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CASE

CASE WESTERN RESERVE UNIVERSITY

Materials Performance Targeted Thrust

Presented to:

Advisory Committee on Nuclear Waste

Nuclear Regulatory Commission

Presented by:

Dr. Joe H. Payer

Thrust Lead-OST&I Materials Performance

Case Western Reserve University

March 23, 2006

Rockville, MD

This presentation has been funded in whole or in part by the U.S. Department of Energy

Technical Scope and Directions

- Good Science
  - Materials Performance; Corrosion; Electrochemistry; Materials Science; Physical Chemistry; Geochemistry
  - Responsive to Office of Science and Technology and International (OST&I) mission, including the distinction between technology development/enhancements issues and Project Baseline & License issues
- Addresses State-of-Science Issues
  - Enhance the understanding of materials corrosion performance
  - Explore technical enhancements

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Participants in Materials Performance Targeted Thrust - Universities

- DOE/OST&I Multi-University Corrosion Cooperative (CorrCoOp)
  - DOE CorrCoOp is based at Case Western Reserve University
  - Comprised of some 14 principal investigators and approximately 20 graduate students and research scientists
- Arizona State University
- Case Western Reserve University
- The Ohio State University
- Pennsylvania State University
- University of California at Berkley
- University of Minnesota
- University of Toronto
- University of Western Ontario
- University of Virginia

Participants in Materials Performance Targeted Thrust - National Laboratories and Others

- National Laboratories
  - Argonne National Laboratory (ANL)
  - Lawrence Livermore National Laboratory (LLNL)
  - Lawrence Berkley National Laboratory (LBNL)
  - Oak Ridge National Laboratory (ORNL)
  - Pacific Northwest National Laboratory (PNNL)
- Other Participants
  - Atomic Energy of Canada Limited (AECL)
  - OLI Systems, Inc., a cutting edge chemical process technology and computer software company

Programmatic Structure

- Focus is on process of corrosion, materials science, electrochemistry, physical chemistry, geochemistry
- Coordinated, multi-investigator approach
  - Complimentary expertise and specialized skills for targeted topics
- Engage leading scientists/engineers from universities and national laboratories
- Coordination projects with Natural Barriers Thrust and Source Term Thrust
- Transition science to advanced technologies and Yucca Mountain Project as appropriate
  - For example, High Performance Corrosion Resistant Metals Project transitioned from Materials Performance thrust to OST&I Advanced Technologies program

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Overview of OST&I Materials Performance Thrust

- Organized to address important topics:
  - Long-term behavior of protective, passive films
  - Rate of penetration and extent of corrosion damage over extremely long times
  - Composition and properties of moisture in contact with metal surfaces
- Three multi-investigator, coordinated projects:
  - Corrosion of metal surfaces under particulate and deposits
  - Evolution of corrosion damage by localized corrosion
  - Evolution of environment on metal surfaces

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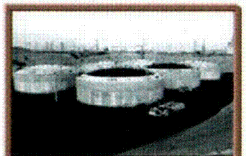
Background/Perspectives

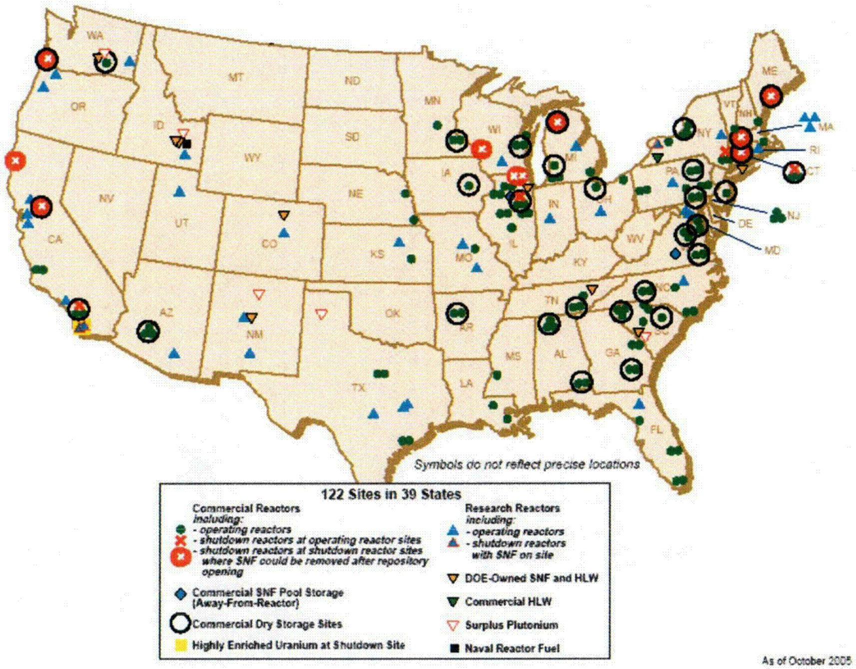
- Corrosion is a primary determinant of waste package performance at the proposed Yucca Mountain Repository
  - The most likely degradation process
  - Controls the delay time for radionuclide transport from the waste package
  - Determines when packages will be penetrated and the shape, size and distribution of those penetrations
- In the remainder of this presentation the proposed Yucca Mountain Repository is viewed from a corrosion perspective

Locations of Spent Nuclear Fuel and High-Level Radioactive Waste



Defense Complex Clean-Up

Support of Nonproliferation Initiatives, e.g. Disposal of DOE Foreign Research Reactor Spent Fuel



Commercial Spent Nuclear Fuel

Disposition of Naval Reactor Spent Nuclear Fuel

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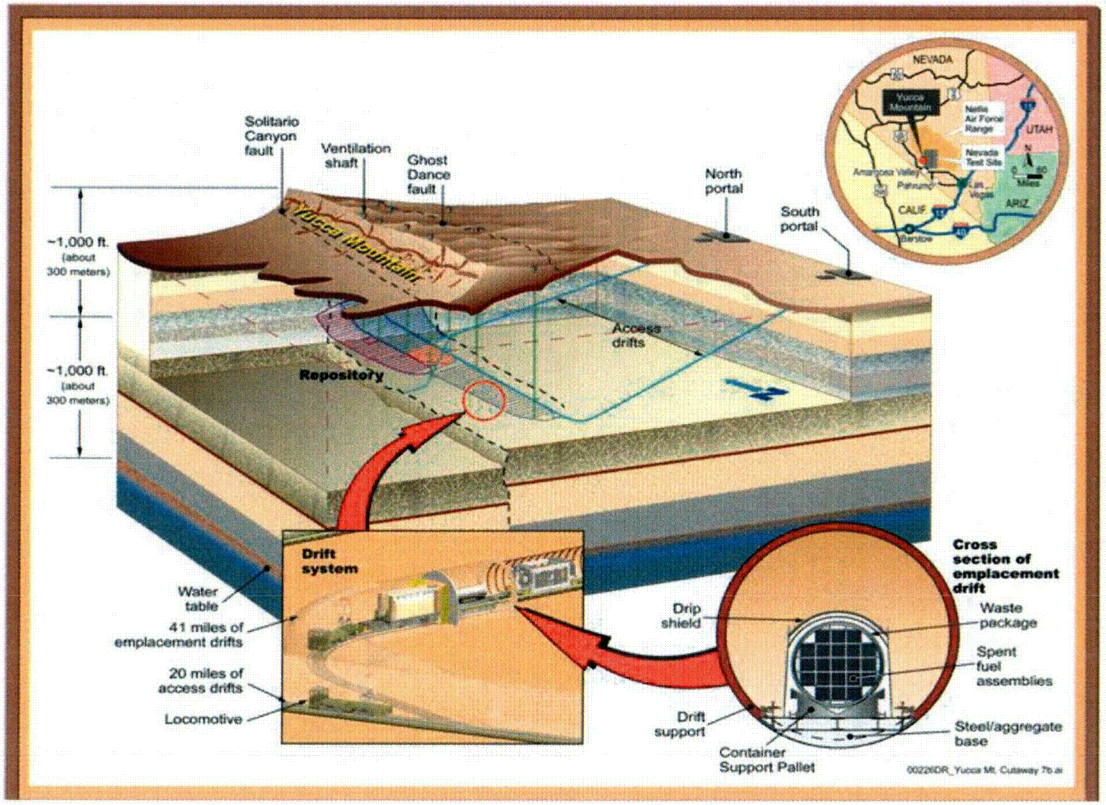
The Proposed Yucca Mountain Repository

Repository Reference Design Concept



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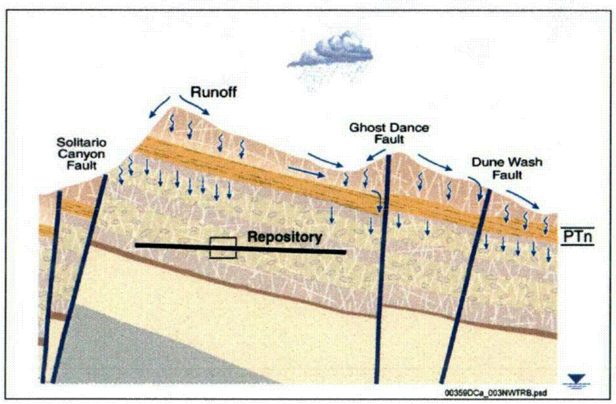
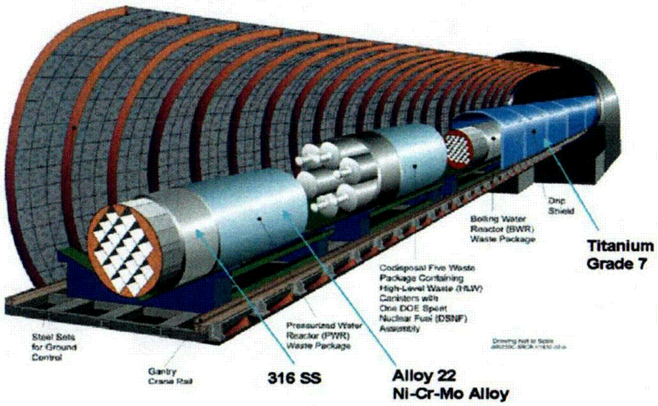
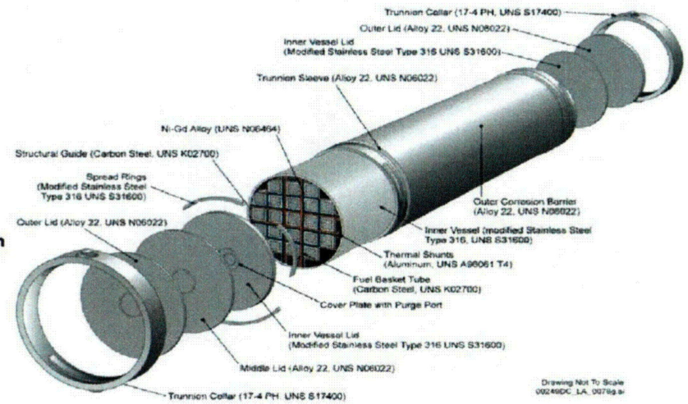
The Proposed Yucca Mountain Repository



- Proposed Repository is about 300 m below the surface and 300 m above the water table
- Unsaturated zone, i.e. fractures and pores in rock are partially filled with water
- Desert area with about 18 cm of rain per year atmospheric pressure
- Ambient waters are dilute and near neutral pH
- Concentrated waters can form by condensation, deliquescence and evaporation

Emplacement Drifts and Waste Packages





- Outer corrosion resistant barrier: Alloy 22 cylinder
- Inner structural vessel: 316 Stainless Steel cylinder
- Drip shield plates: Ti Grade 7
- Drip shield structural supports: Ti Grade 24/29

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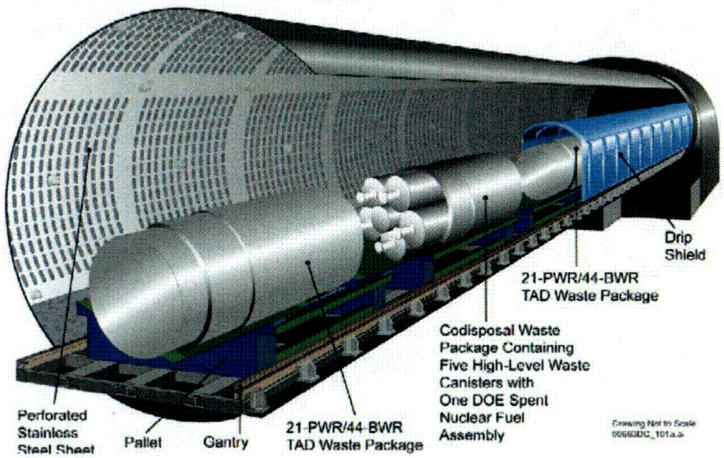
Canistered Fuel Option Under Consideration

- Utilities load fuel into Transport/Age/Dispose Canisters (TADs) which are shipped to YMP
- TADs loaded into waste packages
  - Minimizing handling of bare fuel.
- The outer Alloy 22 WP lid(s) would then be weld sealed.



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Background on Ni-Cr-Mo Alloys

- Alloy 22 belongs to a family of Ni-Cr-Mo alloys
  - Earlier alloys include C-276 and C-4 and later alloys include: Inconel 686, Alloy 59, Hastelloy C-2000 and MAT-21
  - Alloy 22 (N06022) is a solid solution of Ni, Cr, Mo and W as the main alloying elements
  - Cr-Mo-W in Alloy 22 act synergistically to provide resistance to localized corrosion such as crevice corrosion
- Large industrial equipment in service for many years in harsh environments without corrosion
  - Alloy 22 has great toughness and over 50% elongation before failure
  - Can be hot or cold formed and is weldable by many methods
  - Can be fabricated into large structures and components

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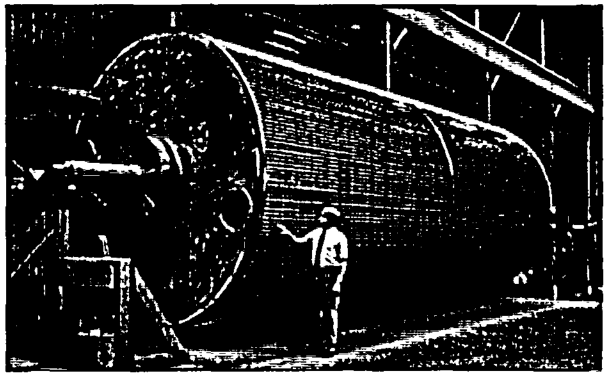
Industrial Experience in Harsh Environments



Pulp and Paper Bleach Washer

Fabricated in 1987 using C-22 material

Went into service for International Paper plant in Texarkana

Operation in highly oxidizing wet chlorine and chlorine dioxide solutions

Agitator in Bleach Plant

C-22 agitator installed in 1985

Environment with chlorine and chlorine dioxide, up to 5000 ppm chloride, temperature up to 60°C

Other alloys such as 904L, 317L SS and 254SMO corroded rapidly

Mixed Waste Incinerator at Los Alamos

Alloy selected by Waste Management Group of the Department of Energy (DOE)

Gaseous effluents from incinerator are treated in a spray quench tower, a venturi scrubber and a packed absorber tower

Tests were carried out in "worst case scenario" to replace previous fiberglass reinforced polyester (FRP) components

3 M NaCl + 0.1M$FeCl_3$ + 0.1 M NaF adjusted to pH 1 with 10 M HCl/1 M H_2SO_4 at 75°C for 39 days

Best combination: C-22 welded with C-22

Corrosion Resistance is Crucial to Waste Package Performance

- Radionuclides are fully isolated if there are no penetrations
  - Even penetrated package can limit radionuclide movement
- Corrosion rates of passive metals are extremely low
  - Realistic rates are less than 1 µm/yr (a millionth of a meter per year) and much less
  - Alloy 22 layer is 2-cm thick (a stack of 12 U.S. quarters)
- Corrosion rates of approximately 0.01 µm/year are measured in exposures of over 5-years at the Long Term Test Facility at Lawrence Livermore National Laboratory

16,000 to 160,000 years to penetrate the thickness of one U.S. quarter for a corrosion rate of 0.1 to 0.01 µm/yr

Methodology for Determination of Materials Performance

- Materials performance at the proposed Yucca Mountain Repository is amenable to a familiar and effective analytical methodology
  - Widely accepted in the energy, transportation and other industries
- Three components comprise the analysis
  - Definition of the performance requirements
  - Determination of the operating conditions to which materials will be exposed
  - Selection of materials of construction that perform well in those conditions
- A special feature of the proposed Repository is the extremely long time frame of interest, i.e. 10,000's of years and longer
  - Time evolution of the environment in contact with waste package surfaces
  - Time evolution of corrosion damage that may result

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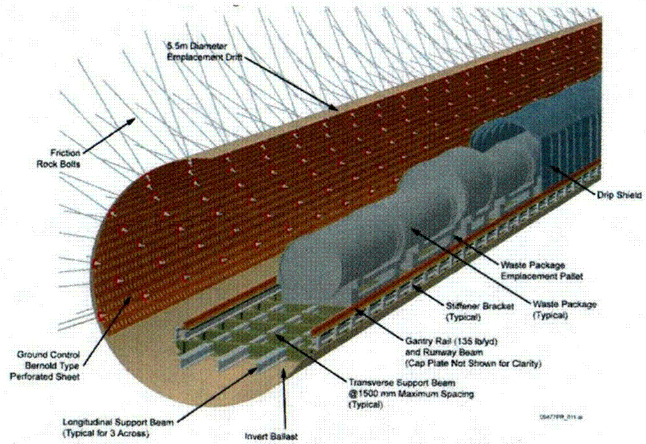
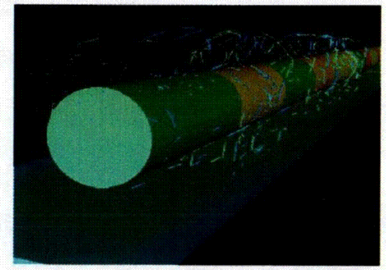
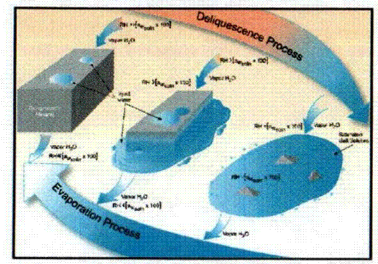
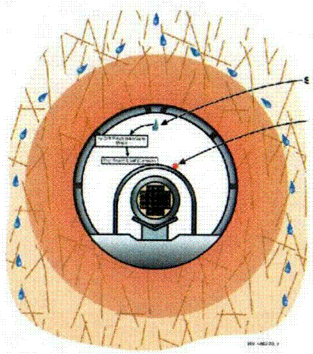
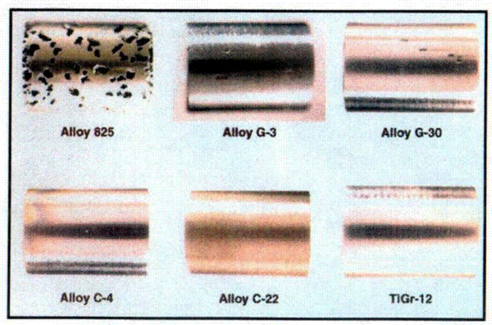
Corrosion and Materials Performance

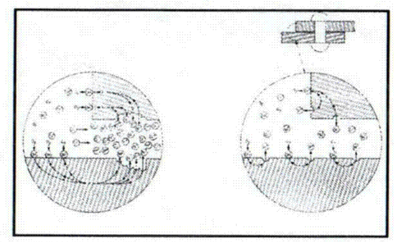












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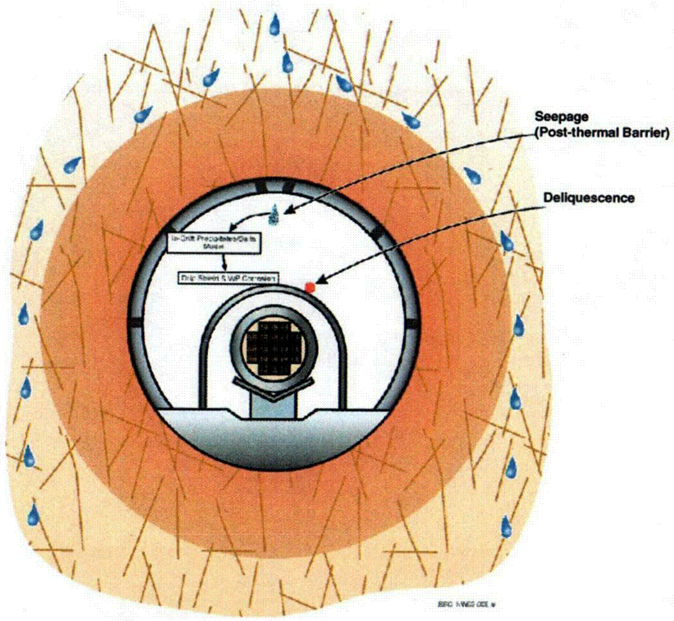
Attributes of the Proposed Yucca Mountain Repository



- One long, slow heating/cooling cycle
  - Packages cool to ambient over several thousands of years
- Waste packages on support pallets
  - No immersion in waters
- No moving parts
- Low heat fluxes, slow heating and cooling, and modest thermal gradients
- Radiation effects at waste package surface negligible after a few hundred years
- Limited amount of water moving through the rock
- Limited salts and minerals carried into drifts by incoming water and dust

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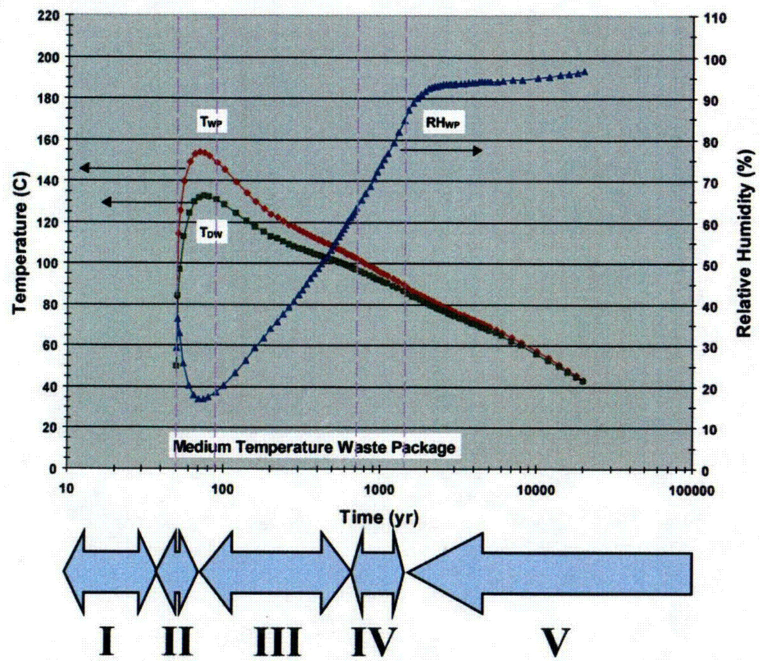
Relevant Time Periods Regards Corrosion



For Conditions Below

Temp-Relative Humidity behavior as shown

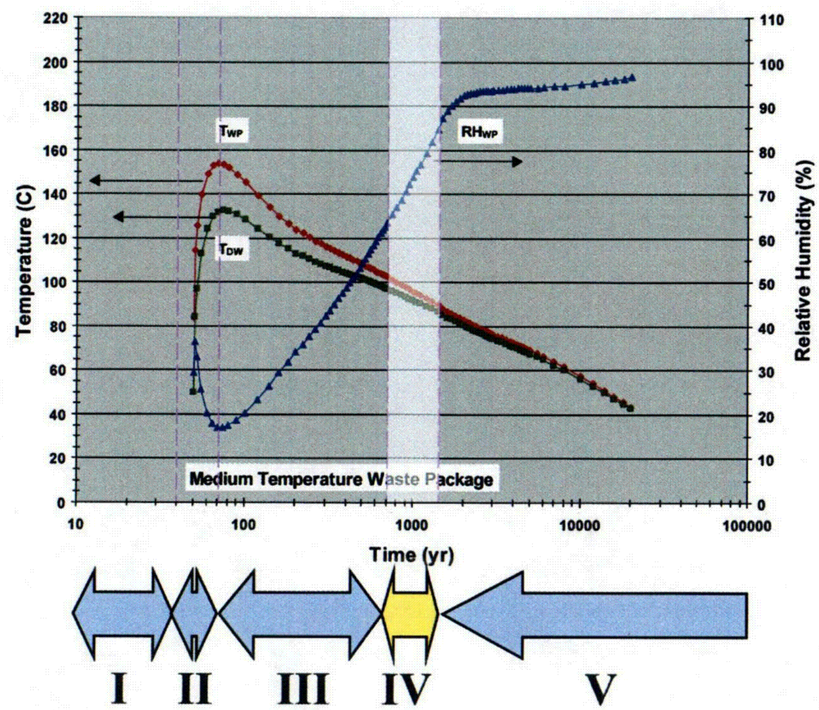
Waste Package at 101°C when Drift Wall cooled to 96°C

Critical Corrosion Temp 90°C

- **I-Preclosure**
  - Start to Year 50
- **II-Heat Up**
  - Year 50 to ~65
- **III-Thermal Barrier**
  - Year ~65 to 750
- **IV-Cool Down Post-Thermal Barrier**
  - Year 750 to 1375
- **V-Packages below Critical Corrosion Temp**
  - Year 1375 and beyond

Period IV-Dripping and Seepage Possible

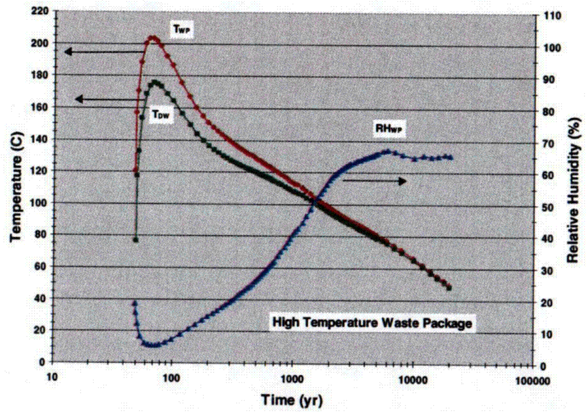
- When drift wall below boiling temperature (96°C) dripping and seepage can occur
- Dripping onto waste package can occur
  - Where both capillary barrier and drip shield are inoperative
  - And dripping location is in alignment
- When these conditions are met
  - If waste package temperature above critical corrosion temperature
  - Then, follow local corrosion logic/fault tree for damage evolution

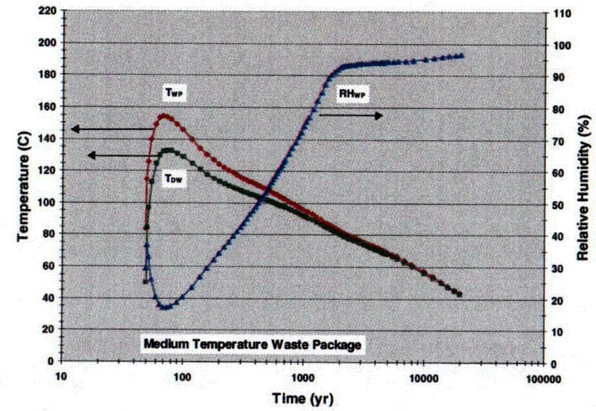


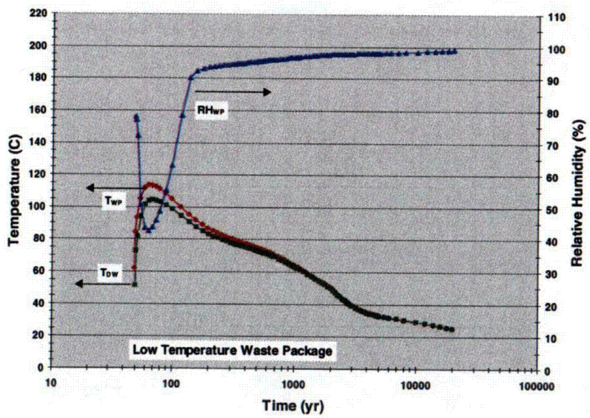
Drift wall boiling at year 750; Waste Package at 101°C: Relative humidity 65%

Waste Package at 90°C at year 1375: Relative Humidity 84%

Period IV Conditions for Mid, Hot and Cool Waste Packages







Drift Wall 96°C	Year	Waste Package Temp °C	Relative Humidity	Waste Package at 90°C
Mid WP	700	101	65	1325
Hot WP	1850	99	56	3000
Cool WP	62	102	72	125

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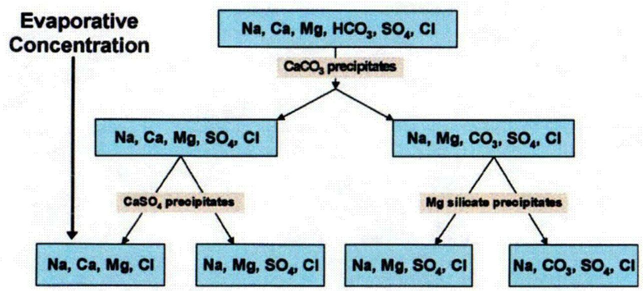
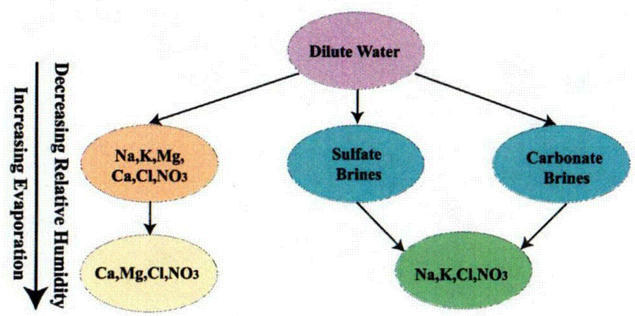
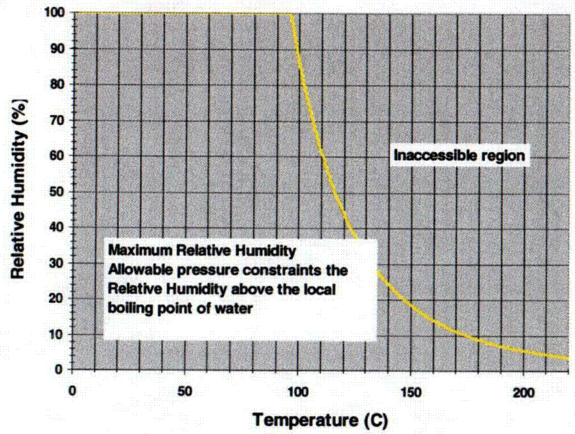
Chemical Divide Processes Determine the Categories of Waters

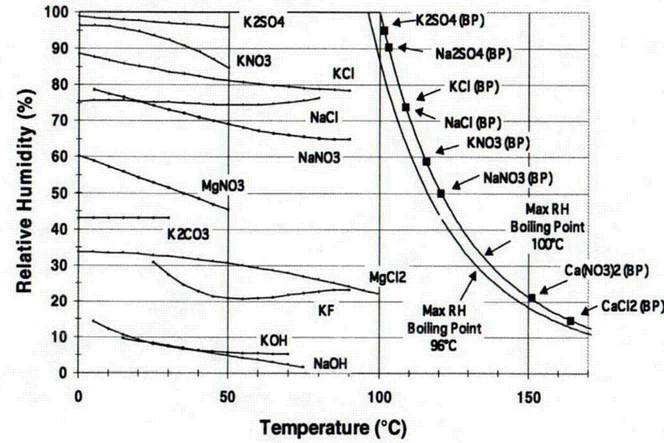


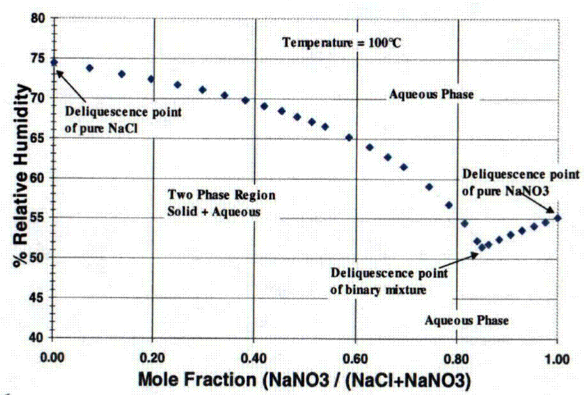


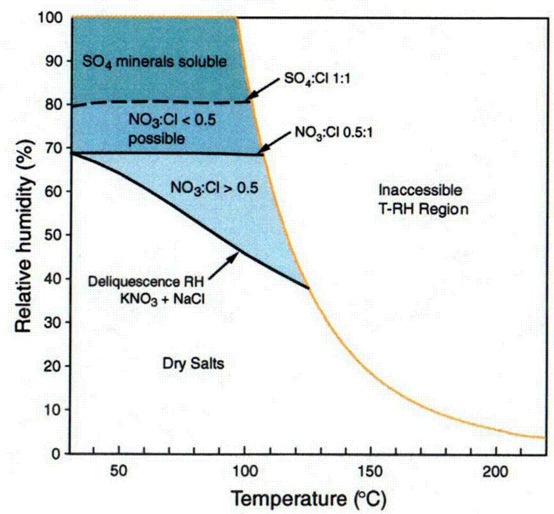
- Ambient Waters
  - Dilute solutions
  - Na-Ca-Mg-HCO_3-CO_3-Cl-NO_3-SO_4
  - Near neutral pH
- Waters can be concentrated
  - Modified during movement
  - Thermal-chemical processes
- Modifications on waste package surface
- Chemical and electrochemical processes

Solution Chemistry Principles









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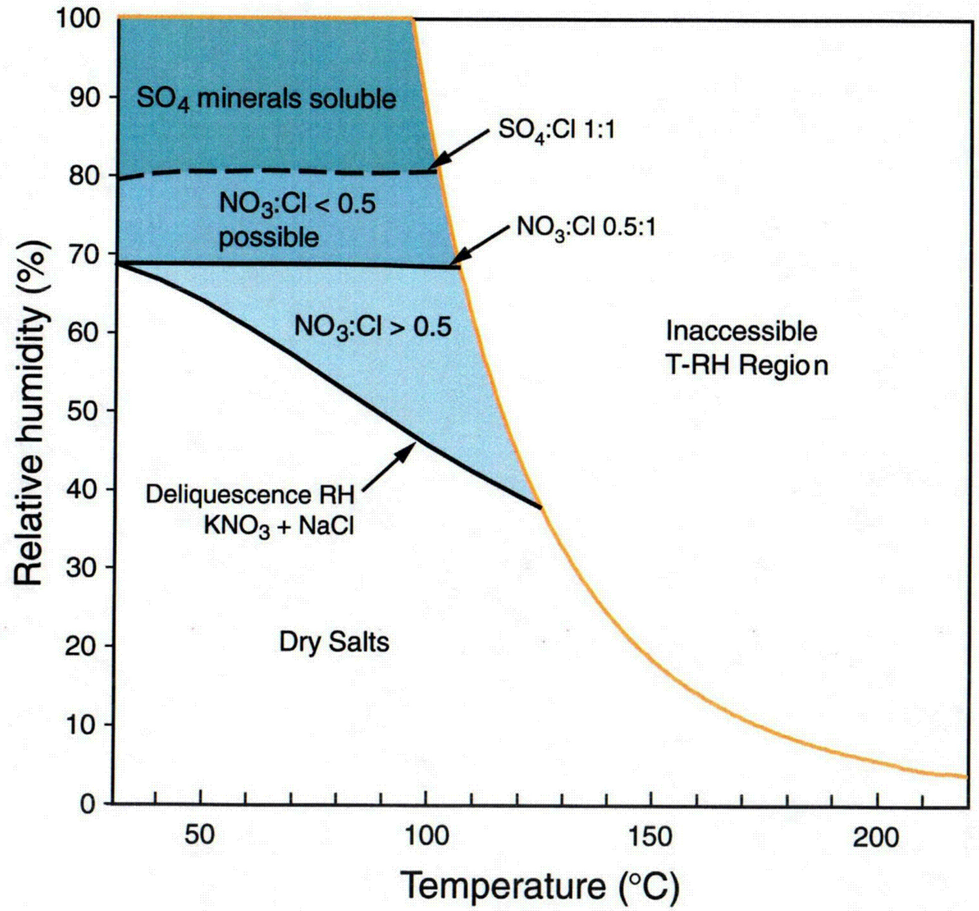
Constraints on Water Compositions for Sodium and Potassium Salts



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J. Payer-Advisory Committee on Nuclear Waste, Nuclear Regulatory Commission, Rockville MD, March 23, 2006

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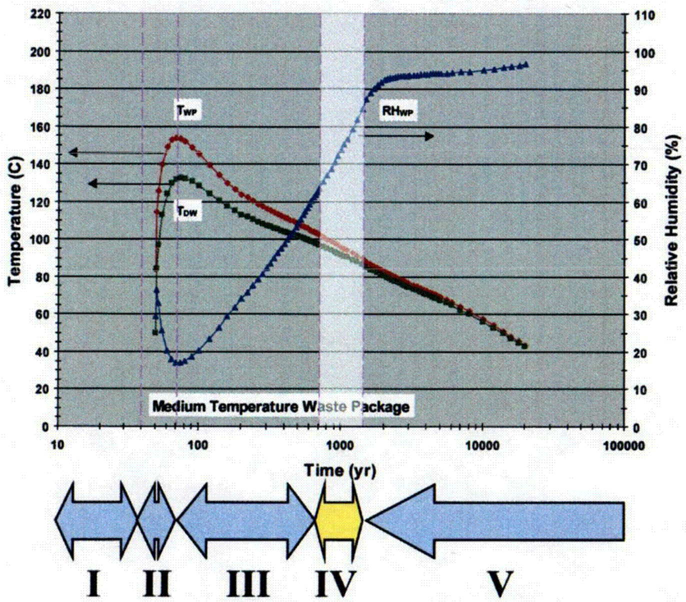
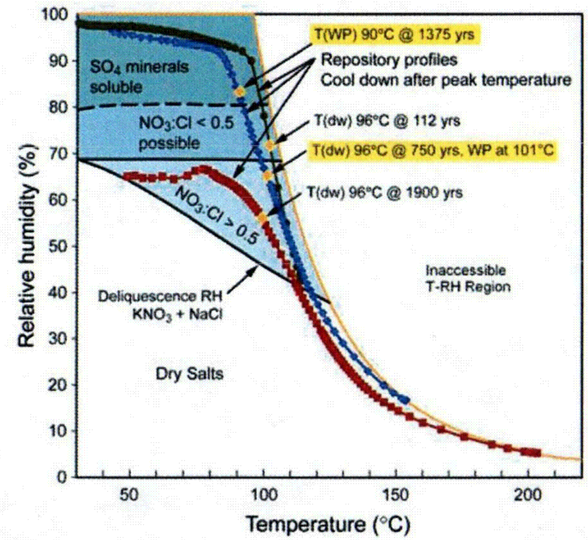
Period IV Analysis of T-RH-Solution Composition



Drift wall 96°C at 750 years;
Waste Package at 101°C;
Relative Humidity 65%

Critical Corrosion Temp 90°C
at year 1375; Relative Humidity 85%



The Temp-RH at any time fixes the possible waters; Can follow the trajectory with time

Number of non-corrosive solutions; Sodium chloride with low nitrate solutions can be corrosive

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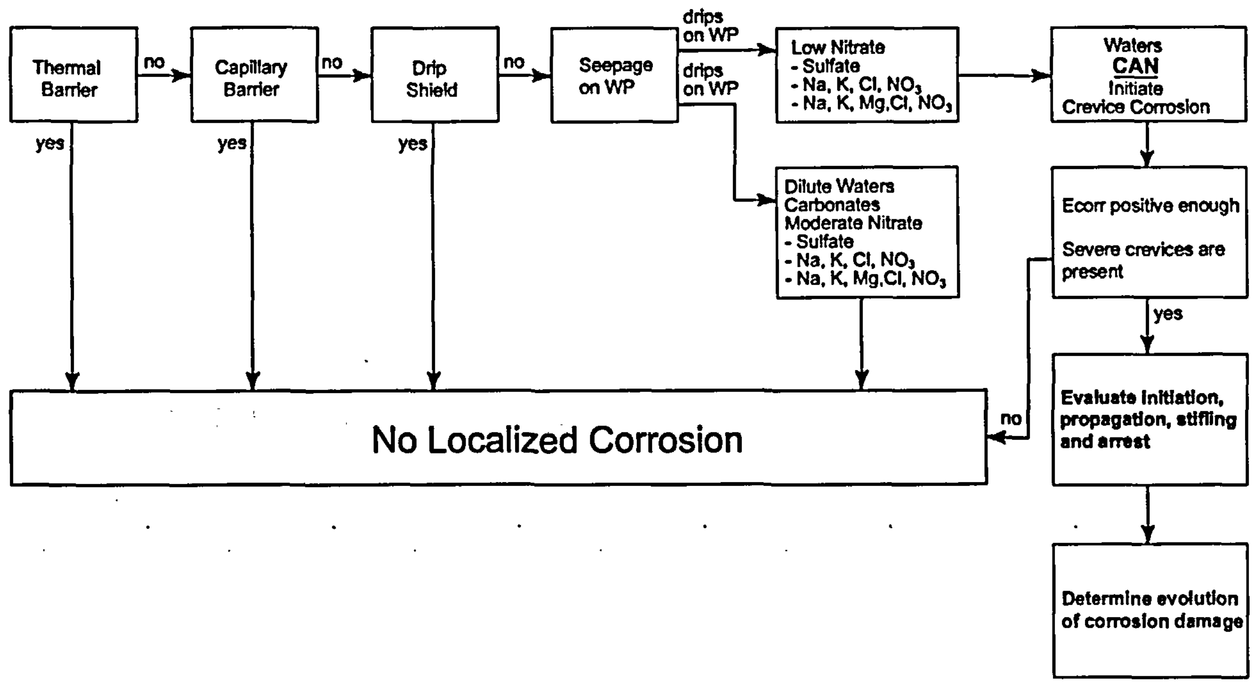
Decision-Tree Analysis

- A decision-tree for localized corrosion
  - Are environments and crevices present to induce localized corrosion?
    - Consider conditions in moist layers of particulate and deposits
  - If localized corrosion initiates, will it persist?
    - Consider stifling and arrest processes as the corrosion proceeds
  - What amount of metal penetration occurs?
  - What is the size and distribution of corrosion sites?

Decision-Tree Analysis

- A decision-tree for localized corrosion



OST&I Materials Performance Thrust

- The objective is to enhance the understanding of materials corrosion performance and to explore technical enhancements via the following technical thrusts
- Corrosion processes on metal surfaces covered with particulate and deposits
  - Effects of moisture on corrosion performance of metals
- Evolution of corrosion damage by localized corrosion
  - Initiation, propagation and arrest phenomena particularly for crevice corrosion of metals
- Evolution of the environment on metal surfaces
  - Moisture content, distribution and chemical composition on metal surfaces

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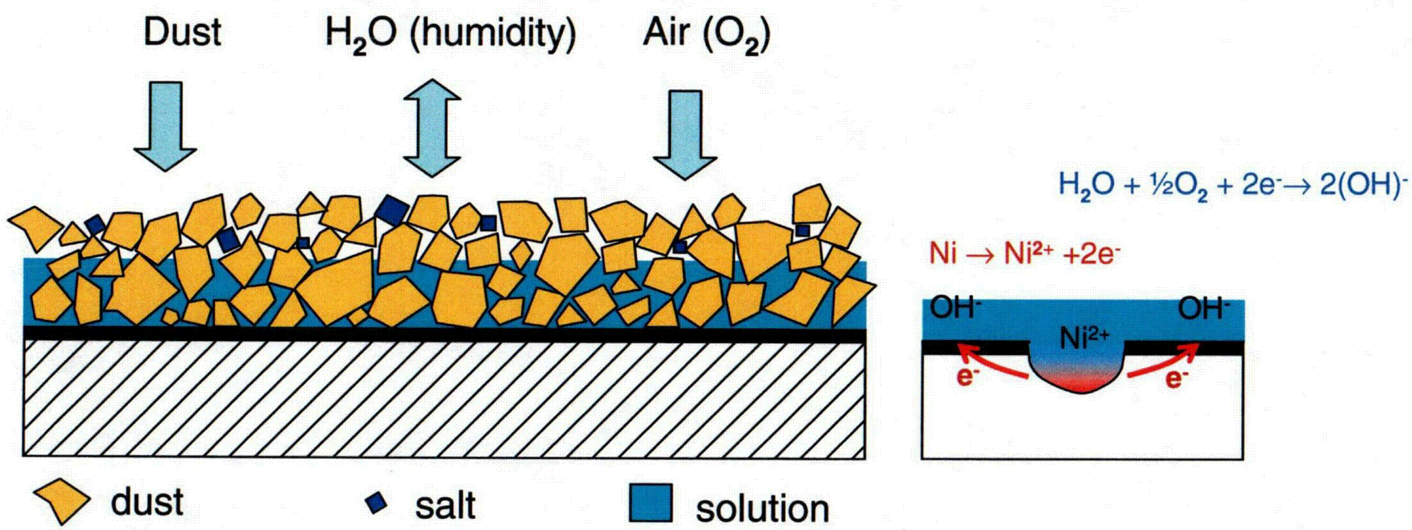
Corrosion in Thin Layers of Particulate



- **Dust deposited**
- **Degree of wetness**
- **Soluble salts**
- **Gas composition and property, T, RH**
- **Particulate layer properties, such as conductivity, temperature, pH, degree of wetness etc.**
- **Localized environment on the surface**
- **Anode: Ni $Ni^{2} + 2e^-$**
- **Cathode: $H_2O + ½O_2 + 2e^- \rightarrow 2(OH)^-$**

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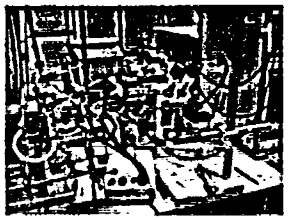
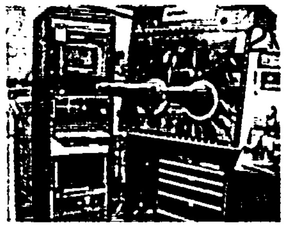
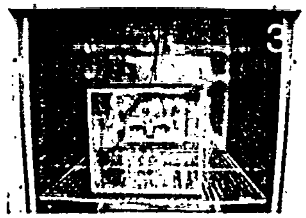
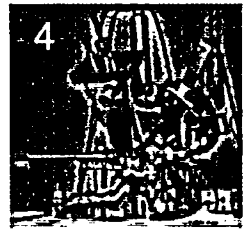
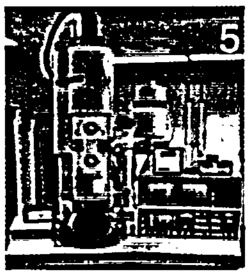
Specialized Capabilities and Facilities

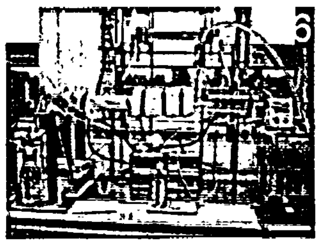


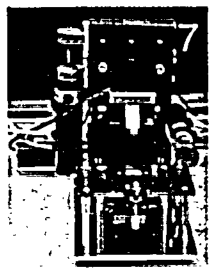


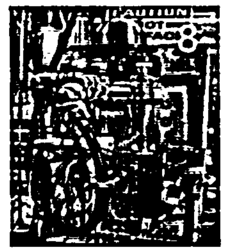


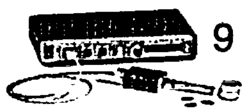


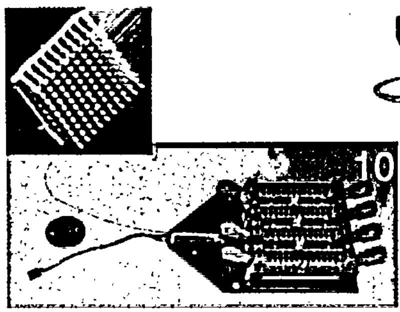












1. Kelvin Probe and Scanning Kelvin Probe
2. Laser-directed powder deposition for graded Ni-Cr-Mo compositions
3. Experimental apparatus for thin-layer electrochemical studies of stability of corrosion sites
4. X-ray Photo-Electron Spectrometry
5. 200KV Transmission Electron Microscope
6. Salt Particle Deposition System
7. Scanning Electrochemical Microscope
8. Thermogravimetric Analysis System at LLNL
9. Electrochemical Quartz Crystal Microbalance
10. Microelectrode Array

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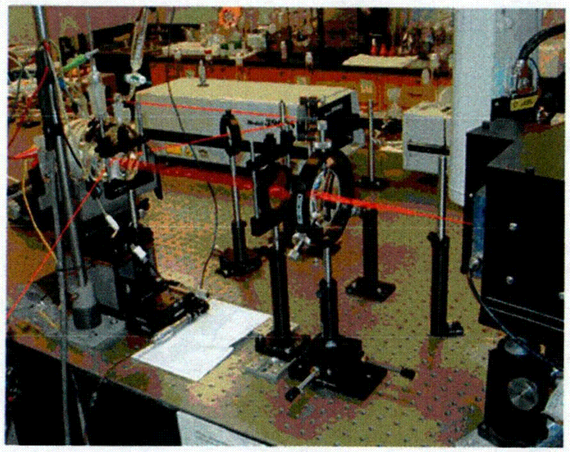
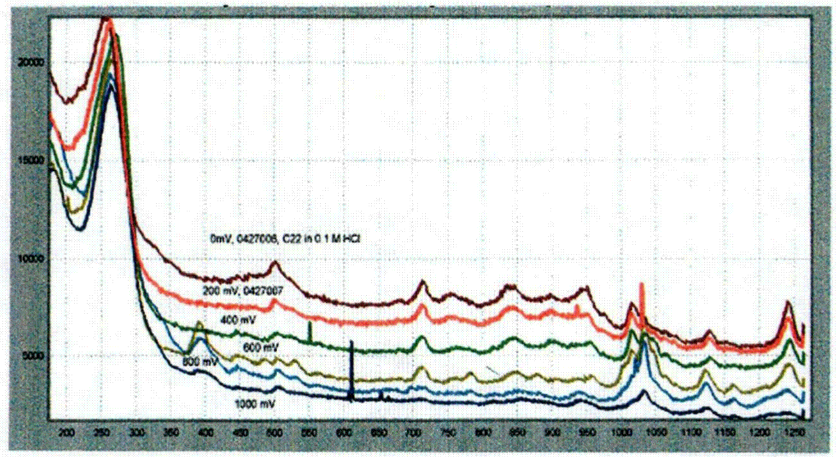
Effect of Environmental Variables on the Structure and Composition of Passive Films

- In-situ surface analysis and characterization
- To determine structure, composition, electrochemical and electronic properties of passive films on Ni-Cr-Mo alloys in hot, chloride solutions



Surface Enhanced Raman Spectroscopy (SERS) – The electrochemical cell containing the sample under investigation (e.g. Alloy 22) by SERS.



SERS of passive film formed on Alloy 22 in 0.1M HCl at potentials of 0V, 0.2V ,0.4V, 0.6V, 0.8V, 1.0V vs. SCE.

Thanks to Thomas M. Devine, University of California - Berkeley

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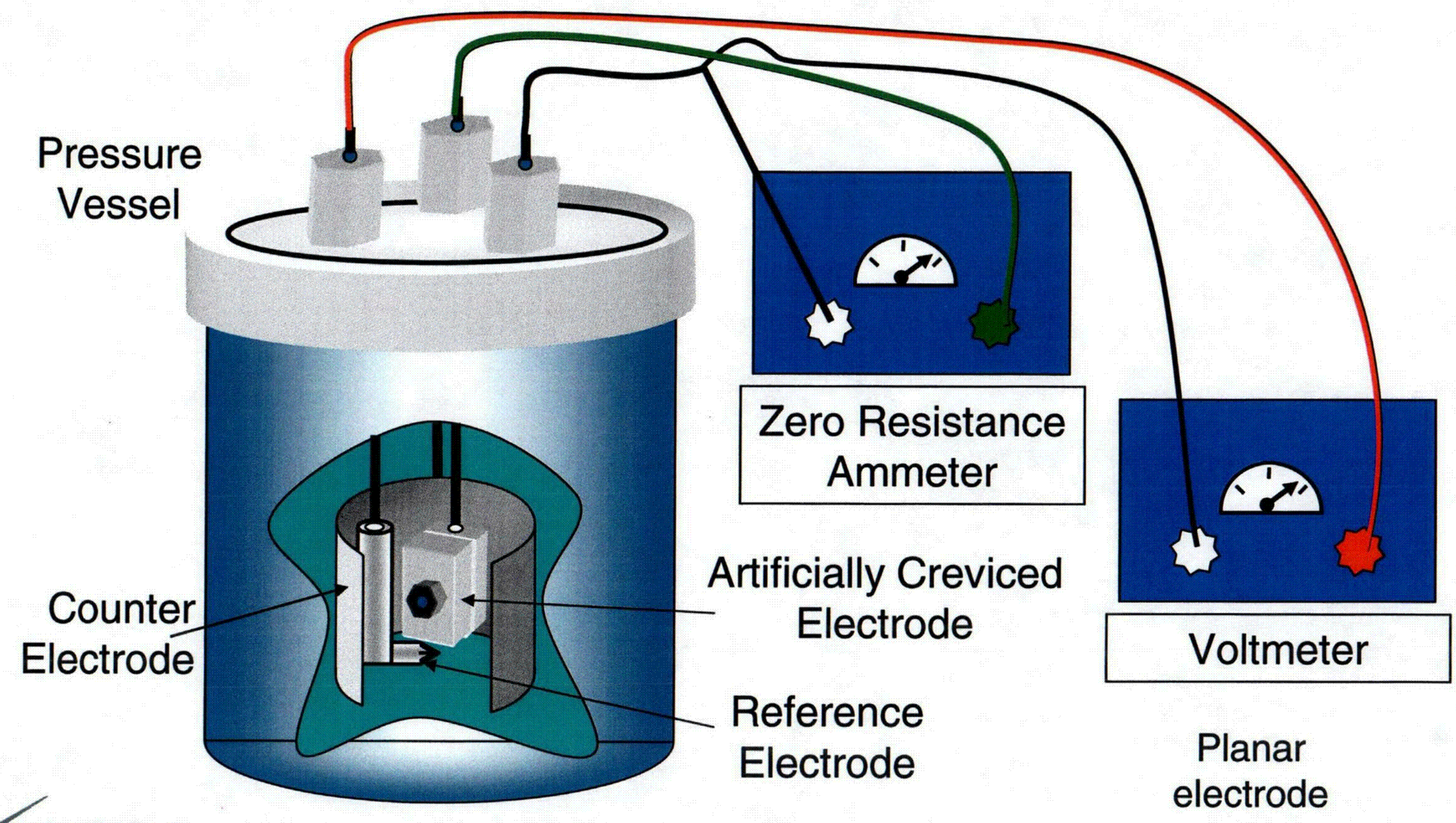
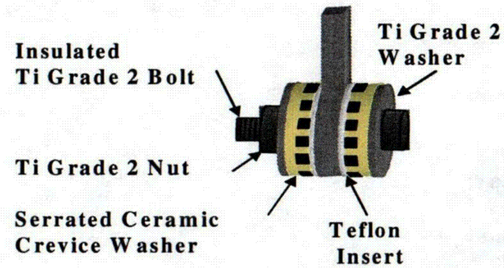
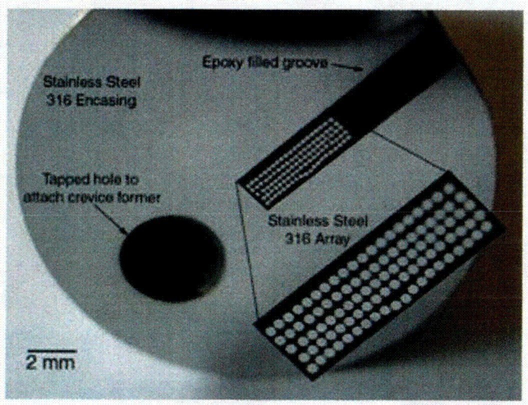
Coupled Crevice Experiment

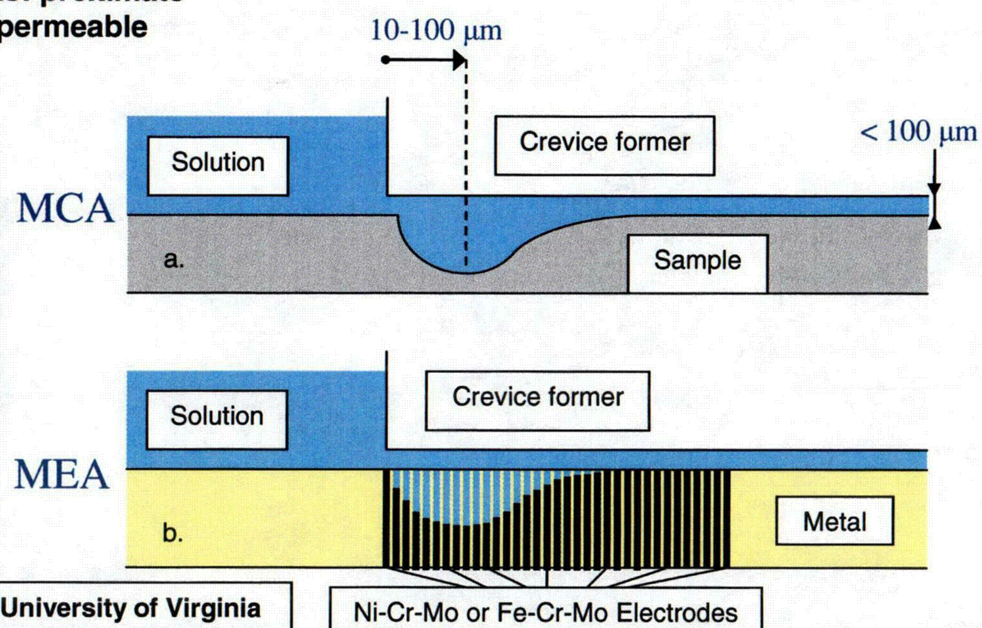


Multi-Crevice Assembly vs. Multi-Electrode Array

- The array is flush-mounted in a metallic rod of the same material, resulting in a metallic surface-volume ratio similar to that of MCA
- Array provides detailed spatial-temporal resolution, important as crevice corrosion behavior is very dependent on position
- Easier study of effects on initiation and propagation of some factors such as: proximate cathode, limited cathode and semi-permeable crevice former



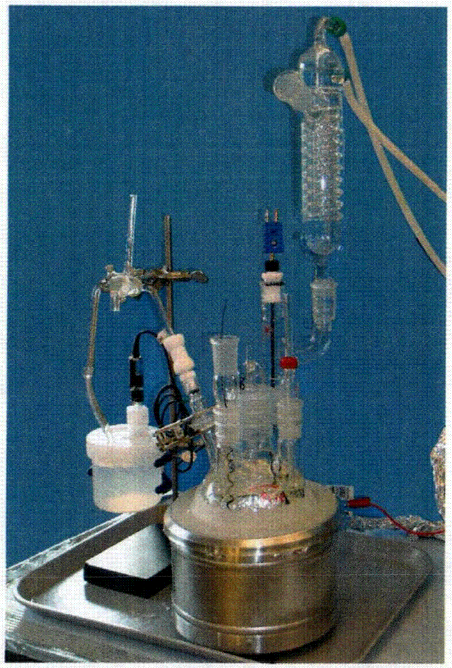




Thanks to John Scully, University of Virginia

Test Cell and Specimen

Test Cell

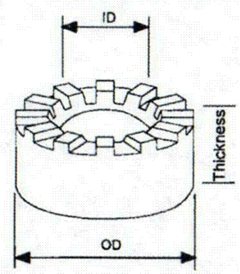


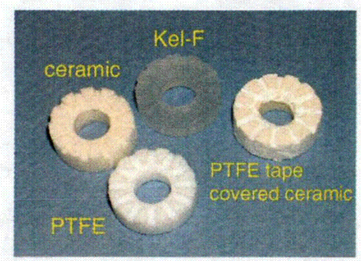
Specimen assembly

Multiple crevice assembly (MCA)

- Two segmented washers
- Applied Torque: 70 in-lb

Crevice formers: after ASTM G48-03

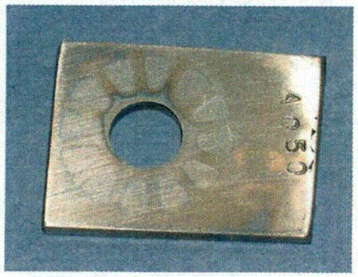




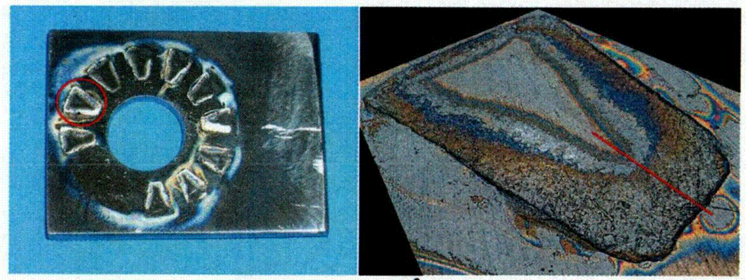
- 12 contact plateaus (feet)
- ID: 9.9 mm   OD: 15.9 mm   Thickness: 6.3 mm
- Contact area: 6 mm^2/contact area (foot)

Effect of Crevice Former on C-22

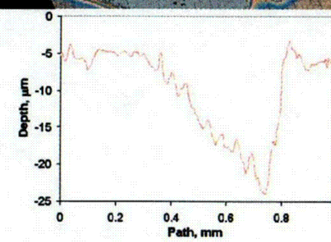
Ceramic vs. PolyTetraFluroEthylene (PTFE) tape covered ceramic



Ceramic side



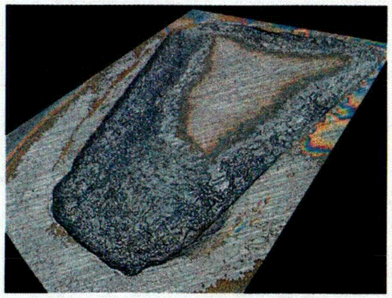
PTFE tape covered ceramic side



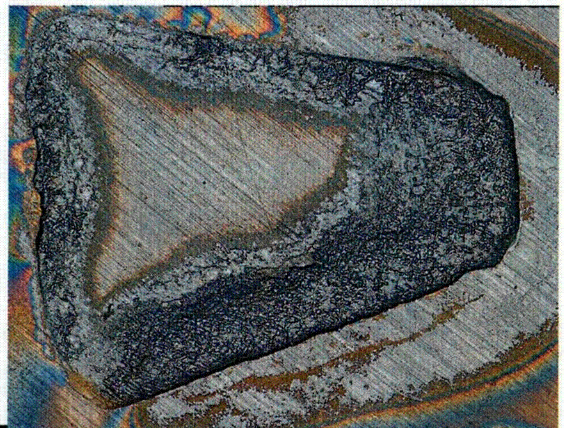
- 4M NaCl, 100°C, potentiostatic, anodic polarizaton to E= -0.15 volts vs. SCE, wet specimens with test solutions before tighten assemblies
- On ceramic side, no crevice corrosion was found
- On PTFE tape covered ceramic side, crevice corrosion to depth of about 25 µm after total flow of charge 10C to the whole specimen (67 hours)

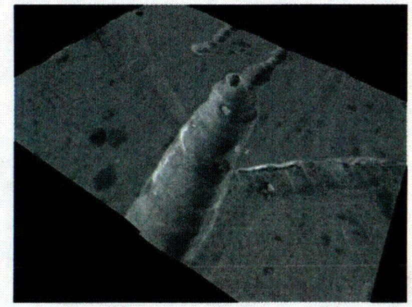
c56

3D Measurement of Corrosion

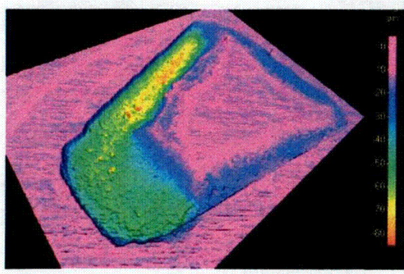


Optical microscopy
3D reconstruction



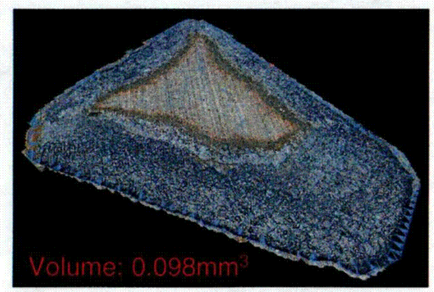


SEM 3D
reconstruction



Depth profile

C-22
4M NaCl 100°C
PTFE tape covered ceramic

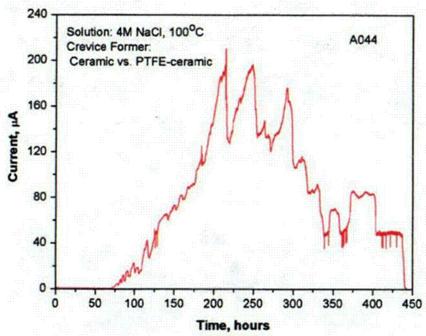


Volume

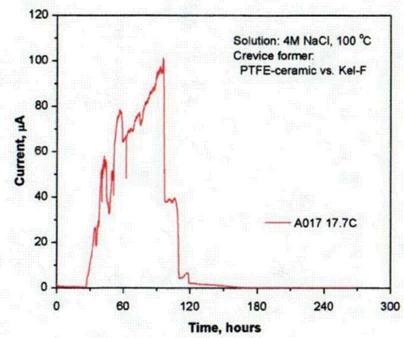
C57

Effect of Crevice Former

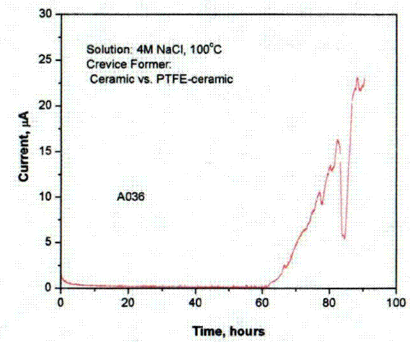
Initiation and arrest of crevice corrosion indicated by specimen current throughout the test



# of feet corroded: 9



# of feet corroded: 4

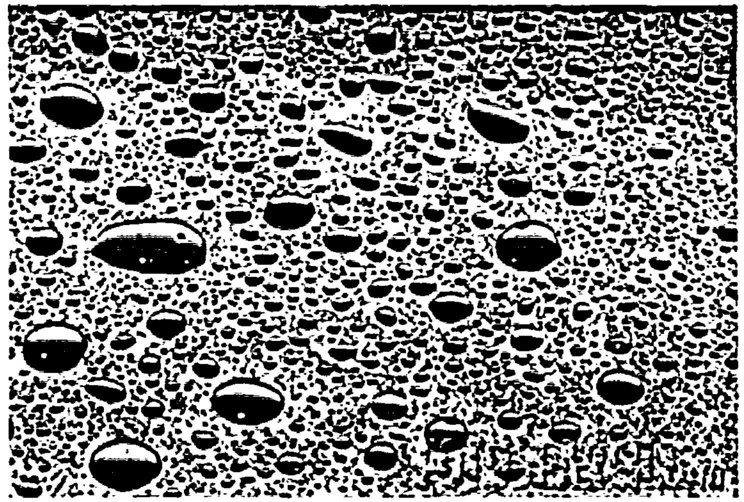


# of feet corroded: 1

- **Specimens become re-passivated after certain period of test**
- **Multiple initiation and arrest of crevice corrosion events indicated during the test**
- **Initiation and arrest events are loosely related to the number of feet corroded; future work will pursue more direct correlation**
- **Initiation and arrest of corrosion also observed on current response of a single crevice foot**

Localized Corrosion can be Stifled by Limits on the Cathodic Processes

- In the proposed repository waste packages will never be fully immersed in solution
- Moisture and particulates may be present on surfaces
- Corrosion behavior in moist particulate can differ from full immersion
  - Limited size of corrosion site
  - Limited cathodic area to support localized corrosion
  - Limited cathodic kinetics could stifle corrosion

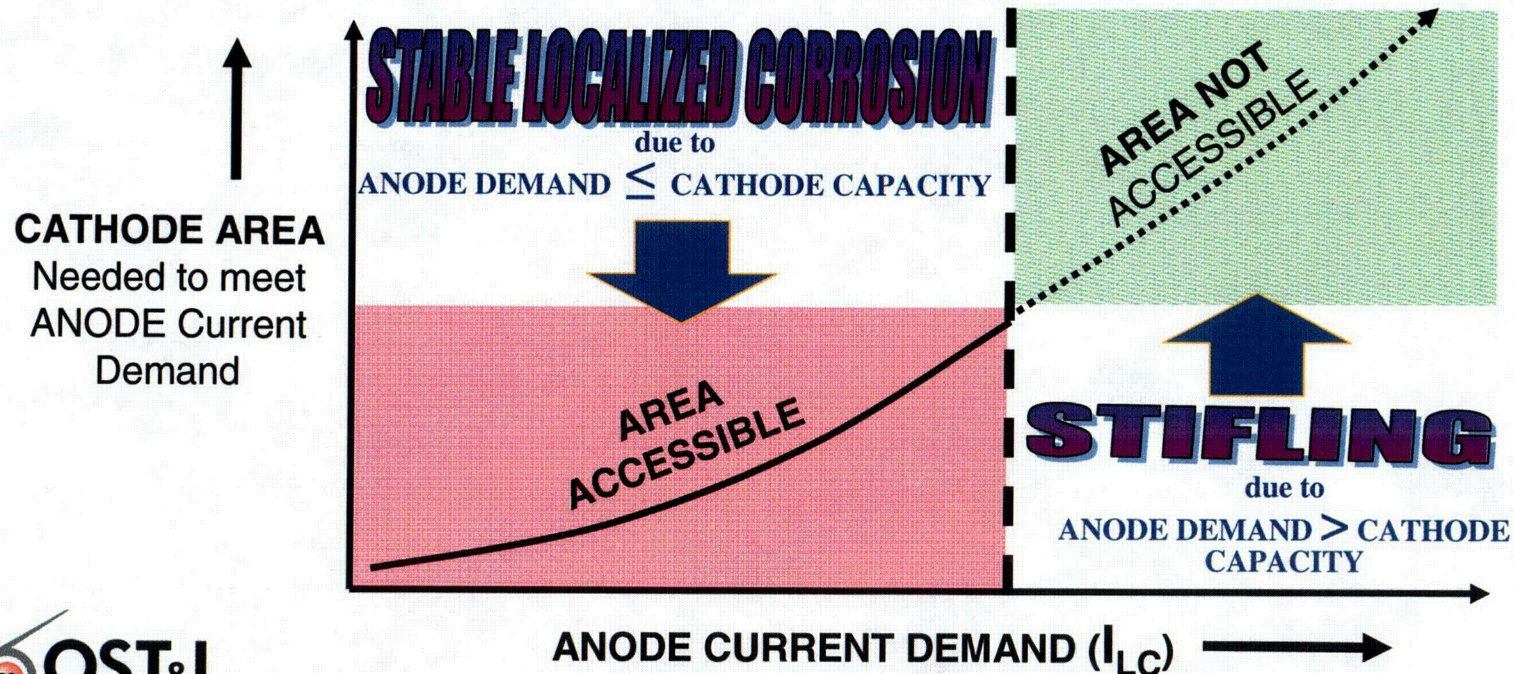


OST&I

C59

Objective

- **Quantification of the total cathodic current that a wetted surface of limited area could deliver under a given set of conditions provides a scientific basis for analyses of both the maximum rate and the stability of localized corrosion.**

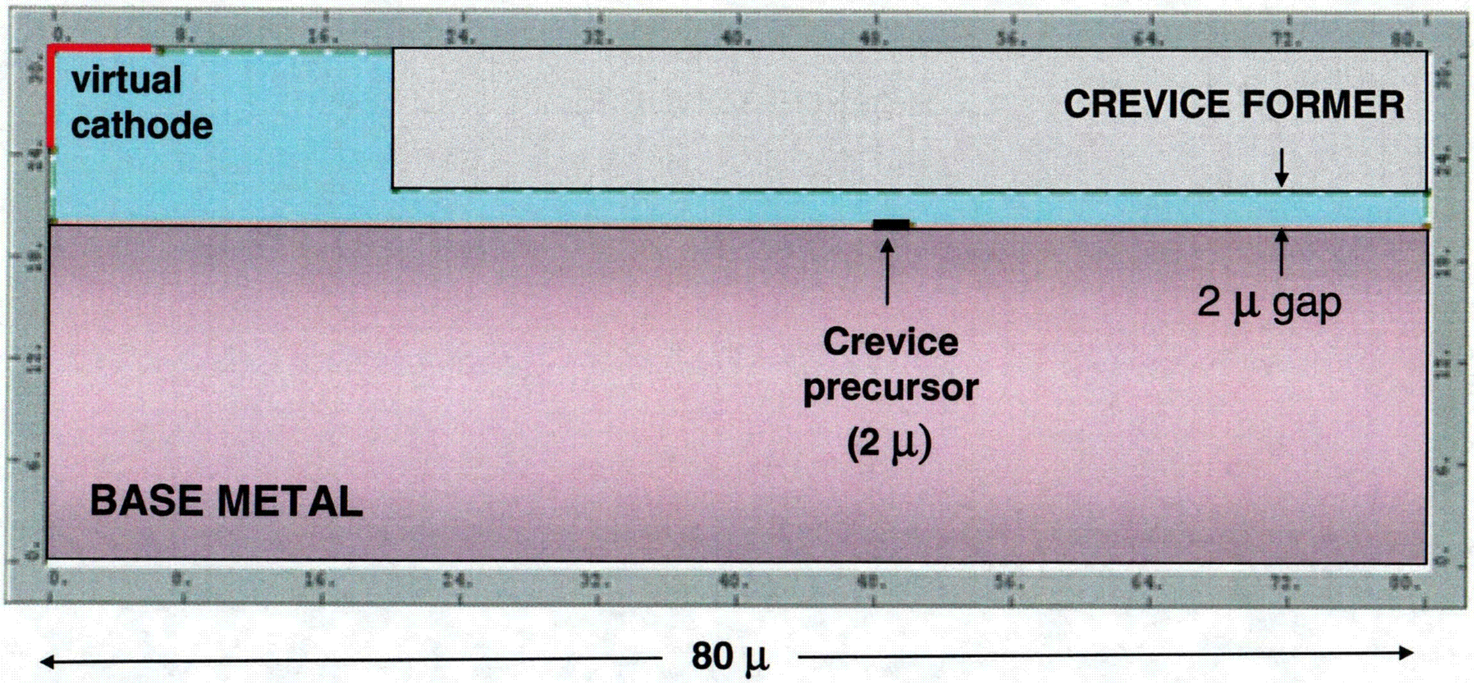


OST&I

39

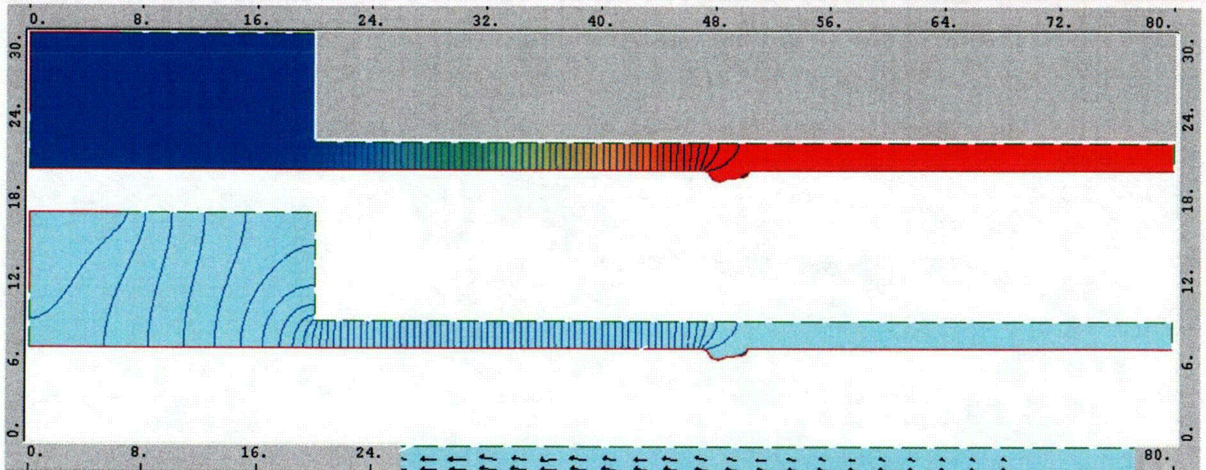
C60

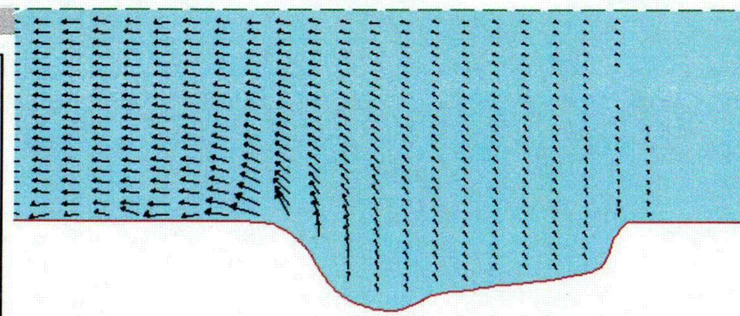
Simulation of Crevice Propagation



C6 I

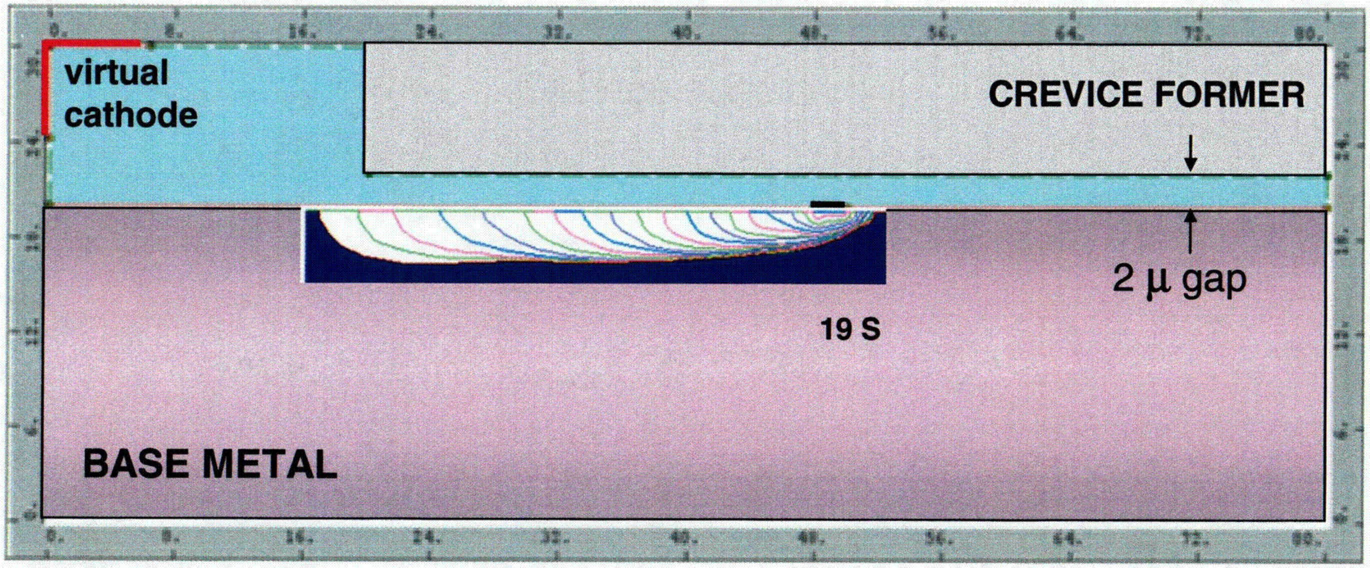
Potential and Current Map in a Crevice





- Most of the potential drop is in front of the crevice
- The current distribution within the crevice is highly non-uniform
- The diffusion field is similar to the potential field

Simulation of Crevice Propagation



C63

Summary of Long-Term Corrosion Behavior

- Corrosion is a primary determinant of waste package performance
  - Controls the delay time for radionuclide transport from the waste package
- Two major aspects
  - Evolution of corrosion damage by localized corrosion
  - Durability of passive films
- Analysis of the potential for damage by corrosion is crucial and a major effort has been undertaken to enhance the technical basis for long-term behavior
  - Can corrosive environments form and persist?
  - Will localized corrosion start and persist?
  - What damage would result?

OST&I Materials Performance Thrust

- Overview of the OST&I Materials Performance Thrust
  - To further enhance the understanding of the role of engineered barriers in waste isolation
  - Supported by Office of Science and Technology and International, U.S. Department of Energy, Office of Civilian Radioactive Waste Management
- Programmatic Milestones
  - Materials Performance (Corrosion) Thrust Start-up Projects; projects in the S&T project portfolio identified and grouped to form the Targeted Thrust area, FY04
  - DARPA/DOE High Performance Corrosion Resistant Metals project transitioned from Materials Performance Thrust to Advanced Technologies, FY05
  - Corrosion Cooperative established June 1, 2004

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Thank You

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OCRWM Office of Science and Technology and International

Overview of the Advanced Technologies Thrust

Presented to:
Advisory Committee on Nuclear Waste
Nuclear Regulatory Commission

Presented by:
Jef Walker
Office of Science & Technology & International

March 23, 2006
Rockville, MD

Program Description

- Mission: Reduce total life cycle costs through the addition of new technology and new information into the Yucca Mountain Project
- Apart from the license application; however,
  - Focused solely on repository applications and eventual incorporation as a modification to the license
  - Closely coordinated with repository performance requirements, designs and operation practices
  - Frequent review and direction by repository staff
- Work is performed by industry, national laboratories, universities and in some cases the OCRWM M&O

Projects

- Waste Package Technology
  - Welding - reduced pressure electron beam welding (RPEB)
  - Materials – Iron-based structural amorphous metal coatings
- Subsurface Operations
  - Construction Material – silica-based cements
  - Improved Operation – longer lasting tunnel boring machine (TBM) disc cutters
  - Backfill – re-evaluation of backfill assumptions
- Surface Operations
  - Reduction of Seismic Hazard – nonlinear ground response model for extreme ground motions

Waste Package Technology

- Welding - reduced pressure electron beam (RPEB) welding

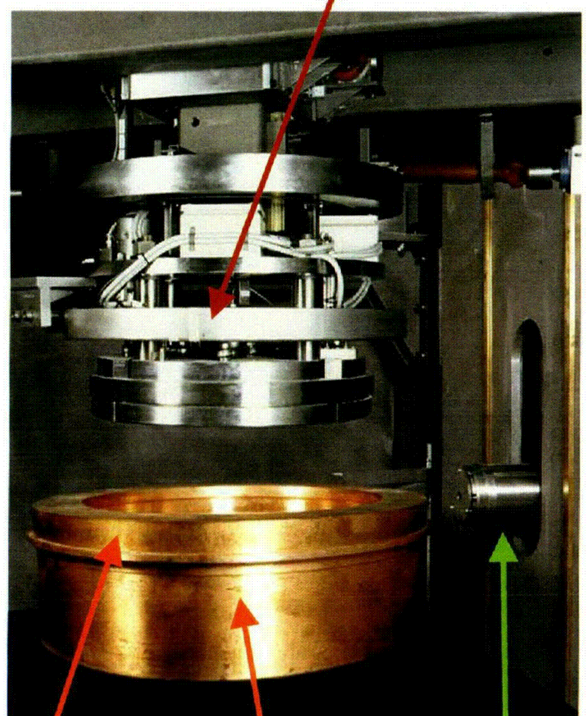
- Materials – iron-based structural amorphous metal coatings

Reduced Pressure Electron Beam (RPEB) Welding

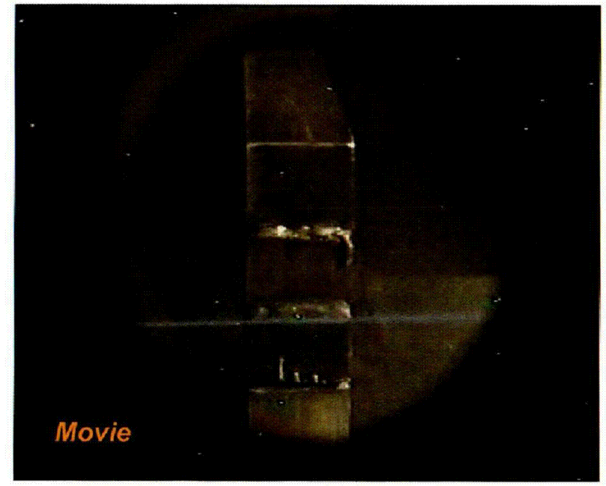
1. Background and Benefits of RPEB welding

- RPEB welding: electron beam welding using reduced pressure (< 1 mbar); enables use of local seals
- RPEB welding enables single-pass, non-contact closure of the waste package
- Leverages 10+ years of engineering and operational experience from the Swedish nuclear waste program
- RPEB welding system: employ a standoff distance of 50 to 500 mm.
- Thus, all of the RPEB welding system electronic components can be maintained **outside** of the welding hot cell

2. RPEB Welding Closure Cell at SKB (Sweden)



3. RPEB Welding of Thick Sections Demonstrating No Weld-Induced Distortion



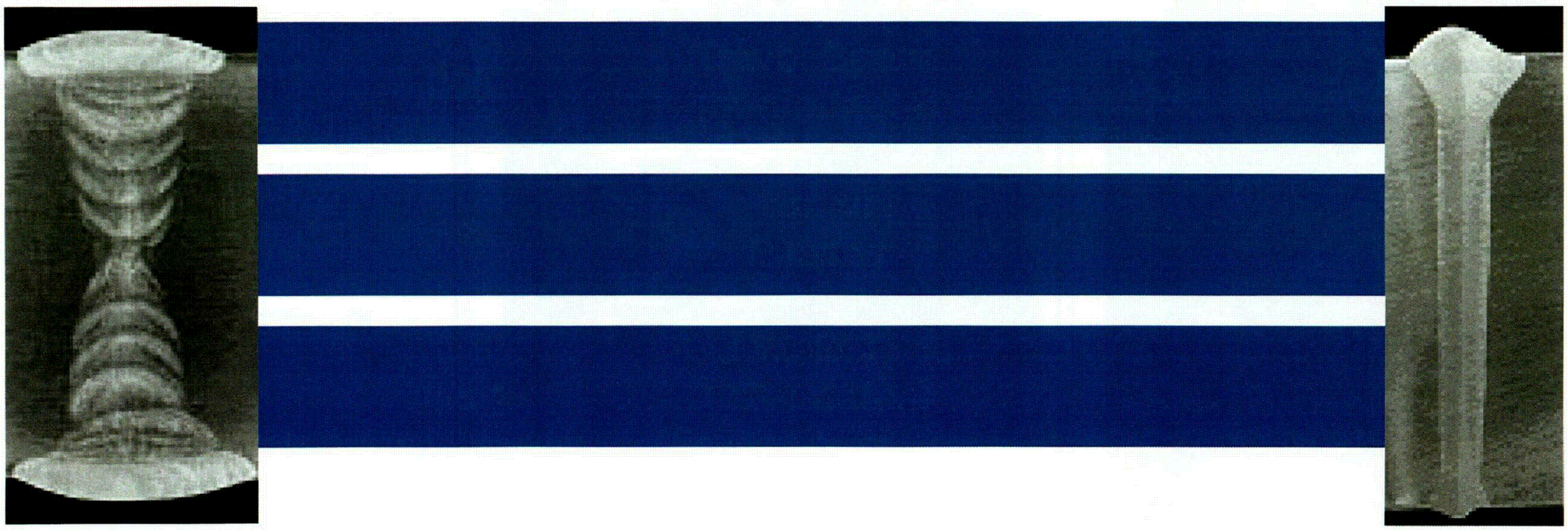
RPEB Welding of 80mm steel 316L

C64

Status of the Technology

Multi-Pass GTAW Weld

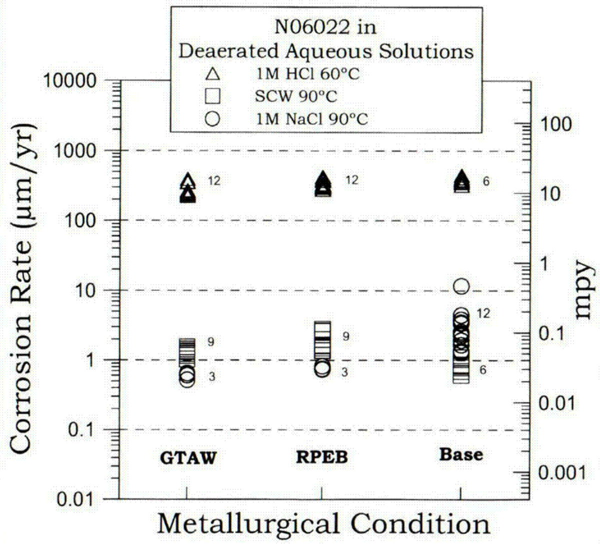
Single-Pass RPEB Weld



Comparison of Estimated Welding Times for Gas Tungsten Arc Welding (GTAW) and Reduced Pressure Electron Beam (RPEB) Welding for Alloy 22

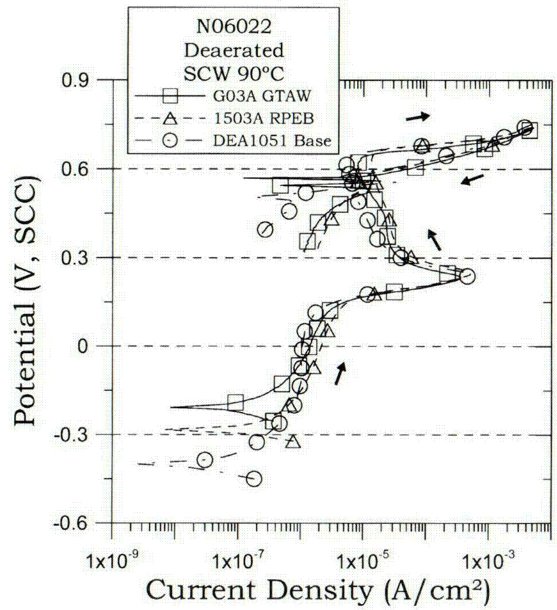
Equal or Better Material Performance Compared to Baseline GTA Welds

1. Comparison of Corrosion Rates in Three Environments



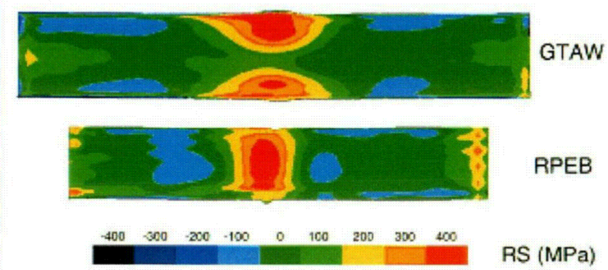
- Comparative corrosion rates for GTAW, RPEB weld, and base metal specimens in SCW, 1M HCl, and NaCl solutions
- Numerals next to the symbols indicate the number of individual points in each cluster

2. Comparison of Cyclic Polarization Data



- Cyclic polarization curves for the two Alloy 22 weld types and base metal in deaerated 90°C SCW
- Arrows indicate the direction of curve trace as the test proceeds

3. RPEB Welding Enables More Favorable Distribution of Residual Stress



- Longitudinal (weld direction) residual stress contour plots in the as-welded condition for the GTAW and RPEB weld samples
- Maximum surface residual tensile stress from RPEBW is located mid-thickness (not at top surface)
- Thus, RPEB welding enables more favorable distribution of residual stress
- Activities in progress to optimize residual stress distribution from RPEB welding (e.g. beam shaping, 2nd pass, etc.)

Design and Performance Compatibility

- Evaluation of Applicable Degradation Models
  - Same as baseline design (general/local corrosion)
  - Possibly more control of stress corrosion cracking (more favorable distribution of residual stress)
- ASME Code Criteria (B&PVC Section IX)
  - Electron beam welding included in ASME Section IX
  - RPEB welding: qualification tests passed
- "Plug & Play" with Baseline Weld Cell Design
  - RPEB welding equipment fits within present arc welding equipment space envelope
  - RPEB welding allows for simplified weld cell and lid designs (e.g. single-pass, non-contact, stand-off distance, self-locating lid)

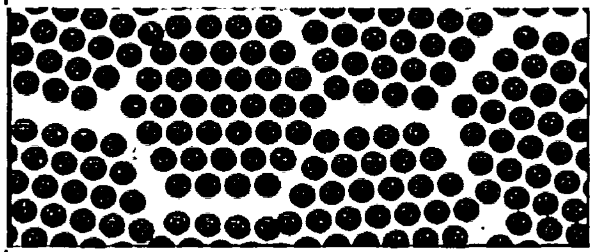
Waste Package Technology

- Welding - reduced pressure electron beam welding

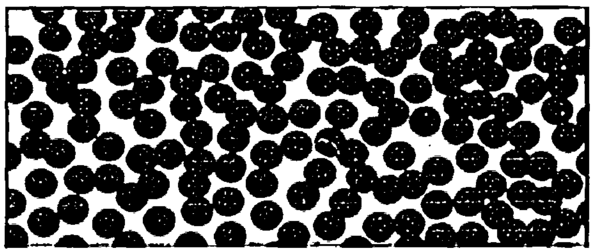
- **Materials – Iron-based structural amorphous metal coatings**

Structurally Amorphous Metal Coatings

Amorphous Metals are Fundamentally Different



- Crystalline (Normal) Metals
  - ✓ Long-range order
  - ✓ Grain boundaries
  - ✓ Slip planes



- Amorphous Metals
  - ✓ No grain boundaries
  - ✓ High impact strength
  - ✓ "Metallic Glass"

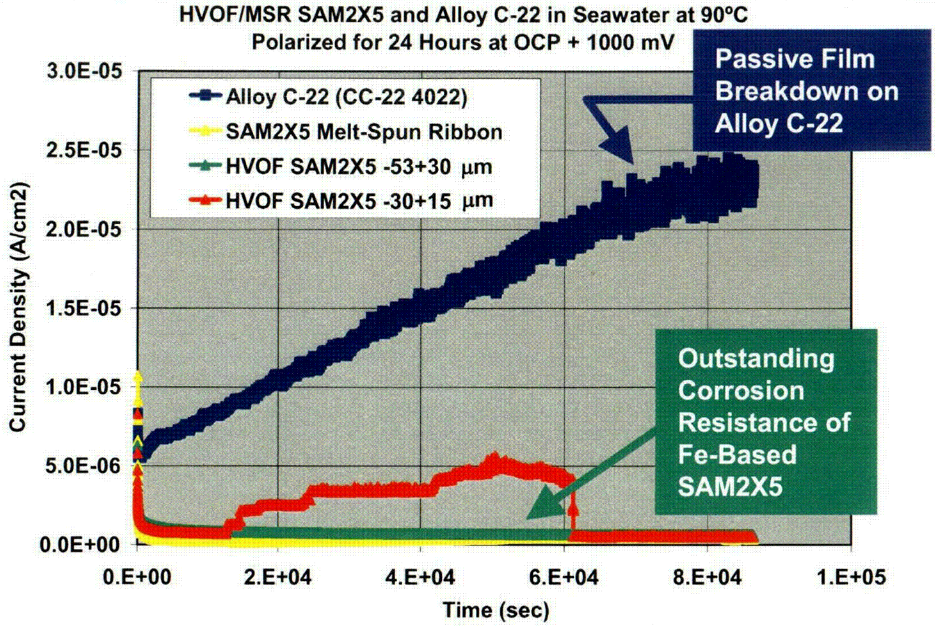
Benefits of Iron-based Structurally Amorphous Metal Coatings

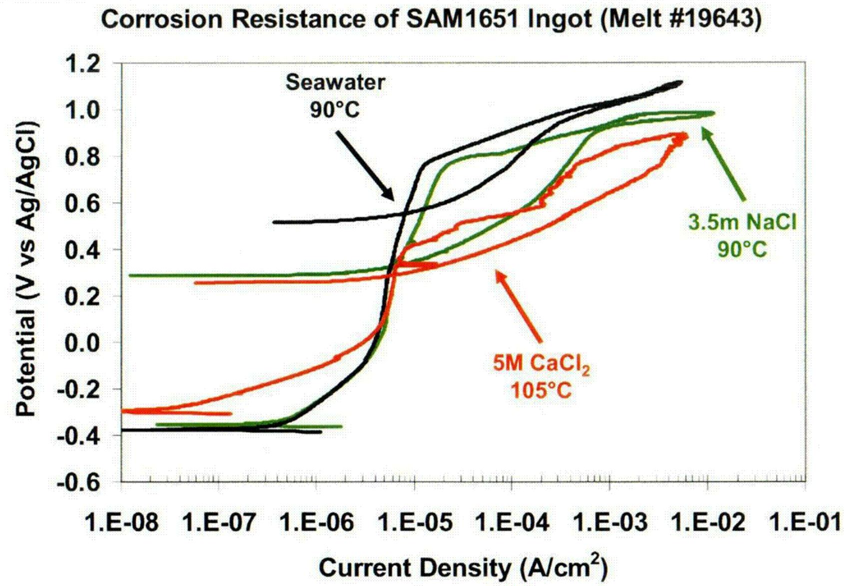
- Fe-based amorphous metal formulations have been identified with corrosion resistance comparable to (or better than) that of Ni-based Alloy 22
- Boron enables glass formation
- Yttrium lowers critical cooling rate
  - SAM1651 ~ 80 K/s (yttrium added)
  - SAM2X5 ~ 600 K/s (no yttrium)
- Cost savings through substitution of Fe-based alloy for Ni-based material

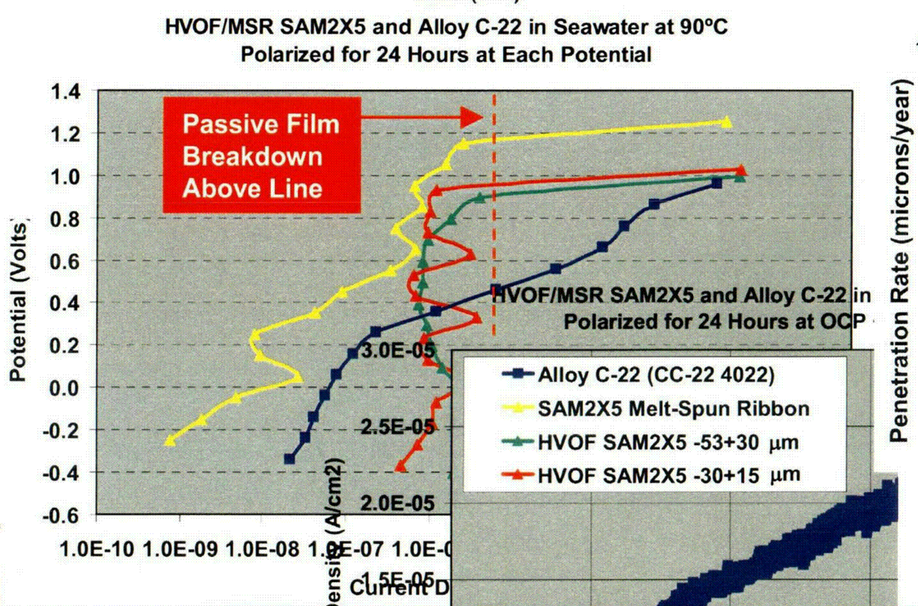
Metal Spray Coatings are Strong and Simple to Apply

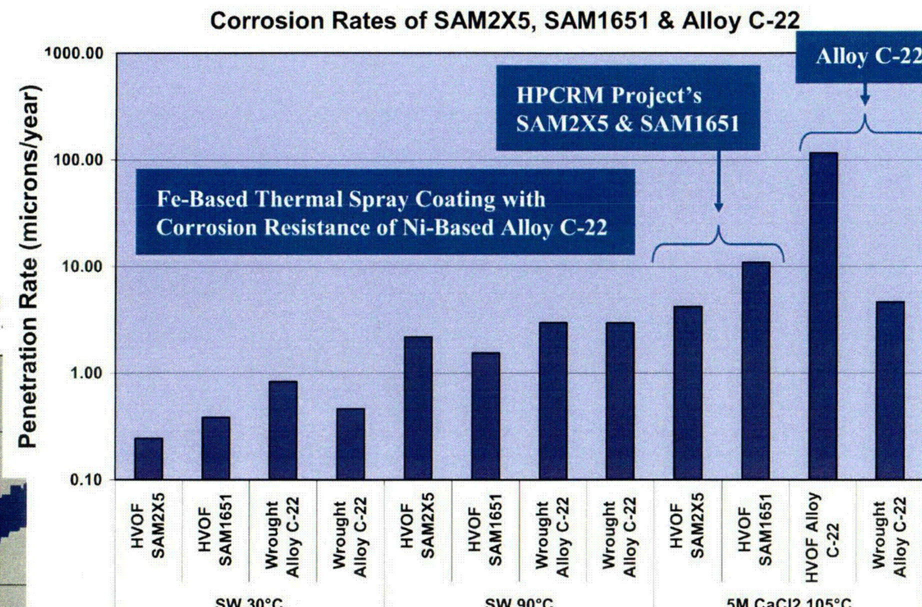
- High-Velocity Oxy-Fuel torches provide high velocity and temperature deposition
- Commercial practice for rebuilding high-wear surfaces and as chrome replacement

Exceptional Corrosion Resistance



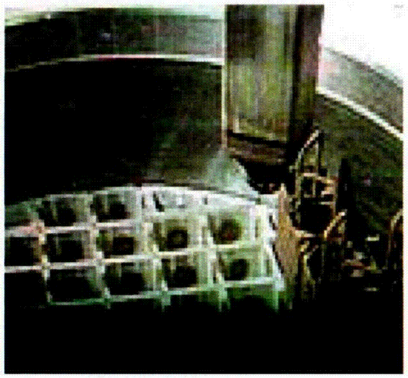






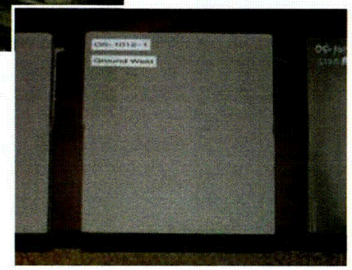
C07

High Boron Content Can Enhance Criticality Safety



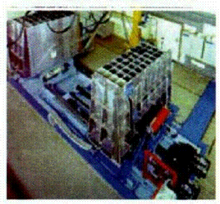
Criticality Model

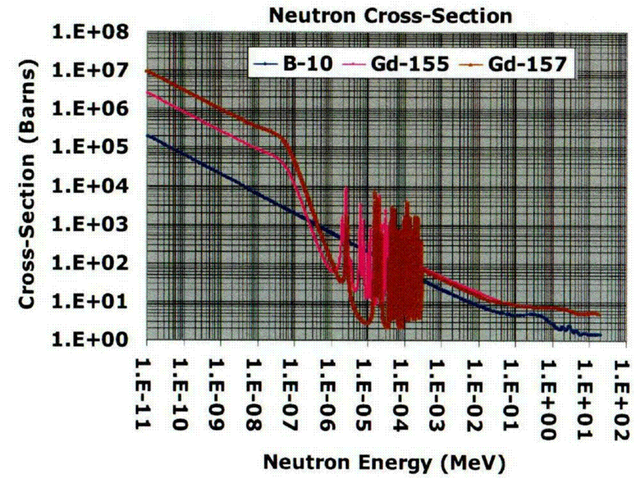
High-B SAM2X5 Coating

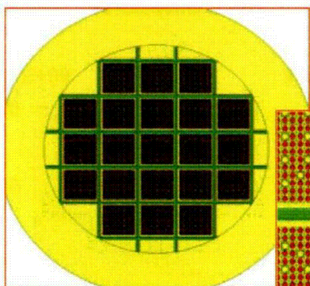


Criticality Benchmark

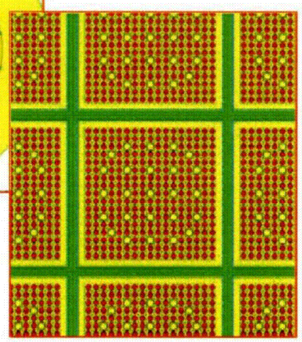
Critical Experiment Benchmark



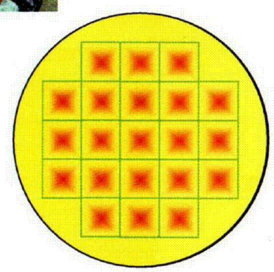




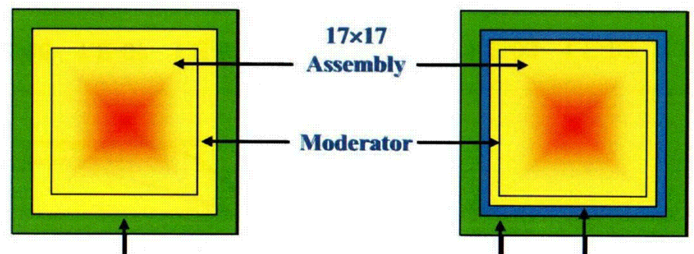
Disposal Container



Support Basket



Spent Fuel Storage Container Holding 21 PWR Assemblies



¼-inch Stainless Steel with 0.12 wt. % Boron

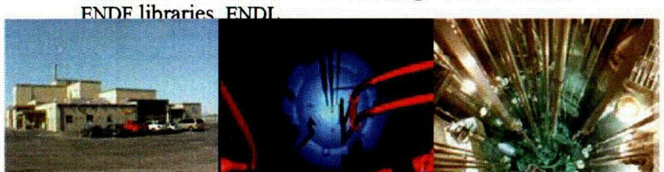
¼-inch Stainless Steel

1-mm SAM2X5 Coating

Computer Codes:
MCNP5, COG, KENO5
Libraries:
ENDF, ENDL

Libraries: ENDF libraries, ENDL

Testing Materials



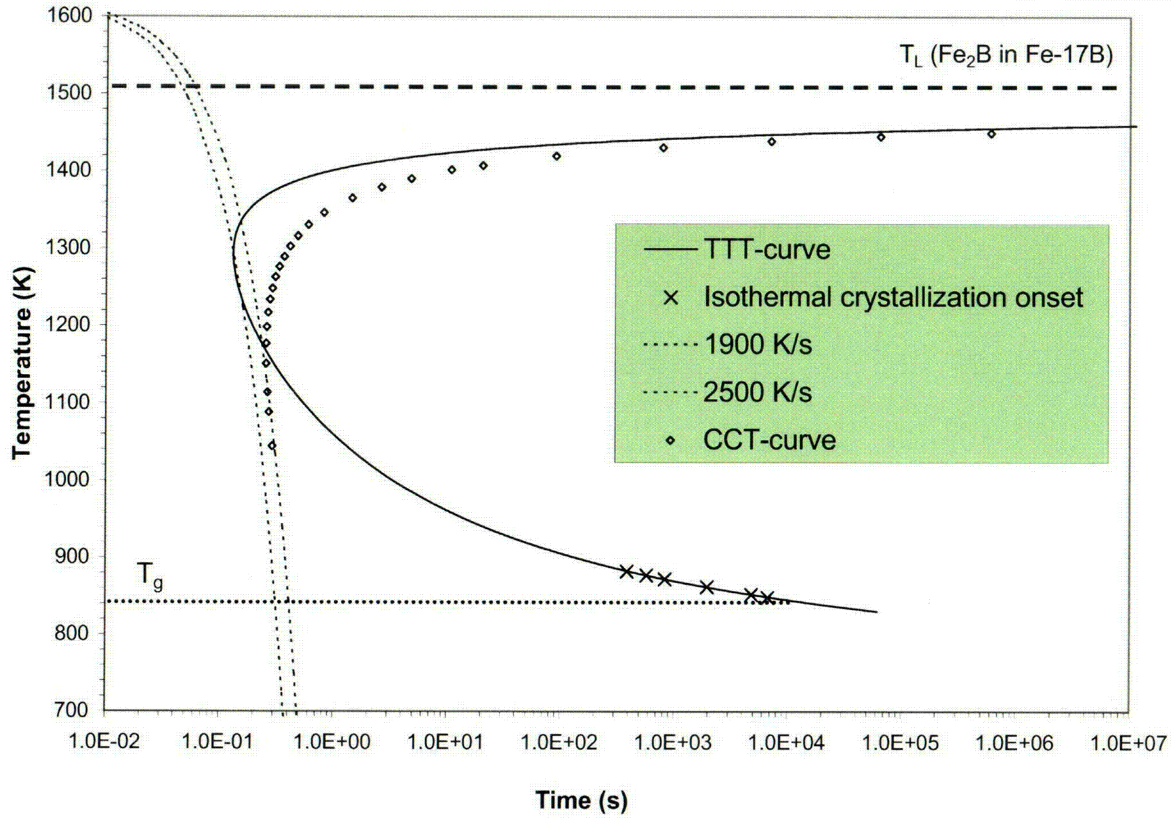
1.5 MW TRIGA Reactor

	¼-inch (6.4 mm) Stainless Steel Basket								¼-inch Ni-Gd Basket Material
	No Boron	0.12 wt. % Boron	1 wt. % Boron	2 wt. % Boron	No Boron 1-mm SAM2X5	0.12 wt. % Boron 1-mm SAM2X5	No Boron 1-mm SAM1651	0.12 wt. % Boron 1-mm SAM1651	
k_{eff}	0.96	0.91	0.85	0.83	0.87	0.86	0.90	0.88	**0.86**
Δk_{eff}	0.0	0.05	0.11	0.13	0.09	0.10	0.06	0.08	**0.10**

Neutron attenuation effectiveness of SAM will be tested at radiation facilities

C68

Stable at High Temperature

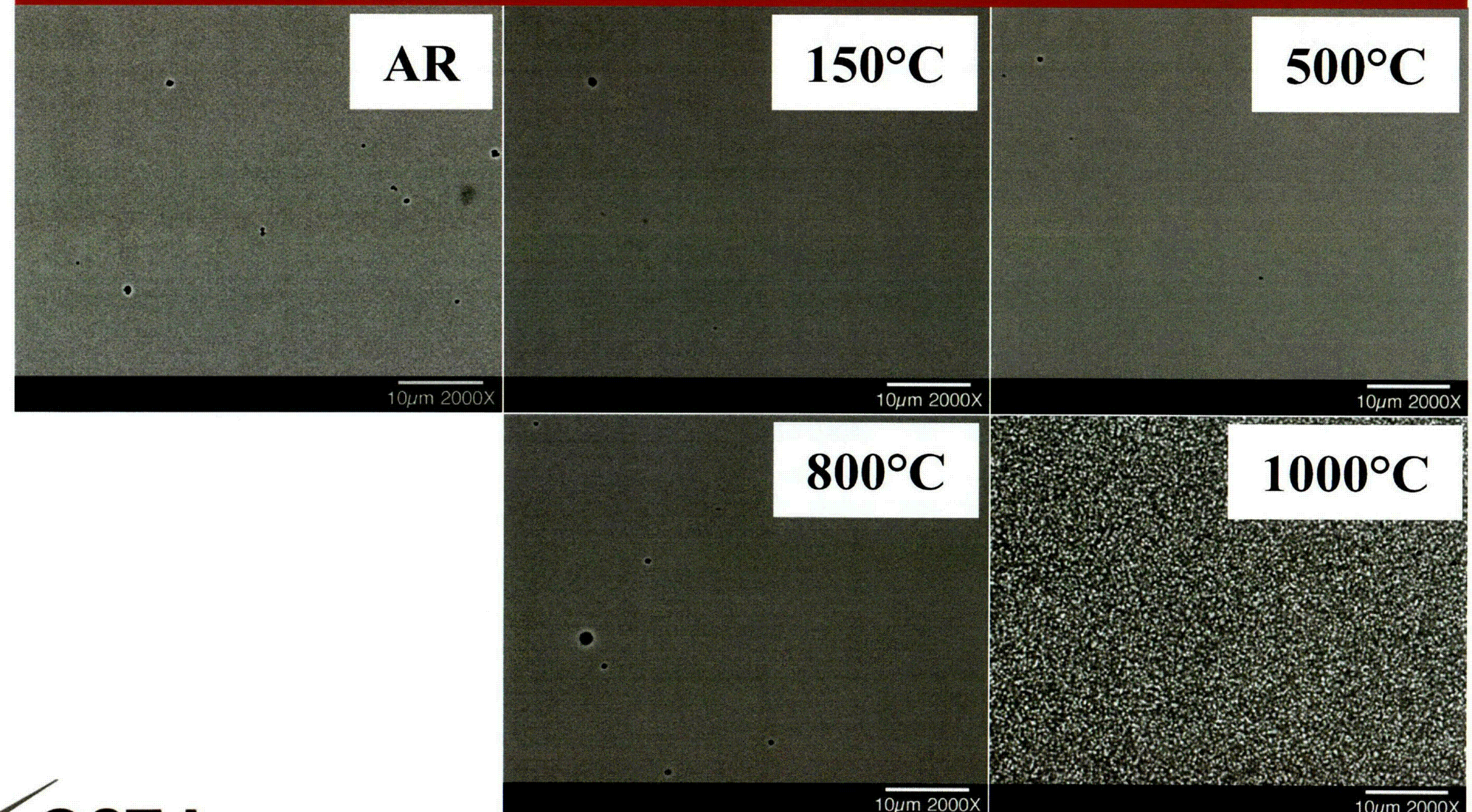


Alloy	T_g(°C)	T_x(°C)	T_m(°C)	T_L(°C)	T_{rg}(°C)
SAM 2X5	579	628	1133	1190-1210	0.57
SAM 1651	584	653	1121	1290	0.55

C69

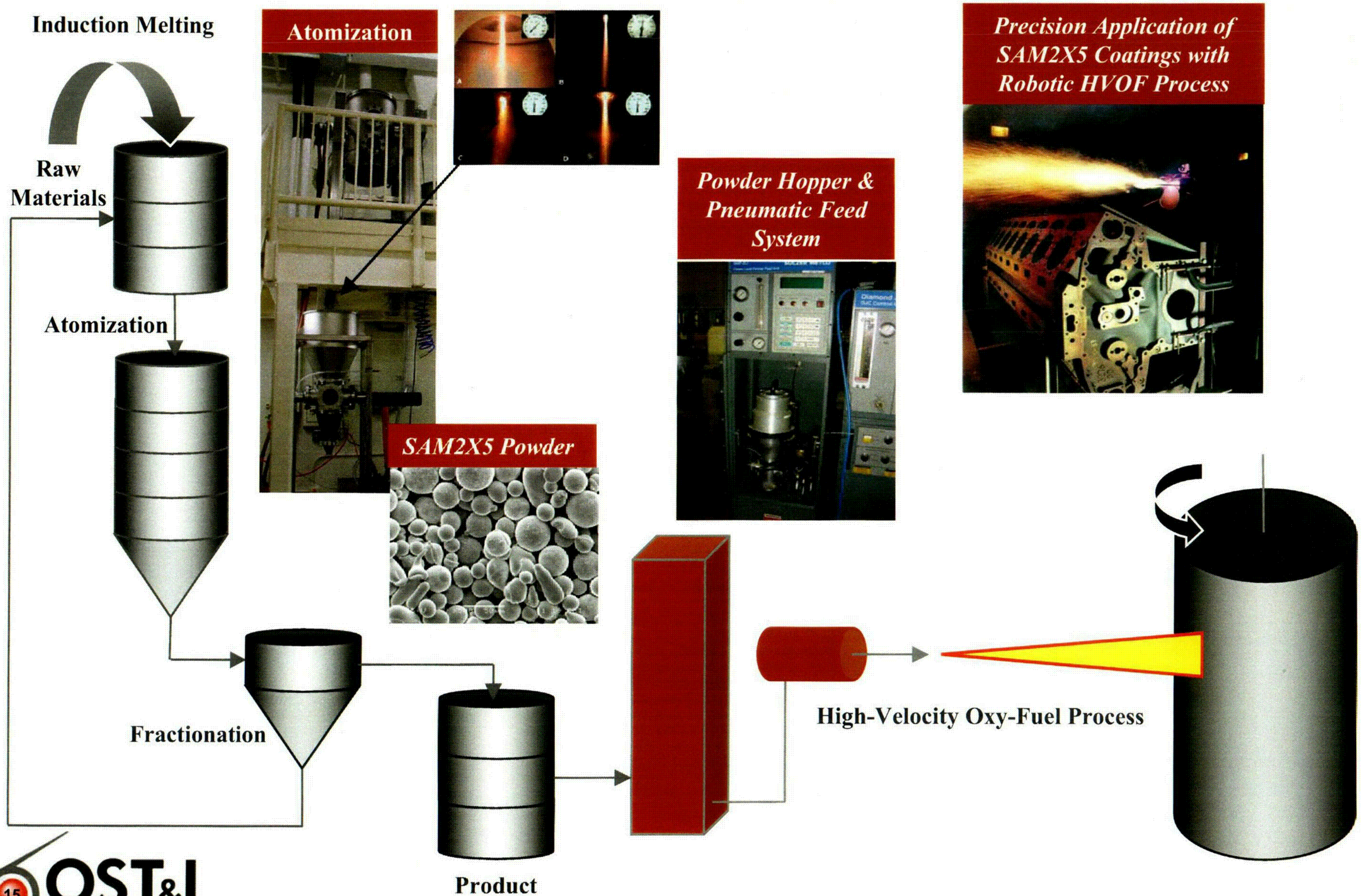
Stable at High Temperature

Microstructure of amorphous SAM1651 appeared to be stable up to 800°C/1hr. Beyond 1000°C, the matrix transformed into submicron crystalline phase(s).



C70

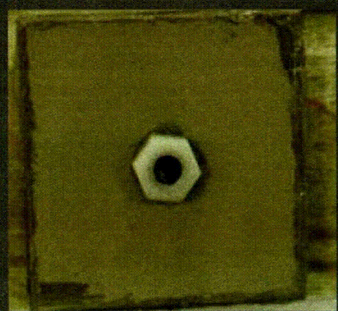
Low-Cost Thermal Spray Process



Potential Applications of Amorphous Metals

1. Corrosion Resistant Coatings

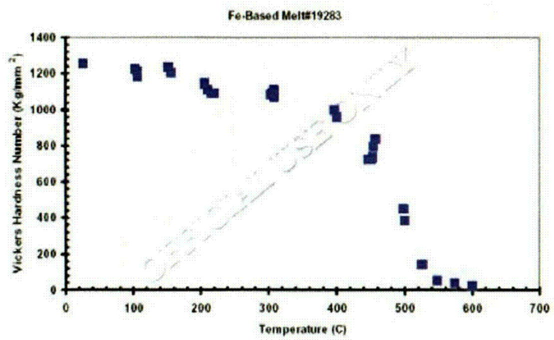
New SAM2X5 Coating



HPCRM SAM2X5 – After Exposure – 30 Cycles

- SAM2X5 & SAM1651 coatings can be applied with thermal spray processes without any significant loss of corrosion resistance
- Corrosion-resistant outer barrier
- Protect closure weld
- Drip shield coating

2. Damage Tolerant



- These materials are extremely hard and provide enhanced resistance to abrasion and gouges from backfill operations

✓Type 316L SS = 150 VHN
✓Alloy C-22 = 250 VHN
✓HVOF SAM2X5 = 1100-1300 VHN

3. High-Boron Content Coatings for Criticality Control Components

- Both SAM2X5 & SAM1651 have high boron content which enable them to absorb neutrons and therefore be used for enhanced criticality control
- Such coatings would enable corrosion resistant properties for criticality control components

Subsurface Operations

- Construction Material – silica-based cements
- Improved Operation – longer lasting tunnel boring machine disc cutters
- Backfill – re-evaluation of backfill assumptions

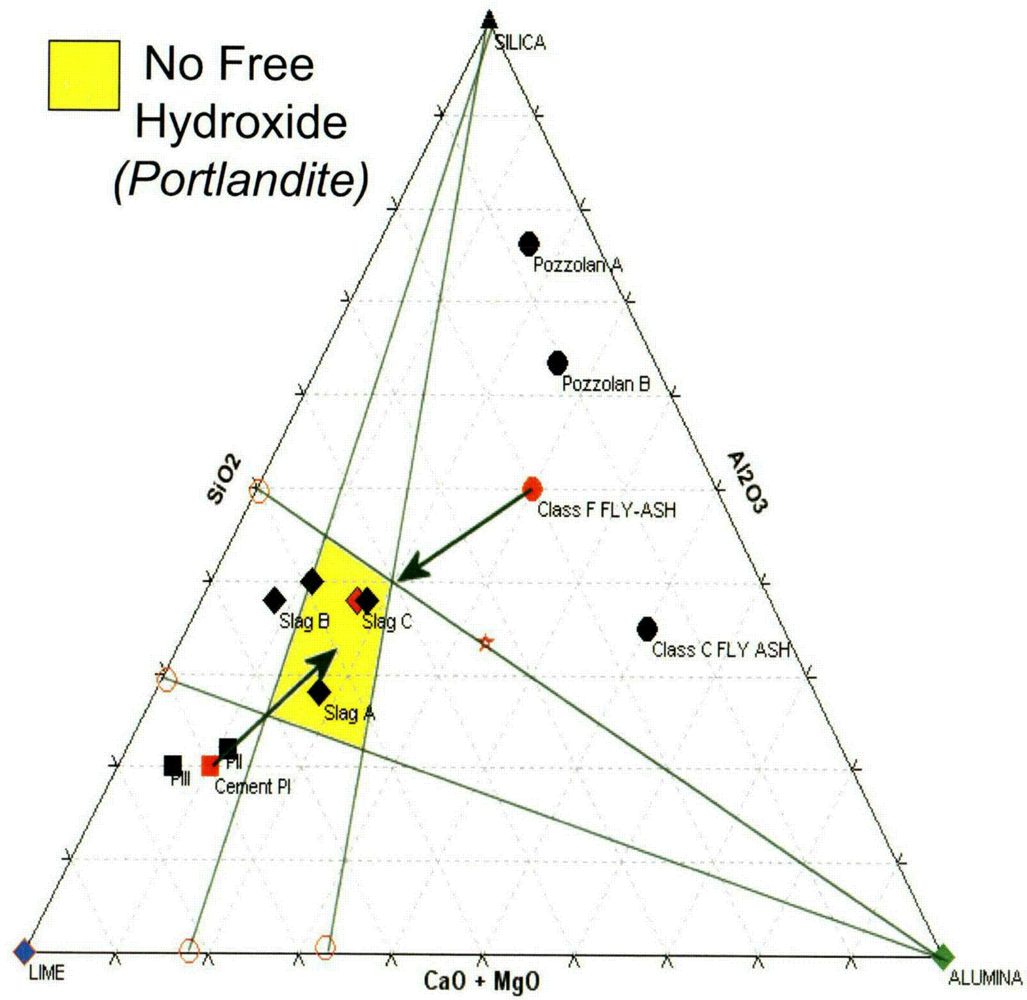
Low Alkalinity Silica-Based Cements

Background and Benefit of Low Alkali Cements

- Allow permanent emplacement of cement in the repository
- Use in shotcrete, roof support and/or invert construction
- pH limit mobility of radionuclides
- Low-cost local materials

Approach

- Shotcrete and slab mixtures comply with current engineering standards and Performance Assessment
- Low-pH silica-rich formula based on materials science, thermodynamic modeling and experience
- Test mechanical properties and chemical interactions under expected service conditions



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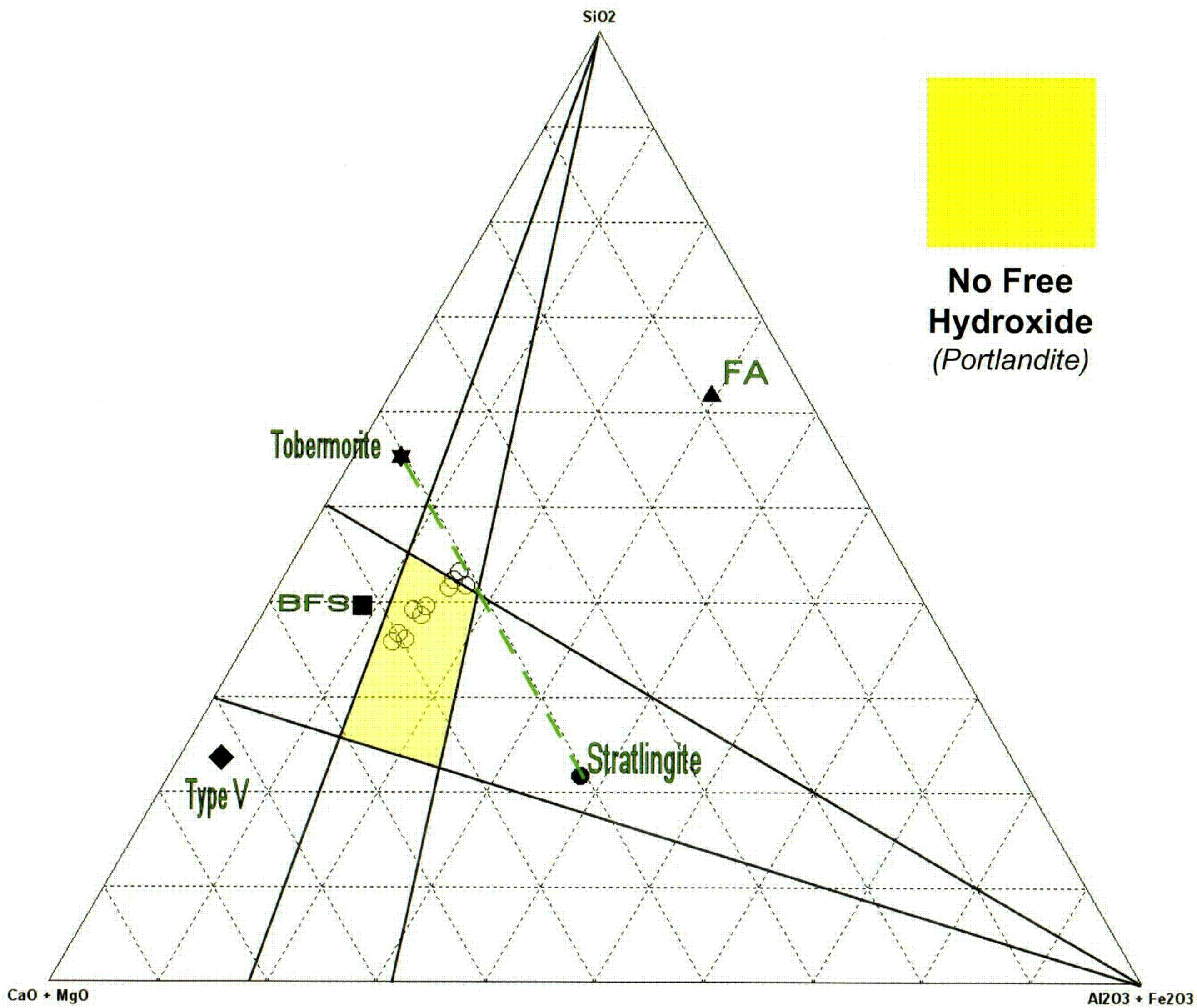
Candidate Mixtures

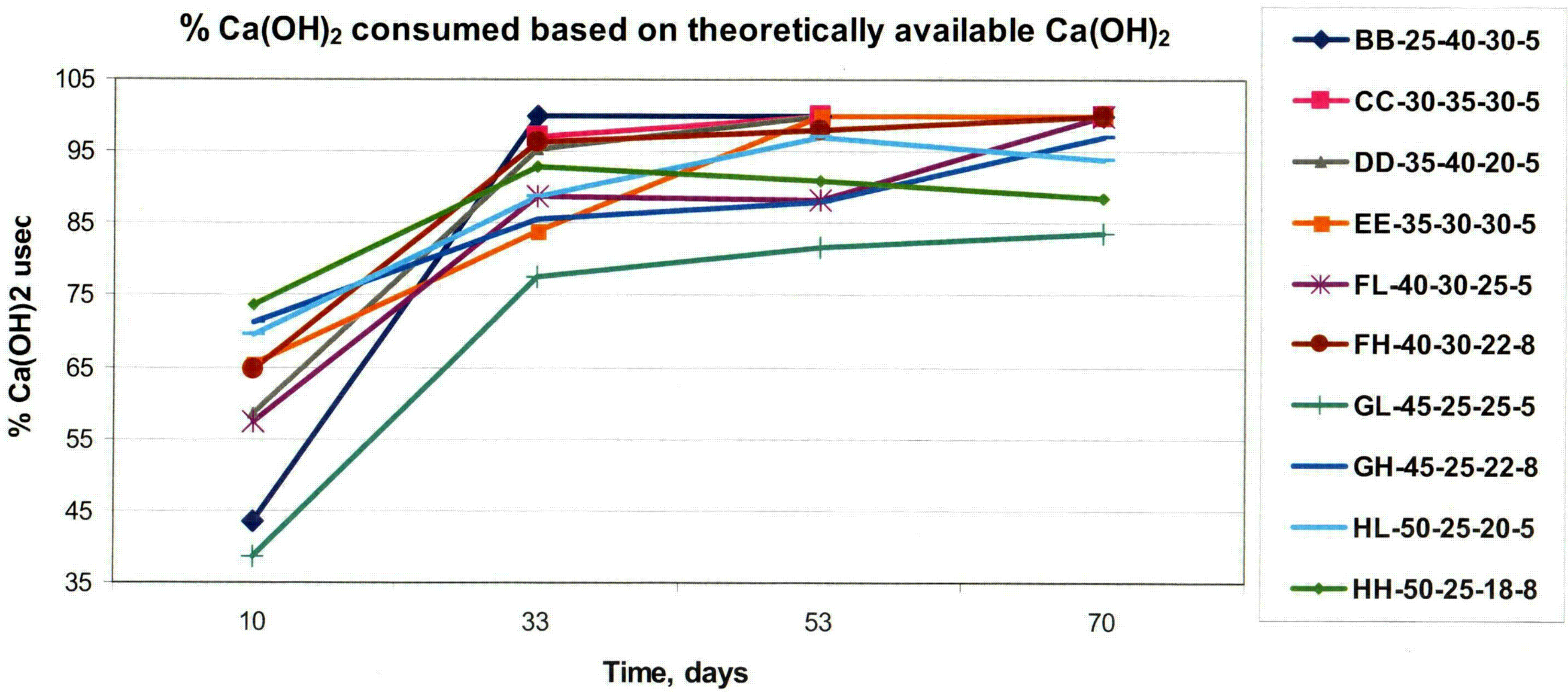
	Weight of mix (g)	4				
Mix Name	Type V target	**Type V**	Blast Furnance Slag	Fly Ash	Silica Fume	Wt water
		(g)	target %	target %	target %	(g)
BB (25-40-30-5)	0.25	**1**	0.4	0.3	**0.05**	40
CC (30-35-30-5)	0.3	**1.2**	0.35	0.3	**0.05**	40
DD (35-40-20-5)	0.35	**1.4**	0.4	0.2	**0.05**	40
EE (35-30-30-5)	0.35	**1.4**	0.3	0.3	**0.05**	40
FL (40-30-25-5)	0.4	**1.6**	0.3	0.25	**0.05**	40
FH (40-30-22-8)	0.4	**1.6**	0.3	0.22	**0.08**	40
GL (45-25-25-5)	0.45	**1.8**	0.25	0.25	**0.05**	40
GH (45-25-22-8)	0.45	**1.8**	0.25	0.22	**0.08**	40
HL (50-25-25-5)	0.5	**2**	0.25	0.25	**0.05**	40
HH (50-25-22-8)	0.5	**2**	0.25	0.22	**0.08**	40

Silica Reactivity of Candidate Mixtures



Curing Reaction Rates

- Silica reactivity tests identify mixtures that balance the suppression of calcium hydroxide with curing reaction rates



Nomenclature: 30-35-30-5 (30 wt% OPC Type V, 35 wt% BFS, 30 wt% FA and 5 wt% SF)

Early Strength Data Adequate for Drift Support

Apparent drops in strengths are statistical artifacts

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Current Proposed Shotcrete Mixture

>5,000 psi (34.5 MPa) w/cm = 0.45

Constituent	S.G.	lb/yd³	kg/m³	ft³/yd³	% vol.
Cementitious:	2.789	725	430	4.166	15.4
Water:	1.0	326	193	5.224	19.3
Steel Fibers:	7.85	101	60	0.206	0.76
Air – 1%:	-	-	-	0.270	1.0
Sub-total:	-	1,152	683	9.866	36.5
3/8" Aggregate:	2.82	908	539	5.160	19.0
Sand:	2.62	1,969	1169	12.044	44.4
WR* Admixtures:	1.06	2	1	0.030	0.1
TOTAL:		**4,031**	**2,392**	**27.100**	**100**

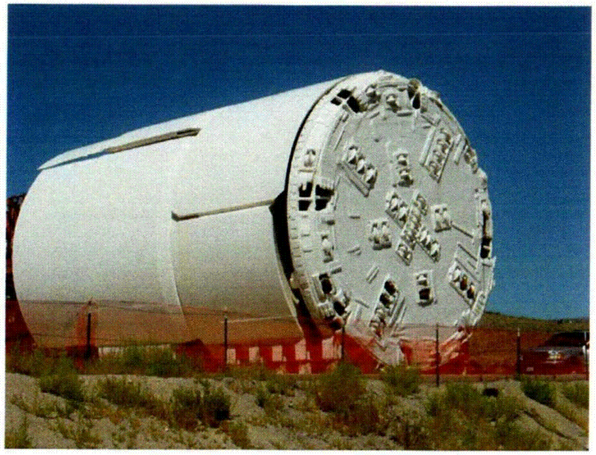
ACI 506 & ASTM C 1436 Combined Grading ***WR = Water Reducer**

Subsurface Operations

- Construction Material – silica-based Cements
- Improved Operation – longer lasting tunnel boring machine disc cutters
- Backfill – re-evaluation of backfill assumptions

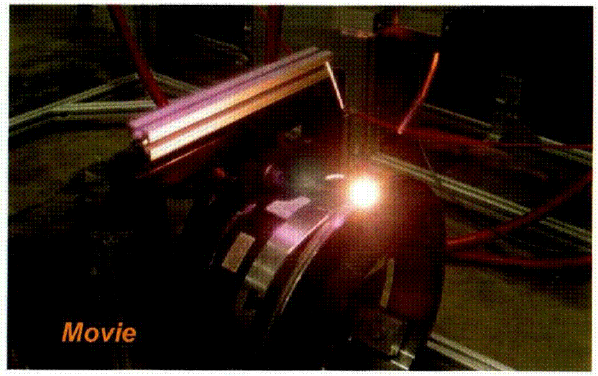
Amorphous Metal Coated TBM Disc Cutters

1. Engineering Improved Cutter Performance



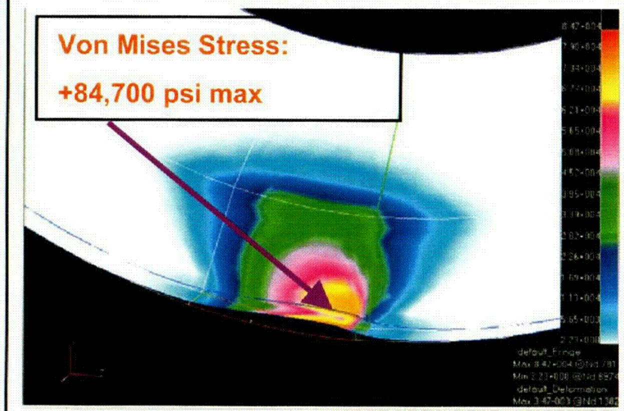
- Excavating ~ 2000 ft emplacement drifts will require 3 to 4 disc cutter changes
- **~ 27 hrs** required for **ONE** complete change of the disc cutters on an 18 ft diameter tunnel boring machine (TBM)
- Minimizing disc cutter changes improves worker safety

2. Fully-Automated Laser-Fusing of Amorphous Metal Coatings



- Current disc cutter materials are at a technological limit of hardness and toughness
- Amorphous metal coatings to extend the operational life of TBM disc cutters was viewed as novel and promising
- Such coatings must be applied economically to state-of-art disc cutters
- Longer lasting disc cutter→ Thinner cutting edge possible→ ***Less dust generation***

3. Finite Element Analyses Provide Insight on Mechanical Behavior of Disc Cutters

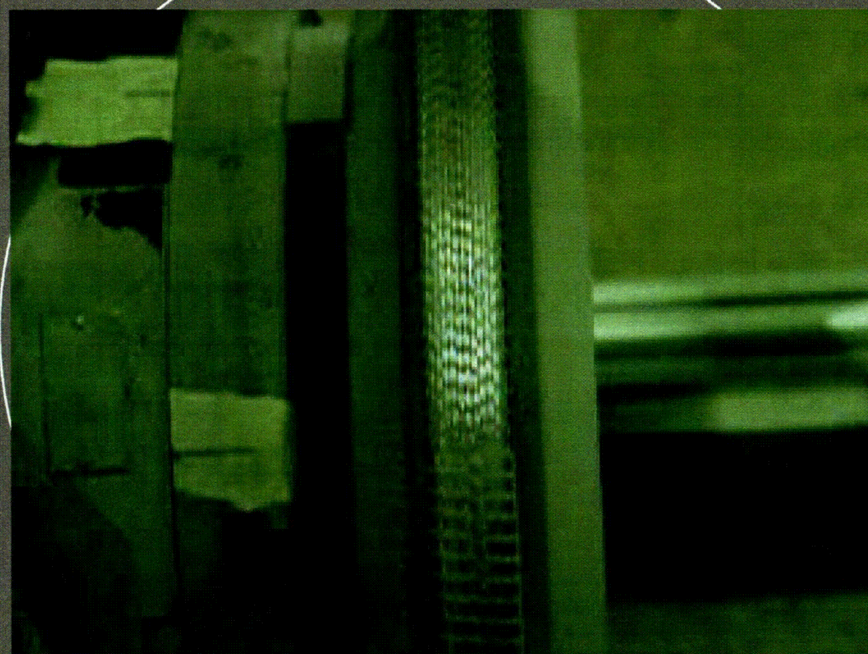


- Local maximum loads, depending on rock faceting: **> 300,000 lbs-force**
- Maximum Von Mises stress is 1/3 of yield strength of tempered tool / die steel
- Local hoop and transverse strain values provide guidance for optimizing stripes / freckle widths

Laser-Fused Coated Disc Cutters

Freckles
Longer
Spacing

Wide
Stripes



Thin
Stripes

Freckles
Shorter
Spacing

OST&I
OCRWM Office of Science and Technology and International

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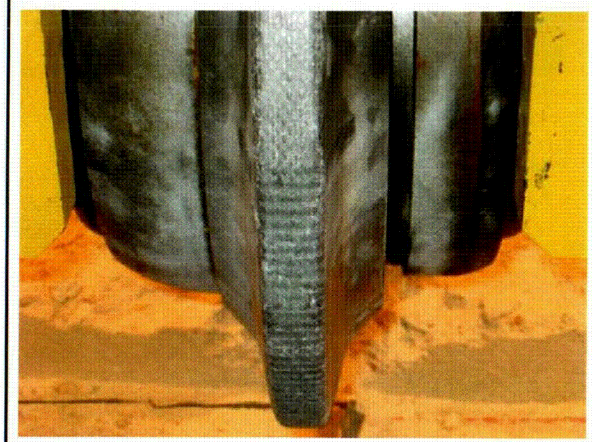
Initial Full-Scale Disc Cutter Testing

1. Initial Full-Scale Testing at Colorado School of Mines (CSM)

- Barre Granite (very hard rock; harder than Yucca Mountain host rock)
- Peak average load on disc cutter: ~ 75,000 lbs-force; limit of testing machine
- Cut depths: 0.1 and 0.2 inches; approx. 100+ total passes per disc cutter

2. Initial Disc Cutter Preliminary Performance Evaluation



- Initial tests showed *NO EVIDENCE OF SPALLING OR CRACKING* of the coating
- *Significance:* According to CSM, in 25 yrs of disc cutter testing, this was the first time that a coating *OF ANY KIND SURVIVED* initial impacts with the rock
- These coatings have shown hardness values and compressive strengths ~ 1.3 to 2 times greater than conventional steels

3. Initial Laser-Fused Coated TBM Disc Cutter Tests are Promising

- Amorphous metal-coated TBM disc cutter effort started in July 2005
- Team is very encouraged by these initial test results on a full-scale disc cutter and the preliminary evaluations
- Post-mortem metallurgical evaluations and refinement of 3D FEA analyses will aid to optimize laser-fusing process and parameters
- Field-testing (e.g. in Atlanta, GA and San Bernadino, CA) planned to commence in Spring 2006

C79

Subsurface Operations

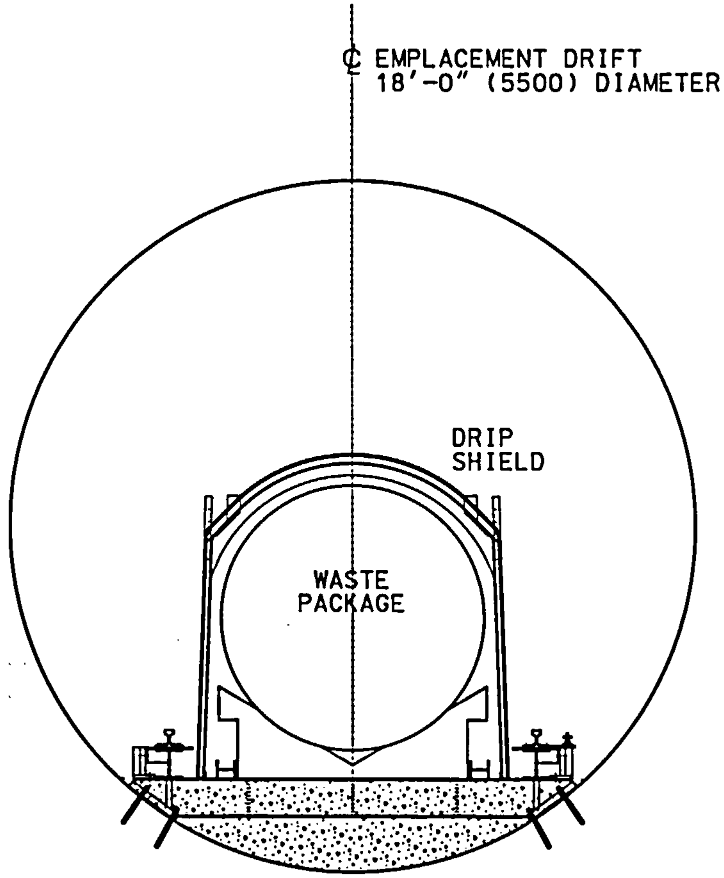
- Construction Material – silica-based cements

- Improved Operation – longer lasting tunnel boring machine disc cutters

- Backfill – re-evaluation of backfill assumptions

Background and History

- Previous studies have consistently indicated that including backfill in the design, with or without a drip shield, could have significant beneficial impacts
- Backfill was removed from the current design (selected during the License Application Design Study (LADS) process) due to concerns over thermal effects
- Preliminary results indicate that disruptive events are the major contributors to dose during postclosure, due to damage to drip shields and waste packages from seismic shaking and magmatic intrusion
- Recent studies also suggest that designing the near-field environment with natural materials to capitalize on the natural attributes of the unsaturated zone (e.g., Richards Barrier) could have beneficial impacts to peak dose

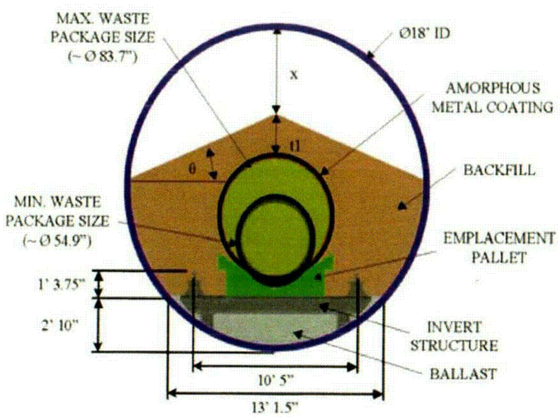


Current Drip Shield and Engineered Barrier System (EBS) Design

Purpose and Scope

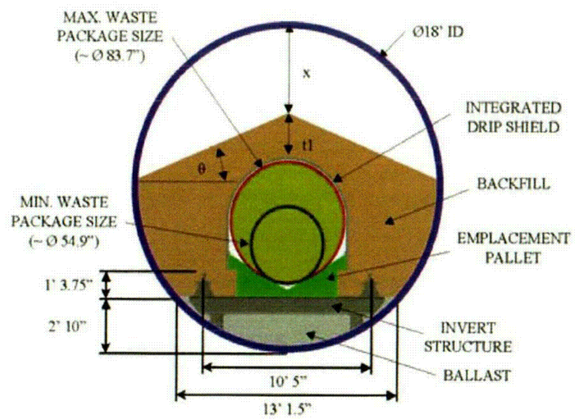
- **Purpose of the Study**
  - Evaluate whether backfill could mitigate performance impacts associated with seismic and volcanic events
  - Perform a preliminary evaluation of other beneficial and detrimental impacts (thermal, hydrological, chemical) of backfill
  - Recommend whether to proceed with S&T studies that could lead to re-incorporating backfill and/or removing the drip shield
- **Scope of Alternatives Considered**
  - Three alternative backfill/drip shield configurations have been analyzed
  - Candidate backfill materials considered include crushed tuff, quartz sand and admixtures that could improve chemical performance
  - Backfill size ranges considered include coarse gravel (5-10 cm) and medium (2 mm) to fine (.25 mm) sand with varying grading/sorting characteristics
  - Richards Barrier analyses are based on well sorted, fine, sand-sized particles (tuff or quartz) rather than medium, sand-sized particles

Design Configurations



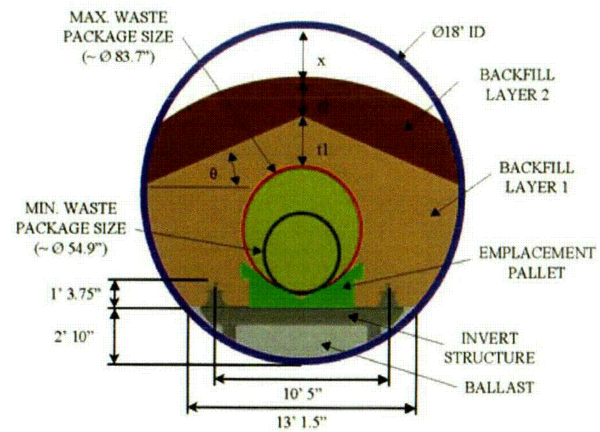
Alternative #1

1) Backfill emplaced directly onto the waste package



Alternative #2

2) Backfill emplaced onto waste package with an integrated shield



Alternative #4

3) Backfill engineered to provide a Richards Barrier to flow (two or more layers), emplaced onto the waste package

For each configuration, two other options have been identified

- The waste package and/or drip shield could be coated with amorphous metal for additional corrosion resistance
- Backfill materials could be engineered for corrosion and abrasion resistance or to affect the near-field environment and chemistry

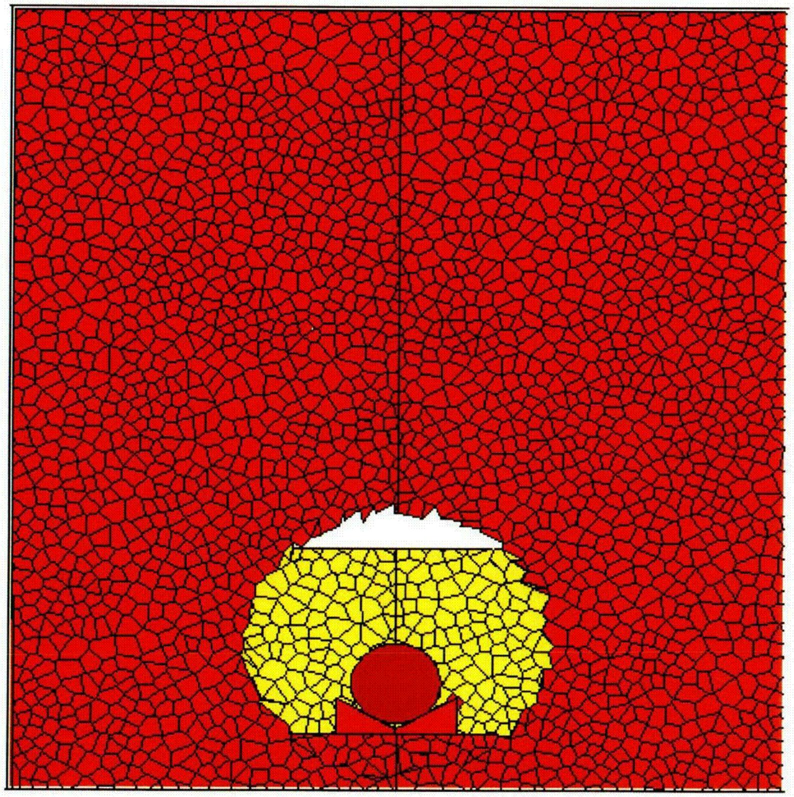
Scope of Process/Performance Analyses

- **Key analyses include:**
  - Effect of backfilled drifts on disruptive event scenarios:
    - Numerical analysis of seismic shaking and damage to the waste package/drip shield in a backfilled drift
    - Analysis of magma flow within partially or completely backfilled drifts, and thermal effects on waste packages
  - Thermal analyses of waste package, cladding and drift wall temperature in backfilled drifts
  - Evaluation of seepage within backfilled drifts
  - Thermal hydrologic analyses of water distribution and humidity
  - Effect of backfill materials on in-drift thermal-hydrological-chemical (THC) environment
  - Effect on corrosion processes and material degradation (total system performance assessment sensitivity analyses)

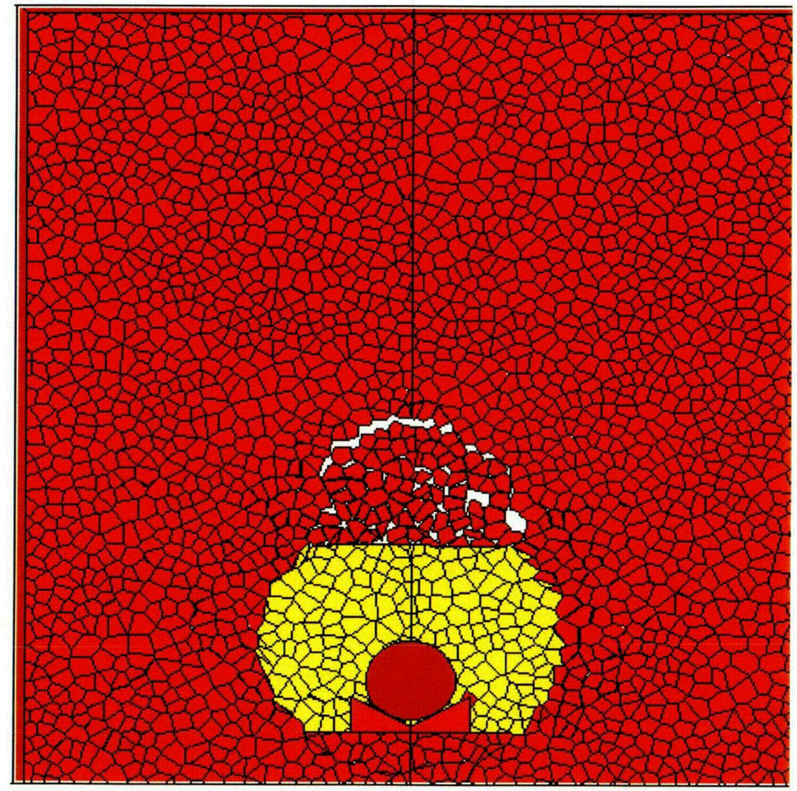
Preliminary Results: Disruptive Events

- **Analyses indicate that the use of backfill significantly limits the effect of seismic shaking on the engineered barriers**
  - Damage caused by the movement of the waste package and drip shield, and by the collapse of the drifts during seismic events is mitigated
  - Richards Barrier designs appear to be stable even during peak events (PGV= 2.44 m/s)
- **The use of backfill eliminates the possibility of magma directly contacting waste packages, except at the dike-drift intersection**
  - Magma flow could occur in openings above backfill, but analyses indicate that drifts will collapse from seismic events at a probability of 10^{-5} to 10^{-6}, compared to a probability of an igneous event of approximately 10^{-8}, so the likelihood of any magma flow in drifts is remote
  - Thermal analyses indicate the effects on waste packages will be small

Crown Collapse Simulation for 2.44 m/s PGV Ground Motion



before shaking



after shaking

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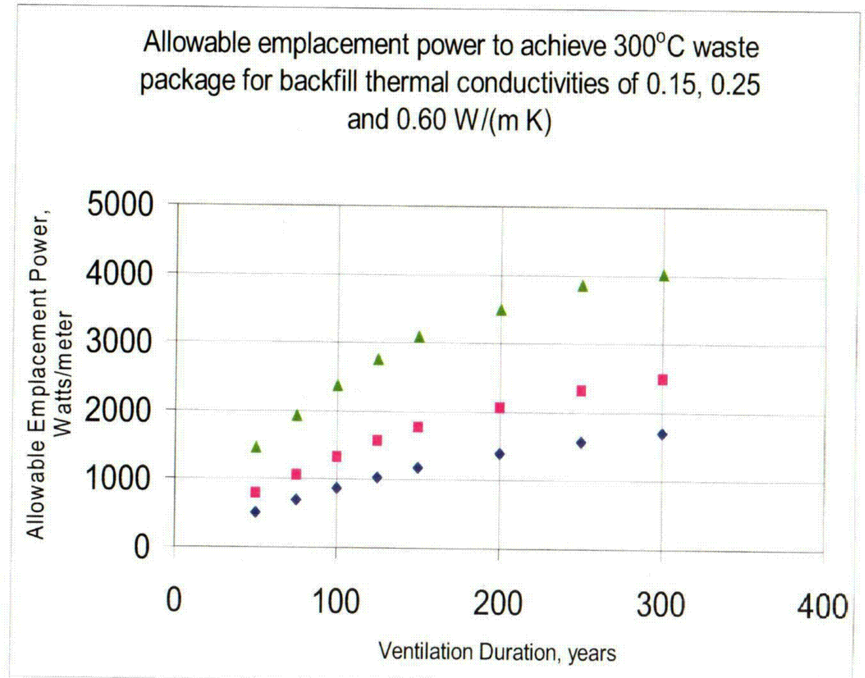
Thermal Effects of Backfill

- Because backfill is an effective thermal thermal insulator, temperatures on the waste package surface will be higher than for packages in an open drift
  - Thermal analyses provide the basis for thermal management strategies necessary to meet design criteria (e.g., maximum waste package temperatures, drift wall temperatures)
  - These analyses consider all relevant parameters (thermal loading of packages, ventilation time, age of fuel, drift spacing, backfill thermal conductivity, etc.)
- Preliminary analysis indicates that current thermal load may require extended ventilation to meet waste package surface temperature criterion



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Scope of Engineering Analyses

- In addition to analyses of the post-closure performance of alternative backfill/drip shield configurations, this study also includes several other preliminary engineering analyses:
  - Engineering analyses of alternative emplacement strategies, sequences and techniques, including identification of Engineered Barrier System (EBS) configurations that could enhance operational flexibility
  - Preliminary analysis of the feasibility of amorphous metal coatings on the waste package or drip shield to limit corrosion or enhance abrasion resistance
  - Analysis of alternative drip shield materials, if additional work on the integrated shield configuration is recommended

Additional Analyses in Progress

- Evaluation of seepage within backfilled drifts
- Thermal-hydrologic analyses of water distribution and humidity
- Effect of backfill materials on in-drift THC environment
- Effect of backfill on corrosion processes and material degradation (TSPA sensitivity analyses)

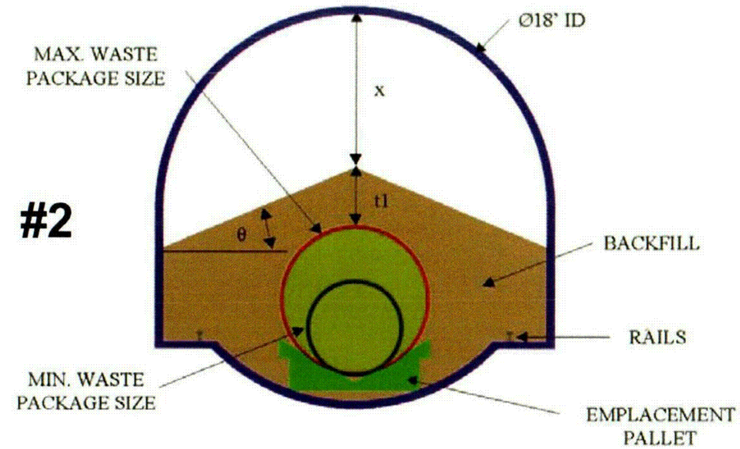
Alternative Drift Concepts

#1. Circular TBM drift invert is squared off using secondary cutters to create a flat bottom. WP pallet rests directly on fill used for floor leveling on drift invert, creating greater headroom for the backfill emplacement equipment

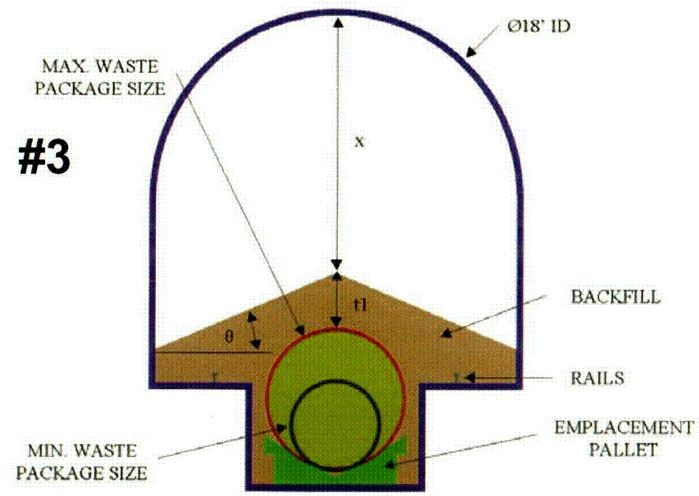
#2. Circular TBM drift walls are trenched using secondary cutters to create base for emplacement gantry rails. WP and pallet can be set directly on invert (leveled with backfill), to increase headroom for backfill equipment

#3. Circular TBM drift with flat floor and with trenched floor created in a secondary pass with mechanical trenching tool. WP is placed below invert grade, confining the WP during seismic events, and increasing headroom for backfill equipment

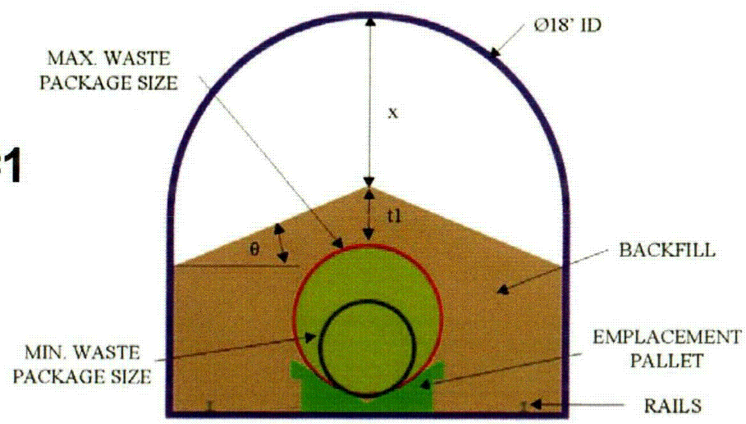
#2



#3



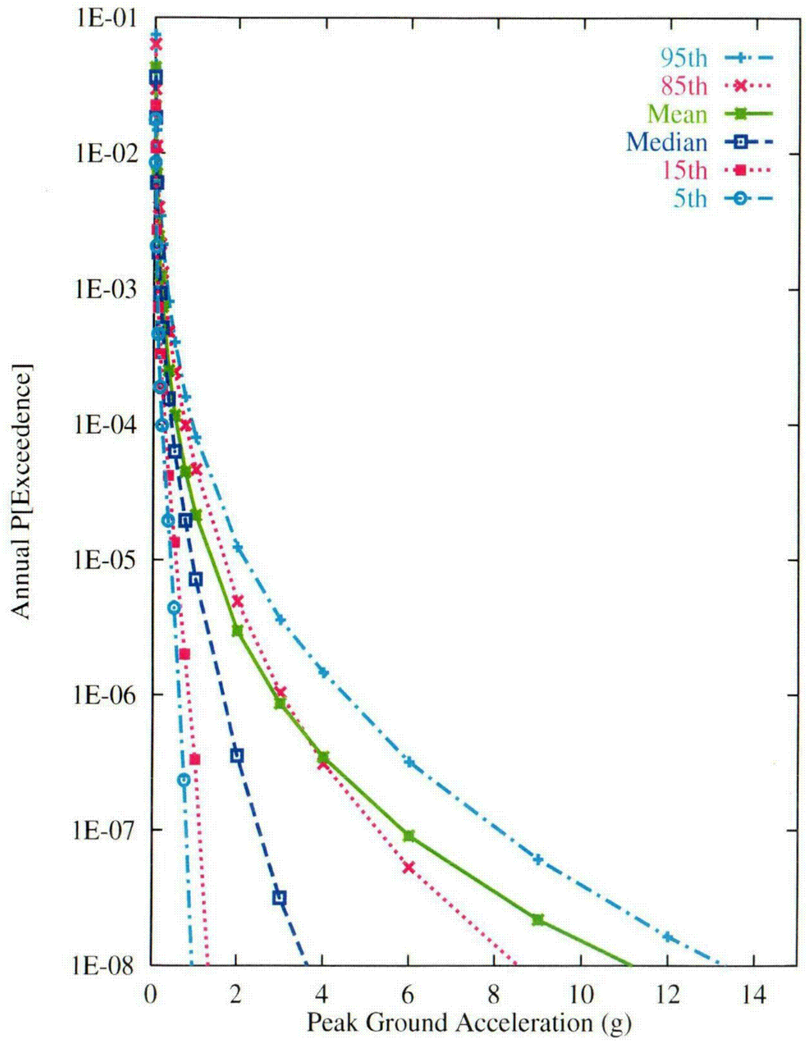
#1



Surface Operations

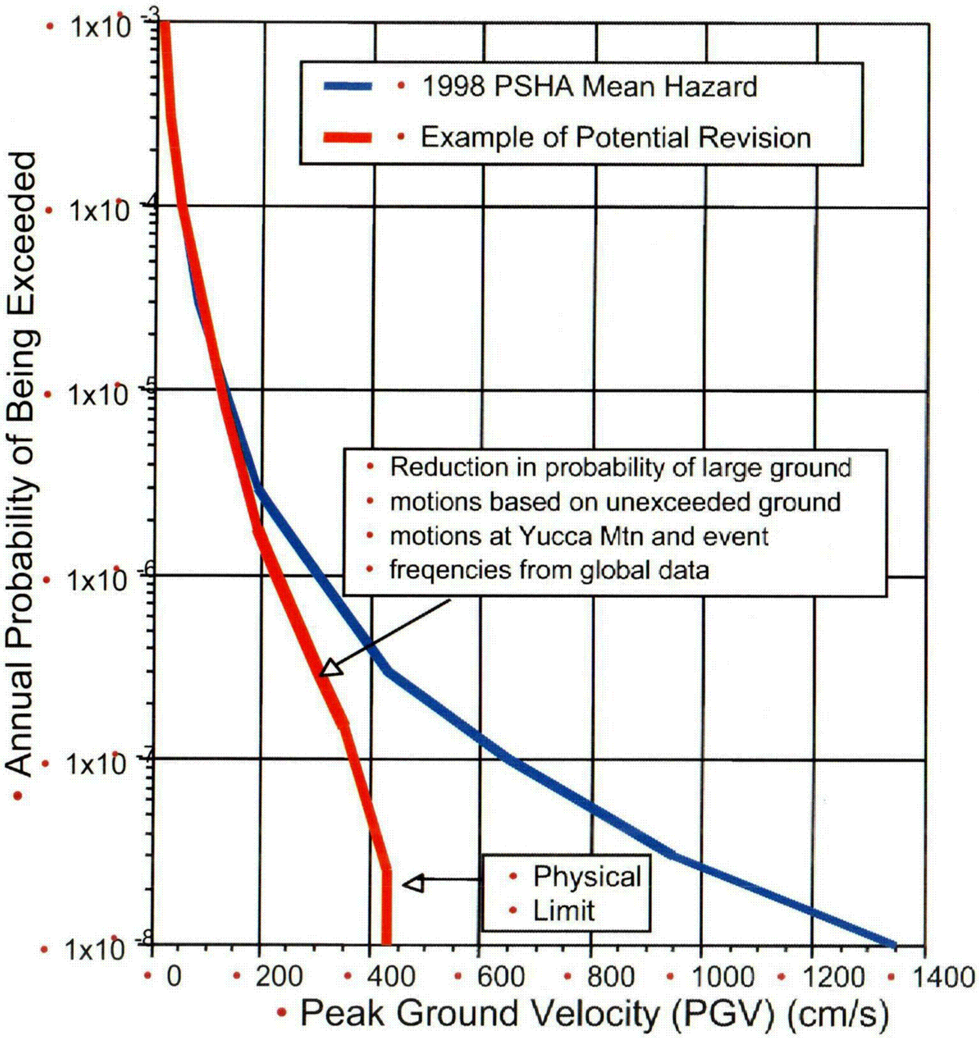
- Reduction of Seismic Hazard – Nonlinear ground response model for extreme ground motions

Extreme Ground Motion Project



- **Issue: The 1998 PSHA led to extremely large ground motions at very low probability levels**
- **Technical Approaches:**
  - **<u>Physical Limits:</u> Limits of ground motion due to the seismic source and strength of rocks underlying the repository**
  - **<u>Unexceeded Ground Motions:</u> Limits on largest ground motions that have occurred at Yucca Mtn over the last millions of years based on observations of undamaged geologic features**
  - **<u>Event Frequencies:</u> Rates at which extreme ground motions occur based on global studies of earthquake sources**

Application of Technology



- Results can be used in a re-evaluation of the hazard
- Physical limits from the source and rock strength will be used to set an absolute limit to the ground motion (zero chance of being exceeded)
- Unexceeded ground motion will be used to constrain the Yucca Mountain site-specific hazard
- Event frequencies will be used to modify the log-normal distribution of the ground motion

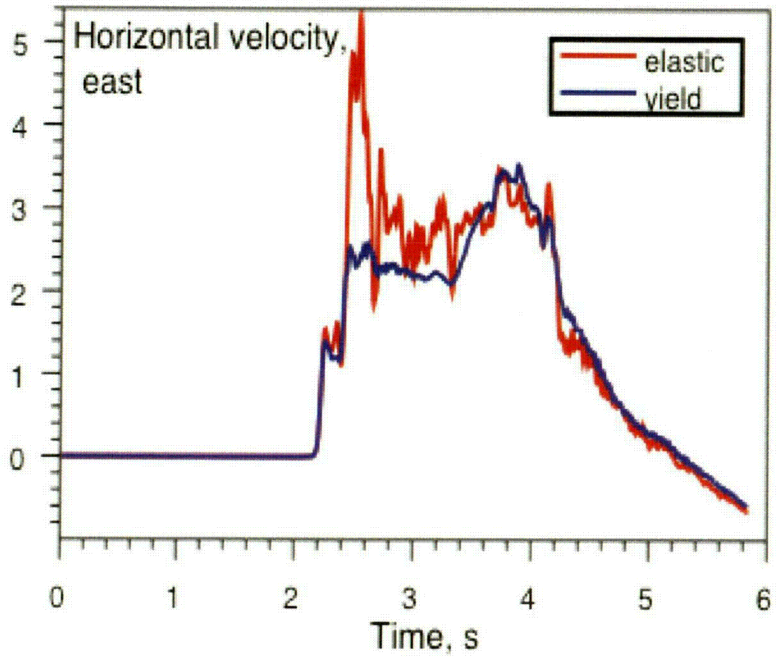
Example of Geologic Constraints

Lithophysae

From Buesch (2004)

- Observe lithophysae at Yucca Mountain that are undamaged in last 12M years
- Compute the strains that would cause observable damage to the lithophysae
- Use numerical modeling to relate these strains to peak velocities
- Results in PGV value that has not been exceeded in 12M years
- Not a physical limit, but can be used to constrain the hazard

Example of Physical Limits

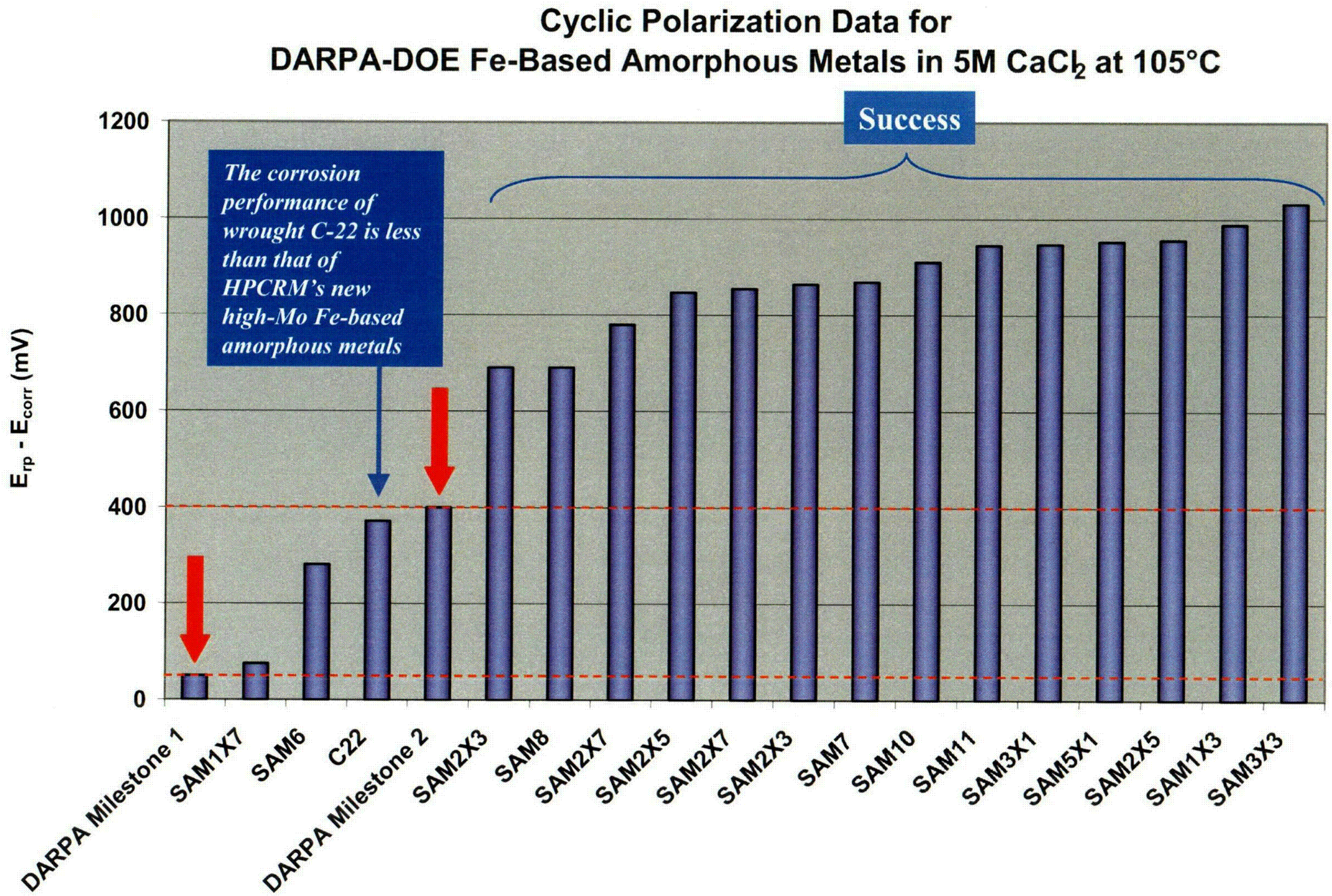


Numerical Simulation of Horizontal Velocity (m/s)

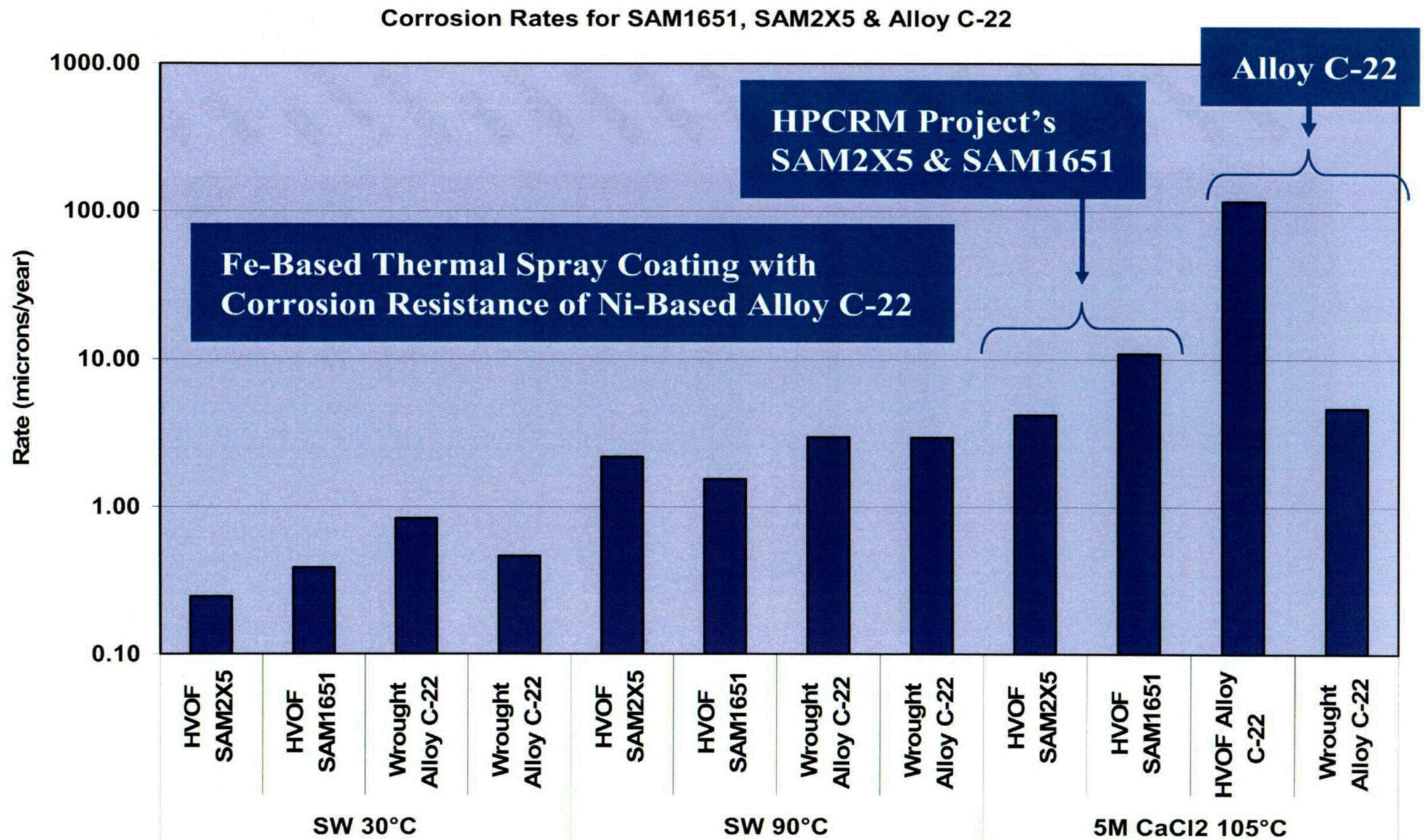
- **Set the seismic source properties to their most severe condition**
  - **Establish the most severe source**
- **Use numerical models to compute the ground motion including non-linear behavior of both the source and rocks**
- **Use equivalent kinematic models for high frequency ground motion**

Backup Slides

Difficult to Initiate Corrosion



Corrosion Resistant (cont'd)



• Low Corrosion Rate