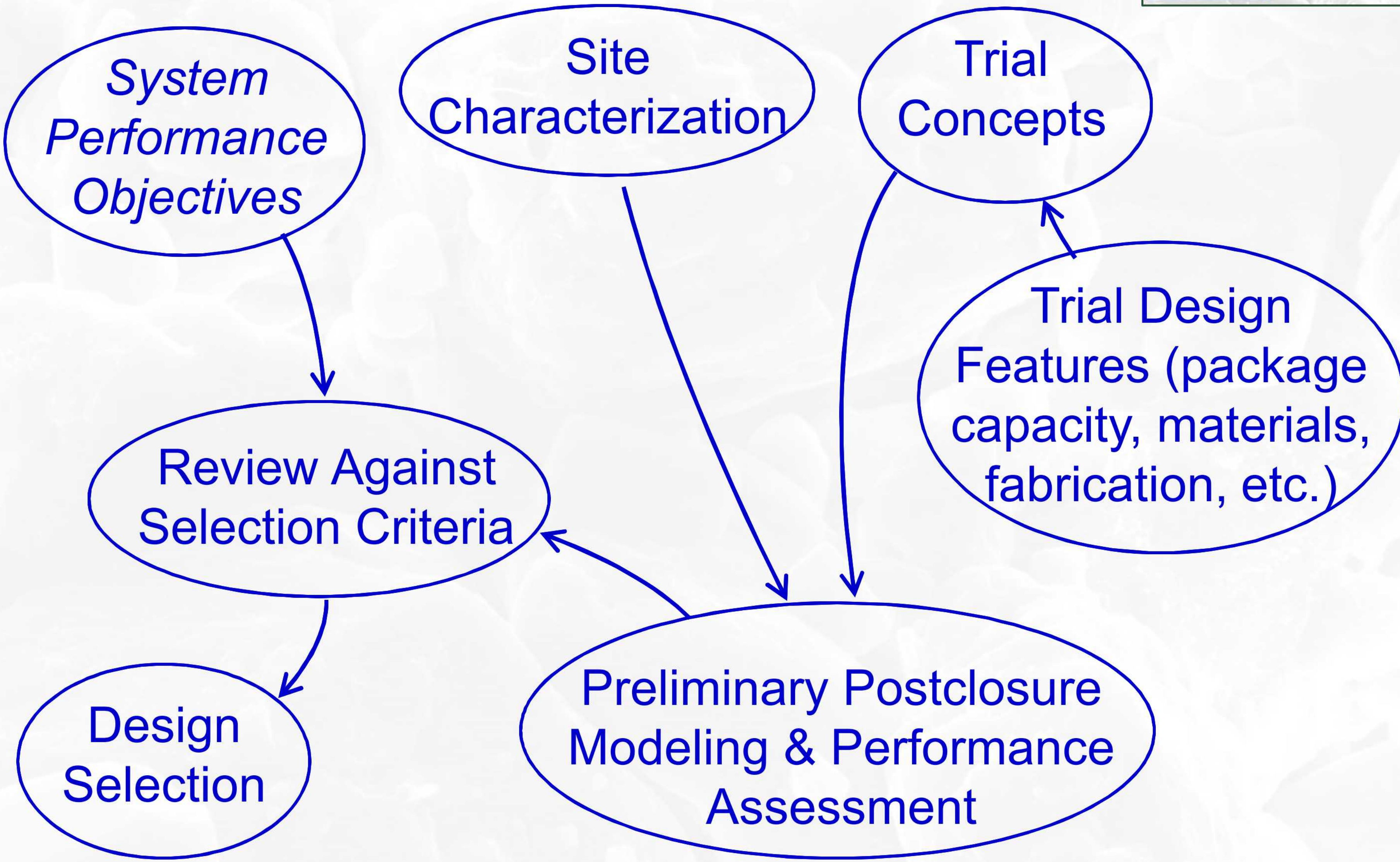
Outline

Spent light-water reactor fuel (UOX)

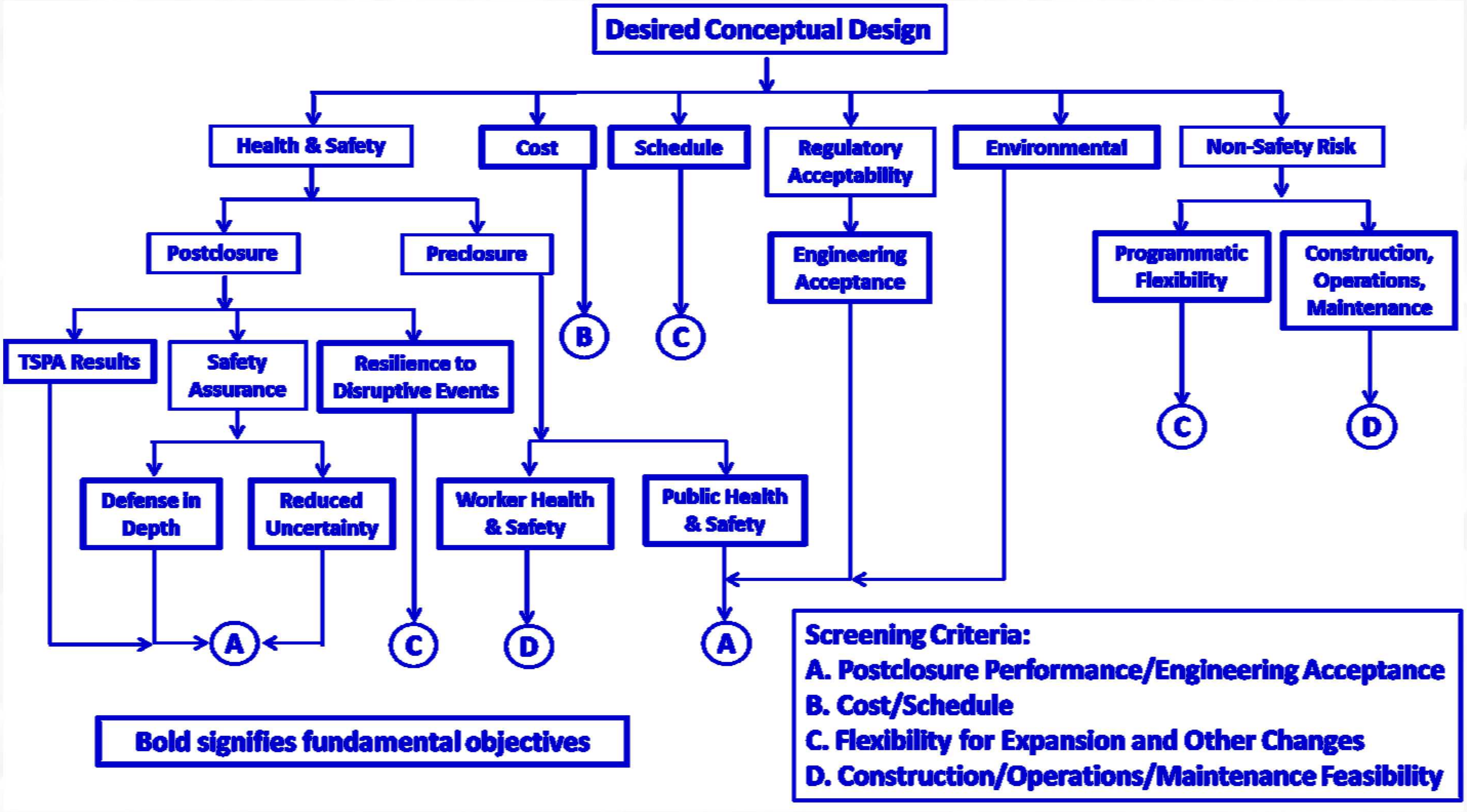
- Design process, a system-level exercise
- Objectives/requirements hierarchy
- Functional analysis
- Overpack vs. canister functions
- Overpack materials
- Yucca Mountain overpack and TAD canister
- Standardized canister specification development in the U.S., for multi-media

Conceptual Design Selection

A System-Level, Iterative, Risk-Informed Process



Objectives Hierarchy
YM LA Design Selection Study



Based on Figure 3-3 of CRWMS M&O 1999. *License Application Design Selection Report*. B00000000-01717-4600-00123 REV 01 ICN 01. Office of Civilian Radioactive Waste Management, U.S. Department of Energy.

Functional Analysis, System-Level

- Engineered barrier requirements evolve, e.g.,
  - 10CFR60 – "…substantially complete" EBS containment for ~10^3 yr
  - 10CFR63 – Risk-informed system performance assessment
- Identify applicable performance requirements, e.g.,
  - Barriers important to waste isolation § 63.21(c)
  - Preclosure safety § 63.112
  - FEPs analysis and other PA requirements § 63.114
  - Multiple barrier strategy § 63.115
- Allocate functions, e.g.,
  - Repository handling (overpack)
  - Disposal containment (overpack)
  - Heat dissipation to protect fuel cladding (canister)
  - Postclosure criticality control (canister)
- Correlate requirements, design features and controlling parameters, and analysis parameters
- Verify by analysis (preclosure safety, postclosure PA)

Performance Allocation to SNF Canister vs. Disposal Overpack

- Canisters are needed now for dry storage and transportation (not repository site-specific functions)
- Disposal overpacks will function in the repository-specific operational environment, with specific postclosure corrosion conditions, and thermal and mechanical loadings

∴ Separate requirements for disposal canisters vs. disposal overpacks

Exception: Standardized canisters (storage-transportation-disposal) require measures for criticality control in multiple media, that are not needed (or generally, provided) for storage and transportation.

“Generic” Overpack Material Selection:
Corrosion Types and Rates (1/2)

- Steel or Cast Iron for “Corrosion Allowance”
  - General corrosion rate $\propto$ to O_2 fugacity e.g., $r = f_{O2} \times 100$ µm/yr [A]
  - Never slower than ~1 µm/yr in water:
    $$3Fe(0) + 4H_2O \rightarrow Fe_3O_4 + 4H_2\uparrow$$
  - Not sensitive to localized corrosion (possible galvanic attack)
- Copper in Anoxic Aqueous Environments
  - Chloride and sulfide sensitive
  - Otherwise corrosion is very slow in reducing conditions except [B] if
    $$f_{H2} < 0.001: \quad 2Cu(0) + H_2O \rightarrow Cu_2O + H_2\uparrow$$
- Stainless Steel
  - General corrosion similar to low alloy steel but much slower
  - SS316 and duplex grades are more resistant than SS304
  - Subject to localized corrosion and stress corrosion cracking

[A] Jovancicevic, V. and Bockris, J.O’M. 1986. *Journal of the Electrochemical Society, 133, (9),* 1797-1807.
[B] Hultqvist et al. 2009. *Catalysis Letters, 132, (3-4), 311-316.* Also *135, (3-4), 165-167.*

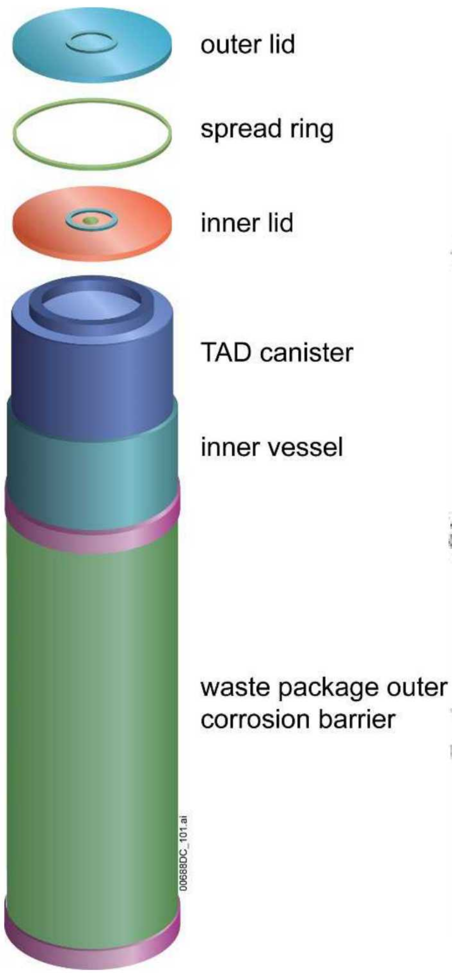
"Generic" Overpack Material Selection:
Corrosion Types and Rates (2/2)

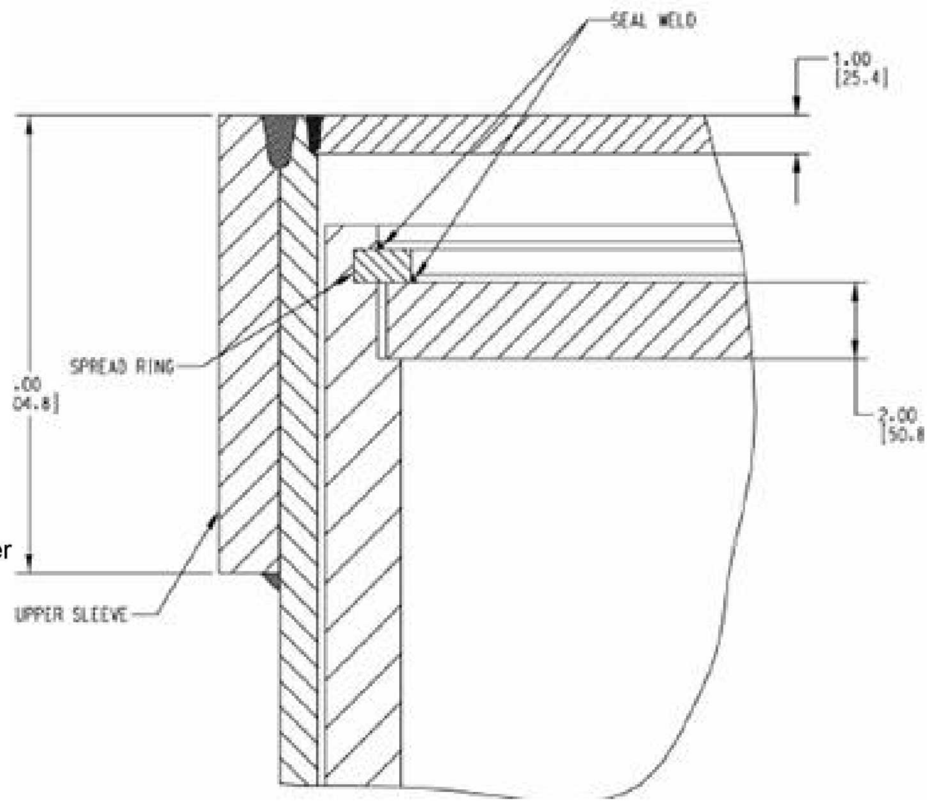
- **Nickel-Chromium Alloys**
  - Hastelloys (e.g., C-4, C-22, etc.; Haynes International)
  - Passive mixed oxide layer ∴ subject to localized corrosion esp. in oxidizing waters
- **Titanium Alloys**
  - Passive TiO_2 layer (probably too noble for localized corrosion)
- **Coatings**
  - Plasma spray
  - Cold spray, amorphous metals [A]

[A] J. Blink, et al. 2007. "Applications in the Nuclear Industry for Thermal Spray Amorphous Metal and Ceramic Coatings." *Materials Science & Technology 2007 Conference and Exhibition*, Detroit, MI, USA. September 16-20, 2007.

YM LA Design: Disposal Overpack Concept

- Unsaturated, oxidizing disposal environment
- Corrosion-resistant (Alloy-22 and SS316)
- Annealed, with stress mitigation of final closure welds

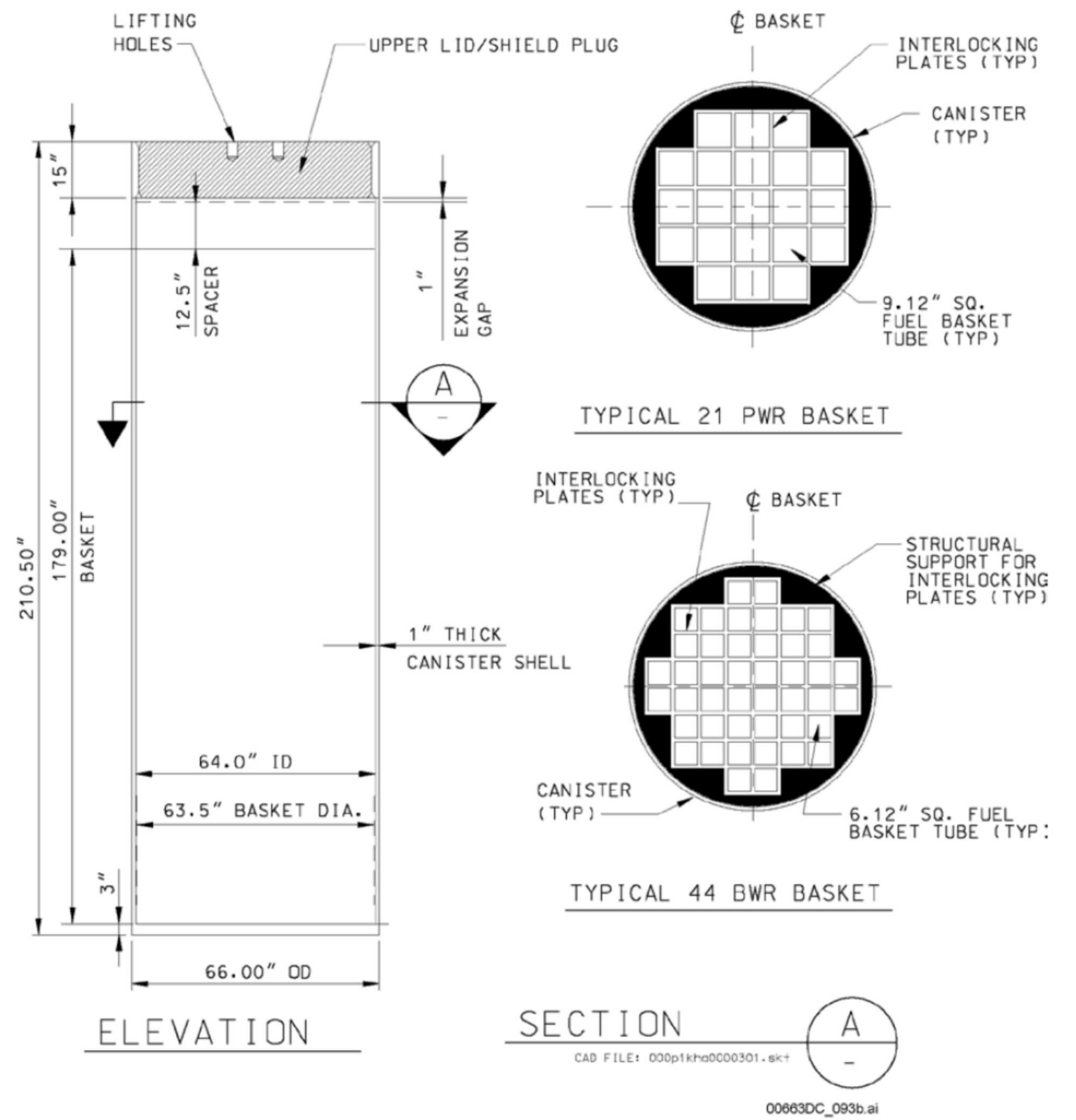




YM TAD Canister

(Performance Specification)

- Capacity: 21-PWR/ 44-BWR
- Weld-sealed
- Material: SS316 (Nuclear grade)
- Fabrication: cold-formed shell and basket, welded
- Basket detail: (TBD)
- Absorber plates: 11-mm borated SS304 (powder metallurgy grade)



Standardized Canister Studies in the U.S.

Mission: Safe and feasible storage, transport, and disposal of 100,000+ MTU commercial spent fuel.

Round 1: Multi-Purpose Canister Concept (1995)

Round 2: *Transport-Aging-Disposal Canister System Performance Specification* for the Yucca Mountain License Application (2008)

Round 3: STAD (standardized for disposal in multiple media, 2015)

Round 4: “TAD+” Study (in process, re-evaluated readiness for disposal in multiple media, 2019)

TAD+ Study Objectives (2019)

- Use previous canister specifications, and recent R&D to update specifications for a large **multi-media** canister
- Integrate a TAD+ canister concept into an overall system for storage, transportation, aging, and disposal
- Update technical readiness evaluations → 4 repository environments:
  - Argillite (clay/shale)
  - Salt
  - Saturated crystalline
  - Unsaturated media (e.g., tuff, granite, alluvium)
- Identify R&D activities that could support implementation and/or improve the TAD+ concept

TAD+ Canister Specifications: Summary

- General (13 specs)
- Structural (3 specs)
- Thermal (5 specs)
- Dose and shielding (3 specs)
- Criticality (2 specs)
- Confinement and containment (5 specs)
- Operations (5 specs)
- Materials (6 specs)

Technical Readiness for Each Specification: Evaluation Categories

- **Category A:** An *engineering solution is evident* or there exists *evidence in the international literature*
- **Category B:** Technically feasible for the generic environment *but requires study* beyond the current literature
- **Category C:** Demonstrating technical feasibility for the generic environment *requires resolution of significant technical challenges*
- **180 evaluations for TAD+ concept:** 45 criteria × 4 media
  - 164 Category A (resolved)
  - 13 Category B (study required)
  - 3 Category C (significant challenges)

TAD+ Technical Evaluation Results

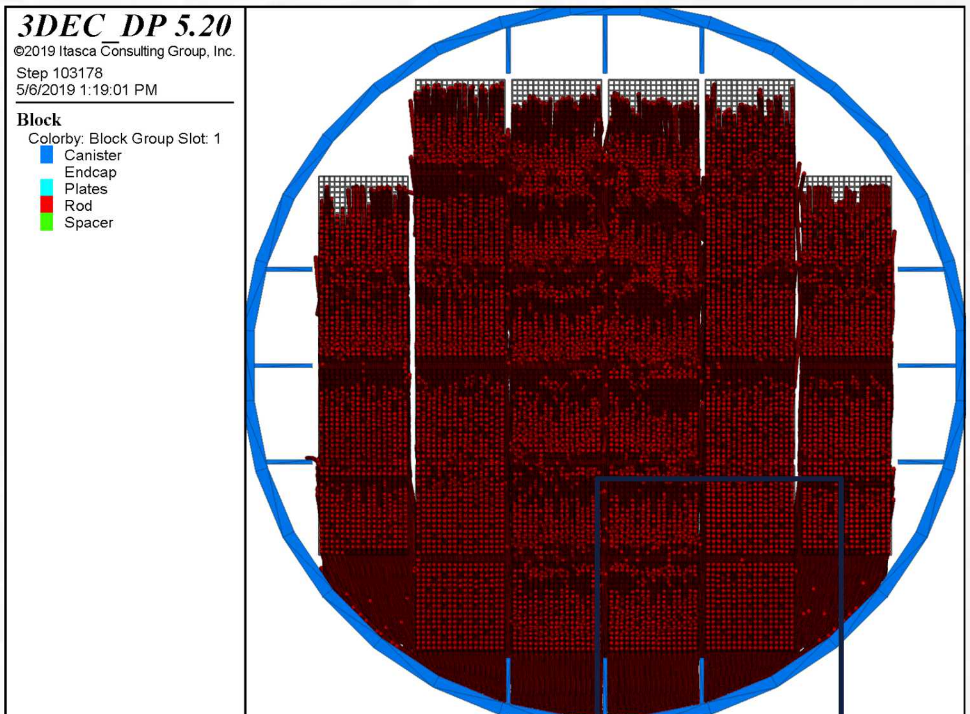
- 13 Category B evaluations (study required)
  - **Clay/Shale**: **Thermal** aspects of *Shape & Dimensions, Loaded Weight, and Capacity* specs.
  - **Clay/Shale** and **Salt**: **Underground transport** aspects of *Shape & Dimensions, Loaded Weight, and Capacity* specs.
  - **Clay/Shale** and **Saturated Crystalline**: *Postclosure Criticality* specs.
  - **Clay/Shale** and **Saturated Crystalline**: *Corrosion* specs.
- 3 Category C evaluations (significant challenges)
  - **Saturated Crystalline**: **Thermal** aspects of *Shape & Dimensions, Loaded Weight, and Capacity* specs.

Potential R&D to Support TAD+

- Disposal Control Rod Assemblies (DCRAs) for postclosure criticality control
- Loading Maps
  - Canister-fuel assembly loading maps that consider thermal + external radiation + criticality control are feasible
- Borated stainless-steel corrosion testing
- Advanced neutron absorbers
  - Ni-Cr-Gd
  - Ceramics

Disposal Control Rod Concept: 3DEC Model for Fuel/Basket Degradation (Preliminary DRAFT) (2/2)

Simulation with Fuel Assembly End Caps Intact, Basket Plates and Spacer Grid Corroded



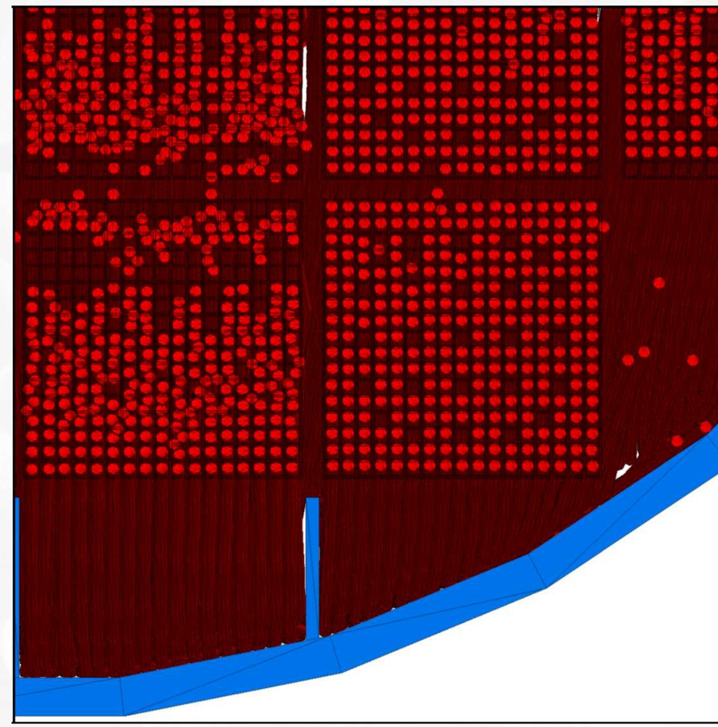
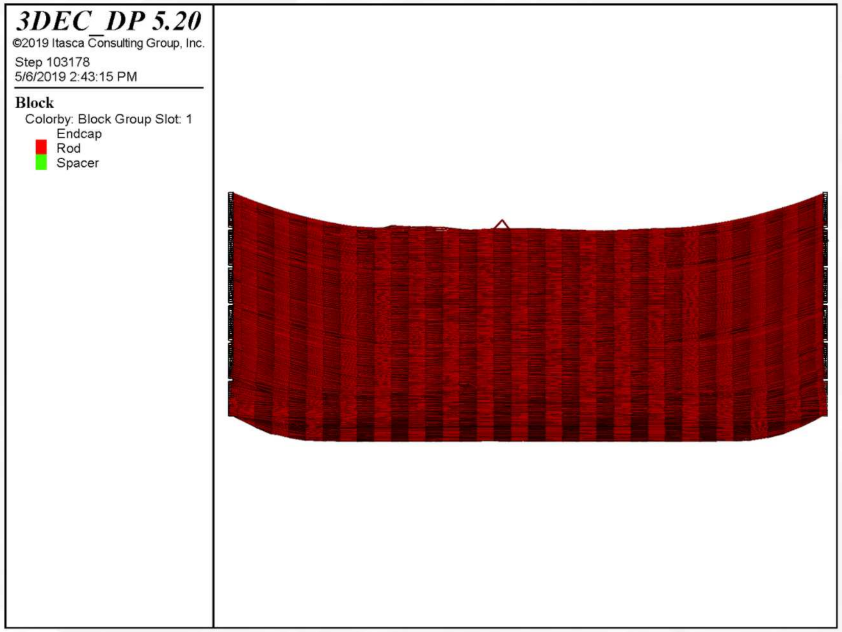
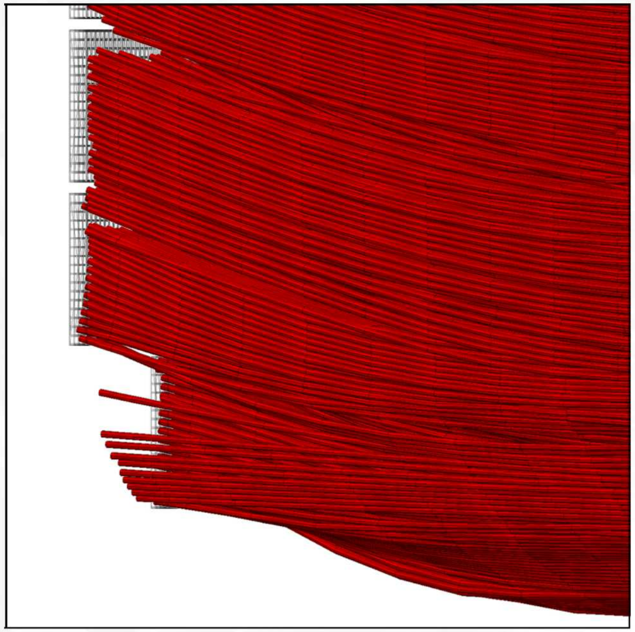


Figure credit: Damjanac et al. 2019, DOE/SFWD Working Group.

Disposal Control Rod Concept: 3DEC Model for Fuel/Basket Degradation (Preliminary, 1/2)

Simulation with Fuel Assembly End Caps Intact, Basket Plates and Spacer Grid Corroded





Rods falling down after sliding out of end caps

Figure credit: Damjanac et al. 2019, DOE/SFWD Working Group.

Waste Package Requirements and Design Approaches – Summary

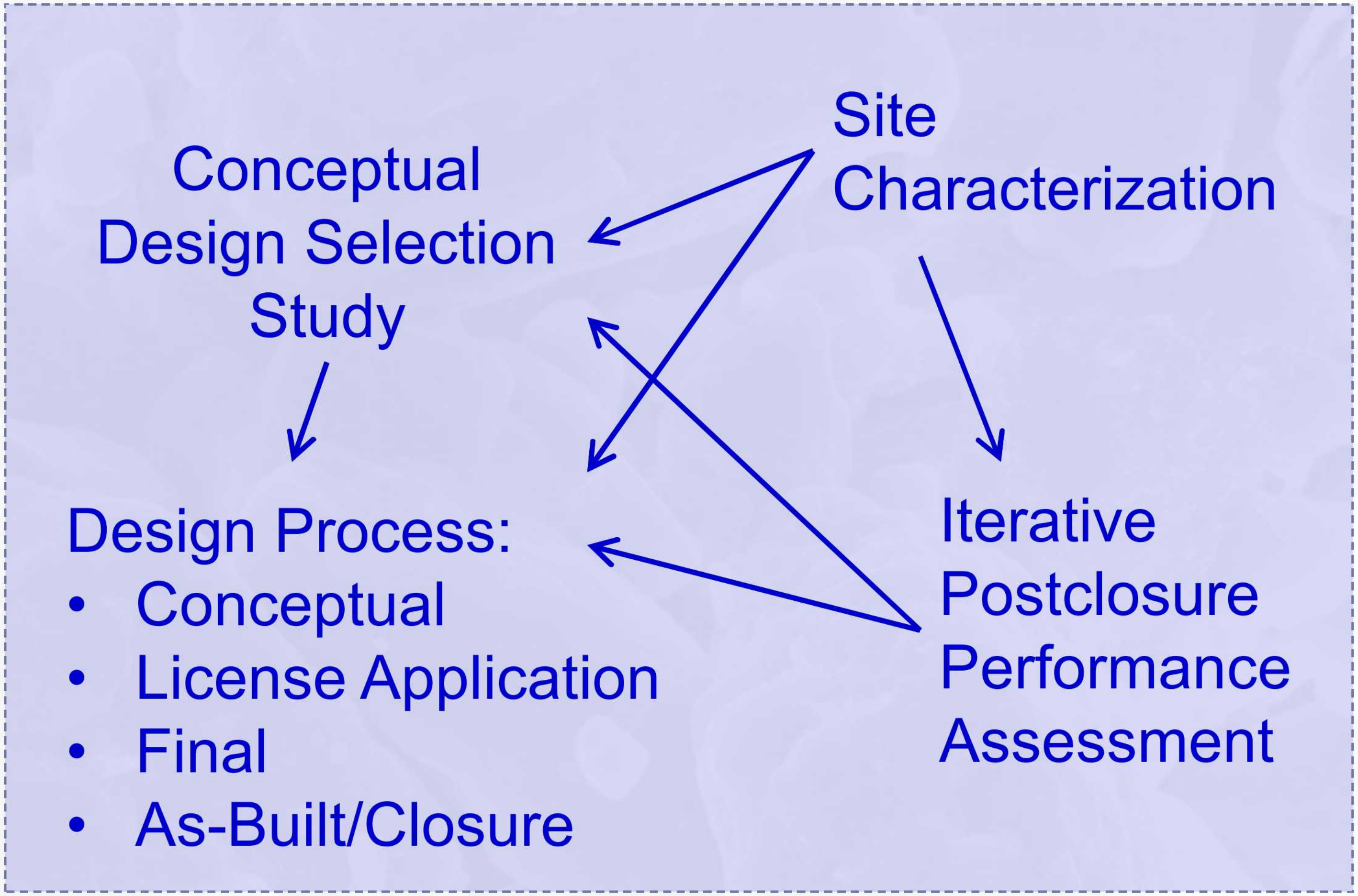
- Conceptual design is a system-level process
- Provision for innovation and trial features/alternatives
- Disposal overpack-canister requirements allocation
- Yucca Mountain example and postclosure criticality exception
- Standardized multi-media canister studies in the U.S.
- TAD+ study technical evaluations
- DCRAs and other R&D needs

BACKUP SLIDES

Design Process

Summary Description – System Level, Iterative, Risk-Informed

Laws, Regulations, & Programmatic Constraints



Conceptual Design Selection Study Approach

- System-level exercise
- Site specific
- Emplacement mode
- All barriers: Optimize reliance on natural and engineered barriers
- Meet postclosure (and preclosure) performance objectives
- Consider licensability

Overpack Requirements

- Containment
  - Preclosure operations + resistance to off-normal events
  - Long-term waste isolation (site specific)
    - Corrosion
    - Disruptive events
- Safety of workers and the public
  - Handling
  - Shielding
- Reliability
  - Stress relief
  - Manufacture (inspection, rework)
  - “Early failure” characteristics
- Engineering feasibility

Canister Requirements

- Containment
  - Safe preclosure operations
  - Transportation requirements (including criticality control)
- Safety of workers and the public
  - Handling for storage and transportation
- Heat dissipation
- Postclosure criticality control
- Engineering feasibility

Material Selection (1/2)

- Canisters for Handling and Storage
  - Stainless steel (e.g., inhibit corrosion and fuel pool contamination)
  - Cast iron or low-alloy steel (e.g., with coatings, or for dry handling)
- Salt
  - Low-alloy steel or cast iron
  - Stainless steel (inner vessel)
- Crystalline
  - Copper & cast iron
  - Low-alloy steel
  - Titanium & stainless steel
- Clay/Shale
  - Low-alloy steel (overpack)
  - Stainless steel (e.g., HLW pour canisters)
- Unsaturated Hard Rock
  - Corrosion resistant, oxidizing conditions (e.g., Hastelloys, titanium)

Alloy ≡ solid solution, mixture of solid solution phases, or "intermetallic."

Material Selection (2/2)

- Disposal Overpack Materials
  - Corrosion Resistant ($10^5 \rightarrow 10^6$ + yr)
    - Nickel-based alloys (e.g.., Hastelloy® 825, C-4, C-22, etc. from Haynes)
    - Titanium
    - Copper (reducing environments)
  - Corrosion Allowance ($10^3 \rightarrow 10^4$ + yr)
    - Low-alloy steel
    - Stainless steel
  - Coatings
    - Plasma spray, cold spray, amorphous metals, plating
- Canister Materials
- Neutron Absorber Materials
    - Matrix (aluminum, stainless steel) + Absorber (boron, rare earths)
- Performance Measures
  - Containment, mechanical and/or chemical lifetimes
  - Compatibility with storage/handling systems
  - Cost, availability, handling constraints, attractiveness, etc.

Specification Areas (1/4)

- General (13 specs)

1	Storage and transportation
2, 3, 4	Shape and dimensions, loaded weight, capacity
5	Submerged opening
6, 7	Waste characteristics, waste source
8	Edge curvature & protuberances
9, 10	Orientation during S&T, and at the repository
11	Canister design lifetime
12	Canister environmental conditions
13	TAD WP spacer (to allow a range of canister lengths to be compatible with a single WP length)

Specification Areas (2/4)

- Structural (3 specs)

1, 2	Canister leakage and cladding temperature due to seismic, and due to environmental conditions
3	Canister bottom shape

- Thermal (5 specs)

1, 2	Cladding temperature prior to disposal during normal operations, and during off-normal conditions
3	Cladding temperature during an engulfing fire
4	Passive cooling of the canister
5	Cladding temperature limit and thermal conditions in the repository

Specification Areas (3/4)

- Dose and shielding (3 specs)

1, 2	Dose rate limits: average and maximum
3	Surface contamination limits

- Criticality (2 specs)

1	Storage and transportation
2	Postclosure

- Confinement and containment (5 specs)

1	Closure weld qualification or leak testing
2	Helium gas
3	ASME Boiler & Pressure Vessel Code
4	Draining, drying, and backfilling
5	Leakage rate and cladding temperature following a drop

Specification Areas (4/4)

- Operations (5 specs)

1	Underwater handling
2	Lid centering and seating
3	Canister lifting using the lid
4	Empty canister lifting
5	ALARA principle during canister draining, drying, and backfilling

- Materials (6 specs)

1, 2	Materials: Required and prohibited
3	Pool water
4	Corrosion
5	Weld stress relief
6	Markings