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An Underground Laboratory in the Context of Salt Disposal RD&D

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Sandia National Laboratories

Albuquerque, NM

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Generic and Site Specific Underground Research Laboratories to Support Siting, Design and Safety Assessment Developments

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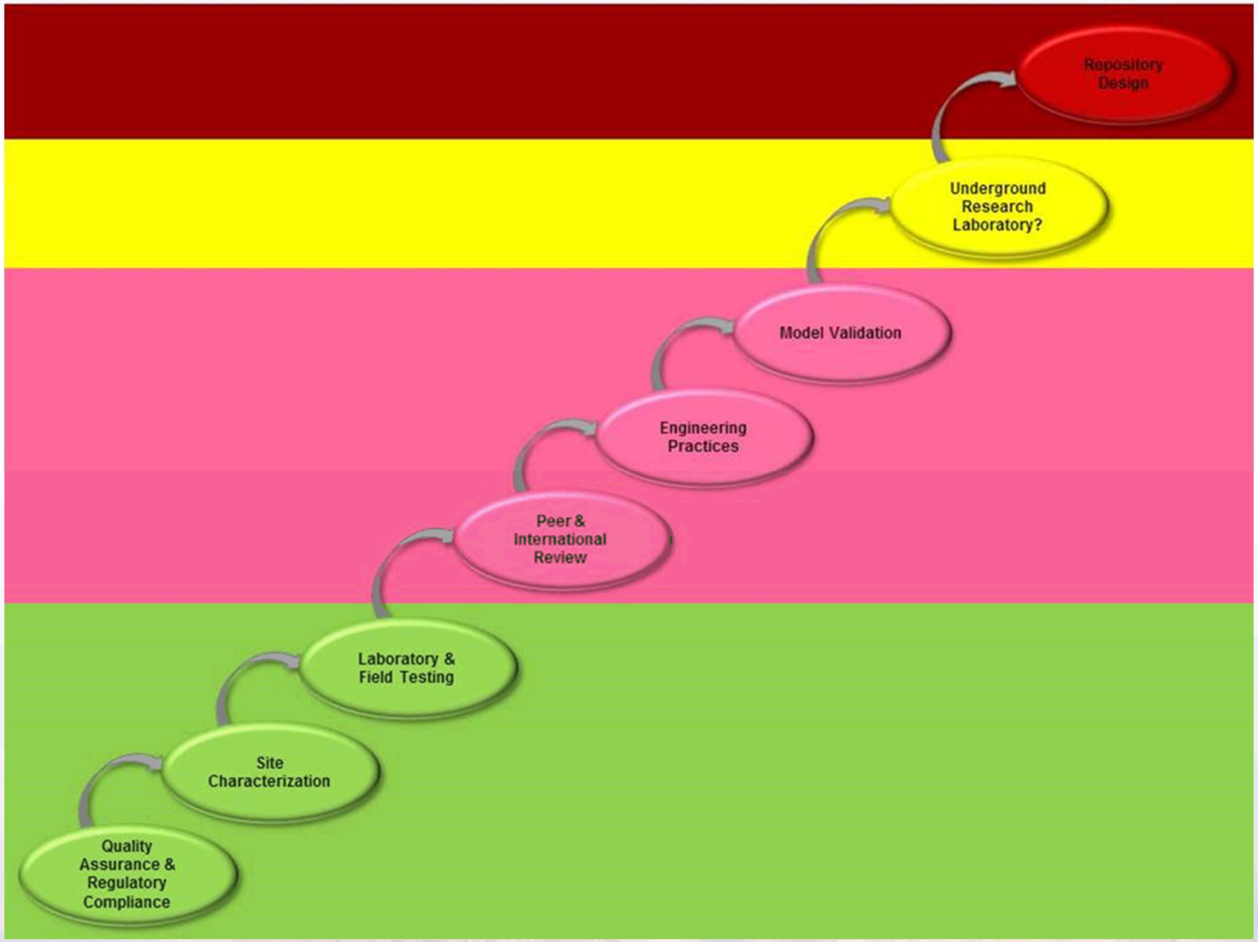
Overview

- Set the stage for today's discussion
- Ideals for underground research laboratory accomplishments
- History of salt repository development
  - Laboratory investigations
  - Field testing
  - Modeling
- Licensing a salt repository
  - Waste Isolation Pilot Plant
  - Vorläufige Sicherheitsanalyse Gorleben (VSG)
  - Industry practices
- International collaboration
- Repository design for heat-generating waste
- How to proceed—Framework for URL implementation

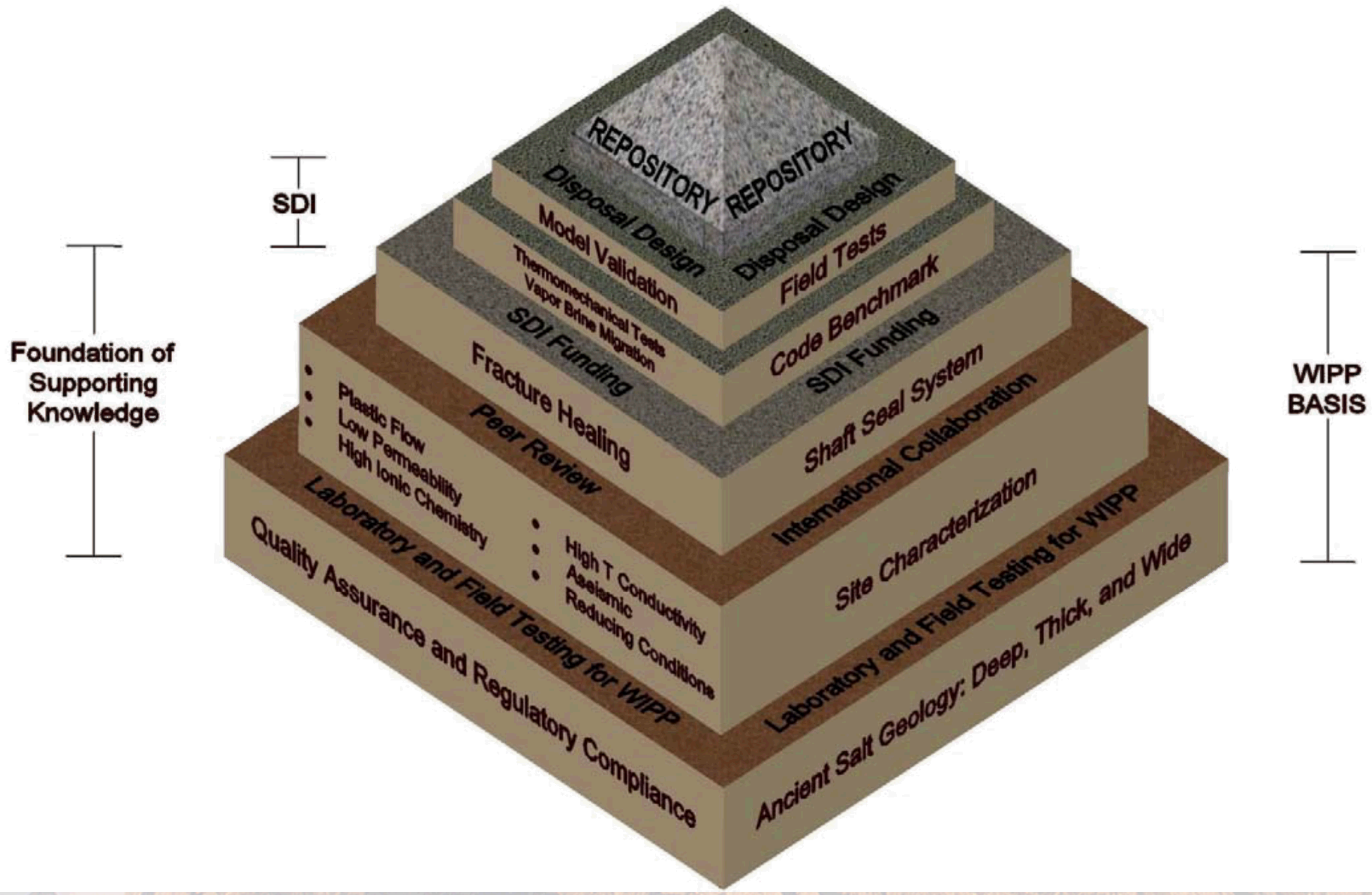
Introduction

- The USA has many geologic settings suitable for deep geologic disposal of nuclear waste
- There is substantial confidence that compliance with regulatory standards can be demonstrated
- Rock types include salt, shale, and granite (and other massive, competent rock types)
- Media-specific, internationally recognized disposal concepts
- Special attention to URLs in salt formations—IAEA Terms of Reference (TOR)

Progress Toward a Salt Repository



How Much is Enough?



Purposes of URLs

- Develop technology and methodology for underground experimentation
- Assess performance of the repository system.
- Optimize engineering components and processes
- Better understand, model and test relevant processes
- Reduce uncertainty and increase confidence in the safety case
- Build confidence and foster international collaboration
- Train personnel

IAEA 2001; NEA 2013

Purposes of URLs

- Addressing FEPs: Confirm our understanding and ability to model features, events and processes that affect performance
- Building Confidence: Build confidence that the safety functions of a deep geologic repository in salt are understood and can be forecast over regulatory time periods
- International collaboration: Enhance technical credibility through engagement of the international community
- Testing Concepts: Evaluate designs and operational practices
- Validating Models: Predict and confirm evolution of processes at full-scale

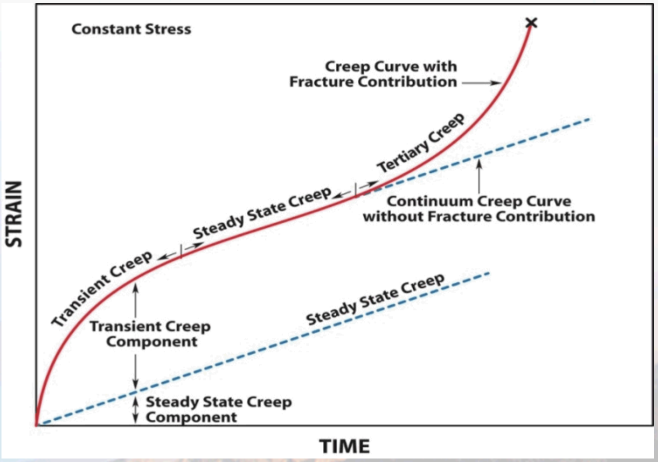
Hansen, 2014

Laboratory Investigations

International Collaboration

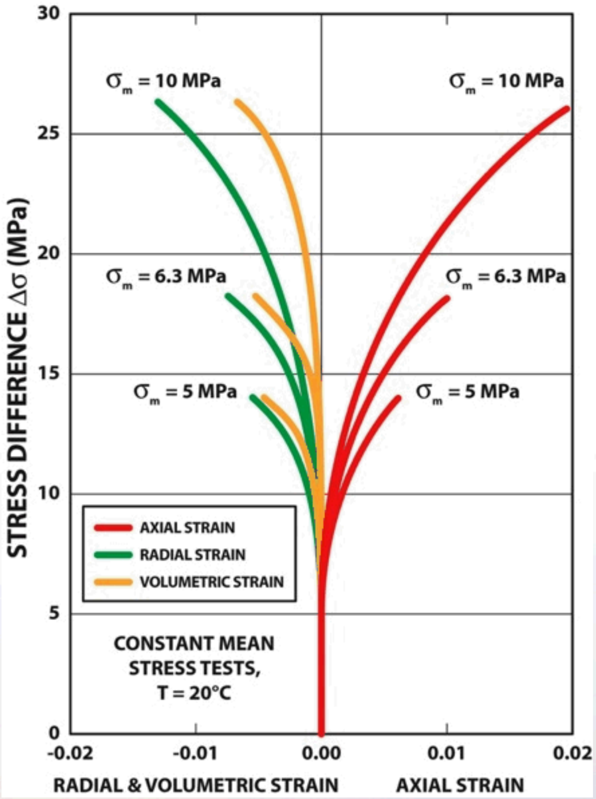
Mechanical Behavior

Large Test Rigs Needed



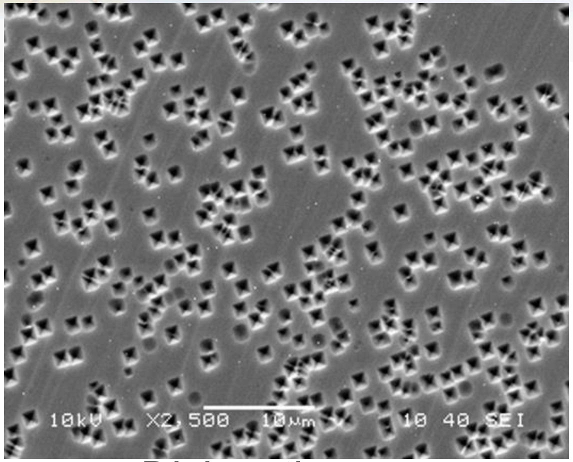
Classic Response

Deformed Salina Basin Salt

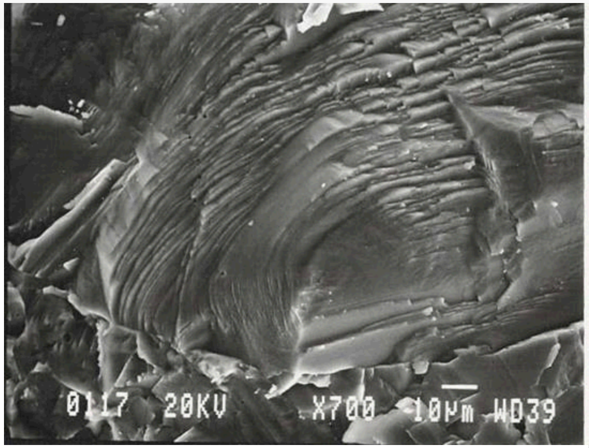


Mean Stress Testing

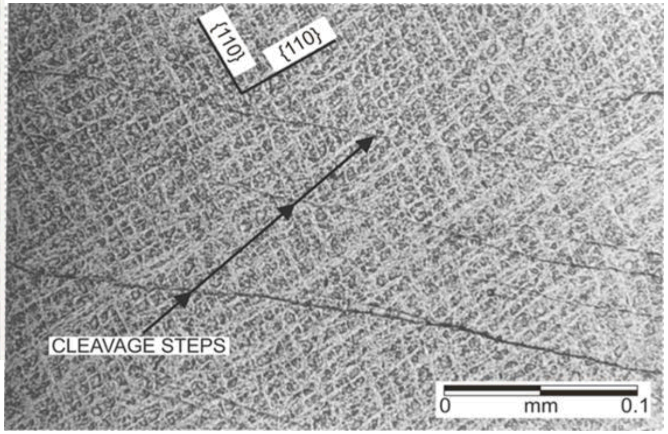
Isochoric Deformation of Salt



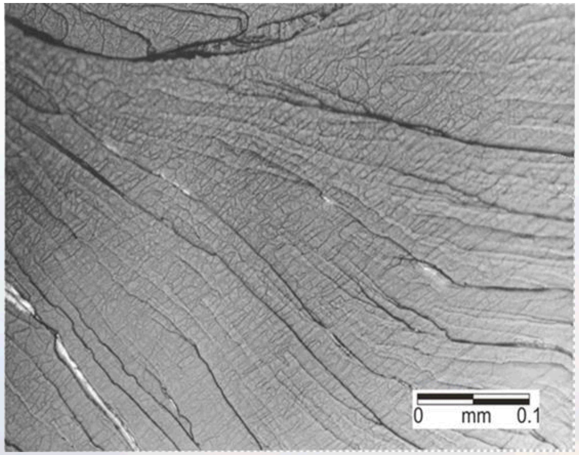
Dislocations



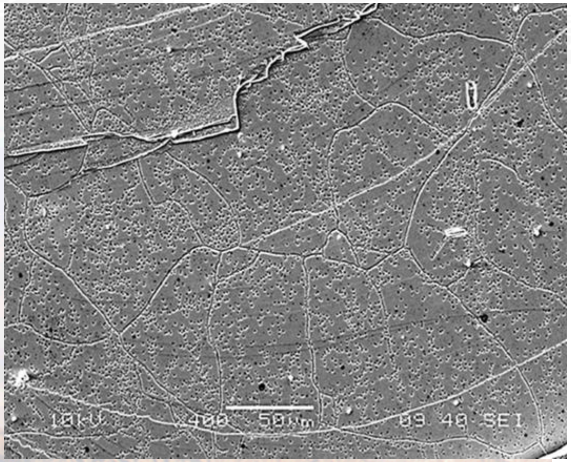
Glide



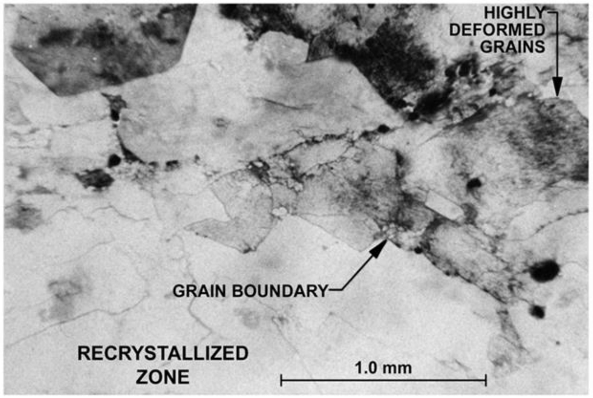
Cross Slip



Cross Slip and Climb



Polygonization



Recrystallization

Hansen, F. D. 2014 in preparation. *Isochoric Deformation of Salt.* American Rock Mechanics Association. Minneapolis MN.

Material Models

Table 1 Simplified Summary of Creep Deformation Mechanisms in Rock Salt Under Repository Conditions

Mechanism	Description	Observation	Phenomenology	Model
Dislocation Multiplication	Generation of New Dislocations	Increase in Dislocation Density	Transient Creep	$\rho_t \; \alpha \; \sigma^2$
Glide	Movement of Dislocations on Crystallographic Planes	Linear Glide Bands	Transient Steady State	$\dot{\varepsilon}_1 = A_1 \left(\frac{\sigma}{\mu}\right)^2 \exp\left[\frac{-Q}{RT}\left(1 - \frac{\tau}{\mu}\right)\right]$
Cross Slip	Movement of Screw Dislocations from One Plane to Another	Wavy Slip Lines	Transient Steady State	$\dot{\varepsilon}_1 = A_o \exp\left[-\frac{Q_{cs}}{RT}\left(\ln\frac{\tau_o}{\mu_o} - \ln\frac{\tau}{\mu}\right)\right]$
Climb	Movement of Dislocations Perpendicular to Their Glide Plane	Subgrains	Steady State	$\dot{\varepsilon}_1 = c \left(\frac{\sigma}{\mu}\right)^n \exp(-Q/RT)$
Recrystallization	Grain Boundary Migration	New Grains	Softening, Steady State	$\dot{\varepsilon}_1 = \frac{\sigma ABC}{kTd^3}$

Modeling Salt Behavior Correctly

- Salt constitutive modeling is very important
- International benchmarking with German collaborators
- Modeling intact salt deformation
- Similarly complex models for crushed salt consolidation
- We are currently investigating the mechanisms
- Need to assess the international capabilities
- Examine potential development of our model & evaluate other existing models
- Identify best features and deficiencies

Room Temperature Triaxial Test Sample of WIPP Salt at 3.0 MPa Confining Stress

Multi-mechanism deformation (MD) model:

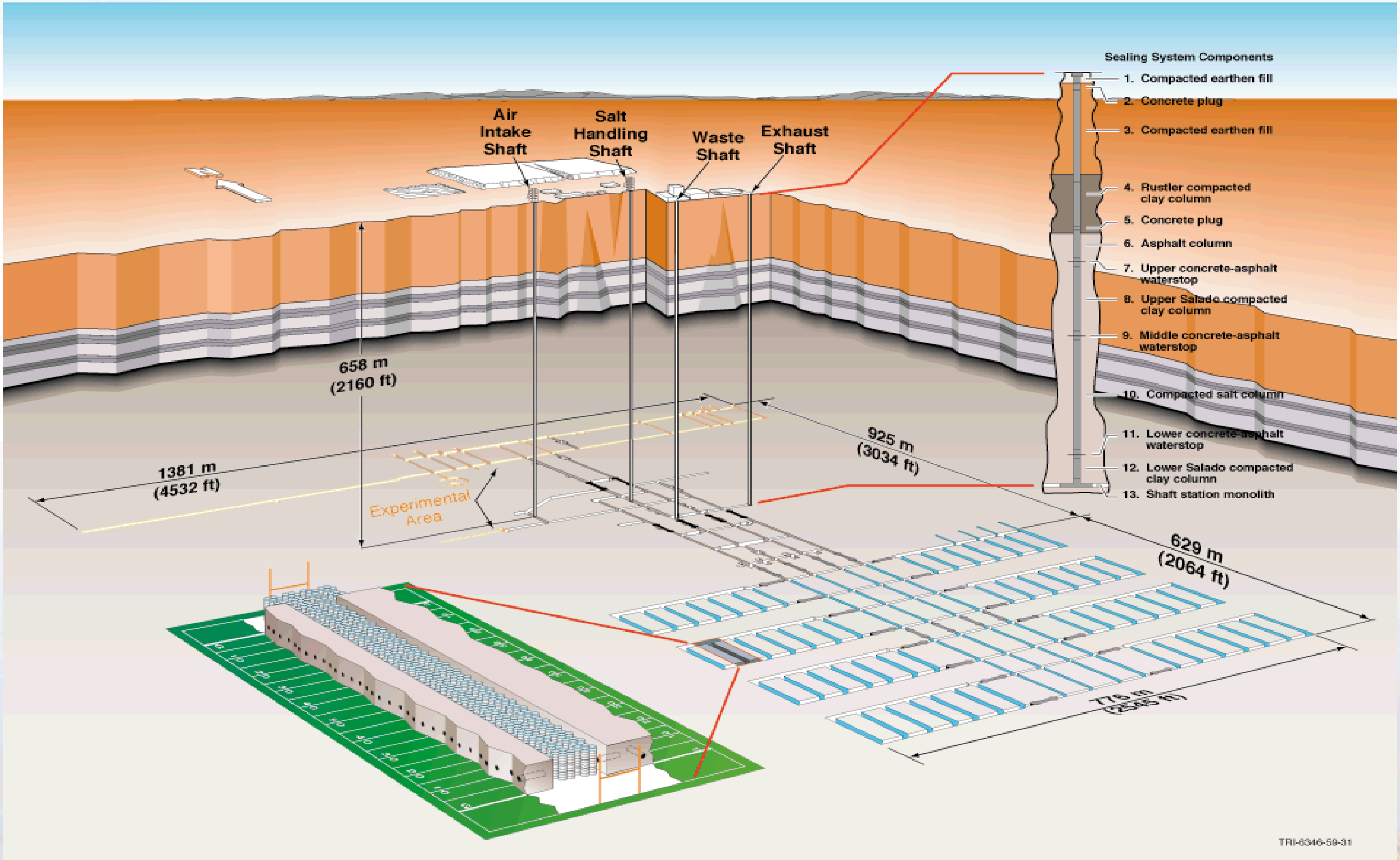
$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{s_i}$$

$$F = \begin{cases} e^{\Delta[1-\zeta/\varepsilon_t^*]^2}, & \zeta < \varepsilon_t^* \\ 1 & \zeta = \varepsilon_t^* \\ e^{-\delta[1-\zeta/\varepsilon_t^*]^2} & \zeta > \varepsilon_t^* \end{cases}$$

$$\dot{\varepsilon}_{ij}^c = F\dot{\varepsilon}_s \frac{\partial\bar{\sigma}}{\partial\sigma_{ij}}$$

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_s$$

WIPP Schematic



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Examples of Field Tests

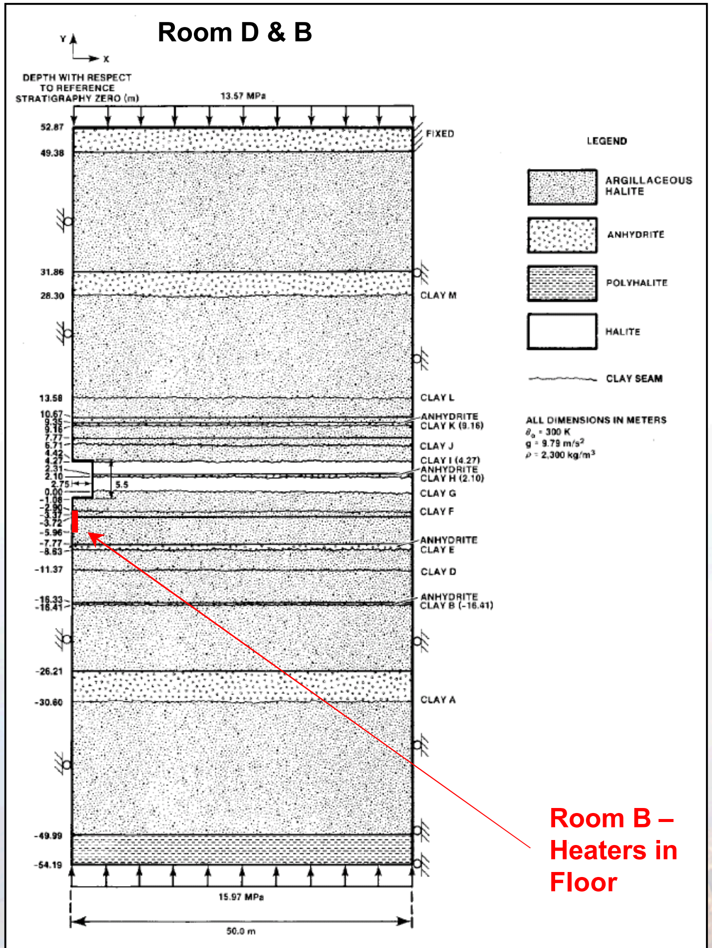
Heated axisymmetric pillar

Heated room

BAMBUS

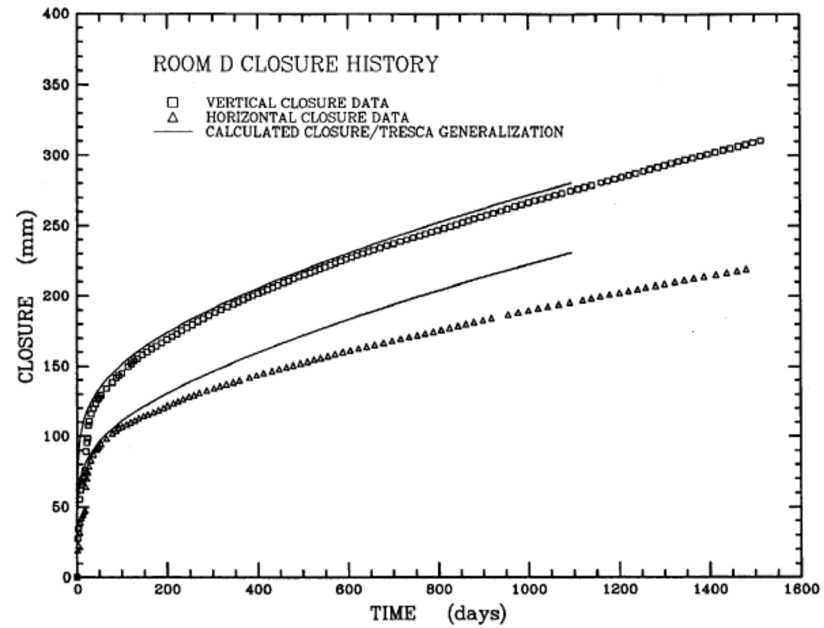
Room D Field Test at WIPP

- **Room D – Mining Development Test Data vs. Calculated Results (Isothermal Room)**

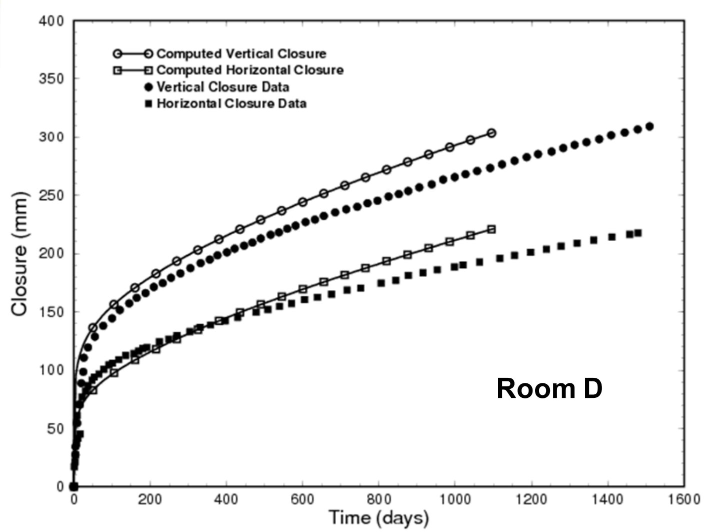


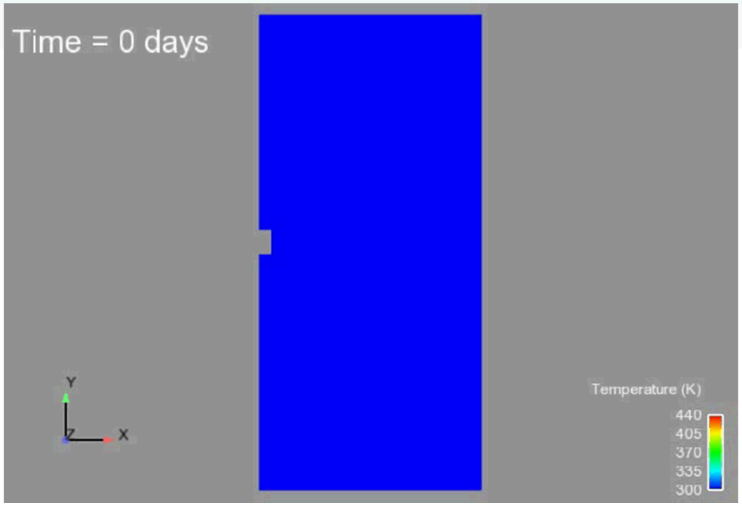
Mining development test (Room D) : in situ data report (March 1984-May 1988) : Waste Isolation Pilot Plant (WIPP) thermal/structural interactions program.

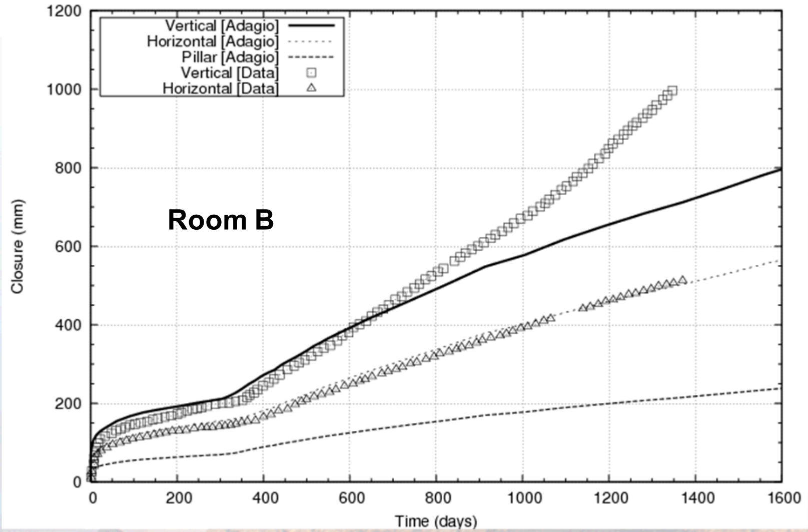
Munson, Darrell Eugene, Jones, Robert L., Hoag, David Leverett, Ball, John R. 1988. *SAND88-1460, Sandia National Laboratories*, Albuquerque, NM

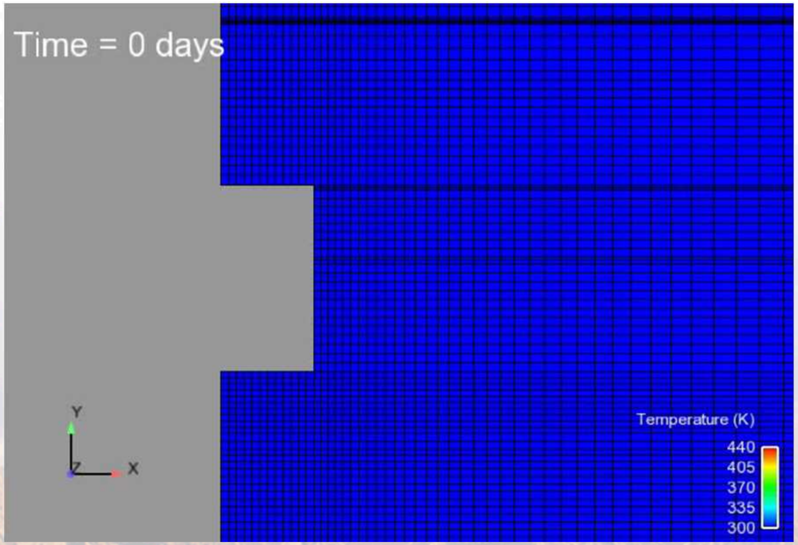


Preliminary Validation of SIERRA Mechanics Against WIPP Rooms D & B Data





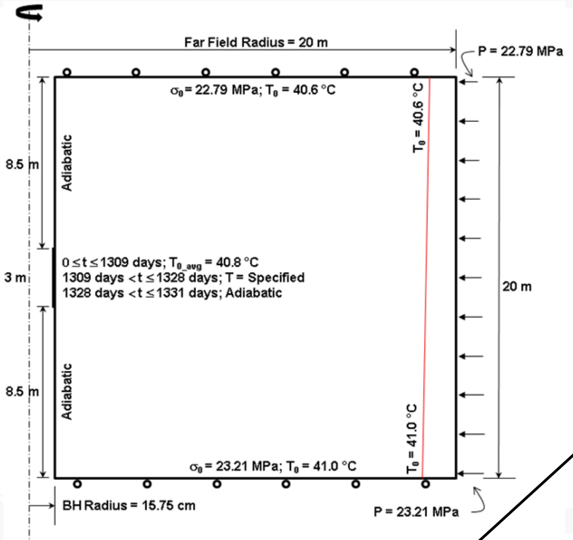


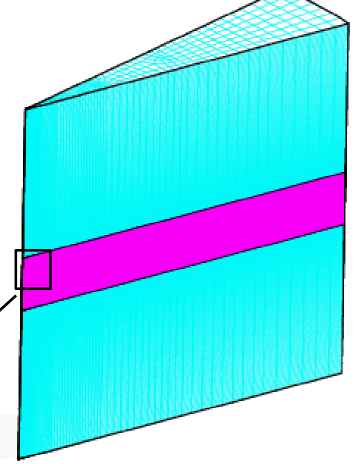


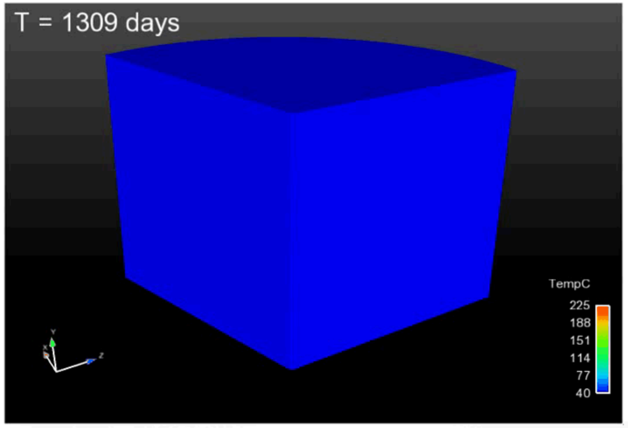
[Argüello, J.G., and J.S. Rath, 2012. SIERRA Mechanics for Coupled Multi-Physics Modeling of Salt Repositories. In P. Bérest, M. Ghoreychi, F. Hadj-Hassen, & M. Tijani (Eds.), *Mechanical Behavior of Salt VII.* Boca Raton: Balkema.]

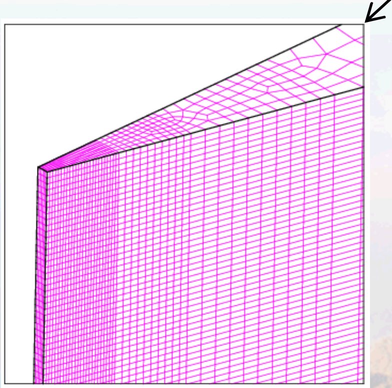
Second JPIII Target Simulation (HFCP) for Comparison with Data

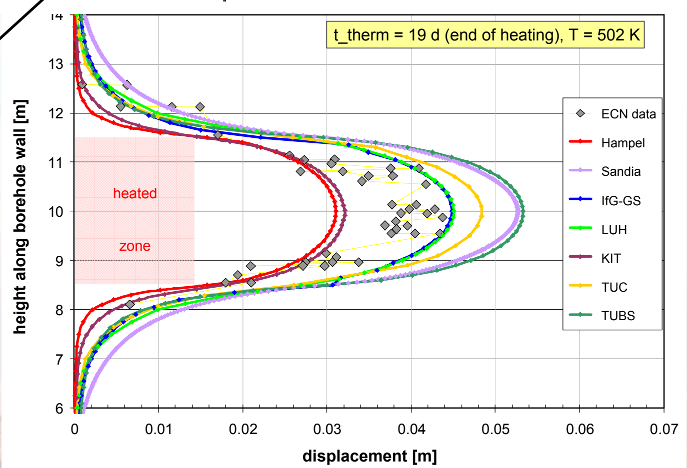
In-situ calculation object “Erhitzerversuche” (heater experiments) in the Asse mine

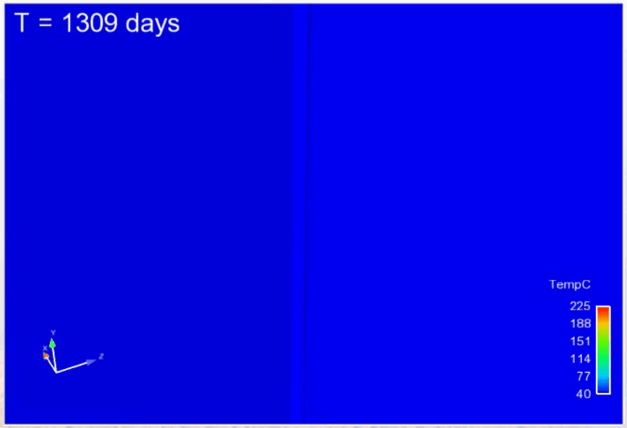








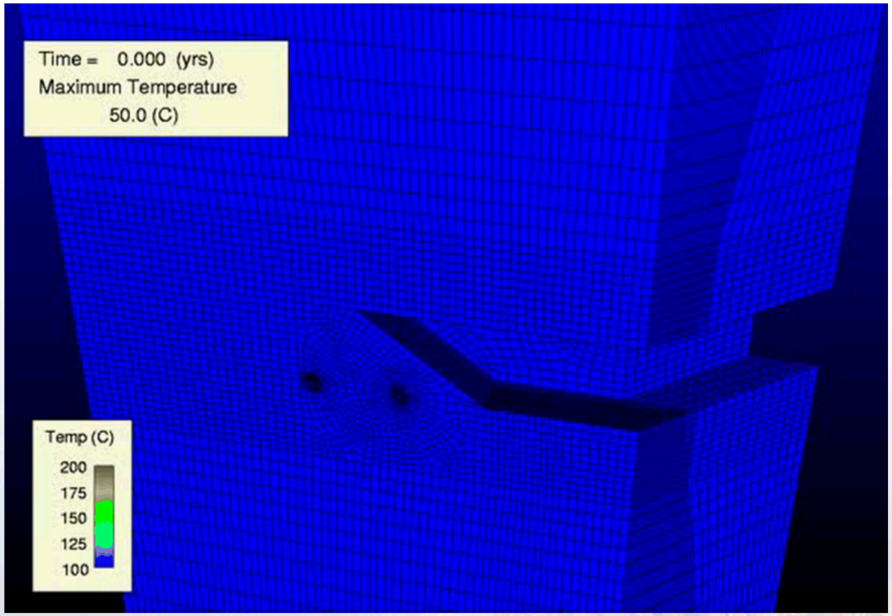




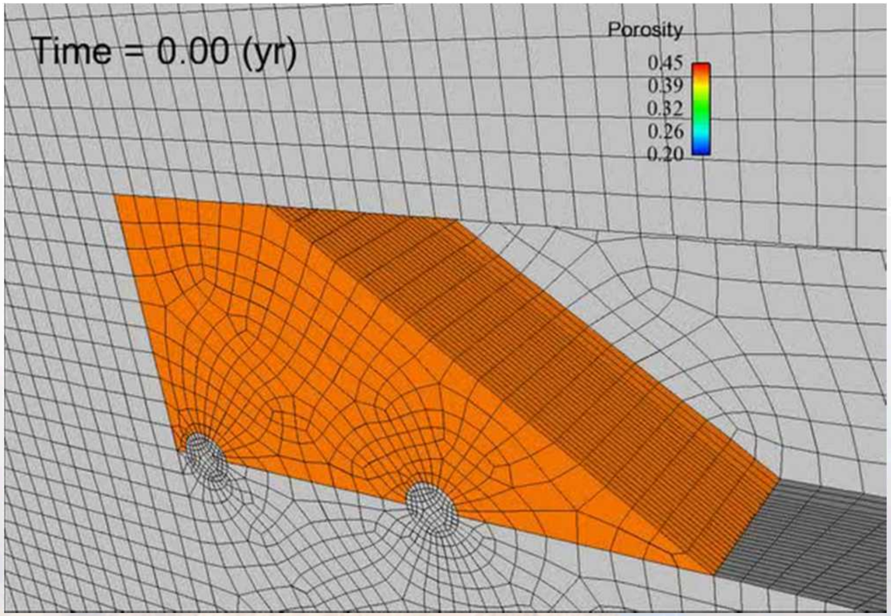
[Hampel, A., et al., 2013. Benchmark Calculations of the Thermo-Mechanical Behavior of Rock Salt – Results from a US-German Joint Project. (ARMA-13-456). *Proc. American Rock Mechanics Association (ARMA) 47th US Rock Mechanics / Geomechanics Symposium, 23-26 June 2013.* San Francisco: American Rock Mechanics Association.]

Closing Remarks and Observations on GSR

- Computational effort is in contact algorithm and integration of constitutive models
- Full MD model is more expensive than the PLC by a factor of 3 (using 2nd mechanism of the MD only for the PLC)
- Stand alone PLC model in Adagio is 3 times slower than using the 2nd mechanism in the MD model to represent PLC behavior (difference due to method of integration)



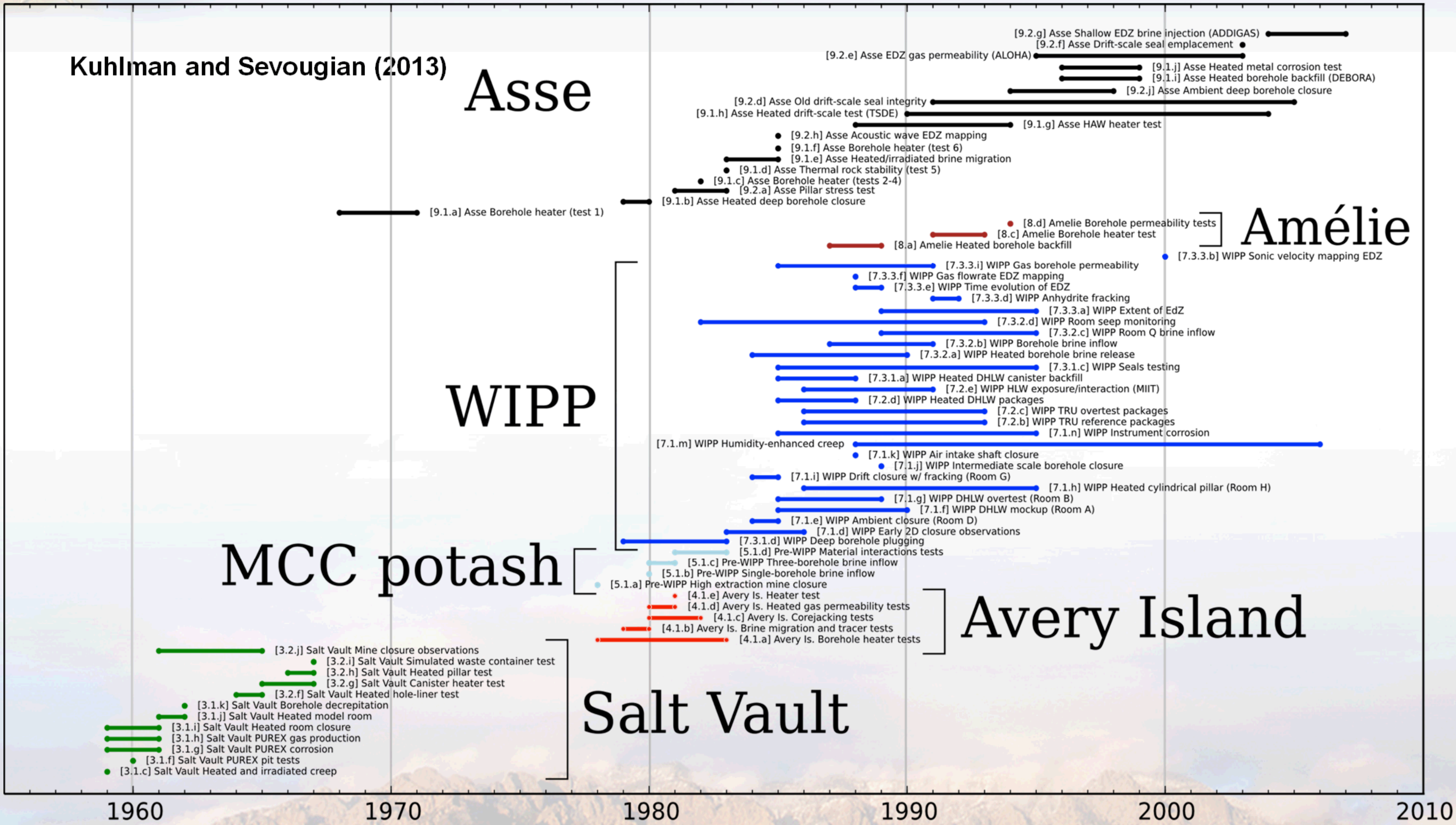
Repository Temperature Contours



Crushed Salt Backfill Porosity Contours

[Stone, C.M., Holland, J.F., Bean, J.E., & Argüello, J.G. 2010. Coupled Thermal- Mechanical Analyses of a Generic Salt Repository for High-Level Waste (ARMA-10-180). *Proc. American Rock Mechanics Association (ARMA) 44th US Rock Mechanics Symposium, 27-30 June 2010.* Salt Lake City: American Rock Mechanics Association.]

In Situ Testing

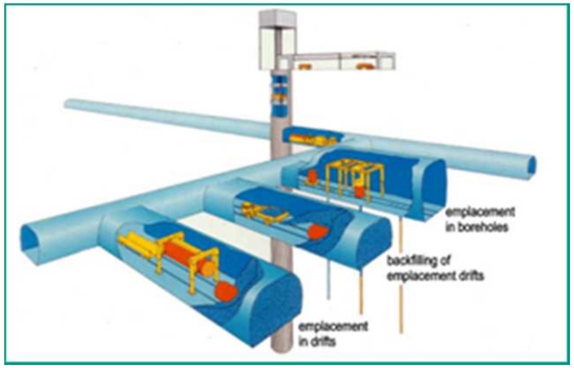


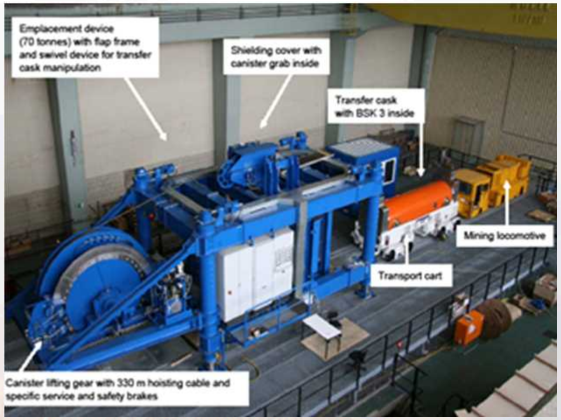
Full-Scale Tests in Salt

YEAR	PROJECT	LOCATION	DESCRIPTION
1965-1969	Lyons mine, Project Salt Vault	Lyons, Kansas	Irradiated fuel & electric heaters
1968	Asse salt and potash mine	Germany	Electric heaters
1979-1982	Avery Island	Louisiana	Brine migration
1983-1985	Asse (U.S./German Cooperative)	Germany	Brine migration under heat & radiation
1984-1994	WIPP	Carlsbad, NM	1.Defense HLW Mockup 2.Defense HLW Over-test 3.Heated axisymmetric

German Accumulation of Expertise in the Past Decades

- Techniques for waste emplacement were developed (Direct Disposal = reference repository concept)
- Feasibility of vertical borehole emplacement of spent fuel & HLW (BSK-3 canister) was shown
- Instruments, tools, and methodologies for modeling and safety analysis were substantially further developed and have been applied in several exercises (e.g. vSG)
- In Germany underground disposal facilities for chemical-toxic wastes are licensed and are operational for years
- A lot of experience in rock salt available from practical application and excellent RD&D





USA Accumulation of Expertise in the Past Decades

- Sandia, as Science Advisor, developed much of the salt expertise for the Waste Isolation Pilot Plant.
- WIPP was a successful operation 1999-2014.
- Solution Mining Research, Strategic Petroleum Reserve, American Rock Mechanics Assoc., Salt Mechanics Symposia
- Salt mining is a world-wide, proven and reliable technology
- Rock salt is highly suitable for hosting a repository for heat-generating nuclear waste

Hansen, F.D. and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste*. SAND2011-0161, Sandia National Laboratories Albuquerque New Mexico.

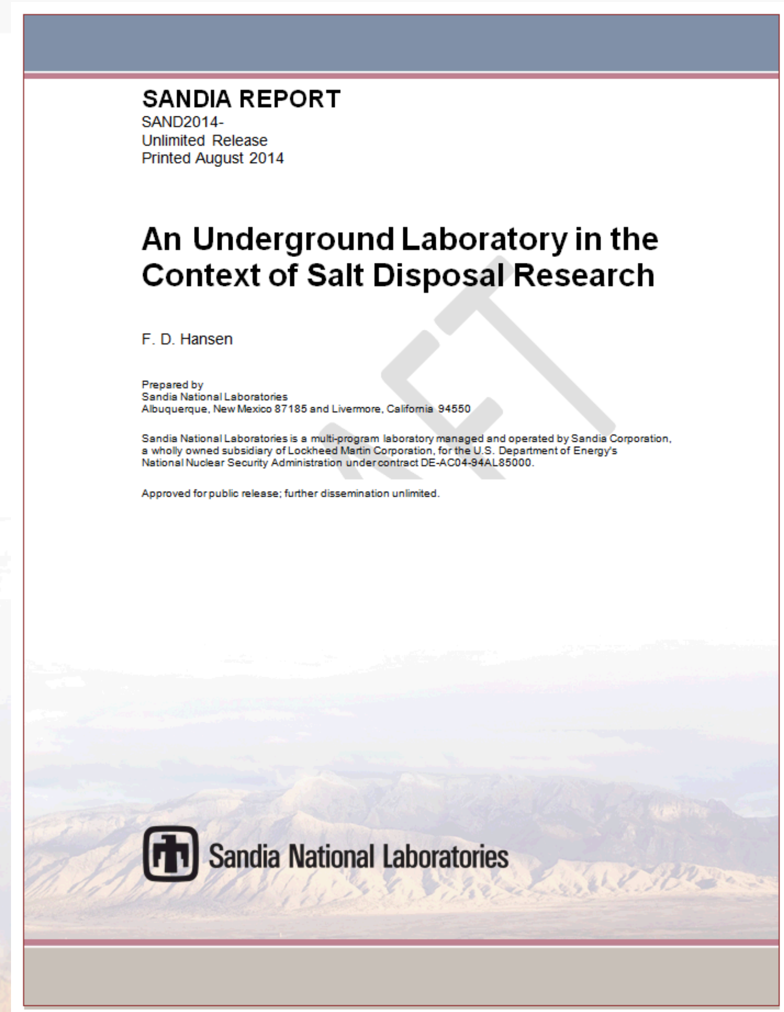
US/German Salt Repository Research Collaboration

- Collaborations between the US and West Germany began in the 1970′s (Asse: Temp.Tests)
- Technical evaluations for salt disposal of heat-generating waste experienced a rather long hiatus because of “priority changes” in both countries
- Salt repository research in Germany slowed down somewhat since 2000 (political decisions, moratorium), but increased in 2010.
- Representatives of institutions in both countries wished to renew collaborations and cooperation on overall salt repository science, to coordinate a potential research agenda of mutual interest, and to leverage collective efforts for the benefit of their respective programs.
- By the first US/German Workshops on Salt Repository Research, Design and Operation collaboration was re-initiated.
- A coordinated research agenda has been pursued to maximize mutual benefit.

- The fifth workshop will highlight Repository Design and Operations and this topic will be the focus of the first day. The focus of the second day will be the Thermomechanical Behavior Of Salt, Plugging And Sealing, And The Safety Case. Special topics will be addressed on the third day.

Sandia Report
SAND2014-

- Unlimited Release
- Printed August 2014
- *An Underground Laboratory in the Context of Salt Disposal Research*
  - Sandia National Laboratories
  - Albuquerque, New Mexico 87185 and Livermore, California 94550
- Contents
  - Salt Attributes/International collaboration
  - Framework for URL Studies
  - Examples of suggested activities
  - Test Plan for URL Characterization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Framework for URL Studies

- Purpose—facilitate conduct of URL studies
- Strategy—because salt has vast foundation, it is essential to demonstrate utility of URL activity in the context of R&D
- Justification
  - Address FEPs
  - Build confidence
  - Promote international collaboration
  - Predict/Test/Confirm
- Functional and operational requirements
- Test plans

Table 1. High-level Review of Possible URL Activities

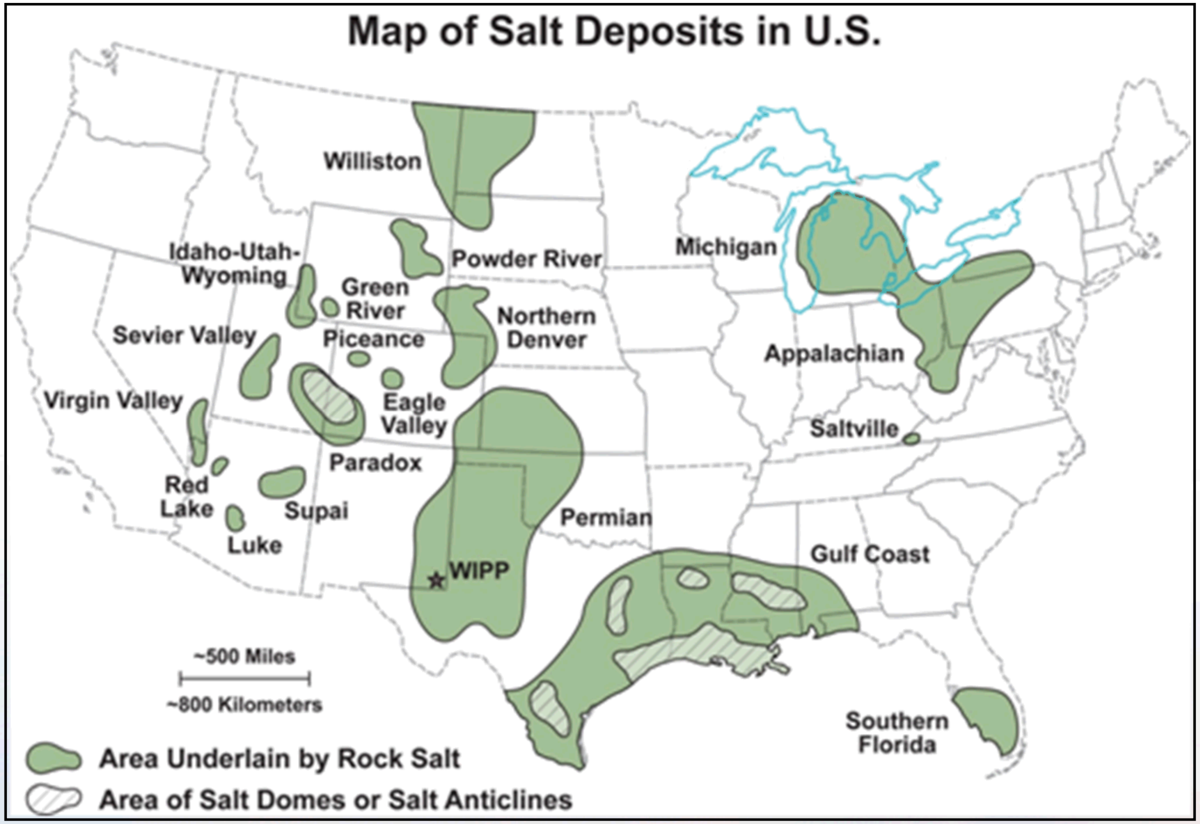
Activity	Purpose	Duration (years)	Cost	Technical Merit
Single Heater	Confirmation	1-5	$$	Model validation
Large-scale Seal	Confirmation and demonstration	5	$$$	Confirmation, demonstration, and performance
SDI-Hot waste	New science	5+	$$$$	Accelerated results, model validation, demonstration
SDDI-Defense Waste	Demonstration	5	$$$$	Demonstration
Wedge Pillar	New science	N/A	N/A	Not supported
Fluid differential pressure test	New science	3	0.5$	Intact permeability in bedded salt
In situ consolidation	New science	<3	$	Consolidation data gap, permeability
Canister movement	New science	5+	$$	Model buoyancy

Summary

What is the role of a URL in the context of salt research and development?

- URL decisions and allocation of resources must be evaluated and compared
  - Decades of laboratory studies
  - Many full-scale field tests
  - Modern computational capabilities
- *If decisions are made to pursue testing activities in the URL*
- Framework provides a process by which to proceed
  - External Review Board
  - Evaluate URL activity merit
  - Functional and Operational Requirements
  - Individual Test Plans
- URL activities could help establish public and political acceptance of salt disposal of heat-generating nuclear waste

Salt Deposits in the United States



- The USA has supported significant salt repository investigations
  - Project Salt Vault
  - **Avery Island**
  - WIPP (limited thermal testing)
- International interest is high (e.g., Germany)