Repository Applications for Depleted Uranium (DU)
(Potential Use of the Entire DU Inventory)

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DU Uses R&D Program Review
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Background: Structure of Presentation

- After each viewgraph there is an additional page
  - *Blank page* (space holder)
  - *Background viewgraph*
- Background viewgraphs will not be presented
- Background viewgraphs provide additional information
  - Detailed explanations
  - References to documents published this year

Outline

- Introduction
- Multipurpose Cask System
- Cask Fabrication
- Enhancing Cermet Cask Capacities
- Waste Package DUO_2 Fill
- Repository Benefits
- Conclusions

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INTRODUCTION

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Task Objectives

The task objectives are to identify, develop, assess, and encourage beneficial uses of DU for repository system applications

This is the only set of applications without end-of-life liabilities—a major commercial issue

Background: Disposal Requirements for Depleted Uranium Are Uncertain: Repository Disposal Is Acceptable

- **Regulatory perspectives**
  - Nuclear Regulatory Commission: Deep disposal (mine or equivalent) preferred
  - Europe (France and Germany) require geological disposal
- **Yucca Mountain Project Evaluation**
  - YM Project evaluated DU disposal (various oxide forms)
  - Disposal in separate drifts in steel drums, no WPs
  - YMP performance assessment indicated no major impacts
- **Commercial perspectives**
  - Liability is a major factor in business decisions
  - End-of-life liability is a major burden for products
  - These applications avoid this major commercial barrier

Task Justification

- Potential beneficial use of the entire DU inventory
- Potential SNF system cost savings (storage at reactor, transport, and disposal)
- Potential repository performance benefits
  - Reduce total repository radionuclide releases
  - Reduce long-term peak radiation dose to public
  - Shielding (simplify operations, dose to employees)
  - Criticality control (particularly for higher-enriched SNFs)
- Minimal regulatory and public acceptance issues
  - DU used in a nuclear application
  - Meets disposal regulatory requirements (NRC, EPA, etc.)

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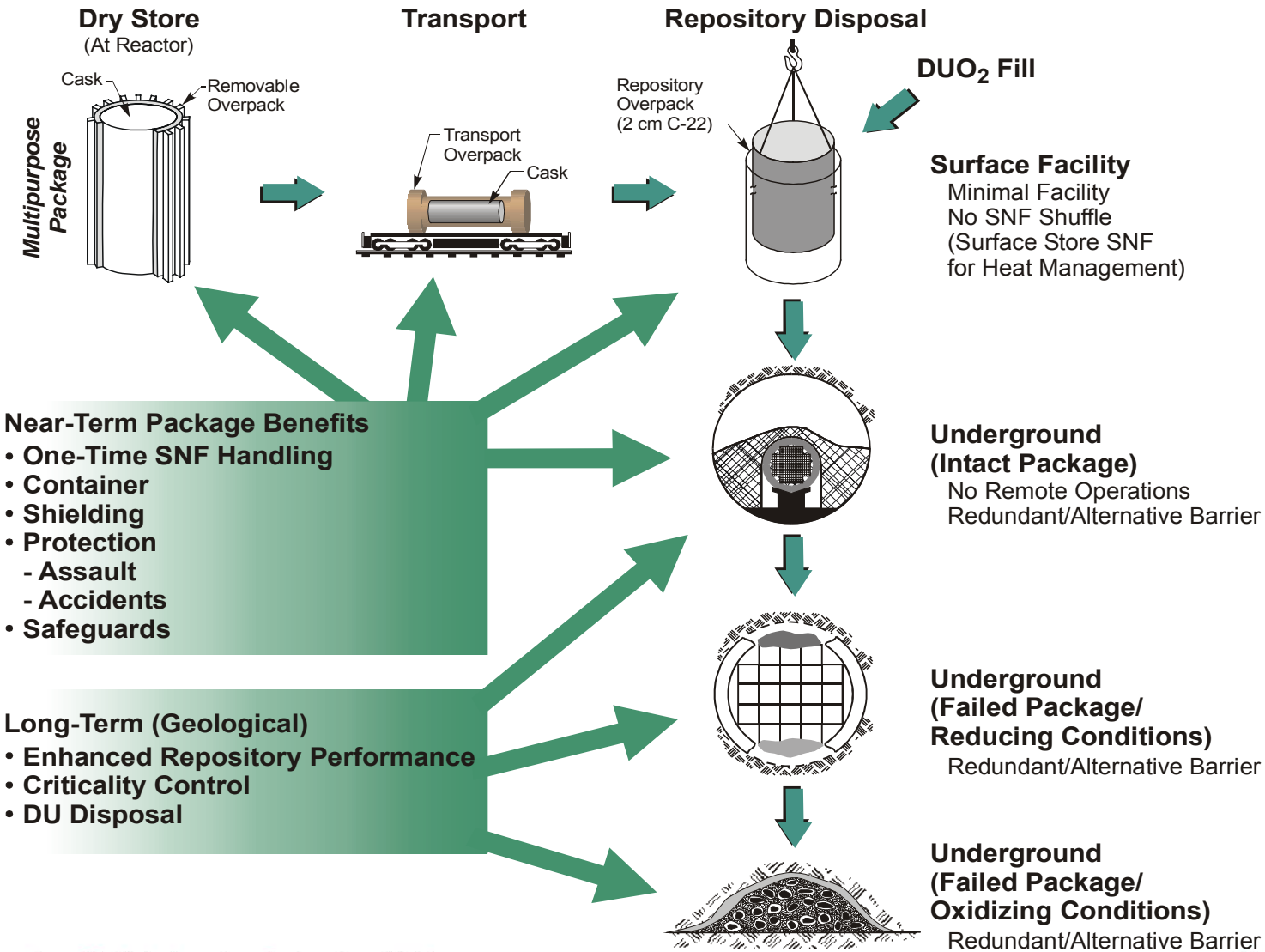
System Applications and Benefits of DU
(Multipurpose Cask, Waste Package, and Fill)



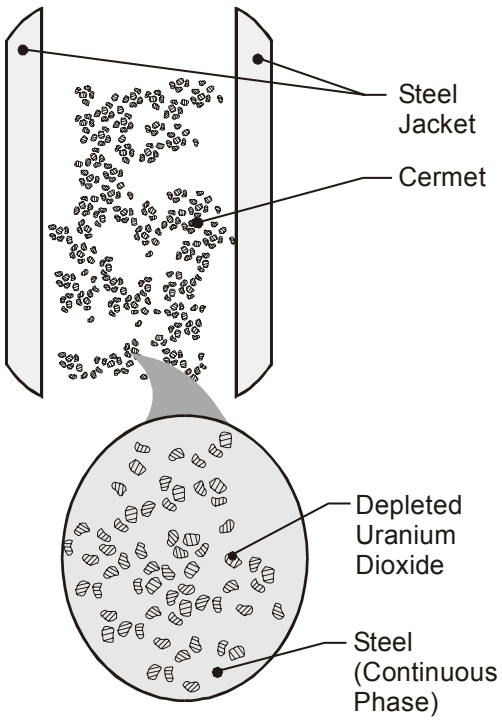
Background: Three Repository Applications for DU

- **Cermet multipurpose cask**
  - **Store SNF at reactor**
  - **Transport SNF to the repository**
  - **Inner waste package at the repository**
- **Cermet waste package**
  - **Inner waste package**
  - **Basket structure**
- **DUO_2 fill in SNF waste package**

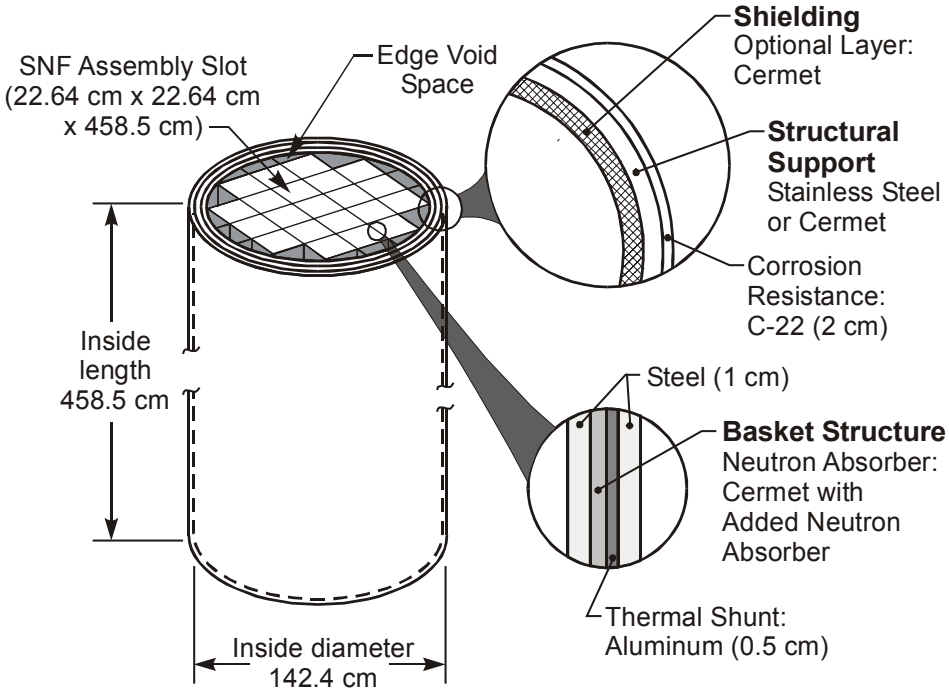
Storage, Transport, and Repository Applications: Casks Can Be Constructed of a DUO_2-Steel Cermet: 3-8 kg DU/kg SNF

(Manufacturing Demonstrated for Small Objects: Cermets Were Used as Fuels In Some Reactors)

Cermet



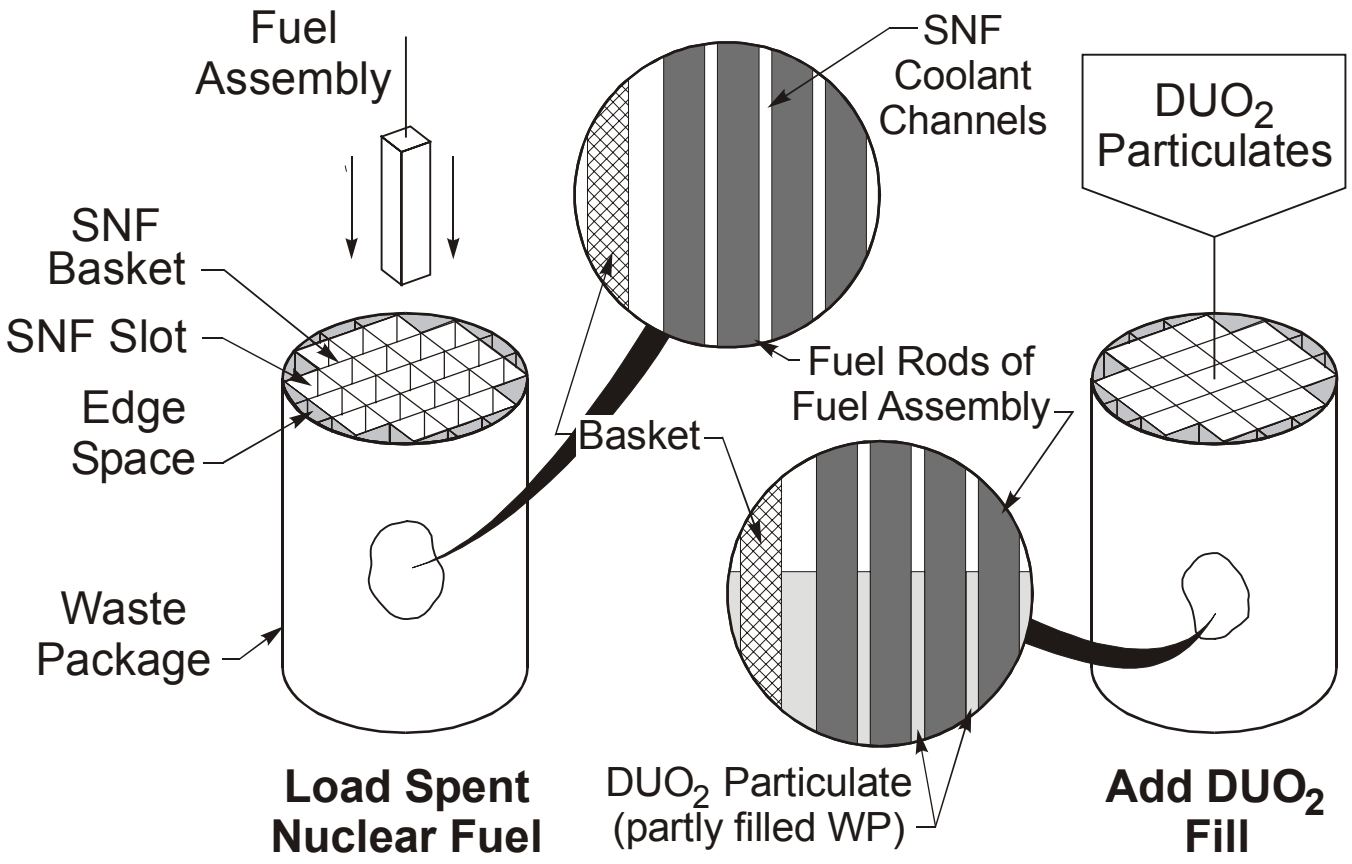
Applications



Background: Depleted Uranium Dioxide (DUO_2) Is the Repository Preferred Form of DU

- **Applications must be consistent with NRC policies and positions**
  - **DU oxides acceptable in repository**
  - **DU metals questionable, fluorides unacceptable**
- **Applications must be consistent with repository performance goals**
  - **Avoid materials defined as unacceptable by YMP: concrete, organics, RCRA materials, etc.**
  - **Use acceptable materials (ideally, materials that are used in the existing repository design): UO_2, steel**
- **DUO_2 is the only acceptable oxide for cermet fabrication**
  - **Cermet fabrication is a high-temperature process**
  - **Other DU oxides decompose to DUO_2 at high temperatures**

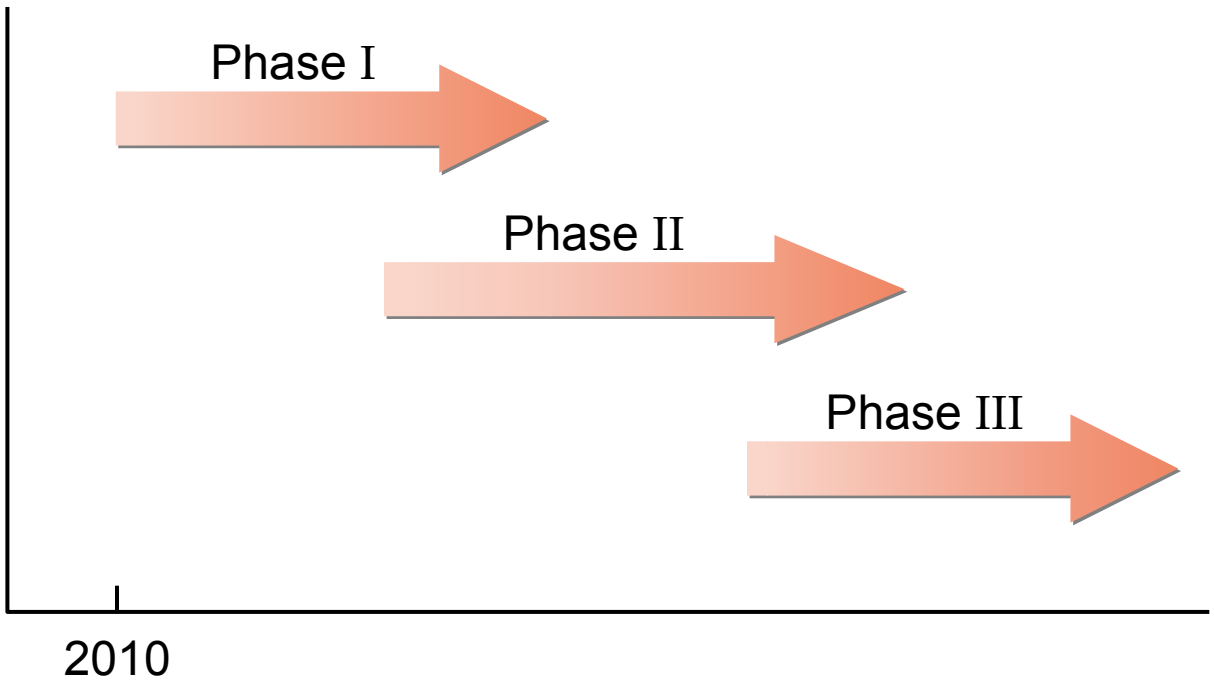
DUO_2 Particulate Fill Can Be Added to SNF Waste Packages (3-4 kg DU/kg SNF)



Background: Large-Scale Canadian Experiments Demonstrated Fill Technology

- Canada developed a thin-wall titanium WP
  - Outstanding corrosion resistance
  - Expensive material: use thin-wall WP to limit quantities
  - Fill to be added to support WP against crushing
- Investigated many fills
  - DUO_2 not investigated because it was not available (no DU in Canada)
  - Filling and emptying technology investigated
    - Tested with full-scale WPs
    - CANDU SNF has smaller dimensions between fuel rods than in LWR SNF, conservative test of fill technology
- Fill does not significantly impact WP thermal performance

The Repository Will Be Developed in Phases with Multiple Introduction Times for New Technologies



Technology Deployment

- **The YM priority is licensing**
  - **Minimize changes to meet schedule**
- **New technologies will be introduced over time**
  - **Repository will operate for many decades**
  - **There will be significant learning with time**
  - **Changes will be made in the repository design and operation**
  - **Licensing amendments will be made**
- **DU applications can be introduced as developed**

MULTIPURPOSE CASK SYSTEM
Development of Policy and Economic Incentives for Using DU

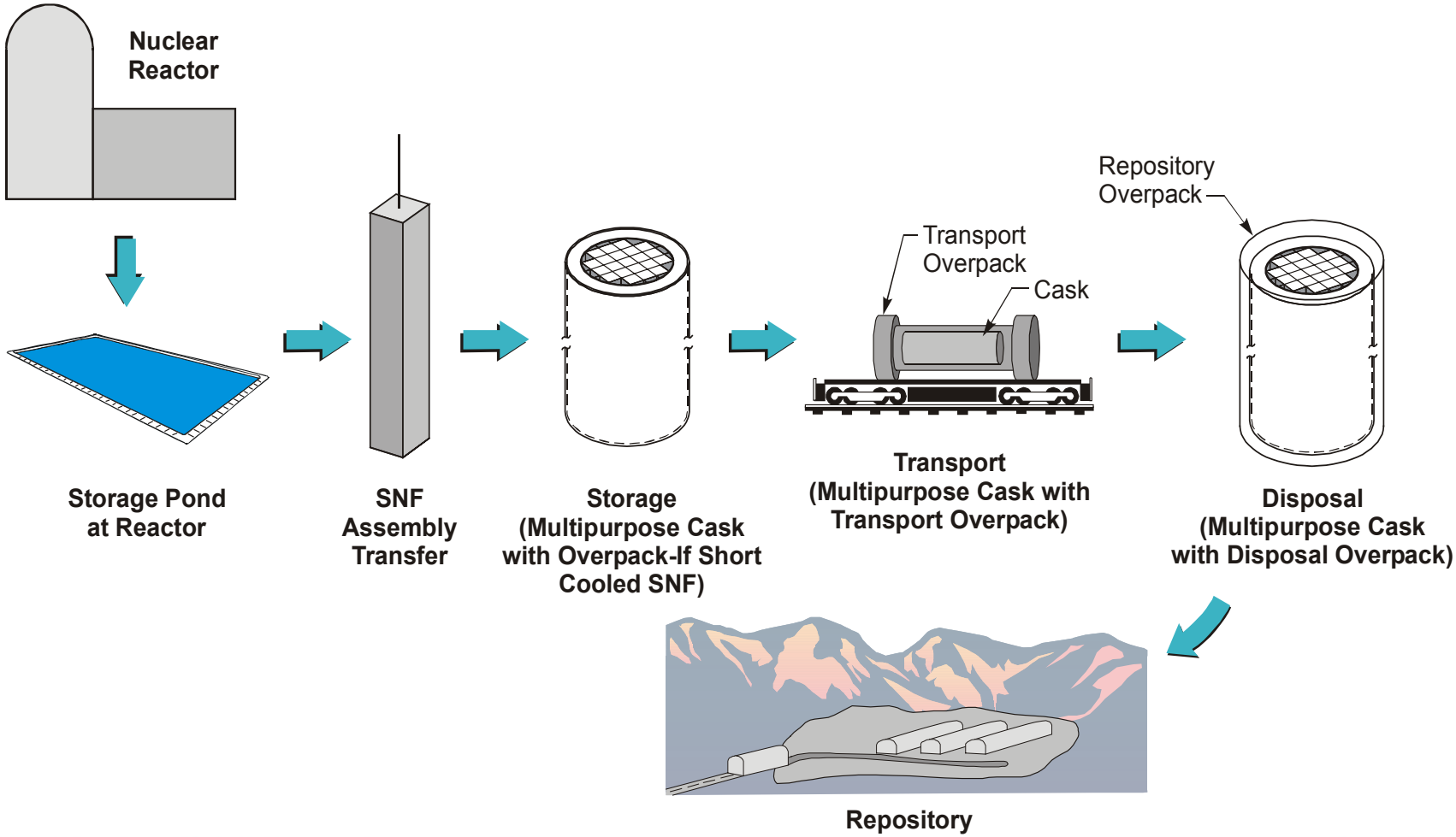
Why a Multipurpose Cask System?

Why a DUO_2-Steel Cermet Cask?

Background: Economics and Security Provide Strong Incentives For a Multipurpose Cask System

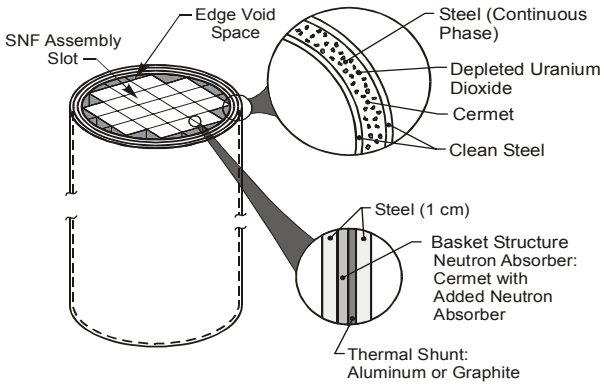
- Economics
  - Minimum SNF handling
  - Minimum equipment (avoid separate storage, transport, and disposal containers)
- Security
  - Casks provide higher security than pools
    - Difficult to steal: Heavy weight
    - Robust
  - Minimum SNF handling
  - Simplified surveillance
    - Follow from orbit
    - Option of transponder on each cask
  - Preferred option when non-proliferation is a concern

Multipurpose Casks May Allow SNF Loading at the Reactor and Disposal at the Repository



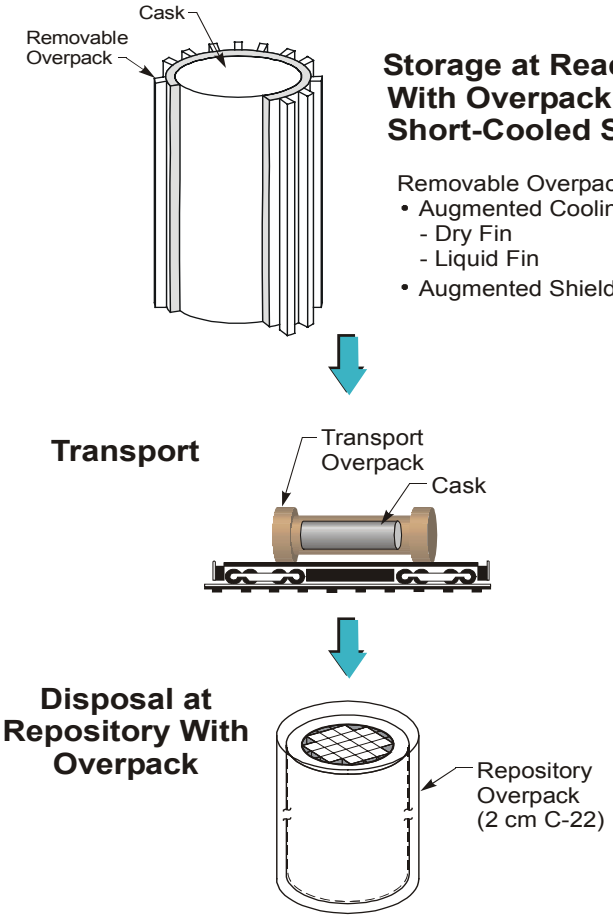
Background: The Multipurpose Cask Has Different Overpacks for Storage, Transport, and Disposal to Meet Different Functional Requirements

Multipurpose Cask



- Radiation Shielding
  - Gamma: High-Density Cermet
  - Neutron Moderation/Absorption
    - Oxygen in Cermet
    - Carbon in Cask
- Assault Protection: Multilayer Cermet
- Safeguards and Theft
  - Large Mass
  - Vault Construction: Multilayer Cermet
- Decay Heat Removal
  - Carbon Shunt (also Neutron Moderator)
  - Aluminum

Multipurpose Cask System



DUO_2–Steel Cermet Casks Maximize Multipurpose Cask Performance

Economics: Greater SNF Capacity for a Given Weight

Security: Better Protection Against Assault

Waste Management: Disposal of DU

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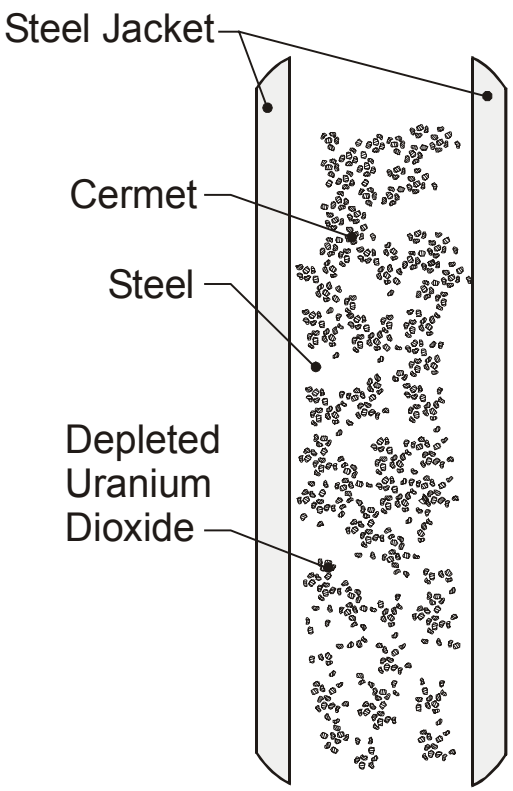
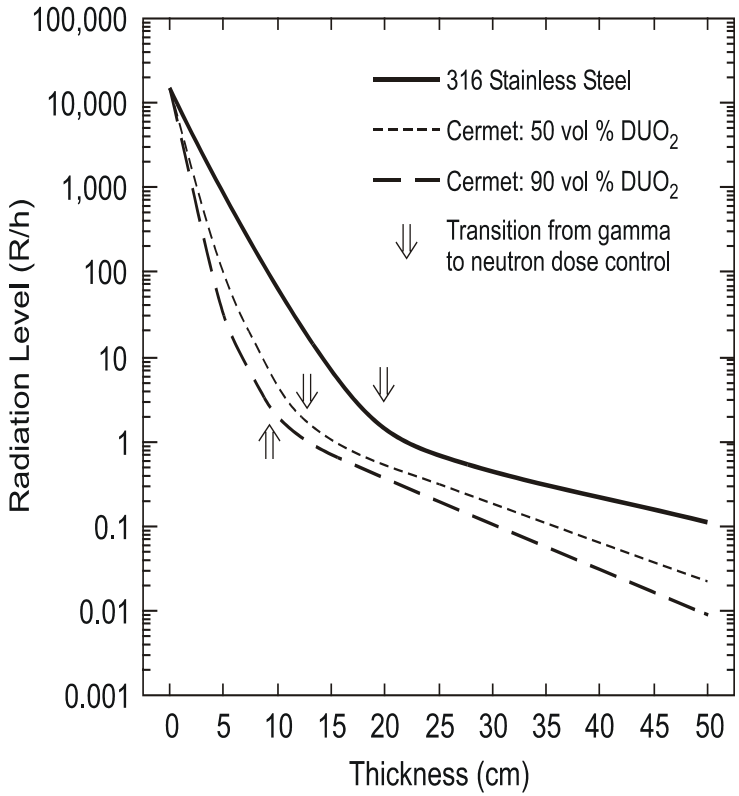
DUO_2-Steel Cermets Maximize Cask SNF Capacity Because of Superior Shielding Capability

(Cask Weight and Size Constrained; Strong Economic Incentives To Maximize Number of Fuel Assemblies per Cask)



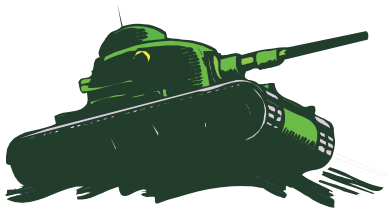
- Gamma Shielding Better Than Steel
  - Steel: 7.86 g/cm^3
  - DUO_2: 10.9 g/cm^3
- Neutron Shielding
  - High-density oxygen (DUO_2) moderator
  - Other neutron absorbers can be added
- Good Physical Properties
  - High thermal conductivity
  - No organics (no fire; acceptable to repository)

Background: DUO_2-Steel Cermets Are the Highest-Performance Shielding Materials Compatible with Multipurpose Casks



- **Repository limits choice of cask materials**
  - **No concrete**
  - **No RCRA metals (lead)**
  - **No organics**
  - **Cost constraints (no tungsten)**
  - **No reactive metals (uranium metal)**
- **DUO_2-steel cermet is the best remaining material**

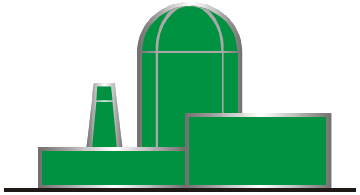
Cermets Provide Protection Against Assault and Accidents



Main Battle Tank Armor

Brake Shoes

Cutting Tools

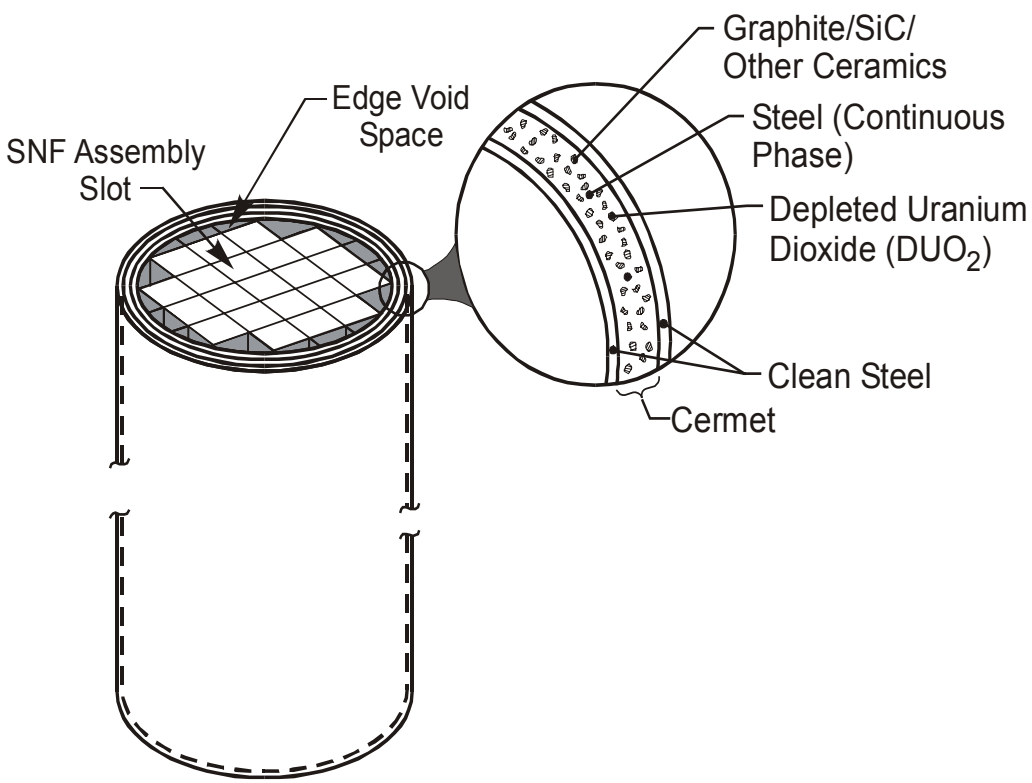


Test Reactors (UO_2-Steel Cermets)

- Cermets (left) are the traditional material for use in extreme environments
- Cermets combine the best properties of metals and ceramics
  - Metals
    - Ductility
    - Thermal conductivity
    - Strength
  - Ceramics
    - Shielding
    - Hardness (Armor)
    - Other

Background: Cermets Are the Enabling Technology for a Super Cask

(Ceramics in Metal Matrix to Obtain Advantages of Both)

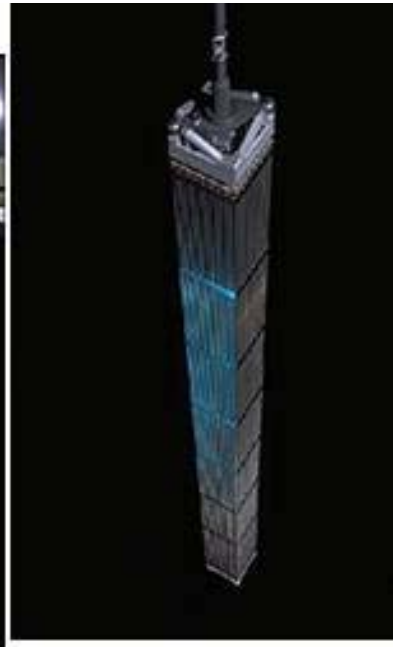


Functions

- Radiation Shielding
  - Gamma: High-Density DUO_2/Other
  - Neutron Moderation/Absorption
    - Oxygen in DUO_2
    - Carbon in SiC and Graphite
- Assault Protection: Multilayer Cermet (Traditional Armor)
  - Ceramic (Al_2O_3, DUO_2, SiC, Other)
  - Metal
- Safeguards and Theft
  - Large Mass
  - Vault Construction: Multilayer Cermet
- Decay Heat Removal
  - High Conductivity Steel Matrix

Cermet SNF Casks Codispose of Two Wastes Simultaneously At One Site vs Two Sites

—Depleted Uranium and Spent Nuclear Fuel—



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Accomplishments and Path Forward

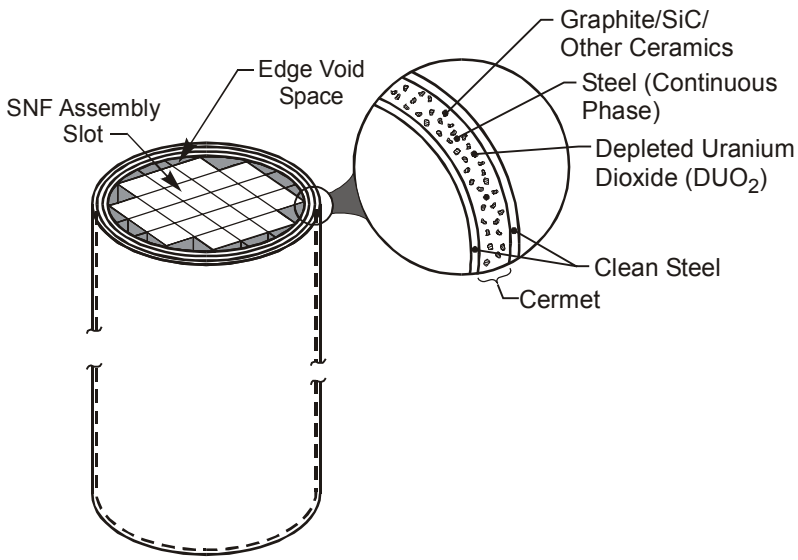
- Completed development of system concept
  - Publications
    - System description (2)
    - Armor description (1)
- Path forward
  - Work with vendors (interactions with GNSI and Holtec), DOE, and utilities
  - Develop a system cost estimate
  - Address other system issues

Background: Systems

- **New Publications**
  - C. W. Forsberg, "Retrievable Depleted Uranium Dioxide-Steel Cermet SNF Multipurpose Casks", *Proc. 10th International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, March 30-April 2, 2003*, American Nuclear Society, La Grange Park, Illinois
  - C. W. Forsberg and J. Haire, "Depleted Uranium Dioxide-Steel Cermets for Spent Nuclear Fuel Multipurpose Casks', *Proc. Fifth Topical Meeting on DOE Spent Nuclear Fuel and Fissile Materials Management, Charleston, South Carolina, September 17-20, 2003,* American Nuclear Society, La Grange Park, Illinois.
- **Multipurpose Cask System Issues**
  - Institutional
    - A viable system requires agreement between utilities, the repository, and owners of DU
    - Distribution of savings and costs between parties may be different than in the existing system
  - Technical
    - Full evaluation of the system is required (including repository performance)
  - Economics
    - Major savings require system integration
    - Economics is dependent upon cask manufacturing costs (See cermet manufacturing)

CASK FABRICATION

Viability Requires Low-Cost Cermet Cask



- **Cermets are difficult to fabricate**
  - **No technology exists for welding thick sections of cermets**
  - **DUO_2 operations must be minimized**
- **New method of cask fabrication has been discovered**
  - **Patent applied for**
  - **Potential low cost technology**

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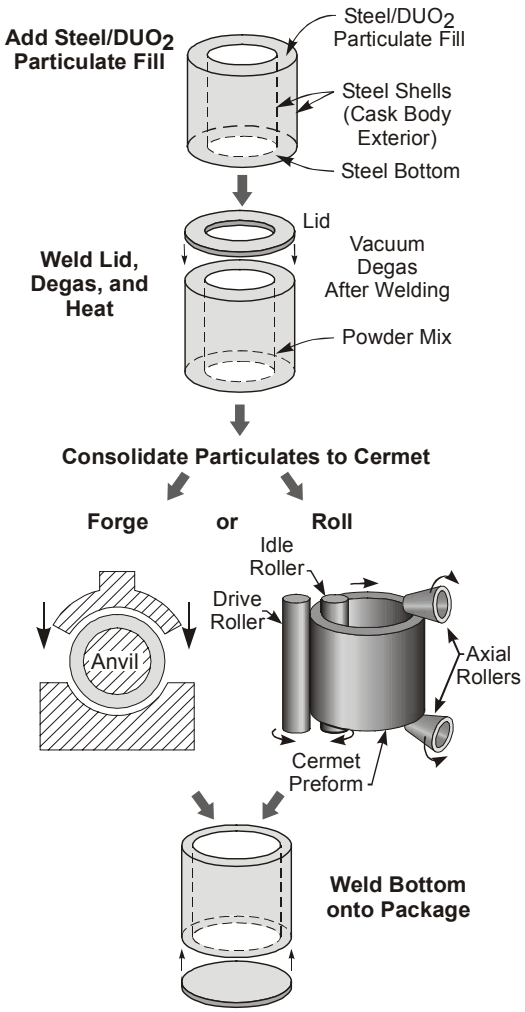
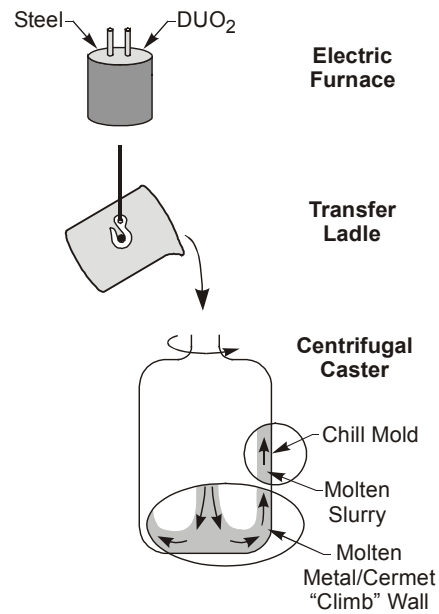
Two Cask Fabrication Methods Are Being Investigated

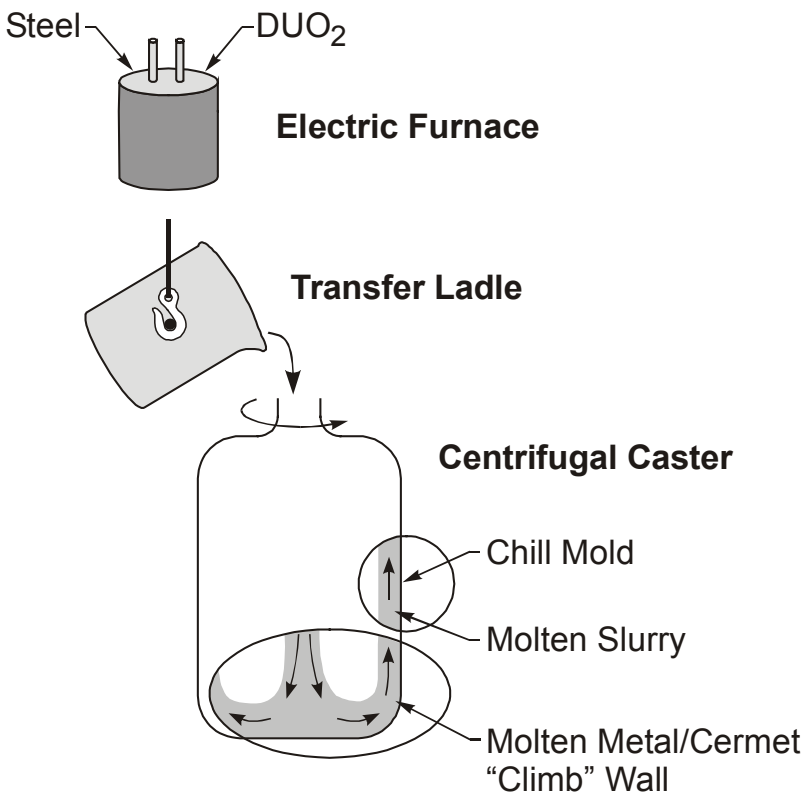
New Powder Metallurgy Method



Centrifugal Casting

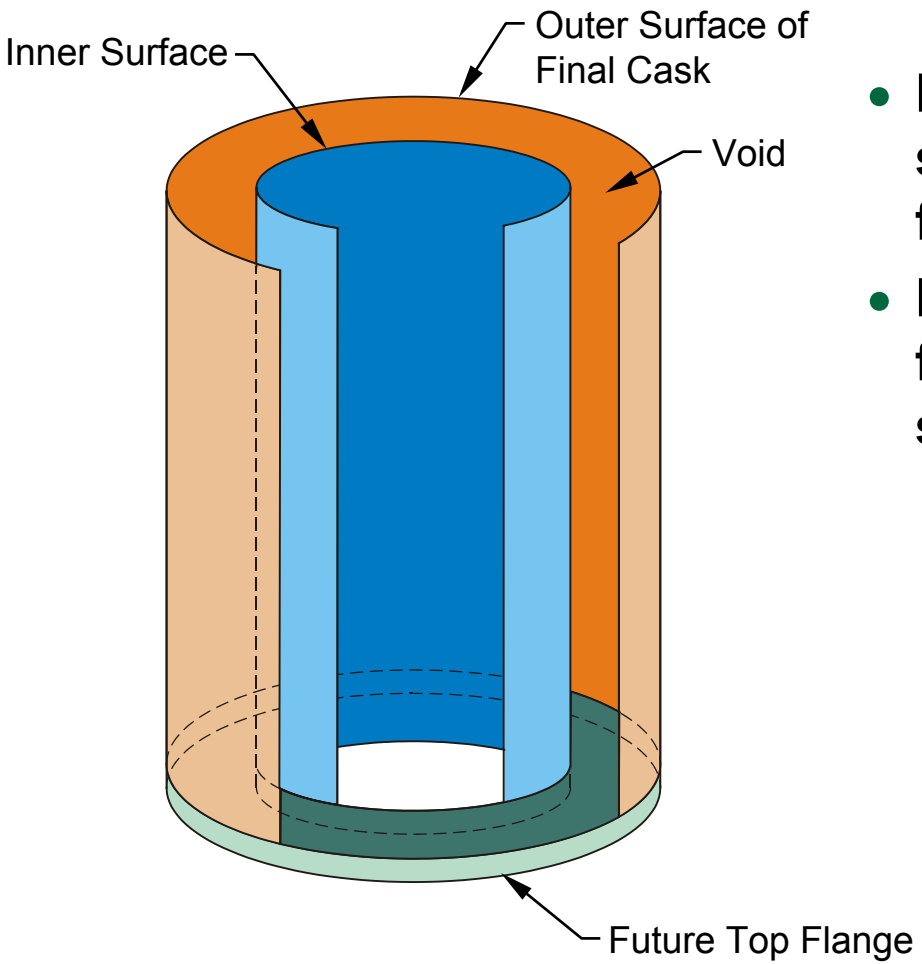


Background: Centrifugal Casting



- Traditional method to cast pipes and rollers
- Advantages
  - Potential for low cost if high throughput: high front-end investment
  - Accepts contaminated steel
- Issues
  - Requires iron to wet the DUO_2 (not demonstrated)
  - Fixed ratio of iron to DUO_2 (or separation of iron from ceramic)

New Fabrication Method (Patent Applied for): Step 1: Manufacture of Cask Preform

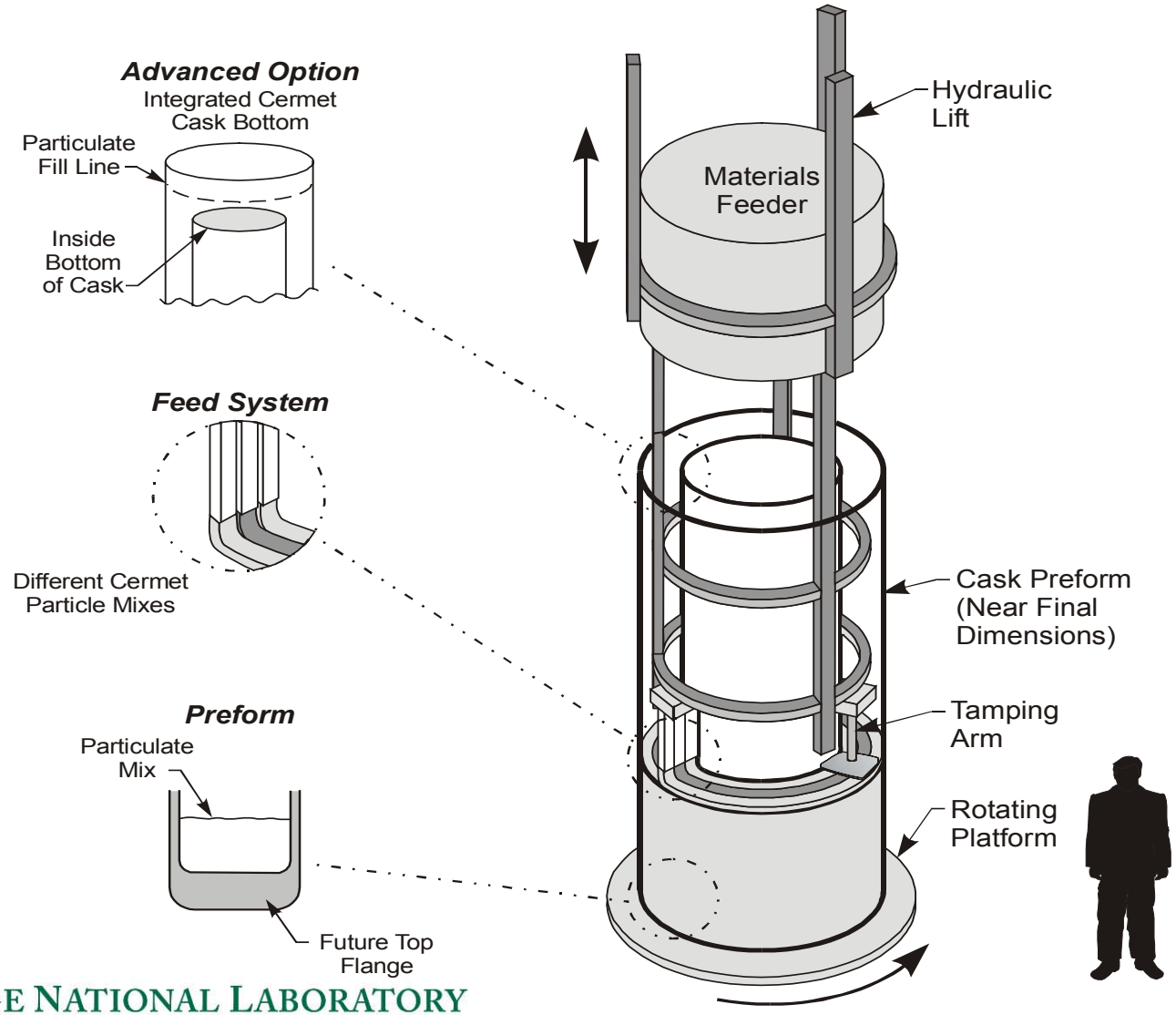


- **Preform dimensions are slightly larger than the final cask**
- **Preform becomes the final inner and outer surfaces of the cask**
  - **Wall thickness: 1-3 cm**
  - **Flange**
    - **Thickness: 10-20 cm**
    - **Face for lid**

Background: Cask Manufacturing Steps

- Step 1: Cermet preform fabricated
  - The preform is the shell (inside, outside, and top) of the final cask body without the bottom
  - Characteristics
    - Preform walls are relatively thin (1 to 3 cm): final outside and inside surfaces of the cask
    - Top of preform is 10s of centimeters thick (lid mating surface)
    - Lid bolts drilled into preform: no drilling or welding of cermet (very difficult)
  - All welding, drilling, and cutting operations in cask fabrication are into this preform
- Step 2: Loading preform with particulate mixture
  - Preform placed on particulate loading machine (upside-down cask)
  - Particulate mixture added in layers and mechanically compacted
  - Powder loading method allows mixture to be varied from inside to outside of cask wall
- Step 3: Seal loaded preform and degas
  - Weld annular ring to seal preform (bottom ring of final cask)
  - Heat and vacuum degas
- Step 4: Convert loaded preform into a monolithic cask body
  - Filled preform is heated before cermet particulate consolidation operations
    - Heating reduces forces required for later forging operations
    - Heating ensures metal particulates are welded by forging operations
  - Pressure (forging) creates monolithic cask (no voids) with preform and cermet welded together
- Step 5: Finishing operations
  - Two options for cask bottom
    - Weld cask bottom (full thickness) to cermet cylindrical cask body (steel-to-steel weld)
    - Integrated cermet cask bottom with cask walls (not shown; requires special forging operations)
  - Machining
    - Smooth surfaces
    - Create mating surface for cask lid
    - Drill holes for cask lid bolts

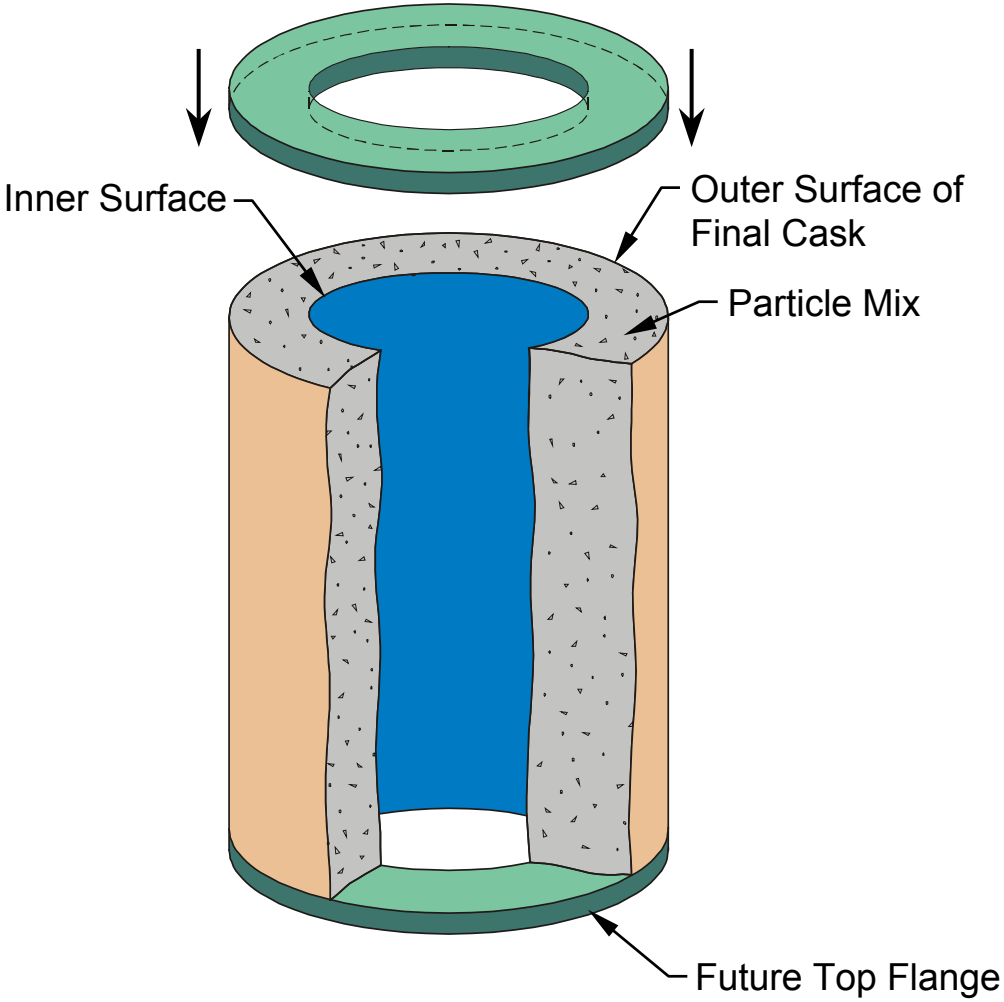
Step 2: Empty Cask Preform Is Mounted Upside Down on Turntable and Filled with Cermet Particulate Mixture



Background: Filling Preform

- Preform mounted with cask-lid mating surface on the turn table
- DUO_2-iron particulates added to preform
  - Layers of particulates added as turn table rotates preform
  - Particulates mechanically compressed in layers after addition
  - Thickness of cask allows different mixtures of ceramics and iron particulates from the inside to the outside of the cask body

Step 3: Loaded Preform Is Sealed and Degassed



- **Weld annular ring to seal preform**
- **Degas**
  - **Heat**
  - **Vacuum**
- **Send sealed package to forging operations**

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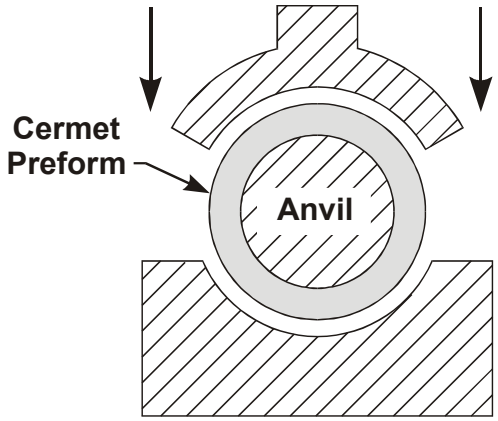
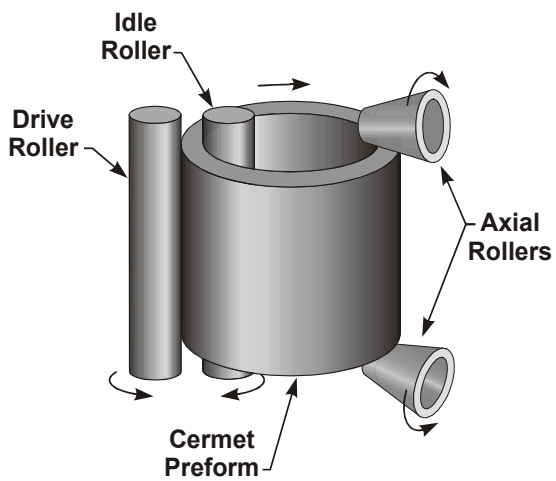
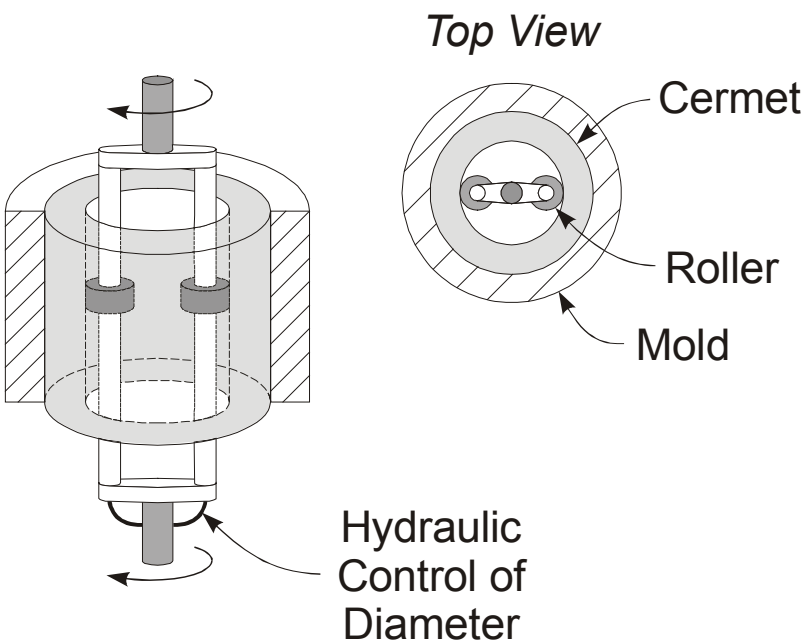
Step 4: Loaded Preform Is Heated and Consolidated into Monolithic Cask





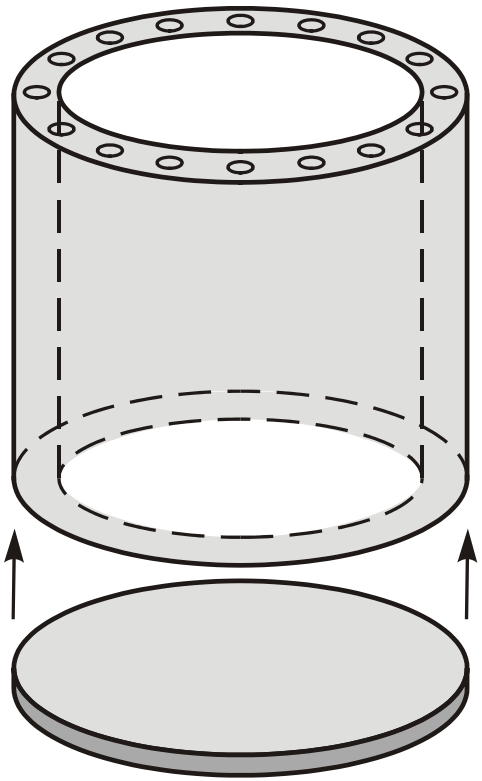
- Preheat to ~1000ºC
  - Reduces required forging pressures
  - Welds iron particulates together
- Two consolidation options
  - Traditional forging (Top)
  - Ring forging (Bottom)
- Yield monolithic final product

Background: Forging



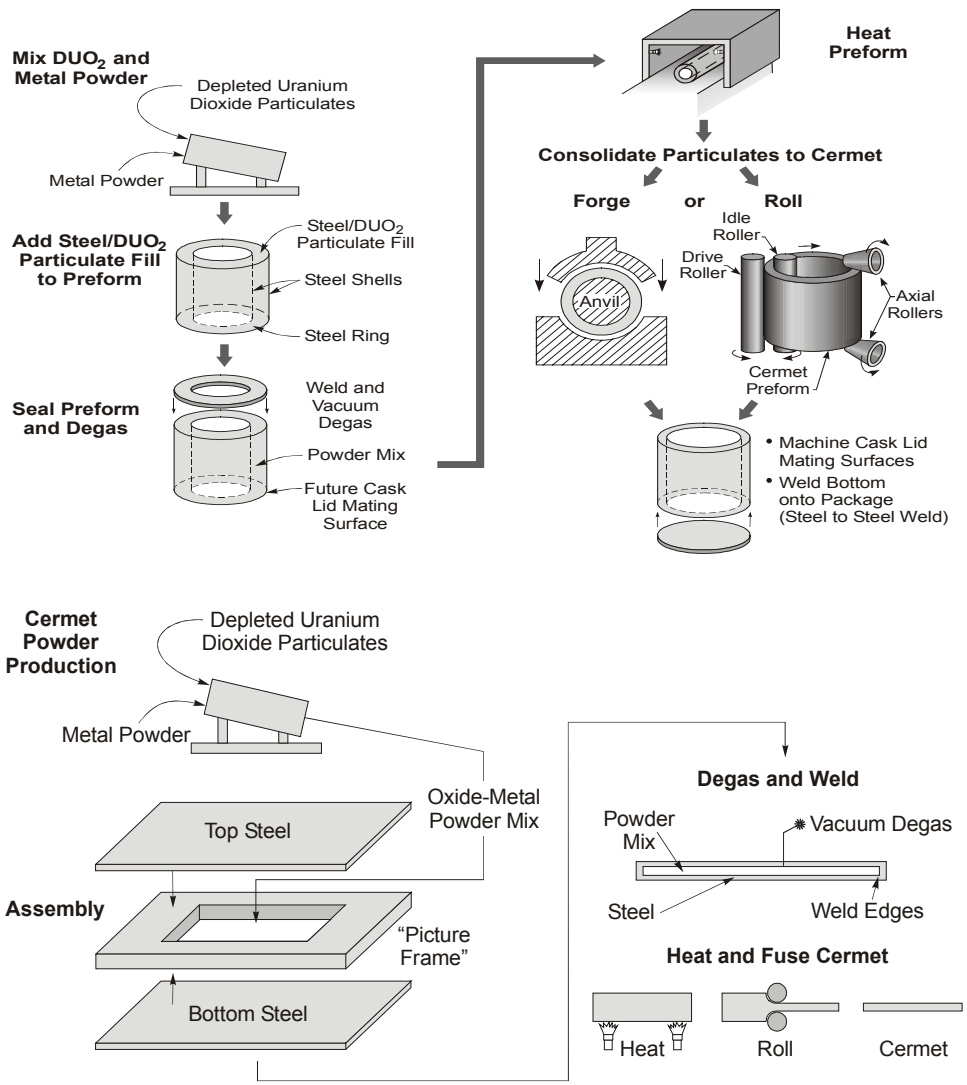
- **Forges handle single parts up to 500 tons**
- **If sealed preform, simplified use of existing forge**
- **Several alternative forging options for special purpose manufacture (see left)**

Step 5: Cask Finishing Operations



- All finishing operations involve steel preform (No contact with cermet)
- Cask bottom is welded to the cask body
  - Option for integrated cask bottom
  - Option requires complex forging operation
- Cask machining
  - Machine lid surface and bolt holes
  - Cask surfaces

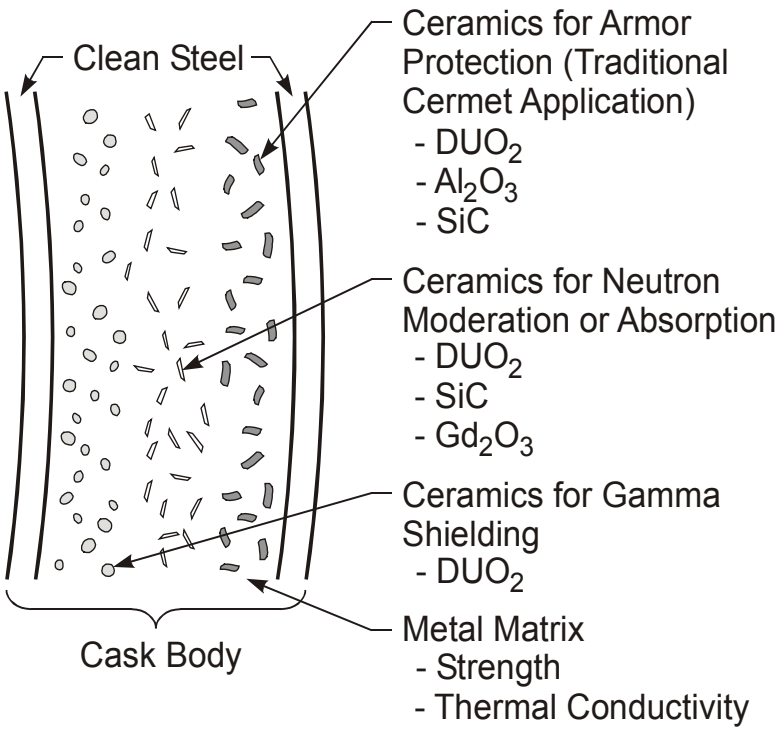
Background: New (Top) and Old (Bottom) Cermet Production Methods



- New method
  - Product: cask
- Old method
  - Product: sheets
  - Same number of steps to produce sheets as to produce cask with the new method
  - Conversion of sheets into cask
    - Roll into circle
    - Weld (very difficult)
    - Alternative: roll into coil to form cask

Major Advantages of New Method

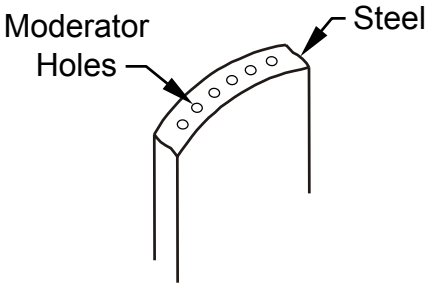
- **Enables manufacture of variable-composition cermet (Right: new options)**
- **Leads to a potentially low-cost cask**
  - **Variable-composition cermet avoids traditional multilayer cask designs**
  - **Involves few manufacturing steps**
    - **Low labor costs**
    - **Single DUO_2 operation**
    - **Reduced machining with near-final form**
  - **Uses existing forges**
  - **Uses low-cost materials**
    - **Iron powder: $600/ton**
    - **Avoided disposal costs for DUO_2**



Background: Cermet Casks May Require Fewer Fabrication Steps than Traditional Casks

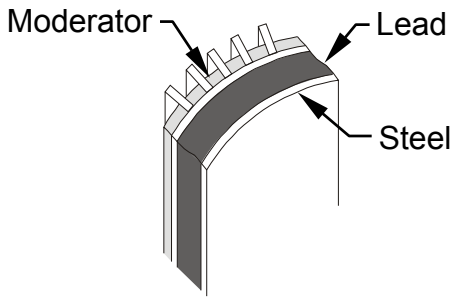
Other Casks

Steel Cask



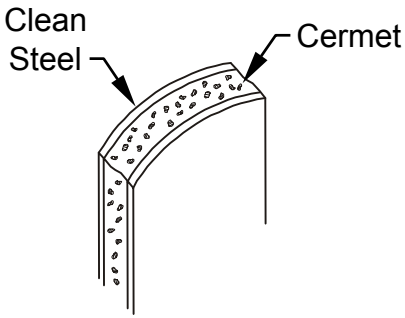
- **Casting**
- **Drilling**
- **Assembly**
- **Machining**

Lead Cask



- **Form Fabrication**
- **Casting**
- **Moderator Placement**

Cermet



- **Form Fabrication**
- **Particulate Addition**
- **Heat and Forge**

Accomplishments and Path Forward

- Patent filed January 2003; publication: March 2003
- Path forward
  - ORNL
    - Fabricate small DUO_2-steel cermet samples
      - Develop required process conditions (FY 2003)
    - Fabricate small cylinders (develop process parameters)
    - Obtain industrial cost estimates from vendors
    - Cask demonstration (non-DUO_2; then DUO_2)
  - Russia
    - ISTC (Department of State) funding (March 2003)
      - Examine casting option (competitive on a large scale)
      - Determine advantages for cask bottom
    - Proposed activity: cold-wall melter to make DUO_2
  - Discussions with cask vendors (GNSI, Holtec)

Background: Fabrication

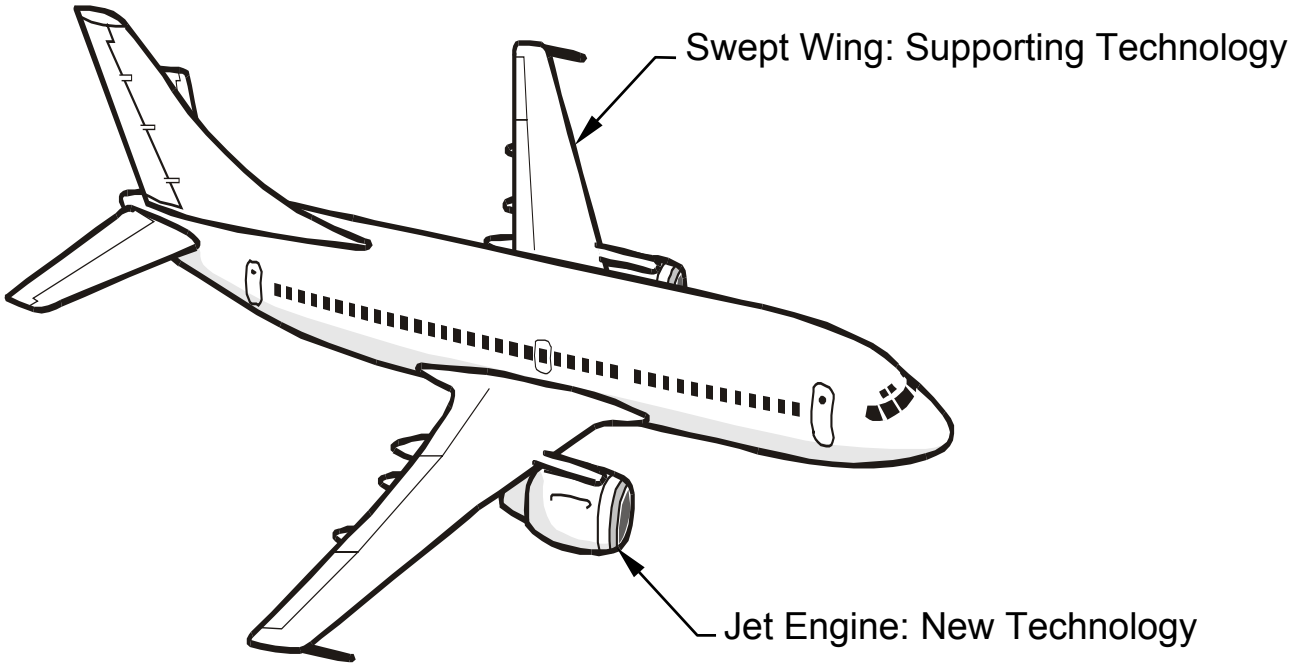
- **Patent: C. W. Forsberg and V. Sikka, *Patent Application: Manufacture of Annular Cermet Objects*, U.S. Patent Office, January 16, 2003**

- **Publication: C. W. Forsberg and V. Sikka, "Alternative Manufacturing Methods for Depleted Uranium Dioxide-Steel Cermet SNF Casks," *Proc. 10th International High-Level Radioactive Waste Conference, Las Vegas, Nevada, March 30-April 2, 2003*, American Nuclear Society, La Grange Park, Illinois**

ENHANCING CERMET CASK CAPABILITIES

(Cooling, Neutron Shielding, Armor)

New Technologies Require
Supporting Technologies to Obtain the Full Benefits



Background: Enhanced Capabilities

- To obtain the full benefits of a DUO_2-steel cermet cask, improvements in other technologies are required.
- Technologies to increase incentives to use cermet casks
  - Improved cask cooling
    - Temperature limits on SNF
      - Larger cask of no benefit if the heat load can not be managed
      - Special issue in storing short-cooled SNF
    - Options for improved cask cooling
      - Removable liquid-cooled fins
      - High-thermal-conductivity basket
  - Improved neutron shielding
    - Cermets provide outstanding gamma shielding
    - Cermets provide some neutron shielding (oxygen neutron moderation)
    - High-burnup SNF has significant neutron emission
    - Options for improved neutron shielding
      - Graphite basket components
      - Graphite/oxides in cermet
  - Improved security
    - Many types of armor are made of cermets; therefore can use existing design methodologies to improve cask capabilities
    - Cermet design can maximize cask assault resistance
    - Fabrication process exists for multicomponent cermet

Cask Cooling Advances Required To Maximize Cermet Cask Advantages

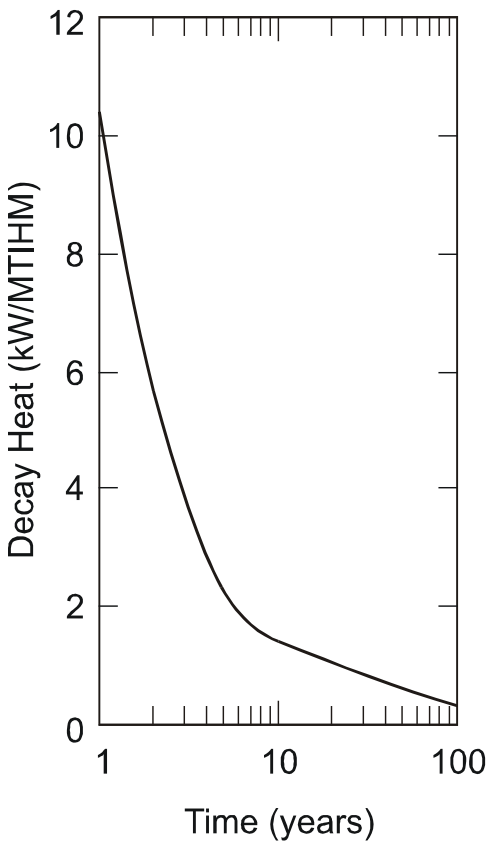
- Strong utility incentives exist for dry storage
  - Maximize pool space availability
  - Enhanced SNF security (better than pools)
- Large casks minimize costs, but there are multiple cask design constraints
  - Weight (Cermet advantage)
  - Diameter (railroads limit cask diameter)
  - Decay heat with short-cooled SNF
- To maximize the incentives to use cermets (higher capacity casks), the other constraints must be removed
- Cermets reduce weight constraints
  - Cask cooling becomes a constraint for short-cooled SNF
  - Rail transport limits cask diameter. Cooling system adds to cask diameter. Cooling system can limit cask diameter separate from weight limits.

Background Information: Ideal SNF Cask Cooling System

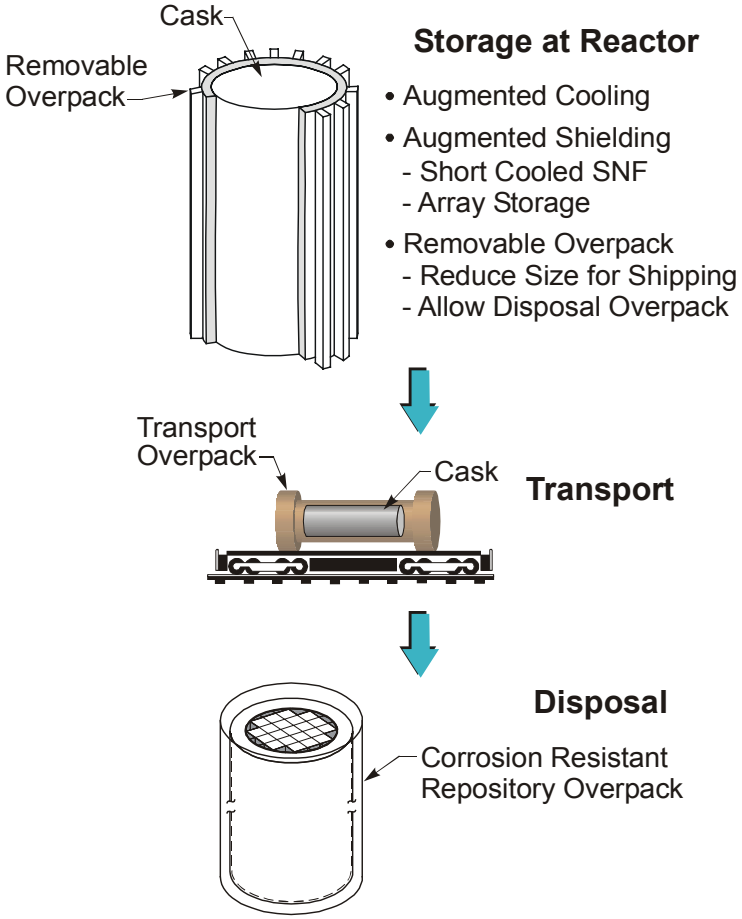
- Efficient: Three sources of resistance to heat transfer to be minimized
  - SNF to cask wall (grid structure)
  - Cask wall (smallest of the three)
  - Cask surface to air
- Constraints
  - Peak temperature of SNF typically limited to 350ºC
  - Multiple temperature drops from SNF to air
  - Reducing any temperature drop provides more temperature drop to use elsewhere and boosts heat removal capability
- Low cost

Removable Cooling Overpack Meets Short-Term Cooling Requirements, Maximizes Cask Transportability, and Assures Disposal Compatibility

SNF Decay Heat



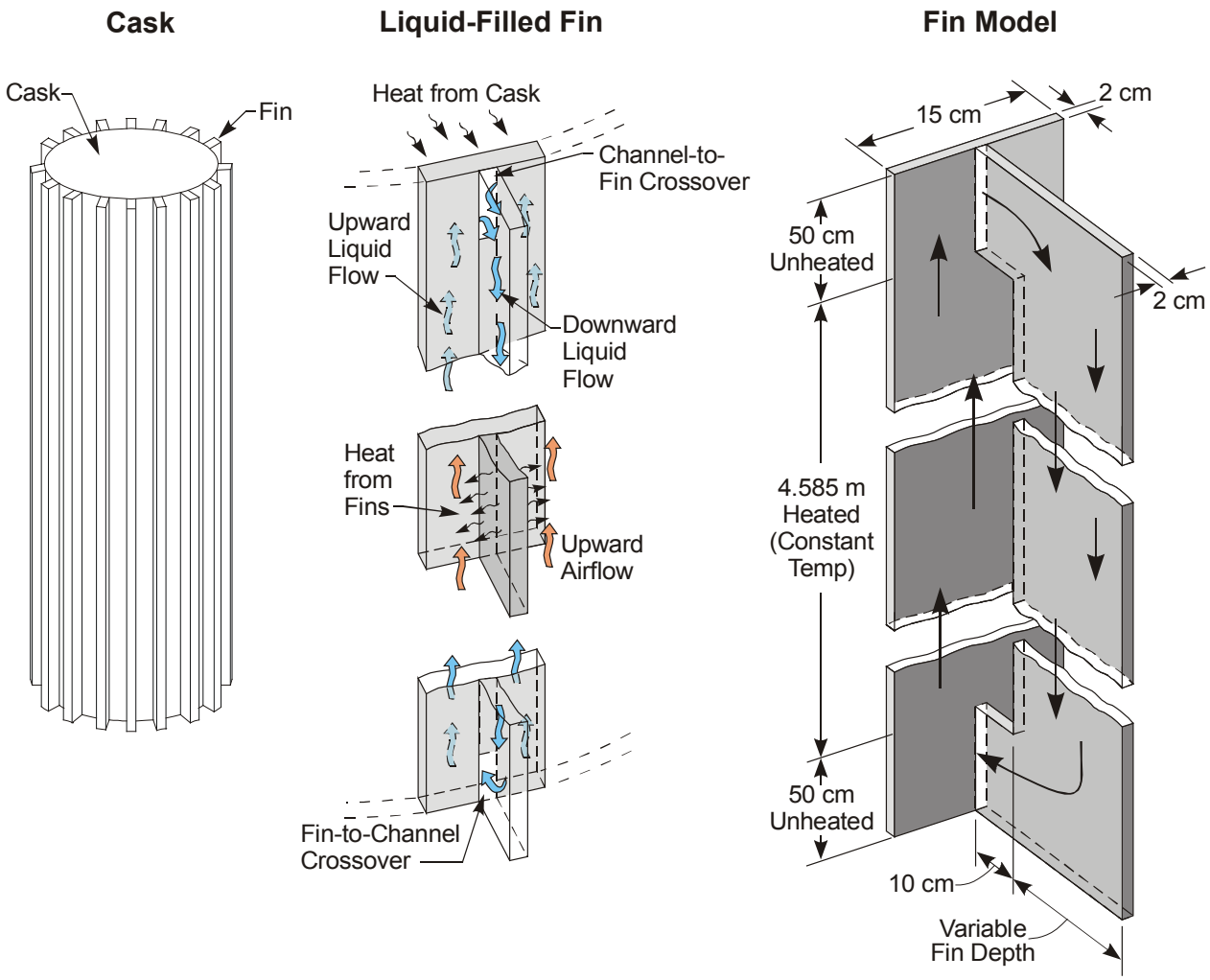
Multipurpose Cask System



Background Information

- Removable fins accomplish multiple goals
  - Fins optimized for storage of short-cooled SNF without the constraints of transport or disposal
    - Rail clearance controls size of transportable cask
      - Removable fins increase allowable transport cask size, once SNF has cooled
      - SNF stored at reactor until fins are not required
    - Simple cylinder required for repository overpack
  - Functional tasks for cooling fins
    - Provide cooling
    - Provide added radiation shielding for cask array storage or short-cooled SNF
- One current cask design (GNSI) uses bolt-on fins
  - Technology demonstrated
  - Technology accepted by the NRC

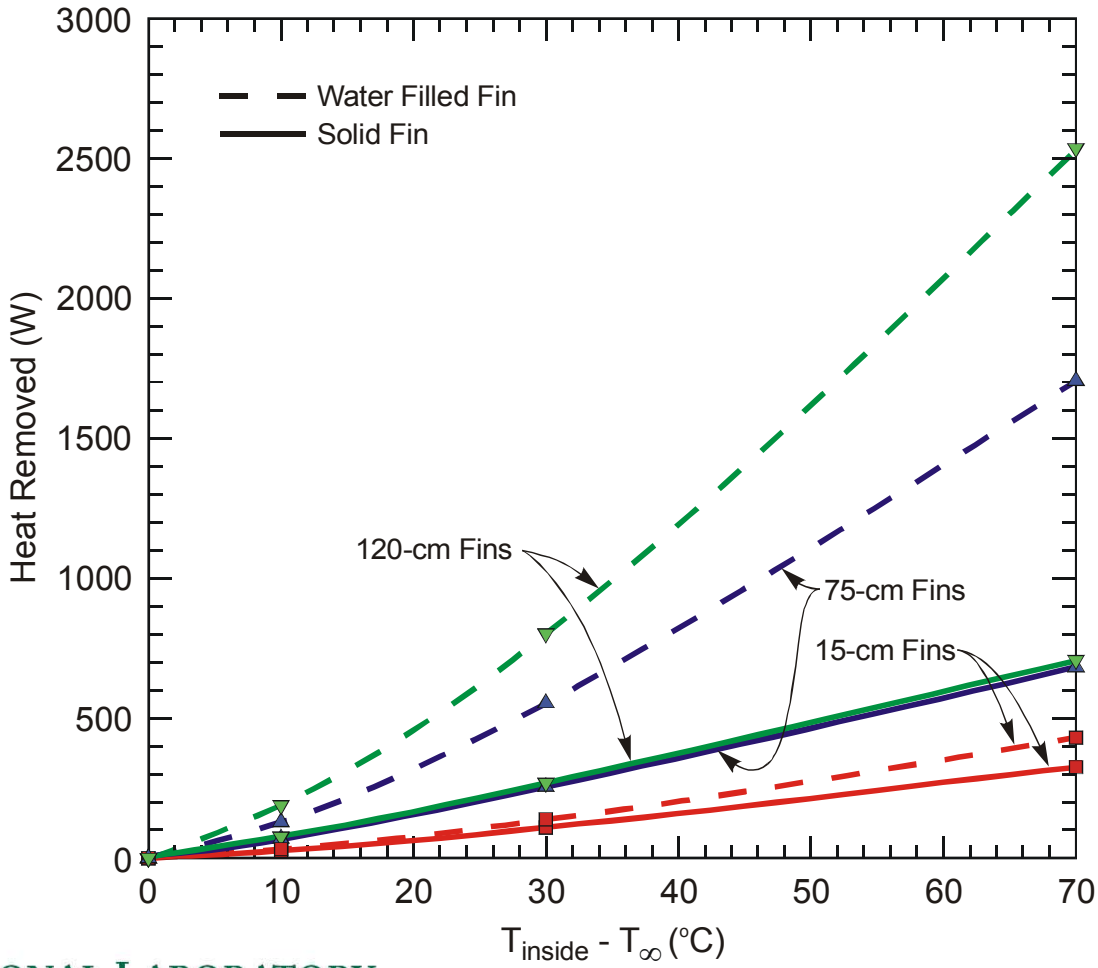
Removable Liquid-Fin Cooling Jackets Were Investigated to Improve Cooling Performance



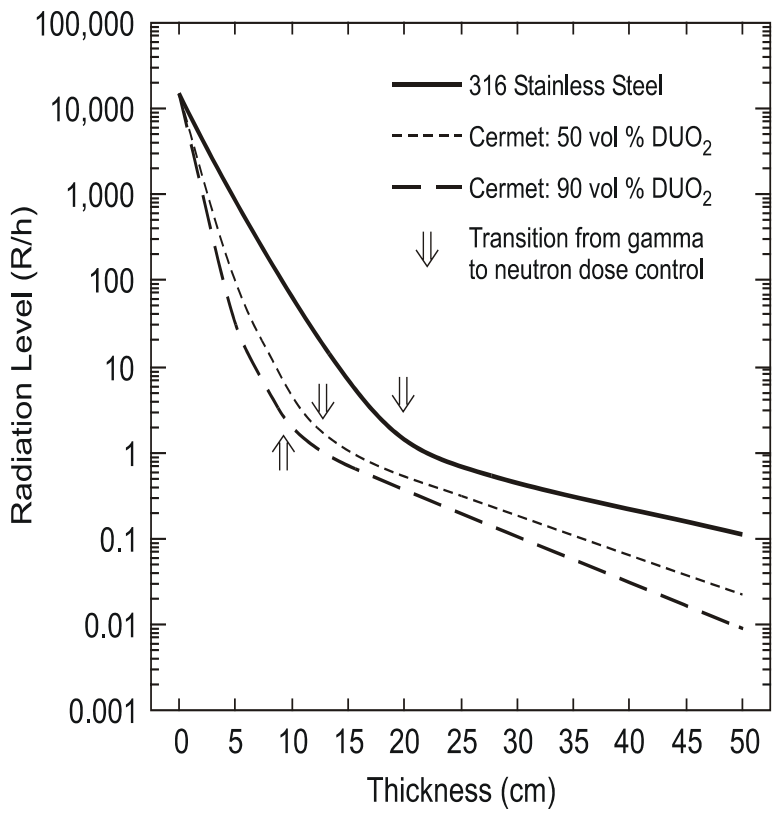
Background Information: Cooling Fins

- Liquid-cooled fins
  - Old technology (electrical equipment)
  - New application
- Each fin is a separate cooling system
  - Redundancy
  - Liquid boil-off (automobile-type radiator cap) provides cooling under fire conditions
  - Infrared camera for inspections
- Cooling water contains antifreeze and corrosion inhibitors

Water-Filled Fins Can Remove More Heat With Smaller Temperature Differences Than Equivalent-Sized Solid Fins



Background: Ongoing Work to Improved Basket Heat Transfer and Neutron Shielding for High-Burnup SNF (High Neutron Dose)



- Cermet outstanding gamma shield
- Cermet acceptable neutron shield (better than steel)
- Current work: Examining graphite basket components
  - Acceptable to repository
  - Excellent heat transfer
  - Neutron shielding (incorporate neutron absorber)

Accomplishments and Path Forward

- Completed analysis of removable cooling system
  - Paper published
- Ongoing activities
  - Graphite basket components (Repository compatible)
    - Provide neutron shielding for high-burnup SNF (limiting factor in cermet shielding performance)
    - Improve basket cooling (high thermal conductivity)
  - Armored super cask (ANS transactions published)
    - Modify cermet cask to improve protection
    - Armor ceramics in cermet may improve neutron shielding for high-burnup SNF
- Path forward
  - Improve performance until cermet performance is the limiting factor under all conditions
  - Conduct discussions with vendors (GNSI, Holtec)

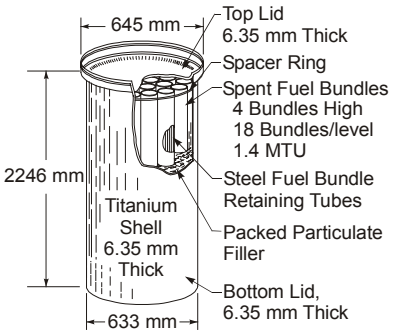
Background on Accomplishments

- **Publications**
  - **C. W. Forsberg and K. W. Childs, "Cooling Multipurpose SNF Casks with Removable Liquid-Filled Fins," *2003 International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 1, 2003,* American Nuclear Society, La Grange Park, Illinois.**
  - **C. W. Forsberg and R. L. Landingham, "Depleted Uranium Dioxide-Steel Cermet Multipurpose Casks for Enhanced SNF Protection," *Trans. American Nuclear Society, 2002 Winter Meeting, p. 313, Washington D.C., November 17-21, 2002*, American Nuclear Society, La Grange Park, Illinois**

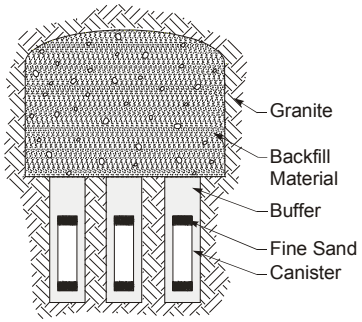
WASTE PACKAGE DUO_2 FILL

Background: Canadian WP Fill Project

Top Left: Canadian WP and emplacement strategy; Collapse of thin wall WP prevented by fill.
Top Right: YM equivalent; Fill prevents WP collapse and thus extends WP lifetime.
Bottom Left: Full scale Canadian WP with simulated SNF, and particulate fill.
Bottom Right: Canadian hydrostatic test chamber; Chamber demonstrated that no WP collapse or significant damage occurred at full lithostatic pressure with a simulated loaded thin-wall WP.

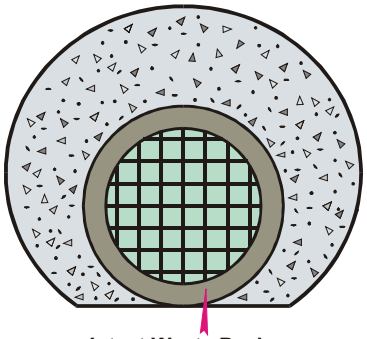


Canister Concept

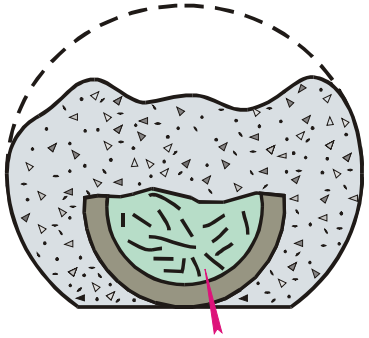


Full Lithostatic Pressure
(Depth = 500-1000 m)

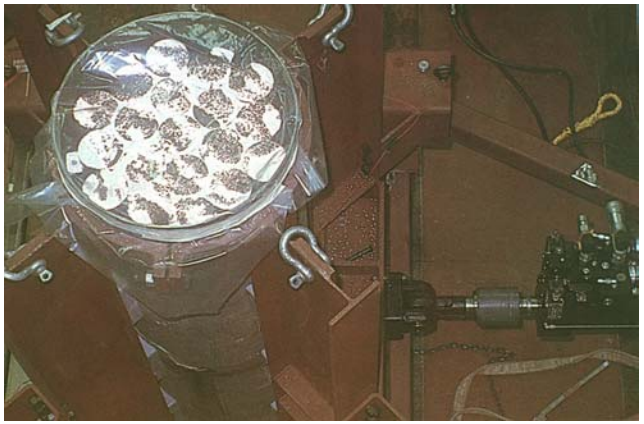
Repository Disposal Concept



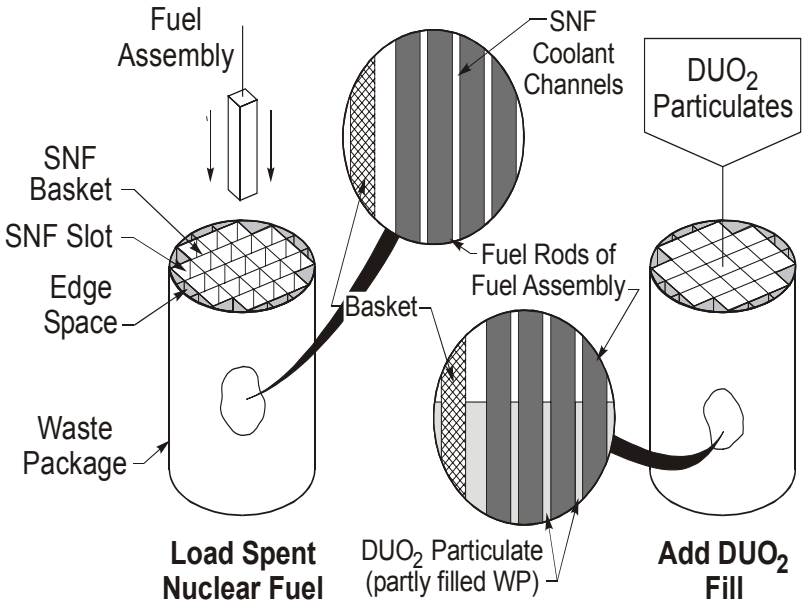
Intact Waste Package or Waste Package with Fill (High Resistance to Collapse)



Failed Waste Package (Collapse With No Internal Support)



Status of DUO_2 Fill Technology
(Previous Year)



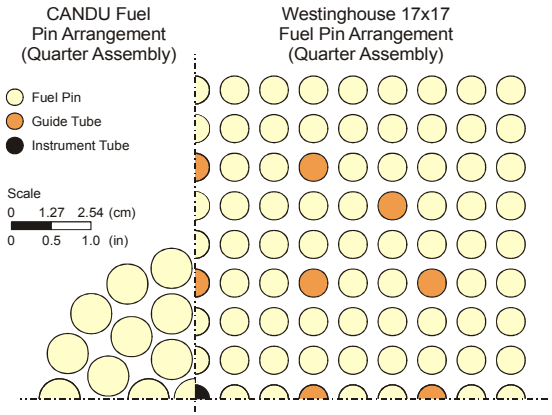
- **Fill technology demonstrated**
  - **Canadian program**
  - **Limited work U.S.**
- **No significant temperature issues**
  - **Thermal conduction because of DUO_2 exceeds thermal convection of helium**

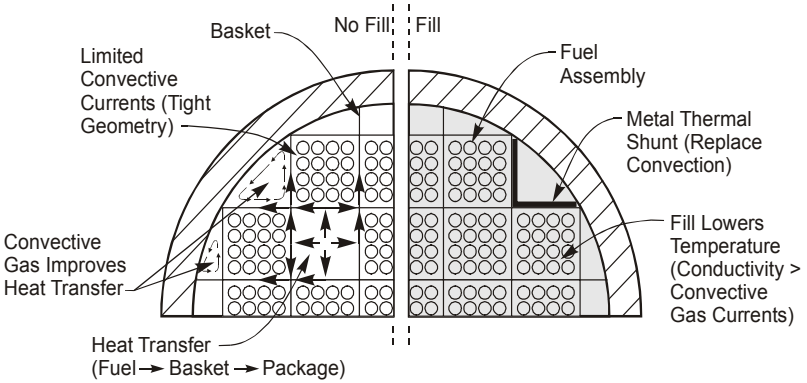
Background: DUO_2 Fill Technology

Top left: Canada demonstrated fill technology with CANDU fuel. Spacing between rods smaller in CANDU SNF than PWRs. Canadian demonstration applicable to LWR SNF

Top right: Fill slightly improves heat transfer because higher thermal conductivity of DUO_2 has a greater impact than elimination of helium convective currents.

Bottom: References on DUO_2 fill





- C. W. Forsberg, *Description of the Canadian Particulate-Fill Waste-Package (WP) System for Spent-Nuclear Fuel (SNF) and Its Applicability to Light-Water Reactor (LWR) WPs with Depleted Uranium-Dioxide Fill*, ORNL/TM-13502, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 20, 1997.
  - Summarizes results of Canadian program on adding fill to WPs.
- C. W. Forsberg, "Depleted Uranium Dioxide As A Spent-Nuclear-Fuel Waste-Package Particulate Fill: Fill Behavior," *Waste Management 2001,* Tucson, Arizona, February 25–March 1, 2001.
  - Describes the evolution of DUO_2 fill under oxidizing groundwater conditions to silicate form. Includes evolution under wet and dry oxidizing conditions.
- C. W. Forsberg, "Effect of Depleted-Uranium-Dioxide Particulate Fill on Spent-Nuclear-Fuel Waste Packages," *Nuclear Technology*, 131: pp. 337–353 (September 2000).
  - Detailed journal article on DUO_2 fill concept.
- C. W. Forsberg, "Depleted Uranium Dioxide as SNF Waste Package Fill: A Disposal Option," *Spectrum 2000: International Conference on Nuclear and Hazardous Waste Management, Chattanooga, Tennessee, September 24–28, 2000*, American Nuclear Society.
  - Describes fill concept, the quantities of DUO_2 fill that can be placed inside a WP under different sets of assumptions, the resultant package weights, and average package enrichments.
- C. W. Forsberg, "Depleted-Uranium Dioxide As SNF Waste Package Particulate Fill: Engineering Properties," *2001 International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 29–May 3, 2001*, American Nuclear Society, La Grange Park, Illinois.
  - Description of particulate fill properties with thermal analysis of SNF WP with DUO_2 fill.

REPOSITORY BENEFITS
(and Issues)

Operations

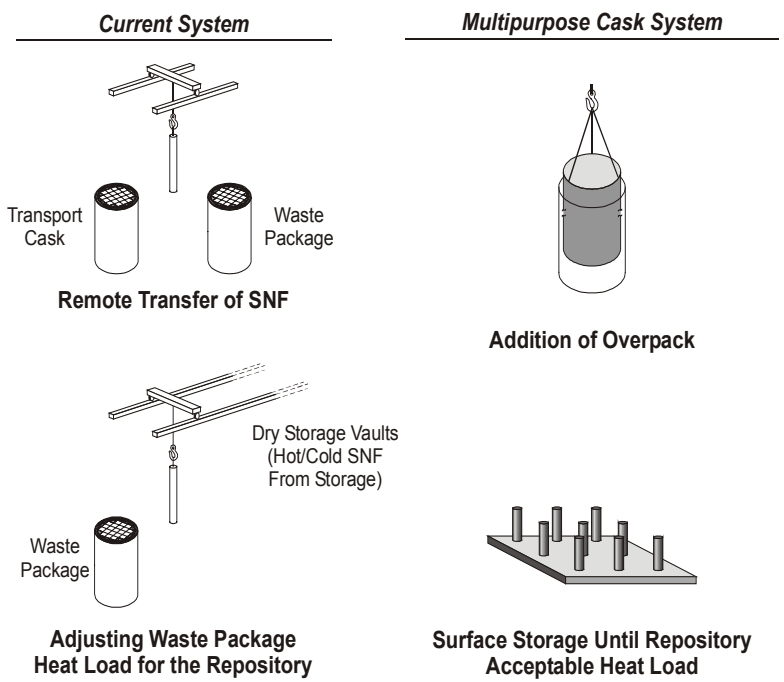
Waste Package Performance

Long-Term Performance

Background: Repository

- **Operational Considerations**
  - The repository limits the decay heat per WP. In the current repository design, mixtures of hot and cold SNF are loaded into each WP to ensure the package decay heat limit is not exceeded. This results in large SNF handling operations. In a multipurpose cask system, the cask is used for surface dry storage until the decay heat is sufficiently low to allow direct placement in the repository. SNF handling is minimized.
  - Multipurpose casks and WPs with DUO_2 fill differ from the YM WP in two ways: (1) the package contains its own shielding, and (2) package weights are higher. Different methods for underground WP heavy haul are required and have been identified.
  - The repository overpack is added to the multipurpose cask at the repository to avoid damage from earlier operations. This is a new repository operation. (In the current design, the overpack is added to the inner WP at the fabricator.)
- **Waste Package Performance (Modified WP helps preserve SNF after WP failure)**
  - Local reducing environment created by iron and DUO_2
  - Waste package permeability to gas and water flow is reduced
  - Hydrated oxides of iron and DUO_2 expected to trap various radionuclides
- **Far-Field Impacts of DU**
  - Isotopic dilution
    - Criticality
    - Reduction in peak dose from U-234, U-235, and U-236
  - Sorption (chromatography column)
    - Potential reduction in neptunium doses

Cermet WP Operational Impacts on Repository



- Surface operations
  - Multipurpose cask storage replaces SNF sorting to meet WP heat limits
  - Contact-handled WP surface operations
    - Add overpack
    - Add fill (optional)
- Underground waste package operations
  - Contact handled
  - Easy retrieval
  - Heavy packages (100 t)
- Separate DU disposal facility is not required

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Underground Transport of 100-ton Self-Shielded WPs Is Required

(Viability Issue: Cermet/Fill WP Heavier than Existing YM WPs)

- Shielding simplifies underground operations but requires heavy-lift vehicle
- Handling option based on Swedish SNF transport system has been identified
  - SNF moved from reactors to central storage facility
  - Operational for a decade
- Meets other repository constraints

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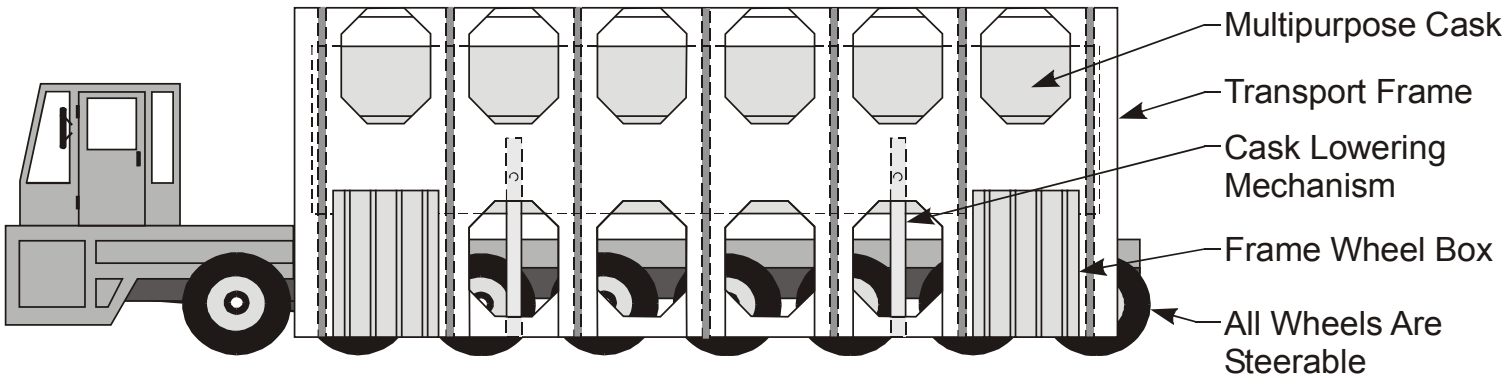
Swedish SNF Transport System

(Courtesy of Swedish Nuclear Fuel & Waste Management Company, Photo by Bengt O. Nordin)

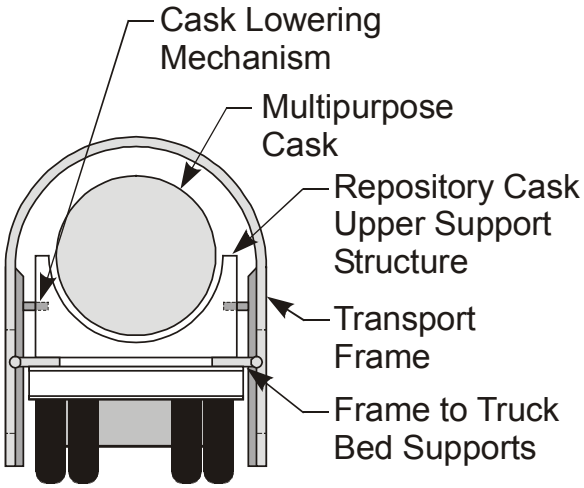
Background: Swedish Transport System

- Transport SNF, HLW, and LLW
- Nominal cask weight: ~110 tons
- Transporter
  - Diesel and electric (underground) drive
  - 28 wheels, all steerable
  - Precision transport frame placement
    - Loaded frames transported by ship
    - Frames couple to ship hold-down clamps

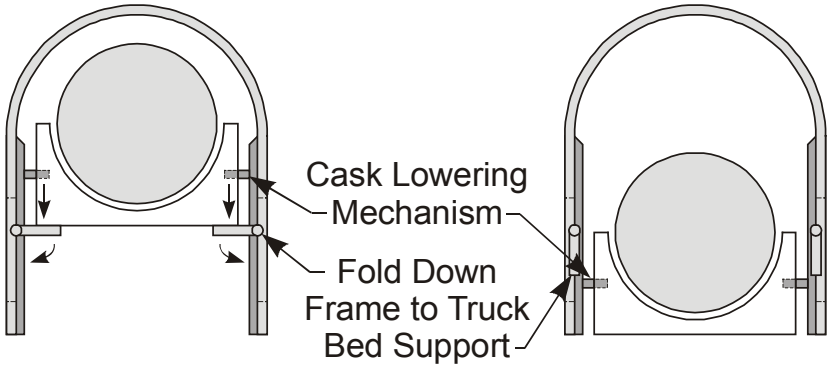
Proposed Repository WP Transport System



Side View



End View

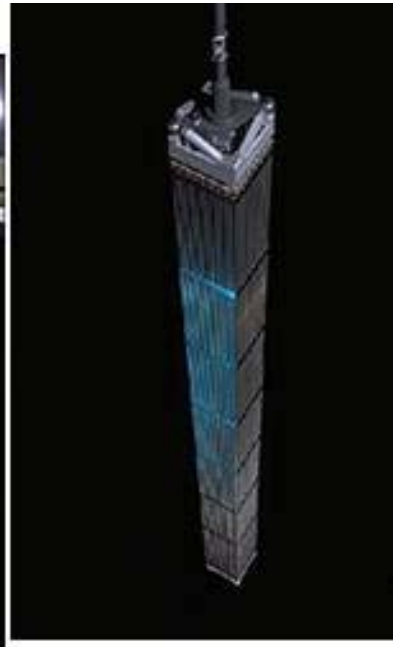


Unloading Cask in Repository

Background: Operation of Heavy Haul System

- **Cask preparation**
  - Fill added to WP, overpack added to WP
  - In-repository cask cradle attached to WP
- **Load cask onto transport frame**
  - WP with repository cradle raised from floor
  - Transport frame lowered and attached to WP with cradle
- **Move transport frame and WP to disposal drift**
  - Transport vehicle backs under transport frame
  - Transport vehicle bed raises frame off floor
  - Transport vehicle and load driven to the disposal drift
  - Transport vehicle lowers frame and drives away from frame with load
- **Unload cask and cradle from frame**
  - WP and cradle lowered from transport frame
  - WP and cradle separated from frame
- **Pull transport frame from cask**
  - Lower dolly wheels from transport frame
  - Pull frame away from WP
  - Raise dolly wheels
  - Transport vehicle picks up empty frame for transport

Cermet/Fill WPs Enable Co-Recovery of Depleted Uranium and Spent Nuclear Fuel—If Needed in the Future
(Shielded WPs Simplify Recovery)



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Accomplishments and Path Forward
(Operations)

- Waste package heavy haul
  - Feasibility issue addressed (complete)
  - Paper published
- Path forward: addressing other constraints
  - How to add repository overpack to DU cask

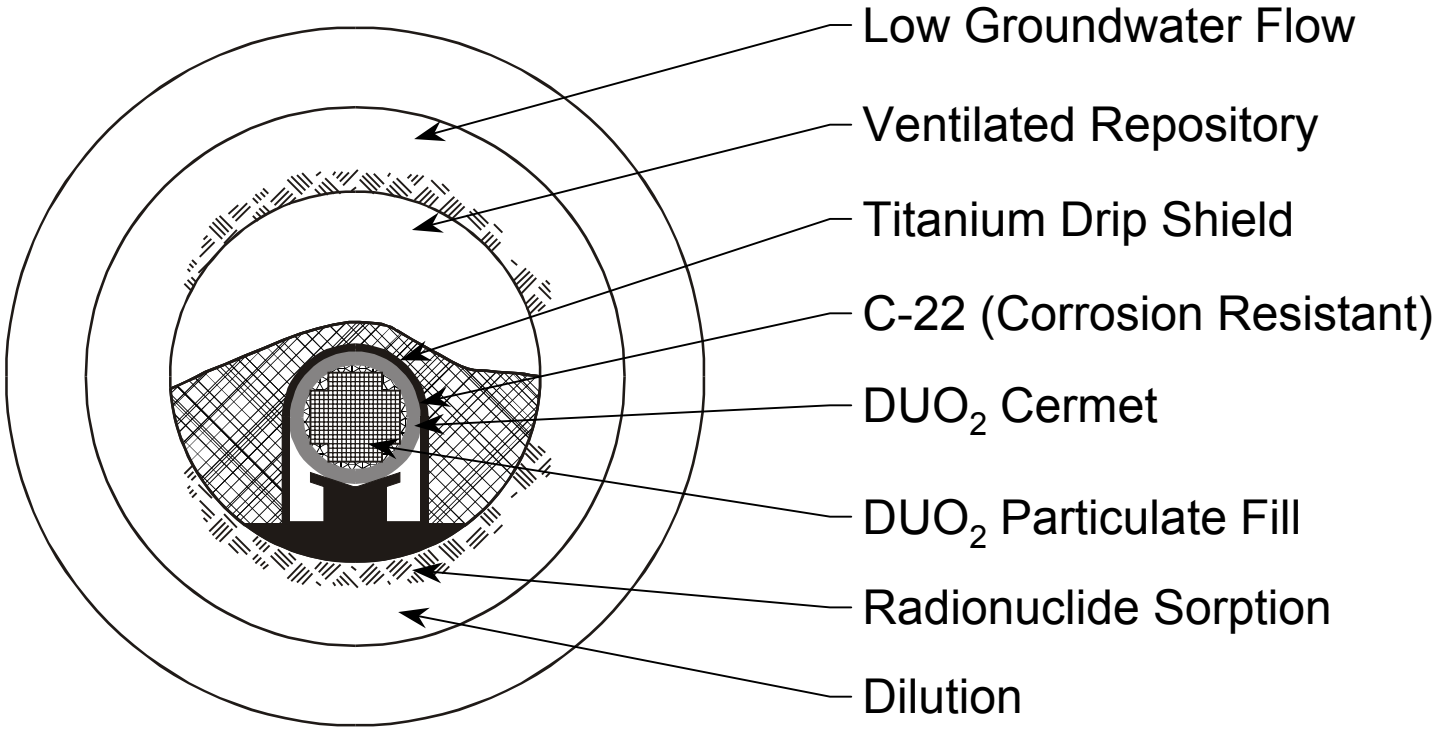
Background: Operations

- **Paper: C. W. Forsberg, "Retrievable Depleted Uranium-Dioxide Cermet Spent-Nuclear-Fuel Multipurpose Cask," *2003 International High-Level Radioactive Waste Management Conference: Las Vegas, Nevada, April 2, 2003*, American Nuclear Society, La Grange Park, Illinois**

Waste Package Performance

Delay Degradation of Spent Nuclear Fuel After WP Failure

Background: The DUO_2 Is an Independent Barrier to Radionuclide Release That Operates Sequentially with Other Barriers



Observations

- The Yucca Mountain Repository has an oxidizing geochemical environment
- Most radionuclides are trapped in the SNF UO_2
- SNF degradation is very slow in reducing environments, fast in oxidizing environments
- Fill and cermet WPs contain large quantities of reducing agents [depleted uranium dioxide (DUO_2) and iron (Fe)]
- The potential exists to create local zones of reducing agents around the SNF to delay SNF degradation and radionuclide releases

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Results from Analysis

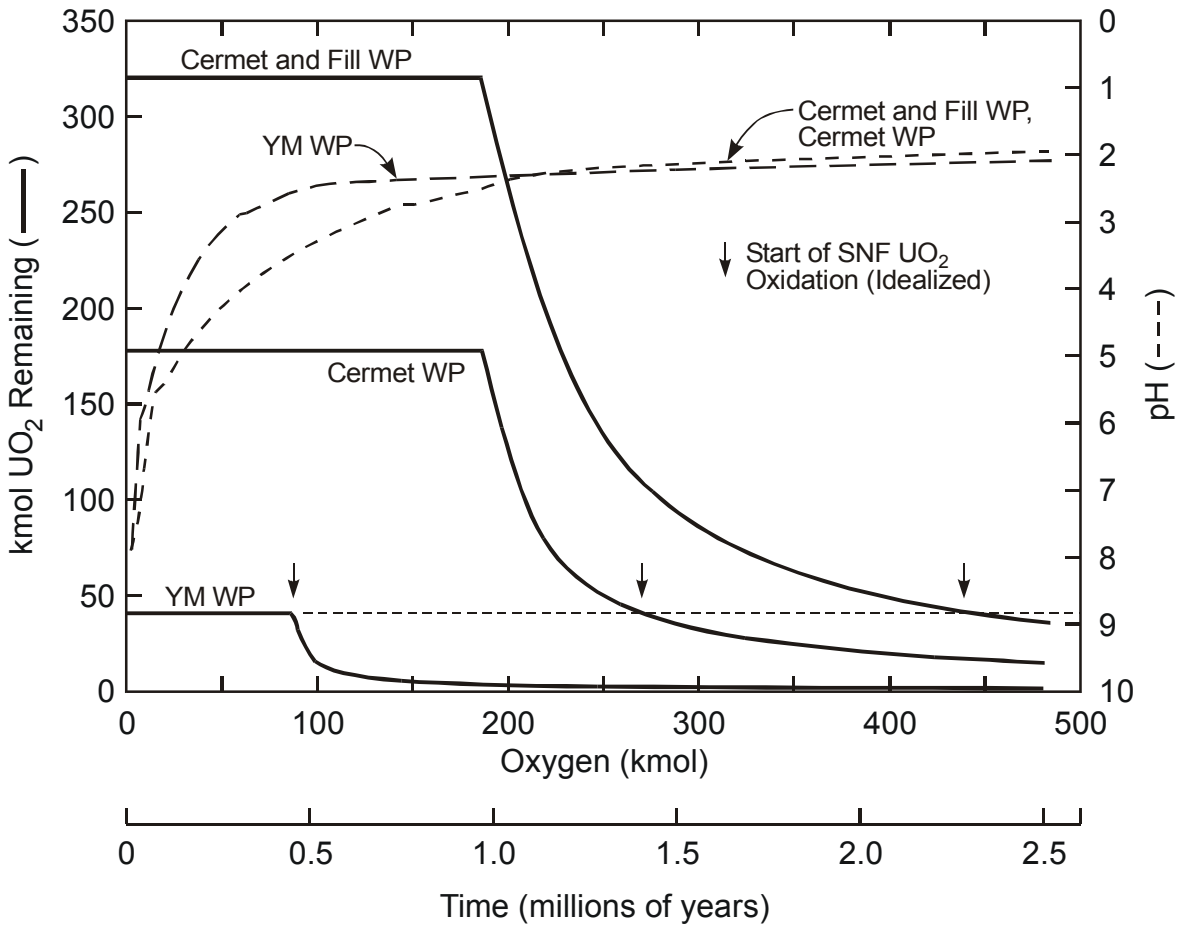
- Oxygen is transported to SNF after WP failure via three mechanisms
  - Groundwater
  - Air
  - Radiolysis of water (Internal mechanism)
- Groundwater transport of oxygen is very slow
- Diffusion of oxygen from air controls SNF degradation rates
- Package characteristics can limit oxygen diffusion and help maintain SNF integrity

Background: SNF Degradation Under Chemically Reducing Conditions

- **YM has oxidizing geochemical environment**
  - **WP becomes oxidizing upon failure**
  - **Little work on reducing environments**
- **Swedish repository models address UO_2 and iron under long-term reducing conditions: conditions that exist if chemically reducing conditions maintained near the SNF**
  - **LWR SNF**
  - **Steel package with copper exterior liner**
- **Swedish work addressing radiation oxidation effects (Liu and Neretnieks, *Nuclear Technology*, March-April 2002)**

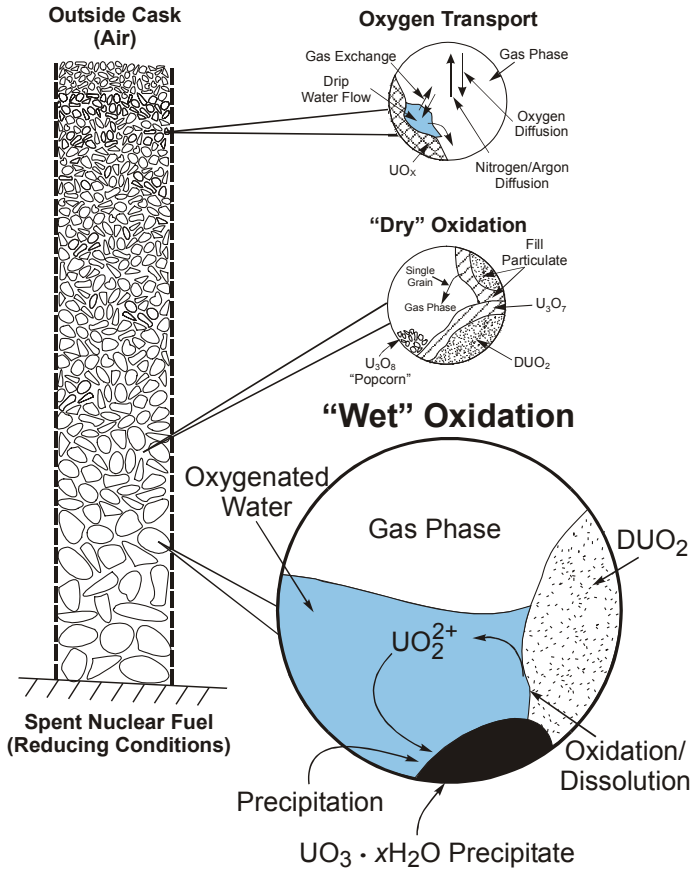
SNF Oxidized Slowly by Oxygen in Groundwater

(Idealized Thermodynamic Calculation: Oxygen Only from Groundwater)

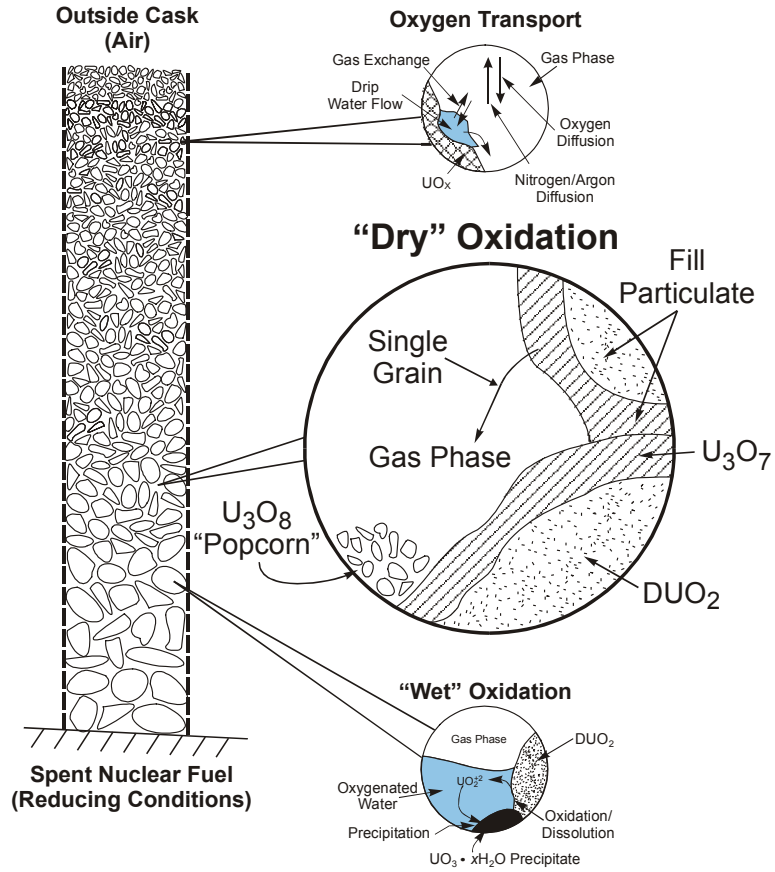


DUO_2 Oxidation Slows SNF Degradation

Wet Oxidation

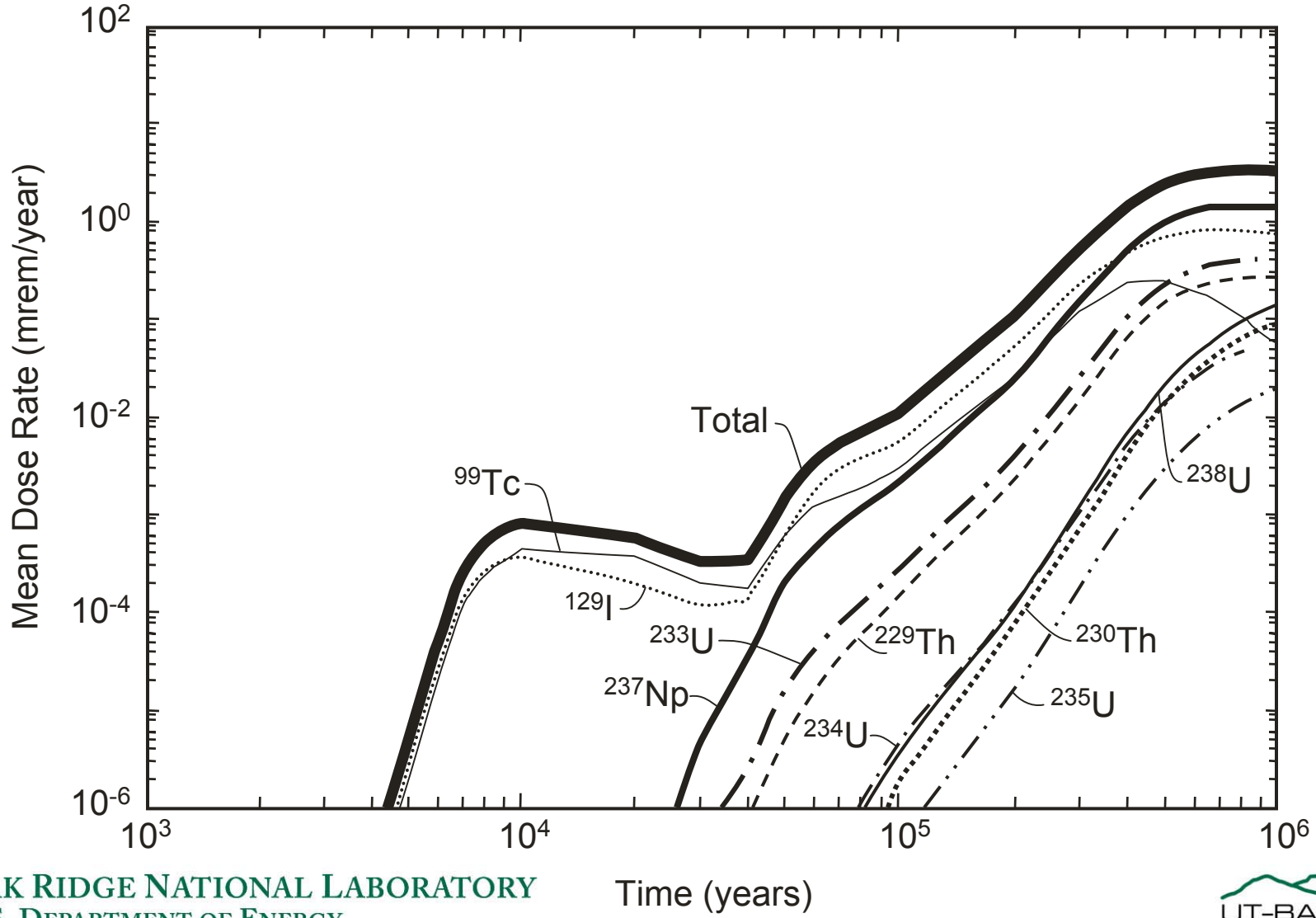


Dry Oxidation



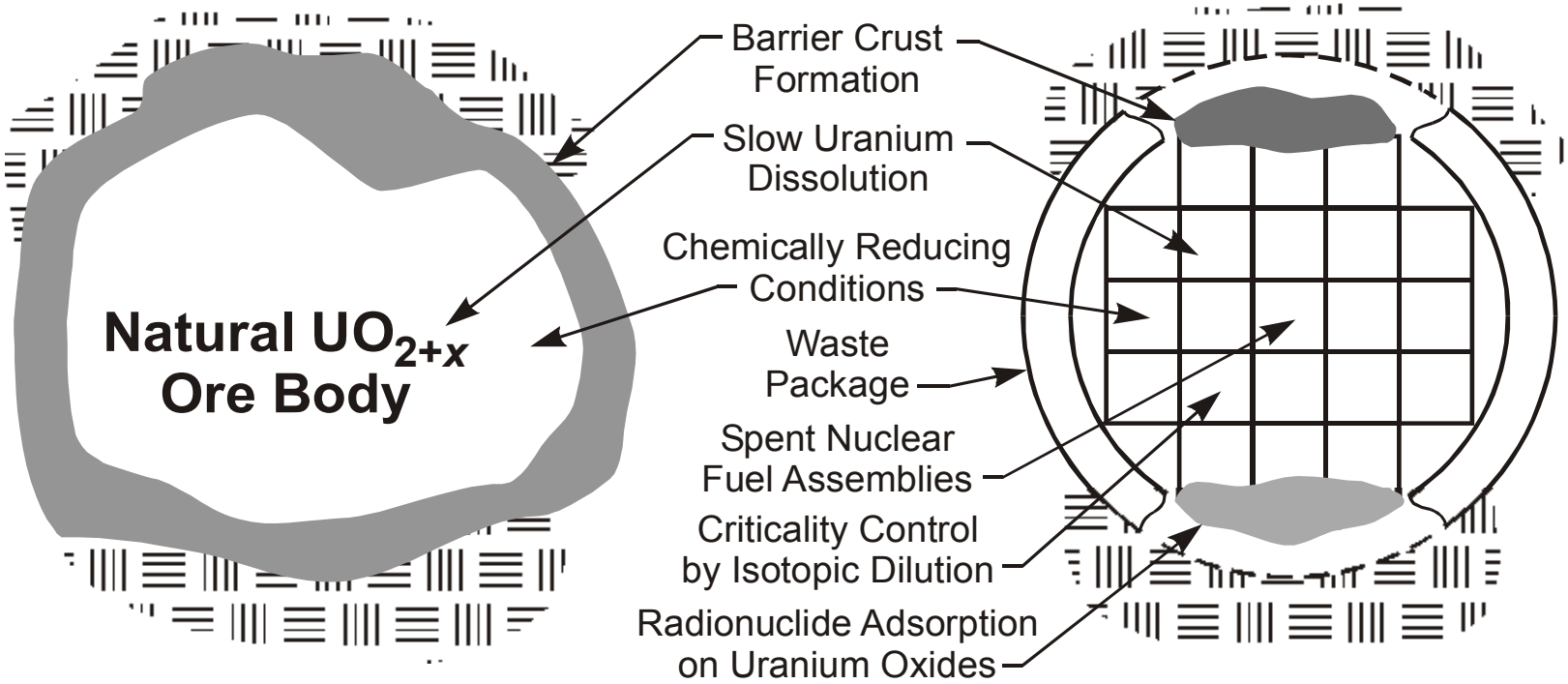
Performance Assessments Show Faster SNF Oxidation

(YM Waste Package Does Not Maintain Reducing Conditions)



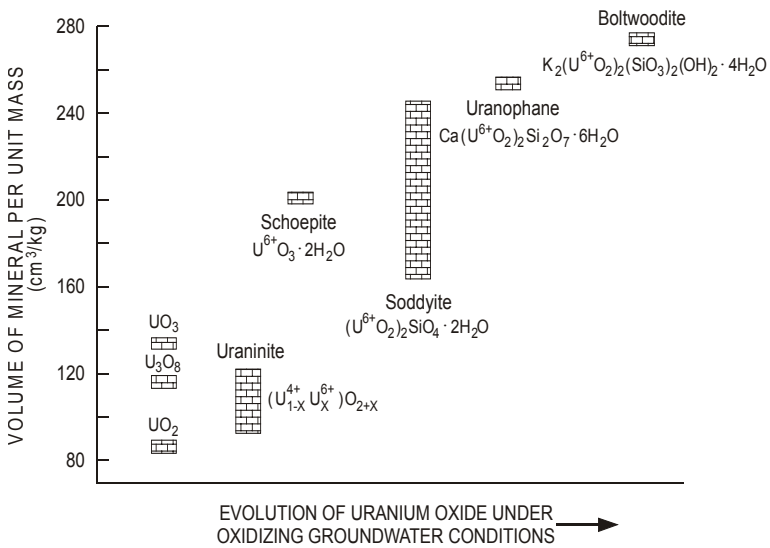
Background: Some Uranium Ore Deposits Have Remained Intact for Millions of Years: The Same Mechanisms Should Delay SNF Degradation in Failed WPs Containing DUO_2

(DUO_2 Is the Only Sacrificial Compound to Preserve SNF UO_2 Under All Conditions)

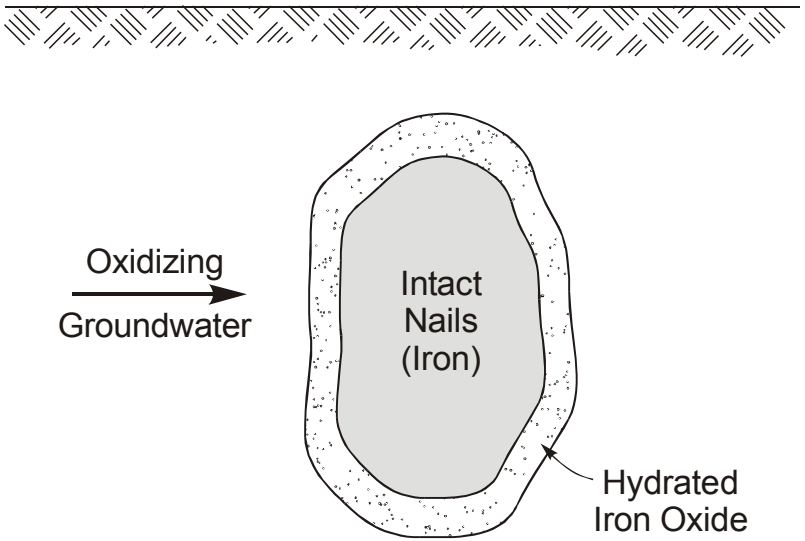


Real-World UO_2 and Iron Deposits Have Slow Water Flow, Slow Gas Diffusion, and Slow Oxidation

Natural UO_2 Ore Deposits



Roman Nail Deposits

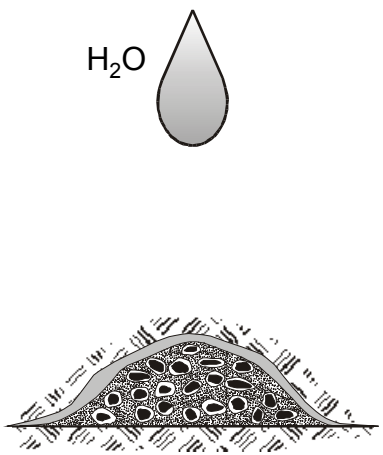


Background on Oxidation

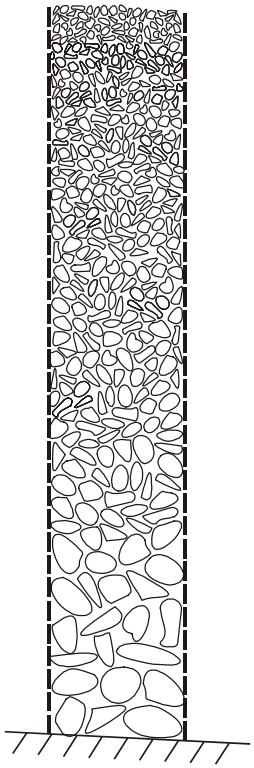
- **DUO_2 Fill**
  - DUO_2 is a reducing agent that slows SNF oxidation
  - DUO_2 partly saturates groundwater that in turn slows SNF UO_2 dissolution
    - SNF dissolution rate depends upon uranium concentration gradient from the SNF uranium surface to the groundwater
    - Fully saturated groundwater can not dissolve more uranium
    - Degree of saturation depends upon kinetics
- **Cermet**
  - Oxidation sequence: iron oxidation followed by DUO_2 oxidation
  - Iron oxidation
    - Assume iron cermet, stainless steel (current YM WP) may not be acceptable because of different corrosion kinetics and corrosion products
    - Iron forms hydrated iron oxide gels
      - Potentially very low permeability
      - Iron used in water treatment to remove impurities
      - Fuller understanding of corrosion sequence required
  - DUO_2 oxidation similar to fill oxidation

Analog Experience Suggests Blocking Oxygen Transport To SNF May Succeed; Design WP To Block Oxygen

Groundwater with Dissolved Oxygen (Slow)



Oxygen in Disposal Drift



- Barometric pumping
- Diffusion of oxygen through gas phase
- Diffusion of oxygen through capillary waste

Background: Oxygen Transport

- Groundwater oxygen transport dependencies
  - Degraded WP cross section to flow
  - Formation of protective crusts
    - Iron gel formation would imply bypass of water
- Gas-phase diffusion of oxygen slow if capillary action fills void spaces with water
  - Oxidation of iron and DUO_2 may fill void spaces
  - DUO_2 and iron degradation products are hydrated oxides with wetted surfaces
  - Diffusion coefficients for oxygen in water are 10,000 times smaller than those for air

Accomplishments and Path Forward
(Chemically Reducing Waste Package)

- Analysis of fill/cermet WPs (paper published)
  - Potential gains in WP performance estimated
  - Factors controlling performance identified
- Ongoing work (Can SNF degradation be slowed to decrease ^{99}Tc, ^{129}I, and ^{237}Np releases?)
  - UC-Berkeley (D. R. Orlander) investigating UO_2 fill oxidation (Cooperative effort; no financial support)
  - ORNL exploring impacts of hydrated iron oxide gel formation
- Path forward
  - Working with DOE and the Russian Academy of Sciences to obtain funding of RAS DUO_2/iron work

Background

- **Publication**
  - **C. W. Forsberg and L. R. Dole, "Maintaining Chemically Reducing Waste Package Conditions in an Oxidizing Geochemical Environment," *Scientific Basis for Nuclear Waste Management XXV I, Materials Research Society Fall Meeting, Boston, Massachusetts, December 2-6, 2002,* Materials Research Society, Warrington, Pennsylvania**

Radionuclide Migration

Uranium Isotopic Dilution

Neptunium Absorption

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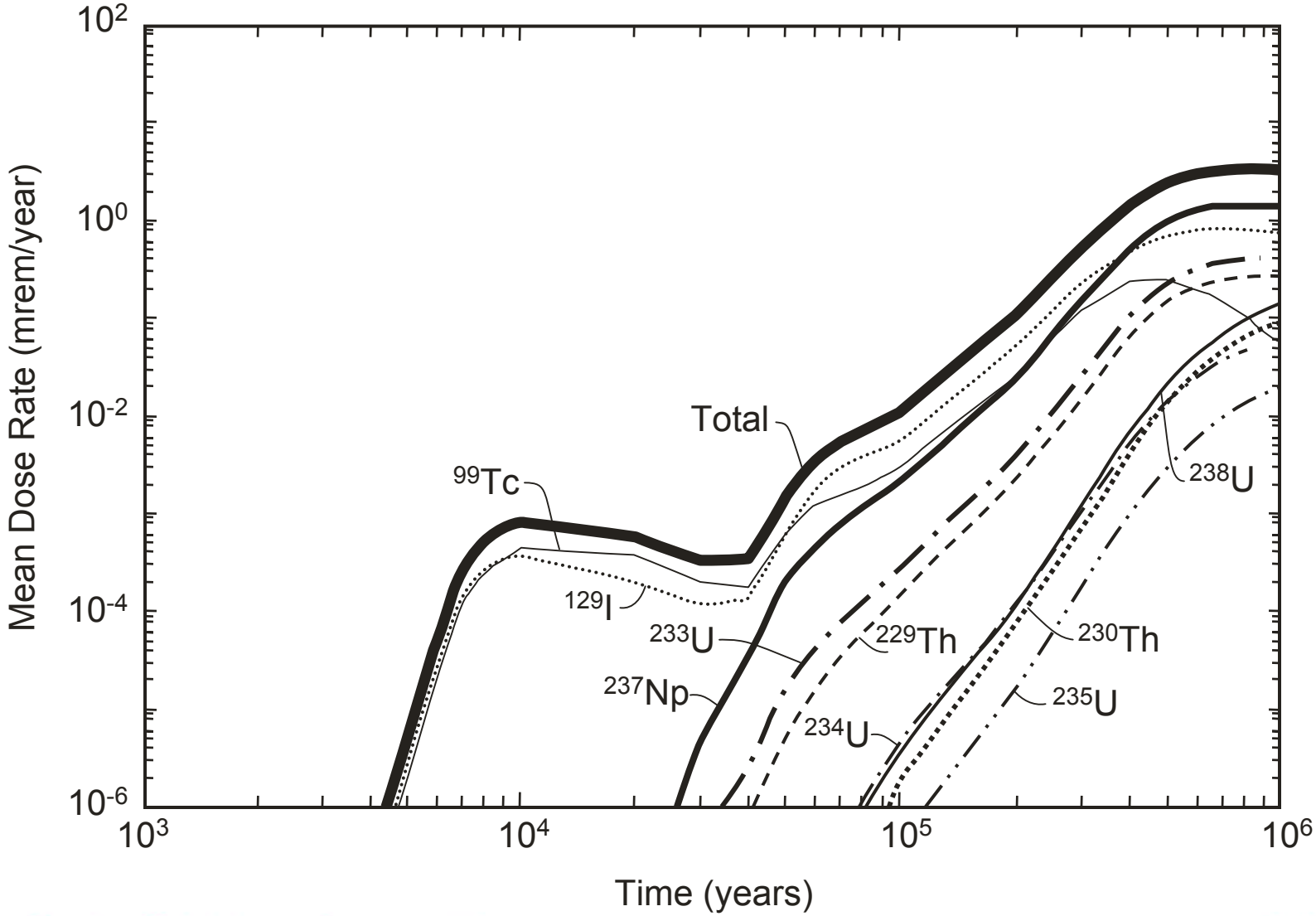
Shorter-Lived Uranium Isotopes and Decay Products Contribute to Expected Yucca Mountain Exposures



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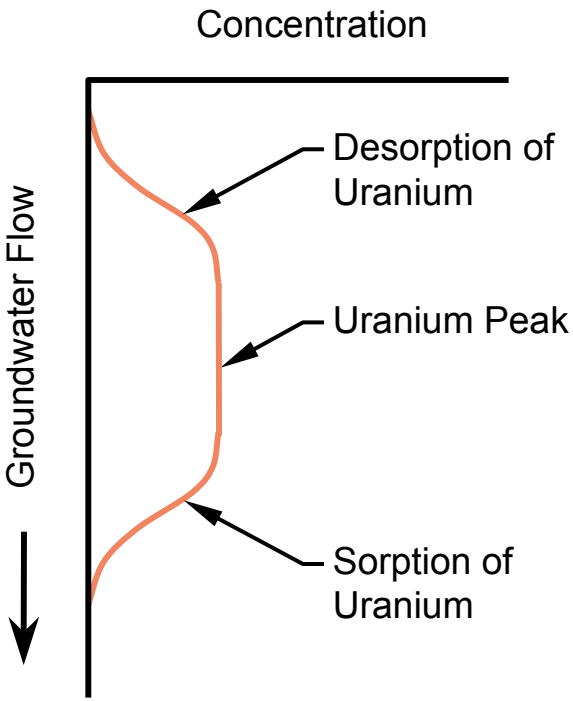
DU Addition May Reduces Radionuclide Dose from Other Uranium Isotopes

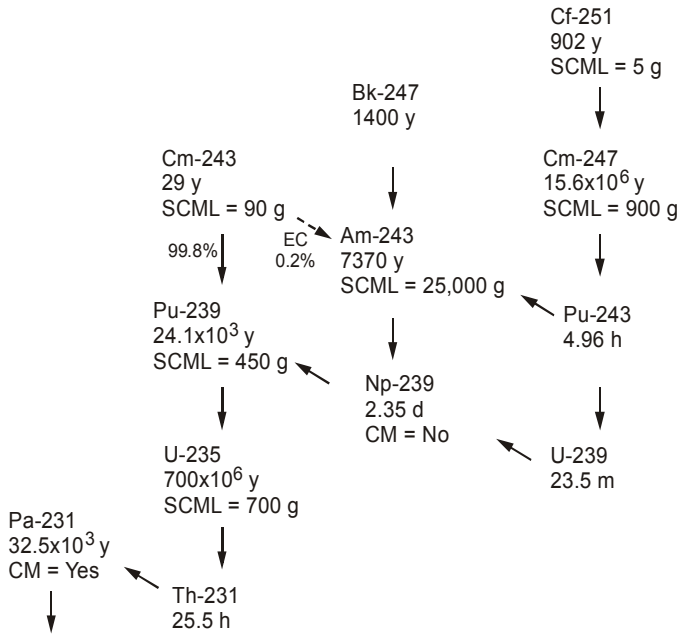
(Under Investigation)

Groundwater Flow Mixes Isotopes



- **Uranium releases**
  - **Controlled by solubility**
  - **Uranium uptake by humans is fixed (for any scenario)**
- **Addition of DU**
  - **Changes uranium isotopics**
  - **Reduces dose from uranium isotopes by dilution with long-lived ^{238}U**
    - **^{233}U: $T_{1/2}$ = 160,000 y**
    - **^{234}U: $T_{1/2}$ = 250,000 y**
    - **^{235}U: $T_{1/2}$ = 700,000,000 y**
    - **^{236}U: $T_{1/2}$ = 24,000,000 y**

Background: The Other Uranium Isotopic Dilution Effect: DU Reduces Long-Term Criticality Issues In the Repository



- Most fissile isotopes decay to longer-lived uranium isotopes before large-scale WP failure
- Long-term repository criticality issues are ^{235}U and ^{233}U
- Large quantities of DU in the WP isotopically dilute the uranium fissile isotopes
  - Cermet: 3+ tons of DU per ton of SNF
  - Fill: 3+ tons of DU per ton of SNF
- Average WP enrichment: <<1%
- Quantity of DU can be varied

Excess Uranium May Delay Neptunium Releases (Work in Progress)

- ANL data suggest sorption of neptunium on various hydrated uranium oxides
  - ANL studying SNF degradation
  - Need data for neptunium in groundwater flowing through hydrated uranium oxides
- U.S.-Russian Academy of Sciences program has been initiated to experimentally investigate effect
  - ISTC (U.S. Department of State) funding
  - Funding approved (March 2003)
  - Kickoff detailed work plan meeting (June 2003)

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Accomplishments and Path Forward

- Accomplishments
  - Developed concept of DU isotopic dilution for shorter-lived uranium isotopes
  - Initiated Russian neptunium study
    - ISTC (Department of State) Funding (March 2003)
- Path forward
  - Develop case for extended SNF lifetimes
  - Follow Russian work
  - Define approach for assessment using YM or EPRI performance code systems

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CONCLUSIONS

- Accomplishments
  - Cermet casks
    - Invented potentially low-cost fabrication method
    - Refined concept of multipurpose cask system
    - Developed cask cooling concept (boost cooling capacity and increase transportable cask size)
  - Repository performance
    - Developed concept of isotopic dilution to reduce dose from shorter lived uranium isotopes
    - Improved understanding of degradation of SNF
  - Developed Russian interactions on Np/Tc sorption and cask development
- Path Forward
  - Develop cask fabrication method
  - Develop vendor, DOE, EPRI interfaces
  - Improve understanding of repository benefits