CAES Modeling

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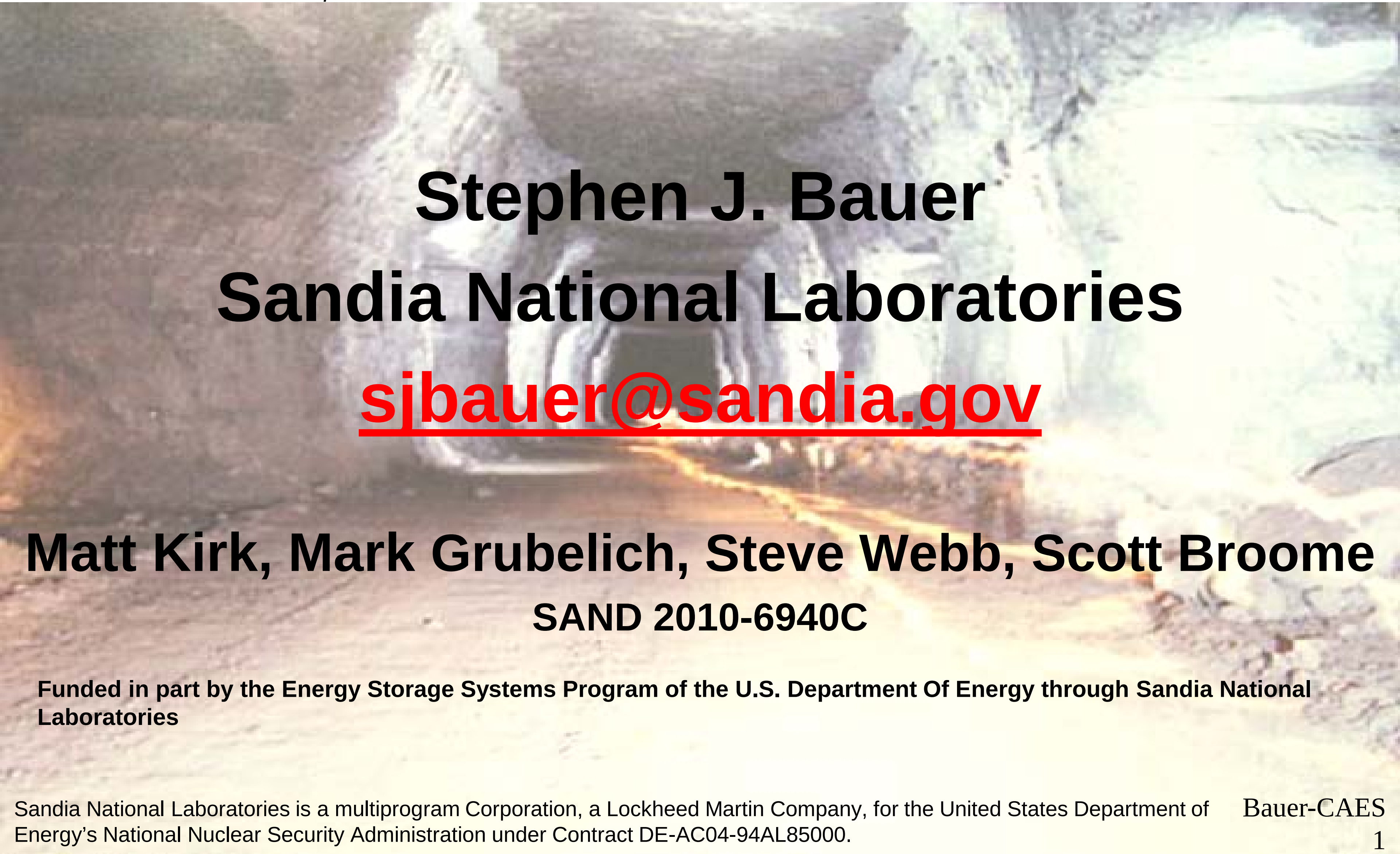

Stephen J. Bauer

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Matt Kirk, Mark Grubelich, Steve Webb, Scott Broome

SAND 2010-6940C

Funded in part by the Energy Storage Systems Program of the U.S. Department Of Energy through Sandia National Laboratories

Specific and existing problems, interests, needs

1-Potential Microbial and Chemical Impact of CAES in a Sandstone, M. Kirk

2-Assessment of Ignition/Explosion Potential in a Depleted Hydrocarbon Reservoir from Air Cycling Associated with CAES, M. Grubelich

3-Flow Analysis Parametric Study: S. Webb

4-Material Degradation (T-M-C-H effects) Due to Cyclic Loading, SJ Bauer and ST Broome

Started November 2009

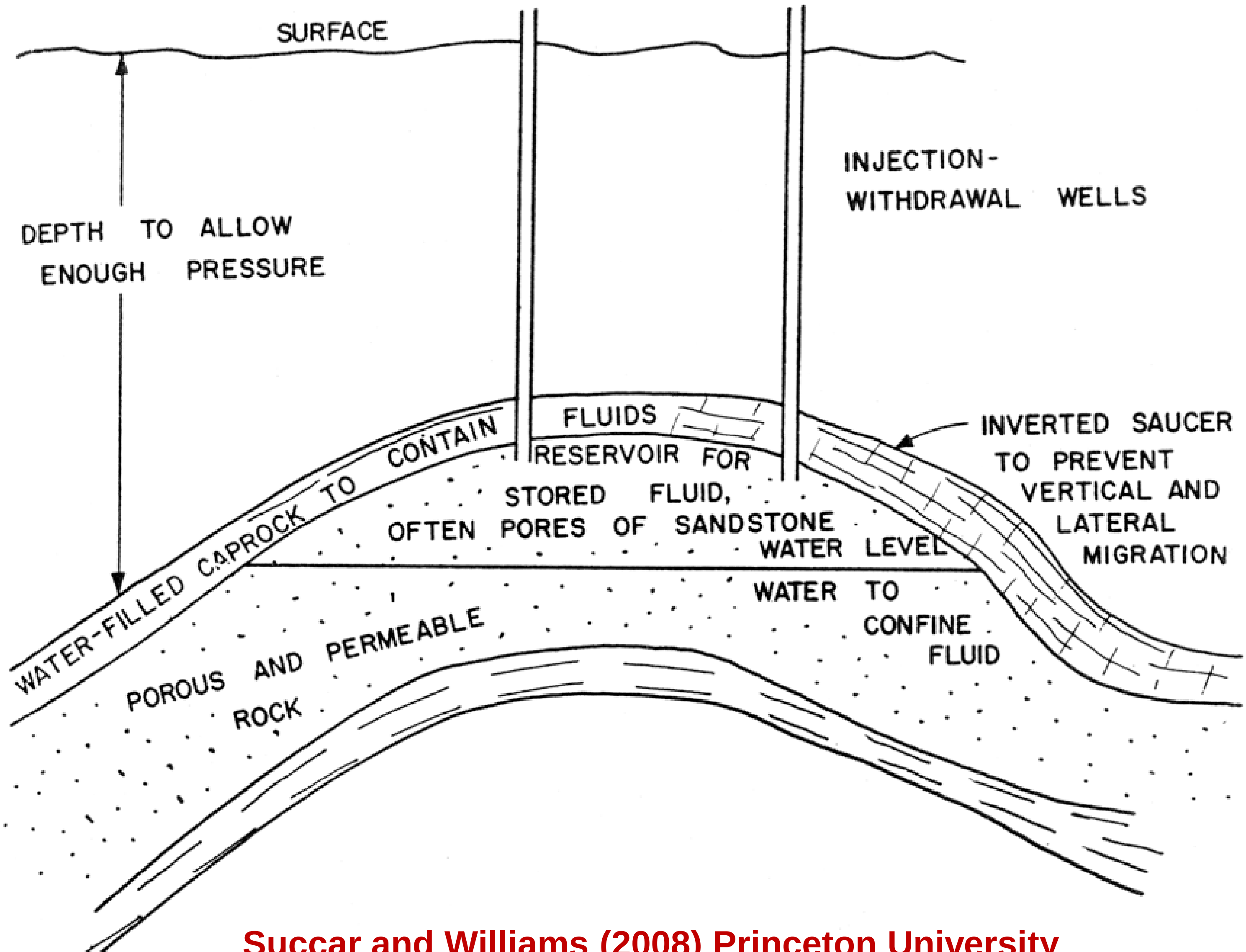
Potential Microbial and Chemical Impact of CAES in a Sandstone

Matthew Kirk

Geochemistry Department

Compressed Air Energy Storage

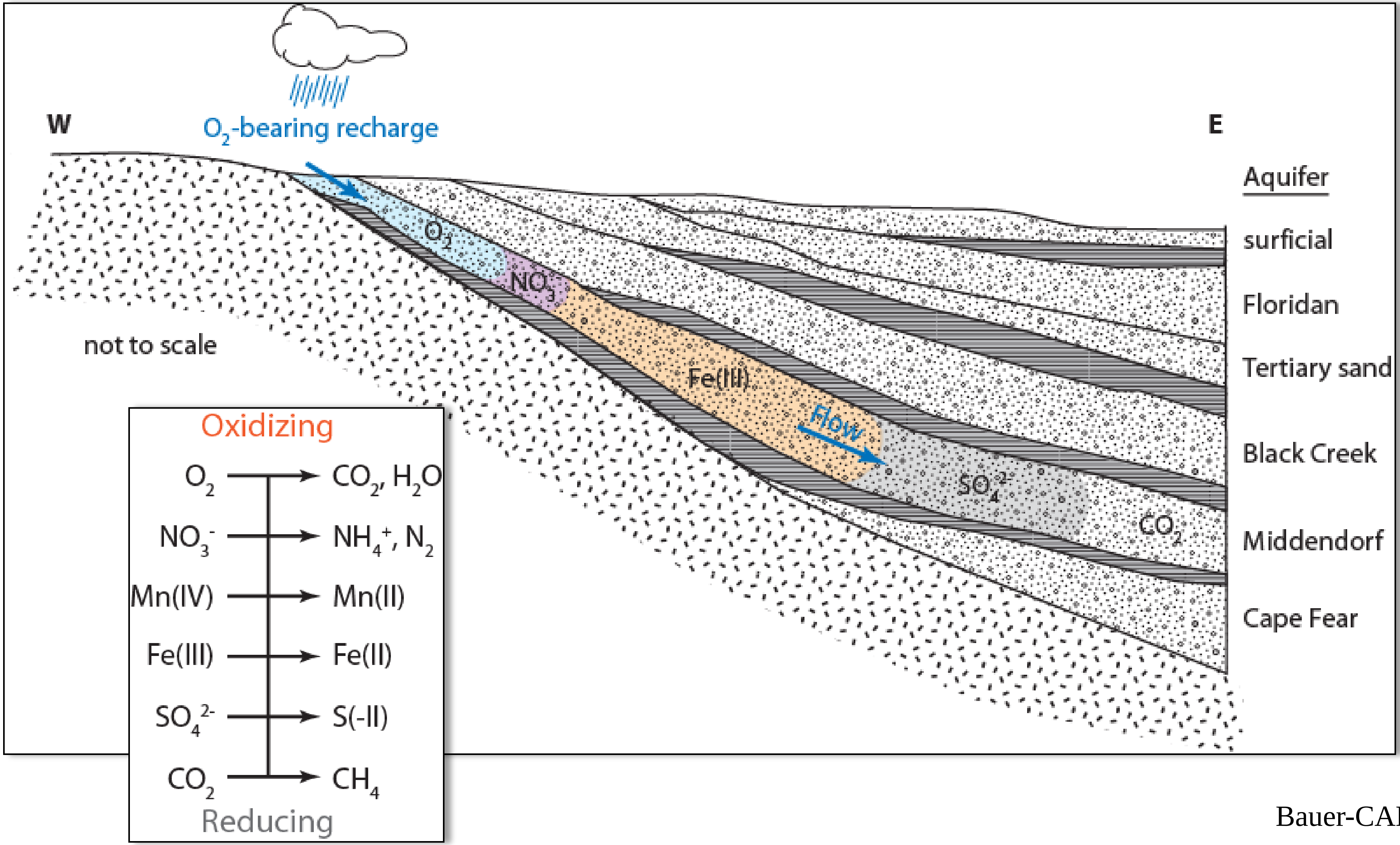
Geomec



Succar and Williams (2008) Princeton University

Groundwater Microbiology

Example: Middendorf coastal plain aquifer, South Carolina



Conclusions: Potential Microbial and Chemical Impact of CAES in a Sandstone

- Sandstone evaluated in a reducing environment
- Microbial Fe(II) and Mn(II) oxidation will become favorable
- Pyrite oxidation could lead to considerable changes in pH, salinity, and mineralogy
- Microbiology and mineralogy changes would impact porosity

Considerations for Explosion Potential for CAES in a Depleted Natural Gas Reservoir

Geomechanics Research Department

Mark Grubelich

Geothermal Energy

Results & Conclusions: Mitigation & Safety

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- **Purge reservoir before use**
- **Low pressure air cycling below UFL to remove gas (~90 psi)**
- **In-situ gas monitor**
- **Never draw down air below the LFL (370 psi)**
- **Insure no surface breach if ignition occurs (sufficient overburden)**
- **Monitor NG content entering surface equipment**
- **Further study required**
  - **Buoyancy issues, etc.**

CAES Borehole Study: Steve Webb

Geomechanics Research Department

- **Objective**
  - **Look at Flow in Individual Boreholes**
  - **Simple 2-d Models**
  - **Estimate Number of Boreholes and CAES Footprint**
- **Assumptions**
  - **Representative Borehole/Formation Geometry**
  - **Include Two-Phase Behavior**
    - **Capillary Pressure and Relative Permeability**
    - **Bubble Formation**
    - **Air Injection and Withdrawal – 10 Weekly Cycles**

Conclusions

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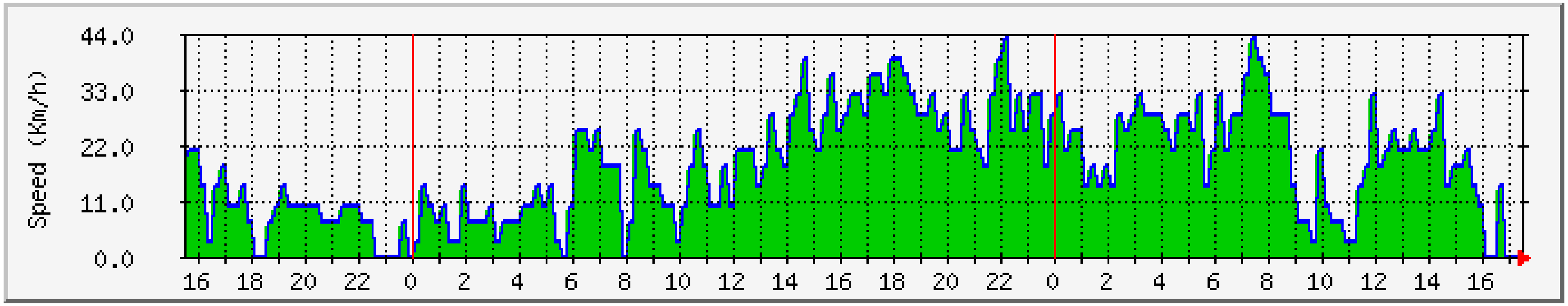
- Permeability Variation Much More Important than Porosity Variation
- Procedure Can Quantify Differences Between Various Sets of Formation Parameters
  - Borehole Spacing, Number of Boreholes
- Borehole Arrays Will Be Investigated in the Future

Material Degradation (T-M-C-H effects)

Due to Cyclic Loading

SJ Bauer and ST Broome



Hourly fluctuations in wind speed could translate to frequent pressurization/depressurizations of salt caverns

Concluding Comments

- Preliminary cyclic tests completed on salt
- Change in volume strain observed
- Young's Modulus changes observed
- Acoustic emissions detected
- Cracks observed in thick sections
- Results consistent with previous work
- Implication that cyclic loading caused cracking at low differential stresses

Summary/Conclusions

1- Sandstone in a reducing environment could effect biologic and mineralogic changes that could lead to changes in porosity and permeability

2-Recommendations given for mitigation of potential use of a natural gas reservoir for CAES

3- Permeability variation much more important than porosity variation; procedure can help determine borehole spacing, number of boreholes (CO$T)

4-Salt strength observed to degrade in cyclic loading

Work Products

1- "*Potential Effects of Compressed Air Energy Storage on Microbiology, Geochemistry, and Hydraulic Properties of Porous Aquifer Reservoirs*", Kirk, Altman, and Bauer, SAND2010-4721

"*Potential Subsurface Environmental Impact of Compressed Air Energy Storage in Porous Bedrock Aquifers*" Env. Sci. & Tech. (in Prep, Kirk et al)

2- *"Considerations for Explosion Potential for CAES in a Depleted Natural Gas Reservoir"* , M. Grubelich

***3-* "*Borehole and Formation Analyses in Reservoirs to Support CAES Development*" , S. Webb**

4- "*Experimental Deformation of Salt in Cyclic Loading*", S. Bauer and S. Broome, Solution Mining Research Institute April 2010 SAND2010-1805

Statement about future tasks

1- Develop map for US regions with geology potentially suitable for CAES

2- Borehole parametric study

3-Continue evaluation of cyclic loading effects on salt and reservoir rocks


thanks
Questions?

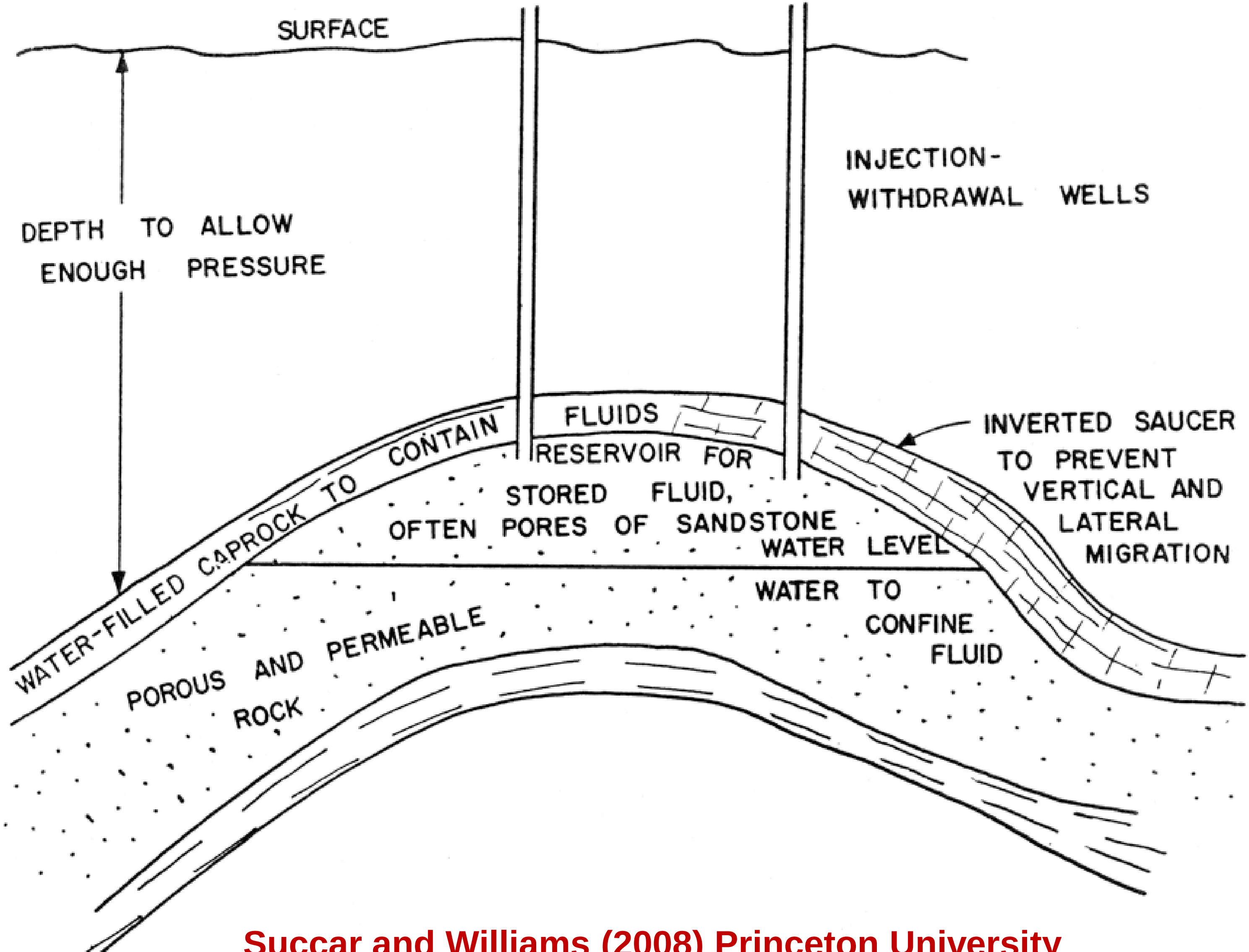
Potential Microbial and Chemical Impact of CAES in a Sandstone

Matthew Kirk

Geochemistry Department

Compressed air energy storage

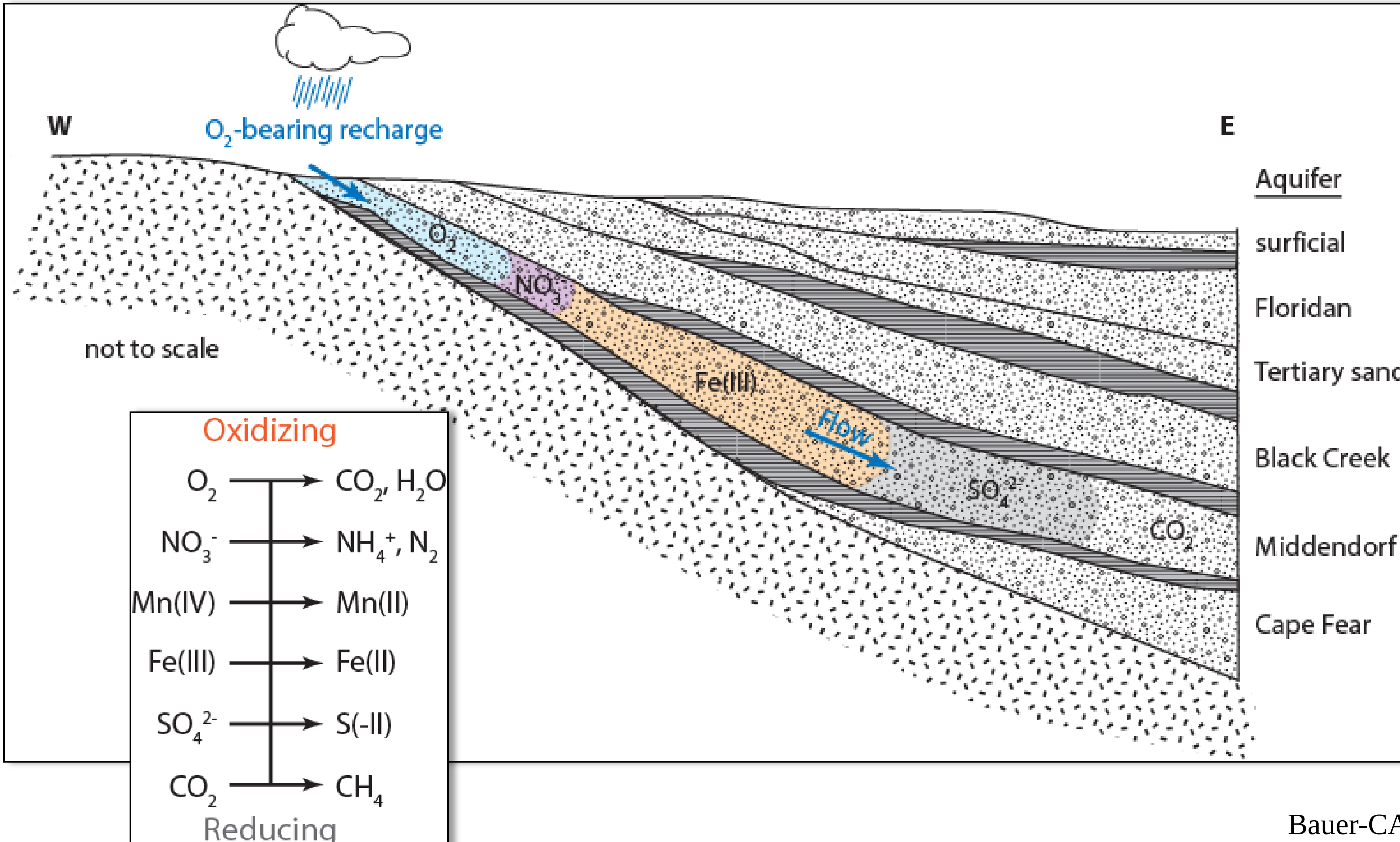
Geomec



Succar and Williams (2008) Princeton University

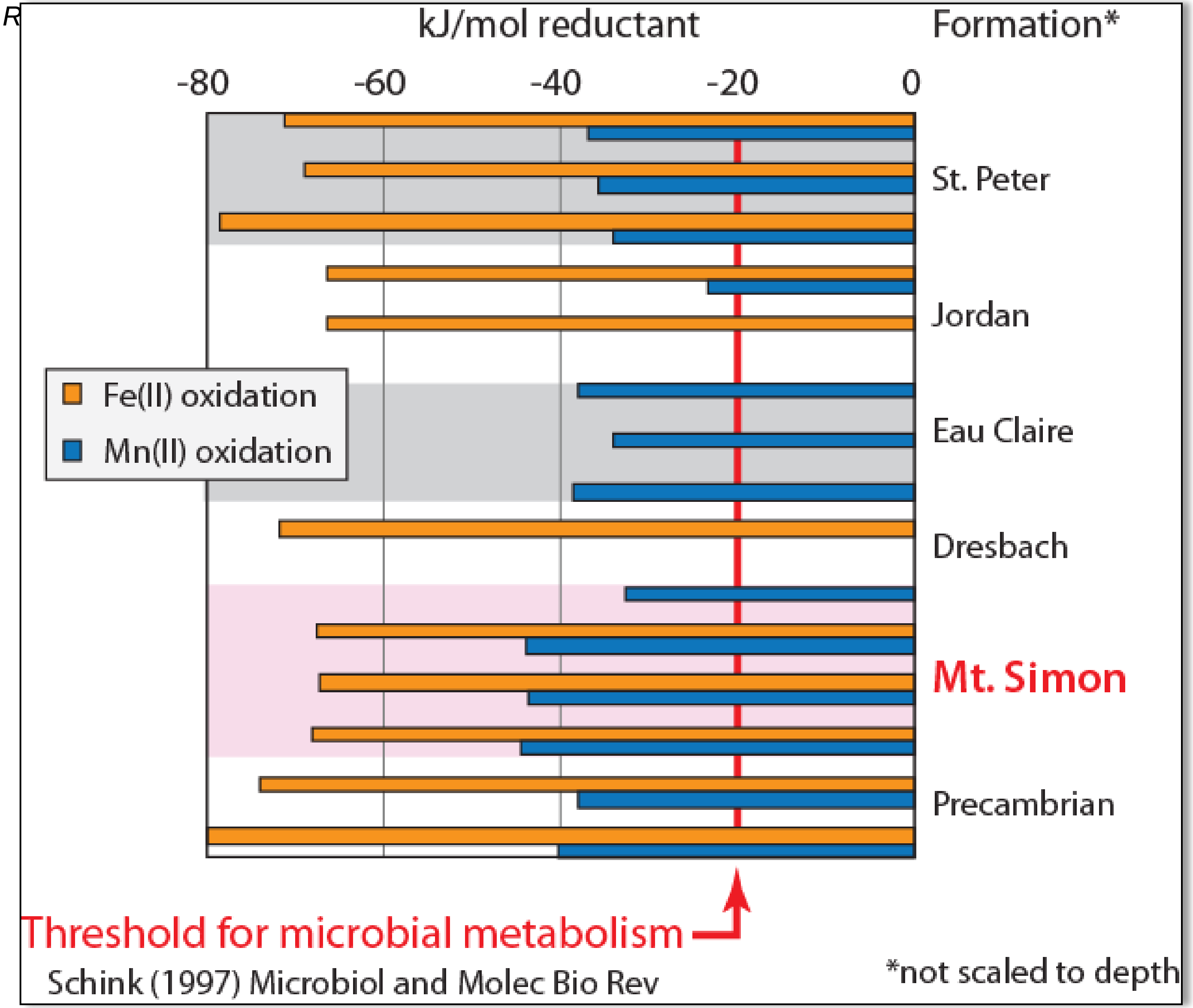
Groundwater microbiology

Example: Middendorf coastal plain aquifer, South Carolina



Bauer-CAES

Metabolic energy available for Fe(II) and Mn(II) oxidation in the Mt. Simon



Effect of pyrite oxidation on groundwater composition

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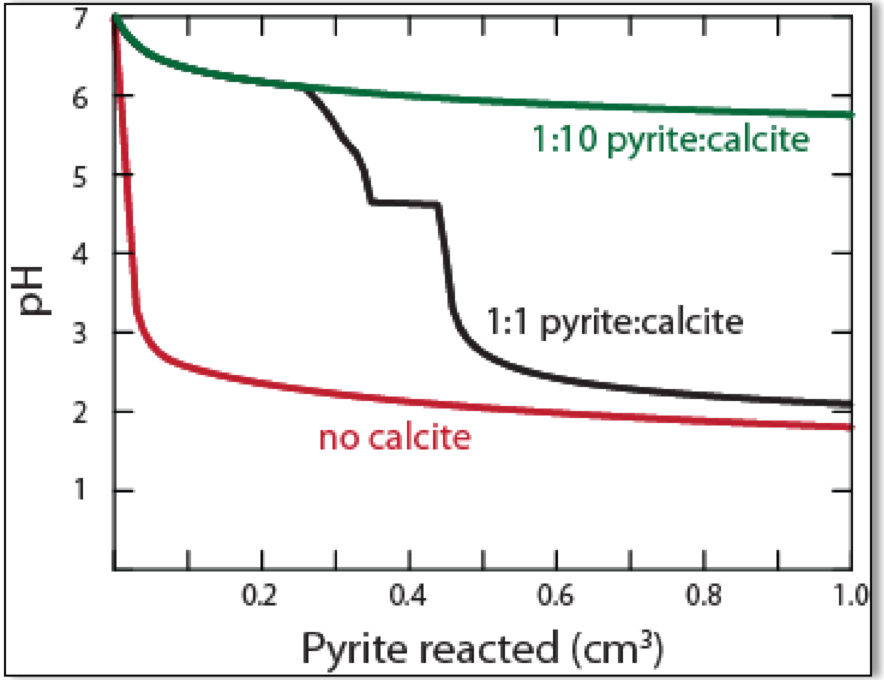

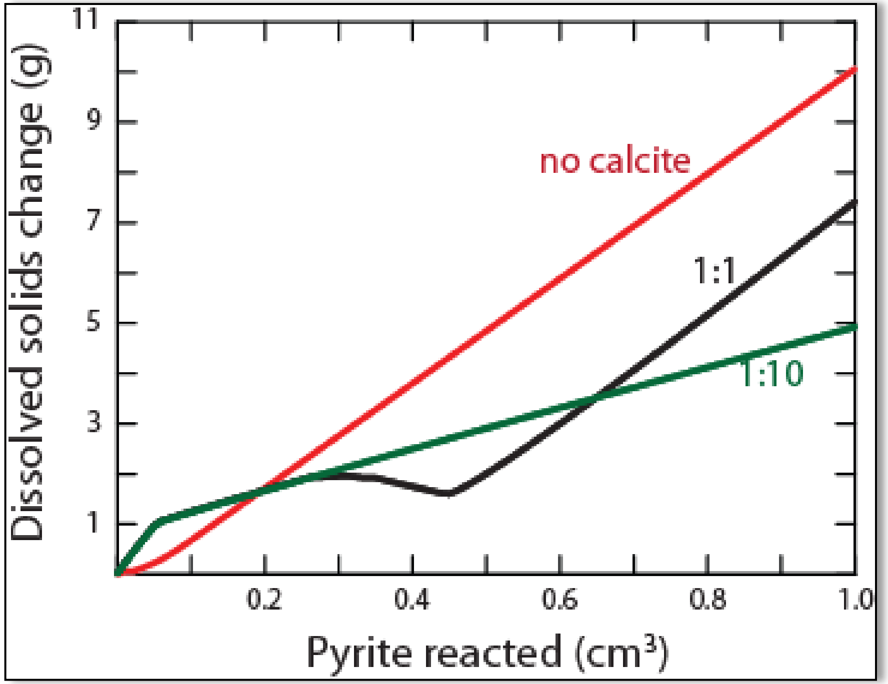

Geochemist's Workbench reaction path model assuming 0.2 fO_2

- **no calcite:** **pyrite + 3.75 O_2 + 3.5 H_2O → $Fe(OH)_3$ + 2 SO_4^{2-} + 4 H^+**
- **with calcite:** **pyrite + 2 calcite + 3.75 O_2 + 1.5 H_2O → $Fe(OH)_3$ + 2 SO_4^{2-} + 2 Ca^{2+} + 2 CO_2**

Effect of Pyrite Oxidation on Porosity

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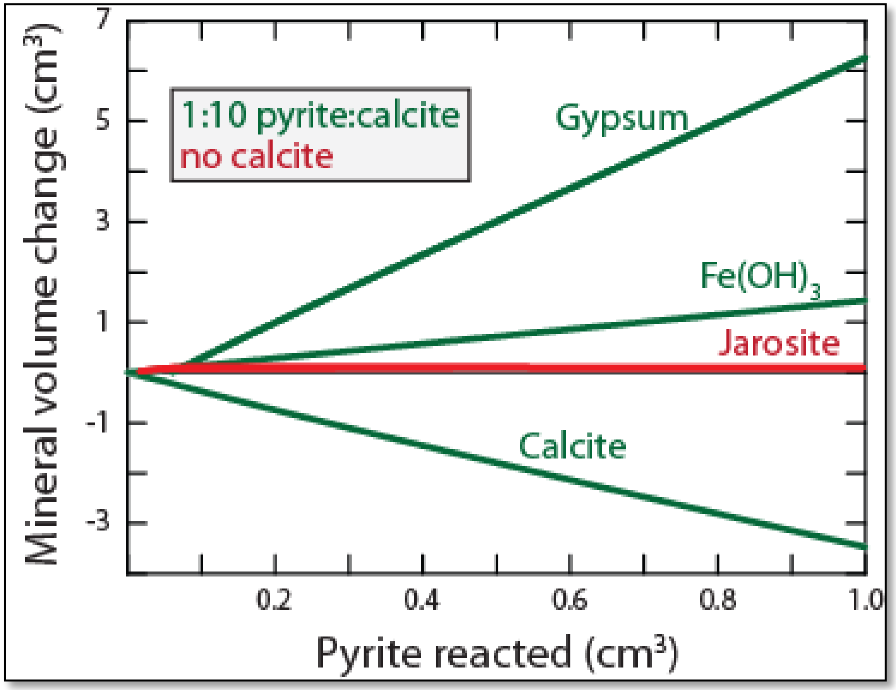
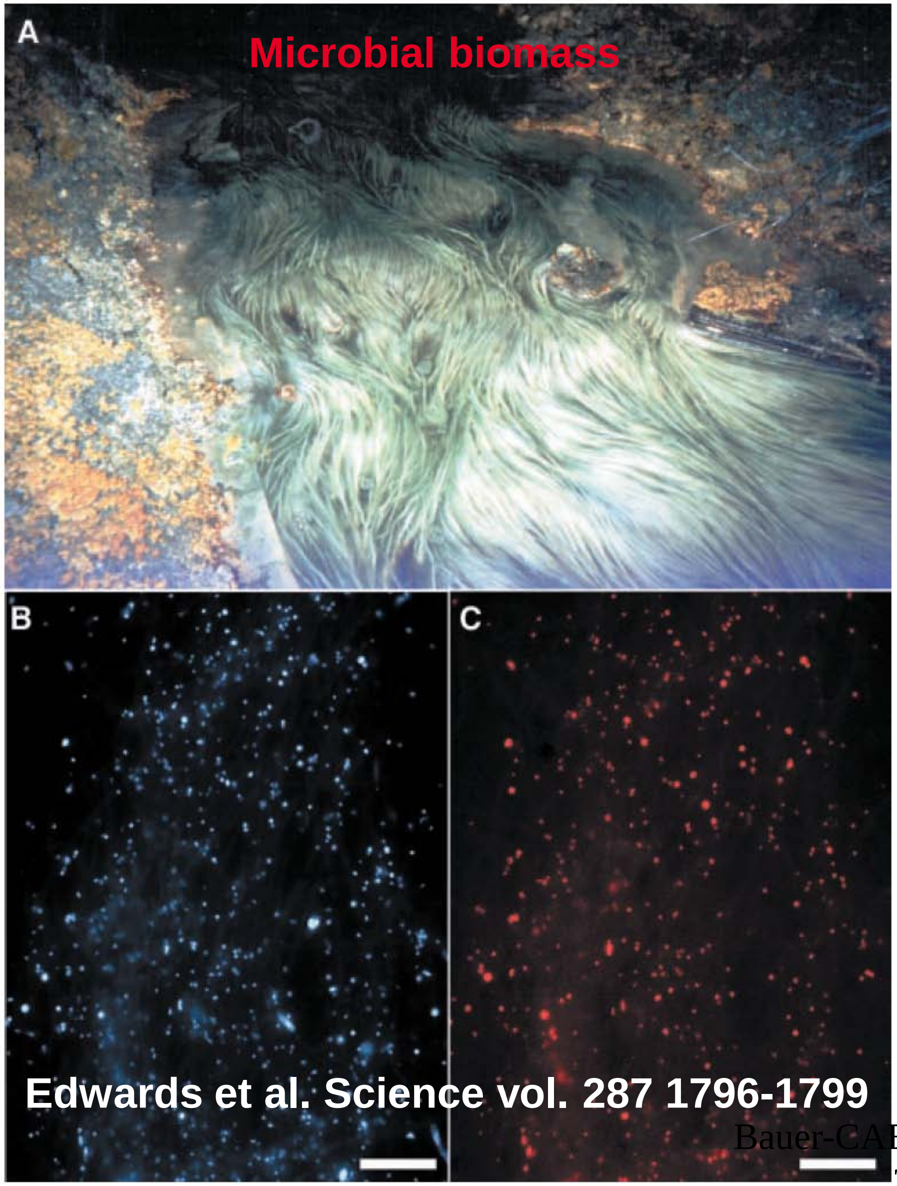
Mineral volume



Microbial biomass



Edwards et al. Science vol. 287 1796-1799

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Geomechanics Research Department

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Compressed Air Energy Storage

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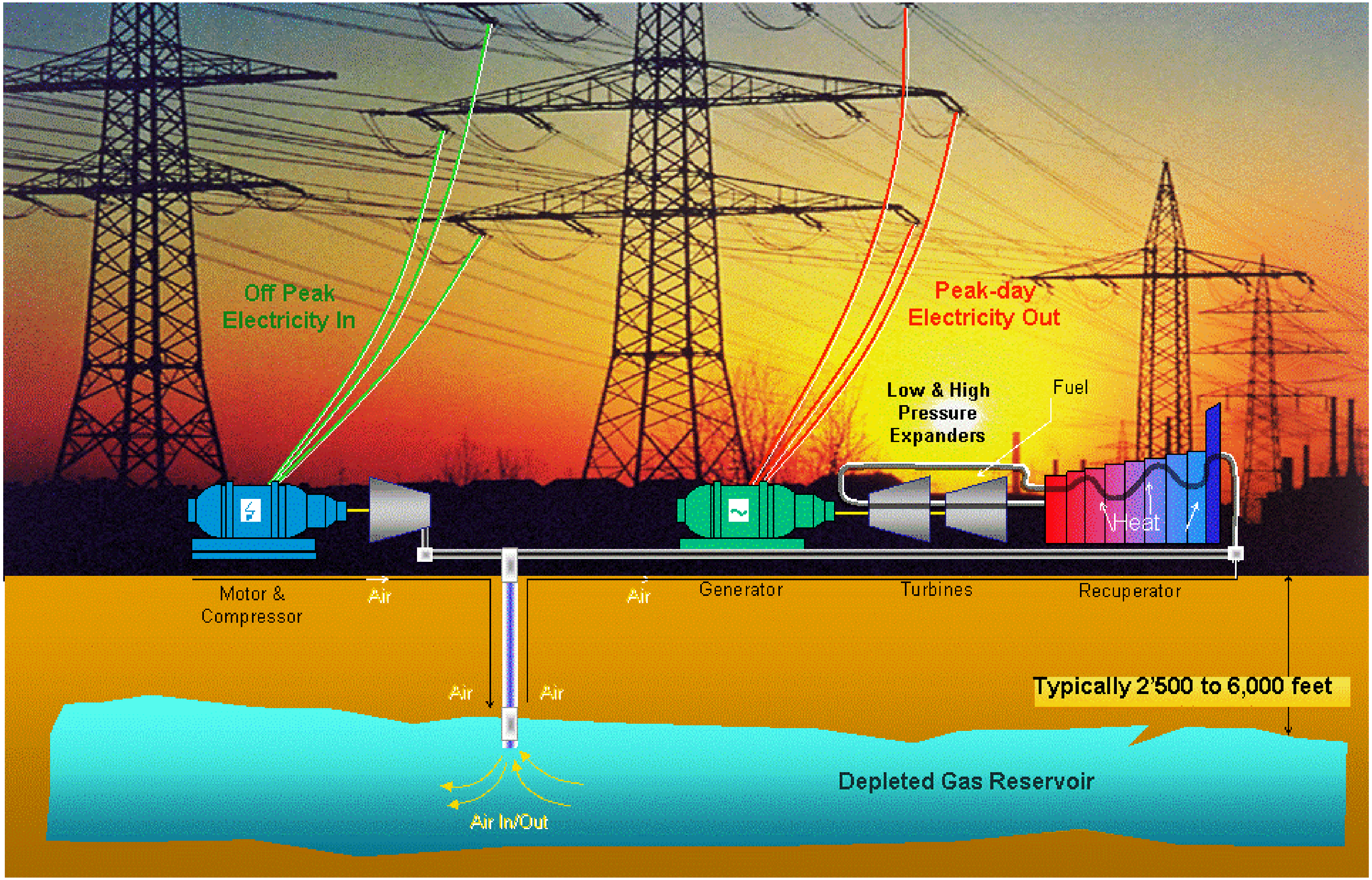

Fuel, Oxygen & Ignition Source

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Detonation, reaction proceeds at supersonic speeds (shock wave).

Combustion or Deflagration
10’s to 100’s of ft/sec reaction rates.

Why worry?

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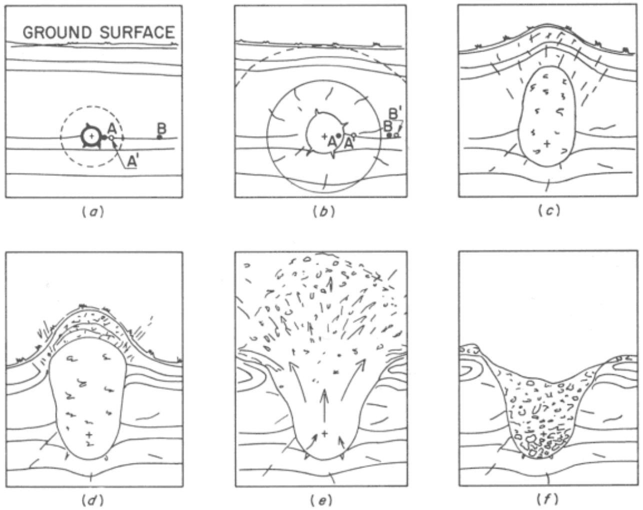
- **The pressure rise ratio for a confined deflagrating (unvented) fuel air mixture is ~9:1**
- **The peak pressure ratio for a detonating fuel air mixture is ~ 18:1**
- **Both events could be severe: (rough calculation in progress)**



Important Points

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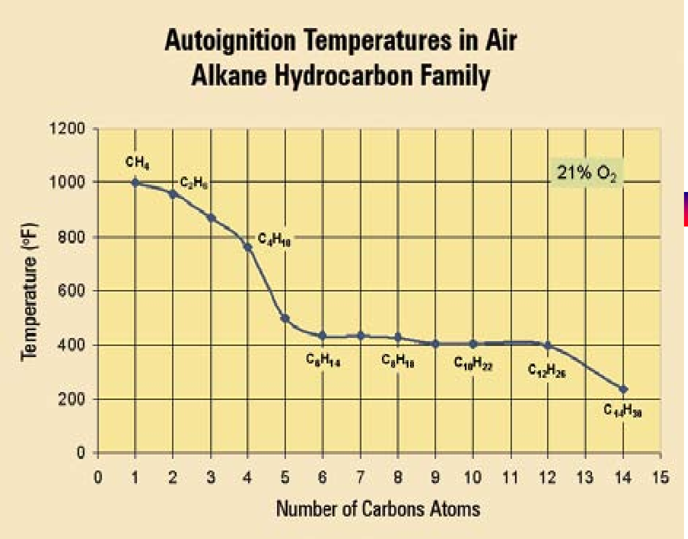

Depleted gas reservoir

- **What does depleted mean?**
- **At atmospheric pressure?**
  - **What is the residual natural gas composition?**
    - **Why is this important?**
      - **Heavy hydrocarbons change the ignition window and decrease the ignition temperature**

Natural gas composition

Component	Typical Analysis (mole %)	Range (mole %)
Methane	95.2	87.0 - 96.0
Ethane	2.5	1.5 - 5.1
Propane	0.2	0.1 - 1.5
iso - Butane	0.03	0.01 - 0.3
normal - Butane	0.03	0.01 - 0.3
iso - Pentane	0.01	trace - 0.14
normal - Pentane	0.01	trace - 0.04
Hexanes plus	0.01	trace - 0.06
Nitrogen	1.3	0.7 - 5.6
Carbon Dioxide	0.7	0.1 - 1.0
Oxygen	0.02	0.01 - 0.1
Hydrogen	trace	trace - 0.02

Table 6. — Limits of flammability of combustible vapors in air and oxygen at 25° C and 1 atm[1]

Combustible	Flammability limits, vol pct			
	Air		Oxygen	
	L_{25}	U_{25}	L_{25}	U_{25}
HYDROCARBONS				
Methane	5.0	15.0	5.0	61
Ethane	3.0	12.4	3.0	66
Propane	2.1	9.5	2.3	55
n-Butane	1.8	8.4	1.8	49
n-Hexane	1.2	7.4	1.2	[2]52
n-Heptane	1.1	6.7	.9	[2]47
Acetylene	2.5	100	≤2.5	100
Ethylene	2.7	36	2.9	80
Propylene	2.4	11	2.1	53
α-Butylene	1.6	10	1.8	58
Cyclopropane	2.4	10.4	2.5	60
Benzene	[2]1.3	[2]7.9	≤1.3	NA

Ignition Window

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- **Lower Flammability Limit** **(aka Lower Explosive Limit, LFL or LEL)**
  - **Below the LFL the mixture of fuel and air lacks sufficient fuel to react**
  - **Above the LFL deflagration or detonation possible**
- **Upper Flammability Limit** **(aka Upper Explosive Limit, UFL or UEL)**
  - **Above the UFL the mixture of fuel and air lacks sufficient air to react.**
  - **Below the UFL deflagration or detonation possible**
- **~Ignition possible between 90 and 370 psi**
  - **Assuming well mixed conditions and starting at 1atmosphere NG**
  - **~Below 90 psi too rich and above 370 psi too lean**
  - **Example: Flight 800 center tank explosion**
    - **Lean on the ground & rich at cruise altitude**
    - **Above the LFL and below the UFL during climb**
    - **Ignition source present**
    - **Boom!**

Ignition Sources 0.3 mJ=0.0002 ft-lb= “not much”

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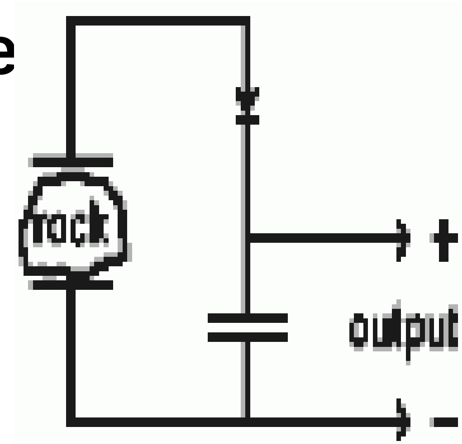
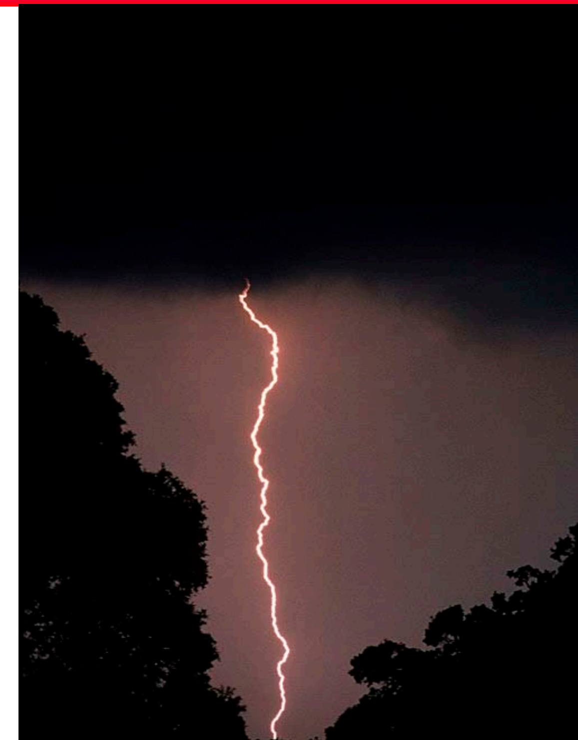
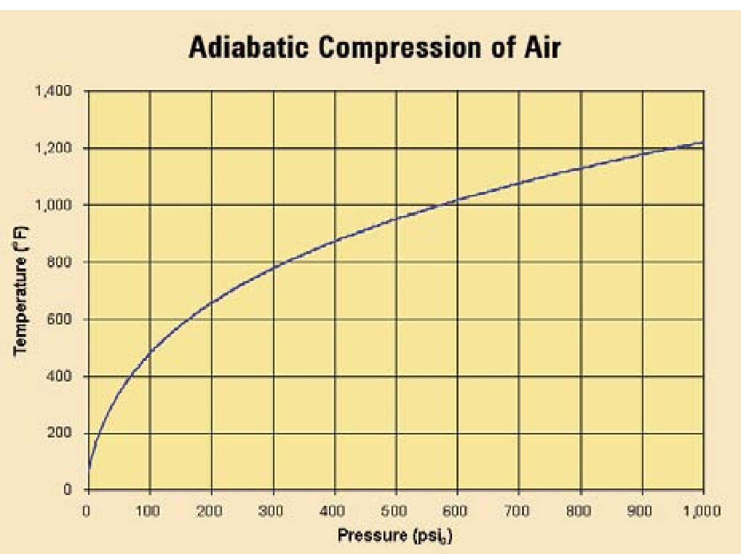
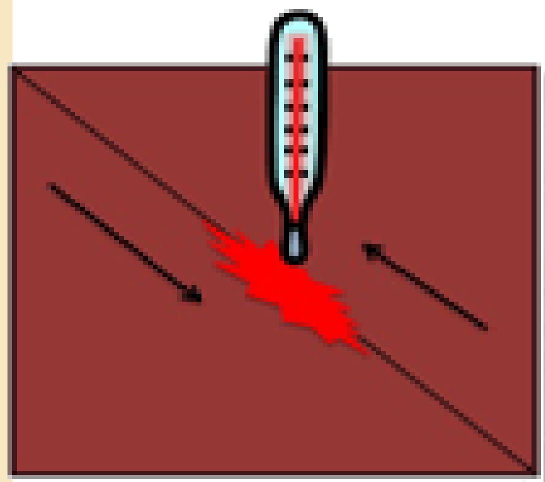
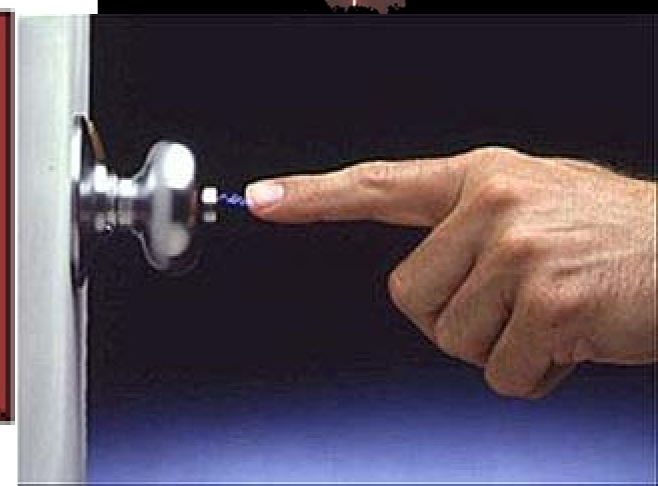
- **Adiabatic compression**
- **Piezo-electric discharge**
- **Static discharge**
- **Lightning strike**
- **Frictional heating**











Results & Conclusions: Mitigation & Safety

- Purge reservoir before use
- Low pressure air cycling below UFL to remove gas (~90 psi)
- In-situ gas monitor
- Never draw down air below the LFL (370 psi)
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CAES Borehole Study

Geomechanics Research Department

Stephen W. Webb

Conclusions

- **Permeability Variation Much More Important then Porosity Variation**
- **Procedure Can Quantify Differences Between Various Sets of Formation Parameters**
  - **Borehole Spacing, Number of Boreholes**
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Study geometry views

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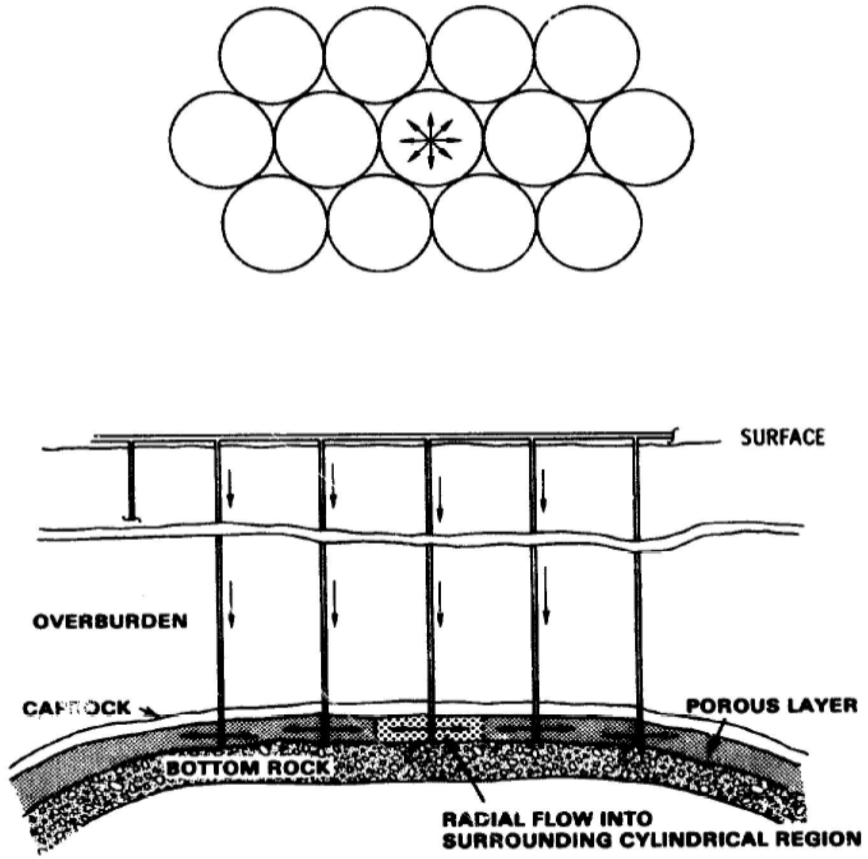

CAES Borehole Schematic (from Smith and Wiles, 1979)

CAES Borehole Study

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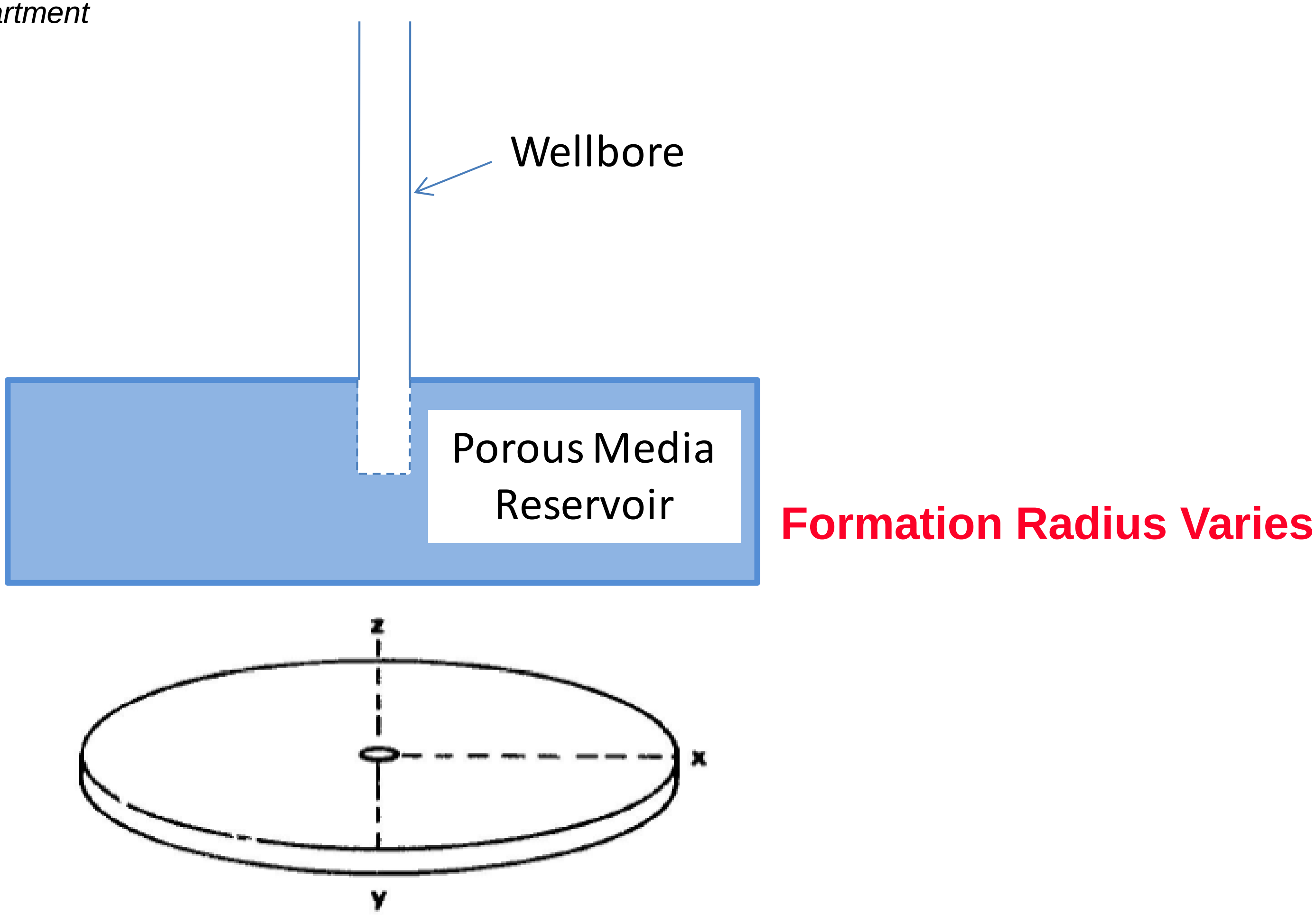

Representative Borehole/Formation Geometry

Study Parameters

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- Formation Height – 100 ft high
- Depth – 2000 ft
- Borehole Diameter – 7 inches
  - Partial Completion
- Permeability – 100 mD to 2000 mD (500 mD Nominal)
- Porosity – 0.1 to 0.3 (0.2 Nominal)
- Formation Radius - Varies
  - Based on P_{max} and P_{min} Values
- Mass Flows
  - See Cycle
- Two-Phase Characteristic Curves
  - Leverett J-Function Scaling

Air Pressure Considerations

P_{min}

- Turbine Inlet Pressure = 45 bar (4.5 MPa)
- Pressure Drop to Surface = ~5 bar (0.5 MPa)
- Minimum Borehole Pressure = 5.0 Bar

P_{max}

- 0.6 x Lithostatic = 8.4 MPa
- Maximum Borehole Pressure = 8.4 MPa

Pressure Cycling Model

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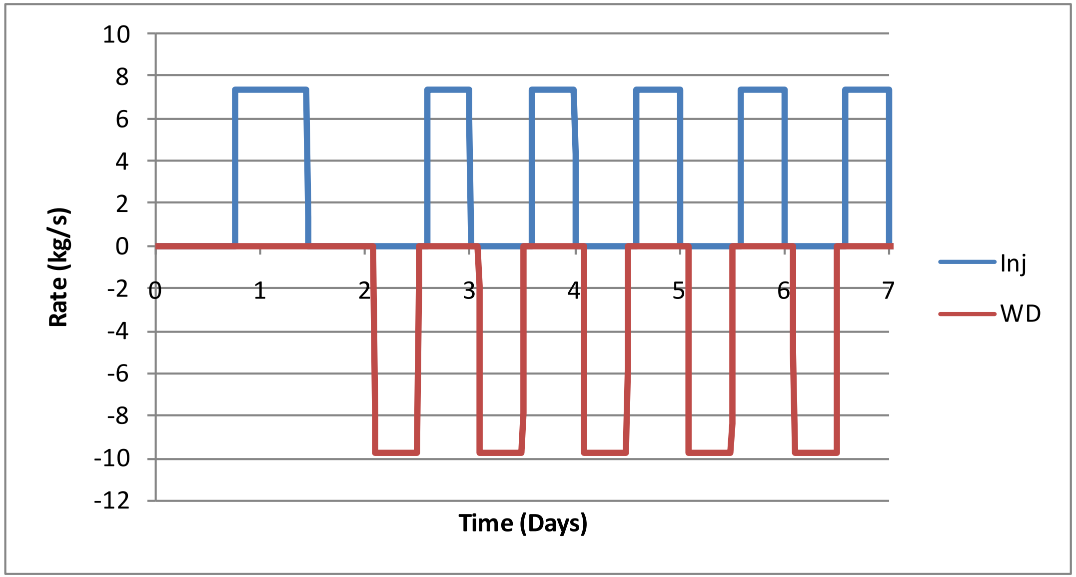
CAES Cycle

- Based on Smith and Liles (1979)
- 10% Mass Cycled Per Week
- 40% Air Added on the Weekend
- Mass Rates Based on Available Mass
  - » Function of Formation Radius, Porosity, Gas Saturation



Typical Cycle

Borehole pressure

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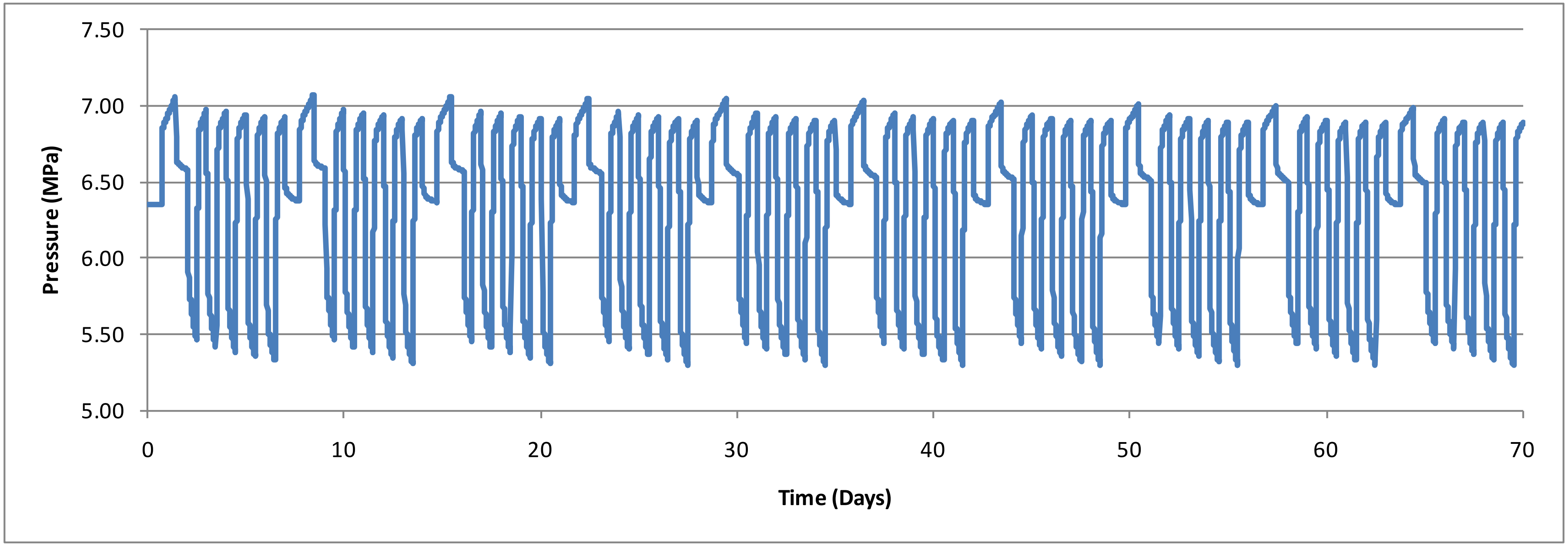
Typical Cycle Results for Borehole Pressure

– After Formation of Bubble



Procedure for Given Permeability and Porosity

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- Formation Radius Increase
  - Mass Rates Increase – Larger Available Mass in Formation
  - P_{max} Increases
  - P_{min} Decreases
- Optimum Formation Radius and Mass Flow Rate When P_{max} and/or P_{min} Met

CAES Borehole Study

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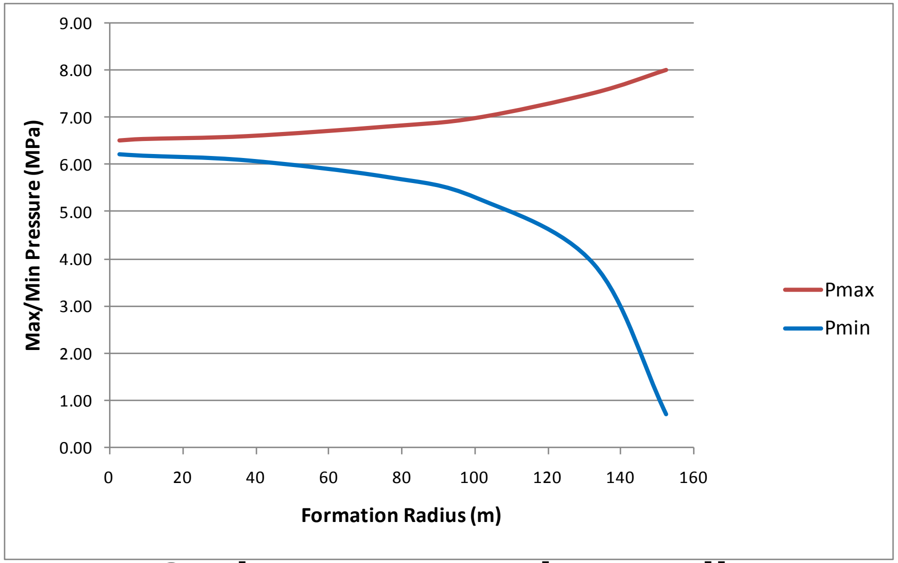
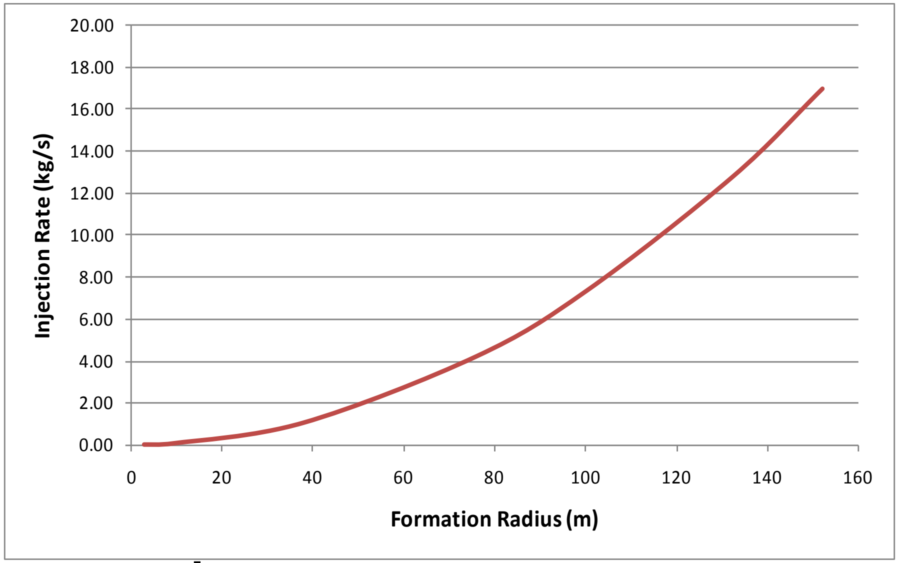
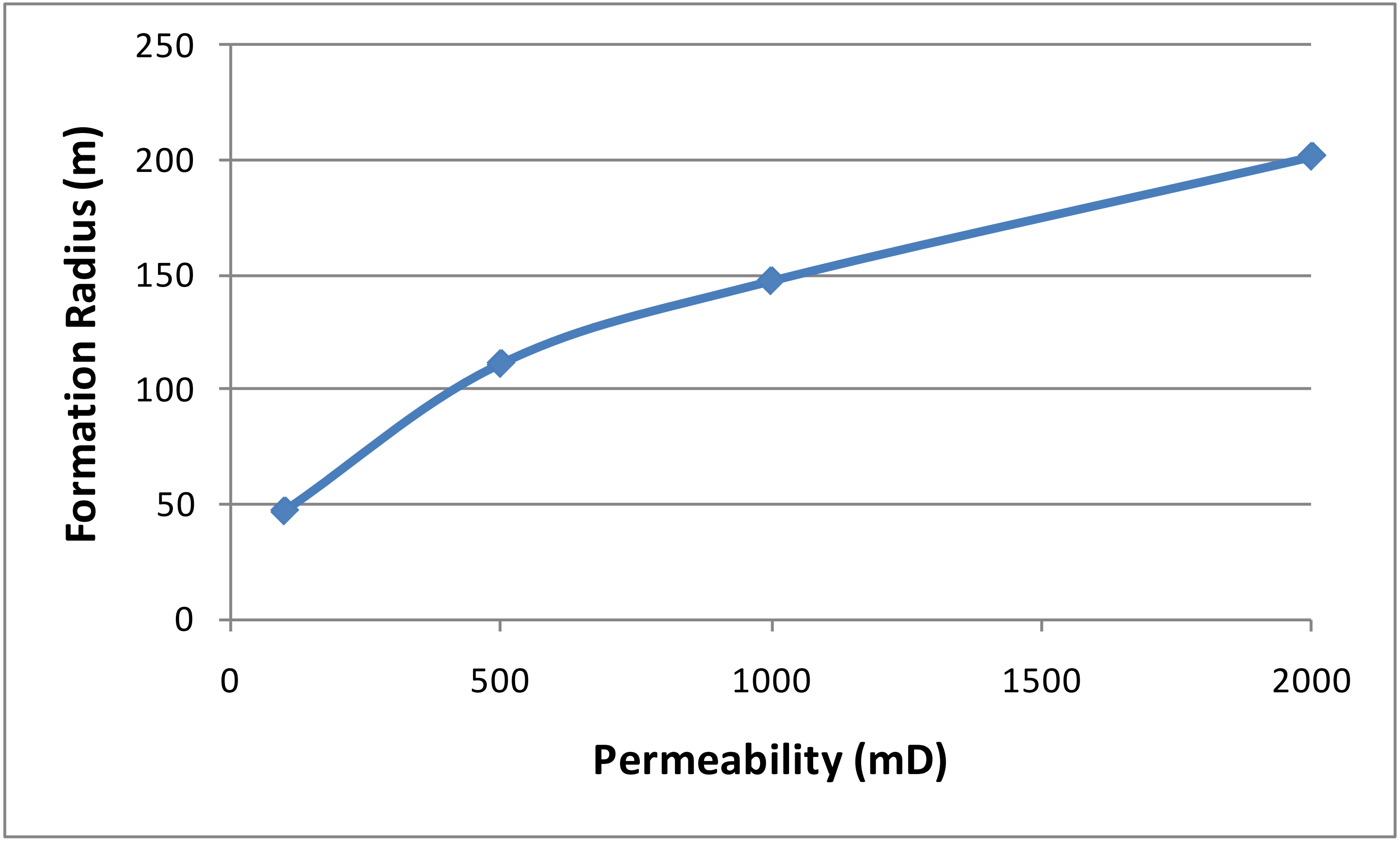
Typical Results (k = 500 mD, ϕ = 0.2)





Optimum Formation Radius = 111 m Based on P_{min}

Permeability Variation



Porosity Variation

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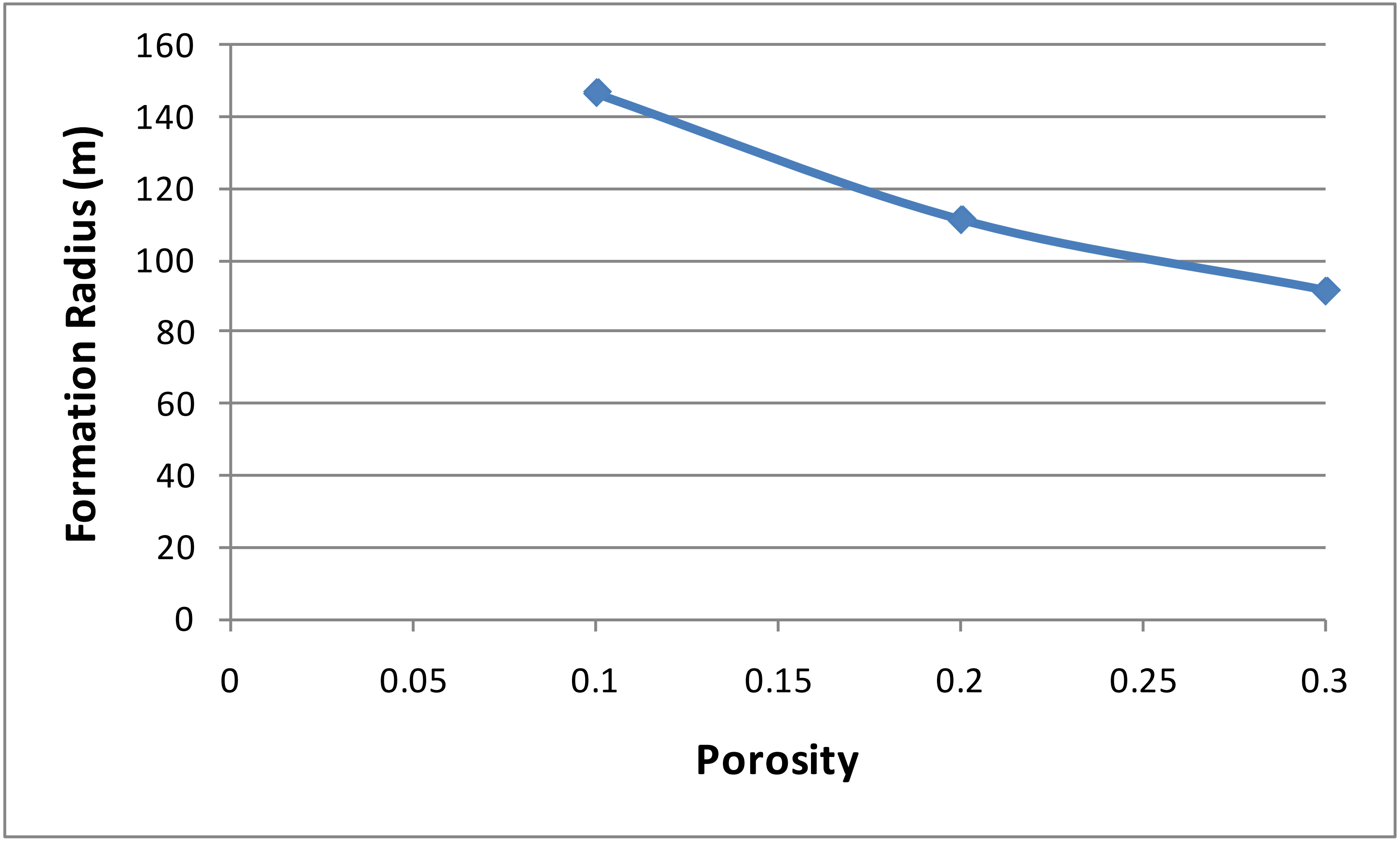

Permeability/Porosity vs. Power

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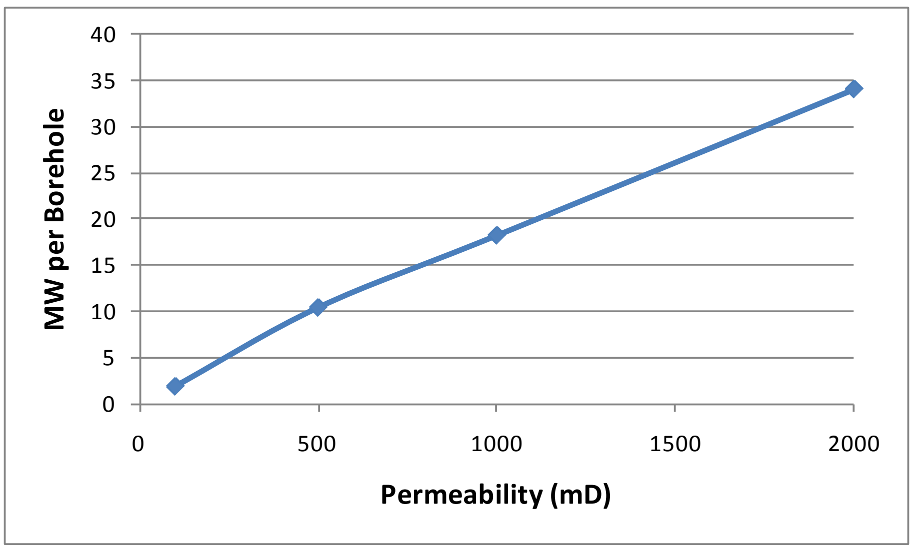
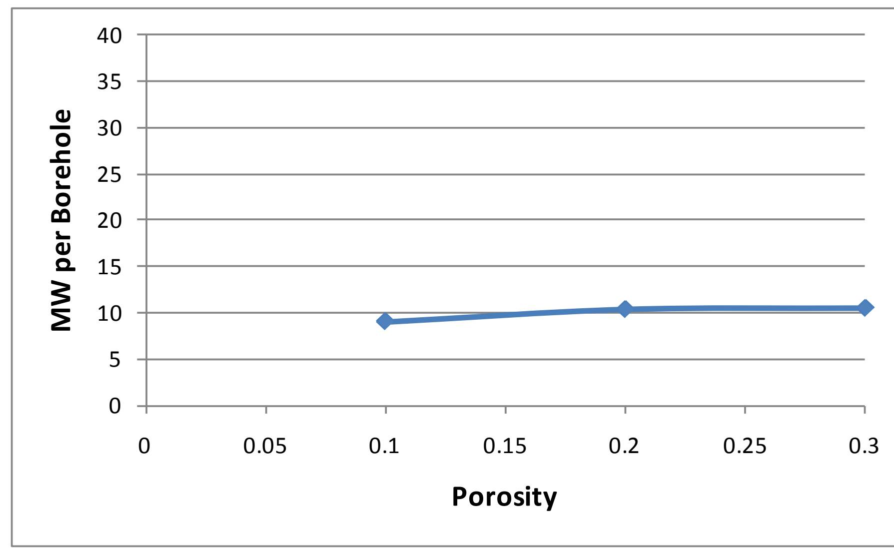
Using Typical Turbine Parameters

Based on Iowa CAES Power Density (~5 MW/m^3) Scaled by Formation Pressure (Succar, 2008)





Number of Boreholes vs Permeability & Porosity

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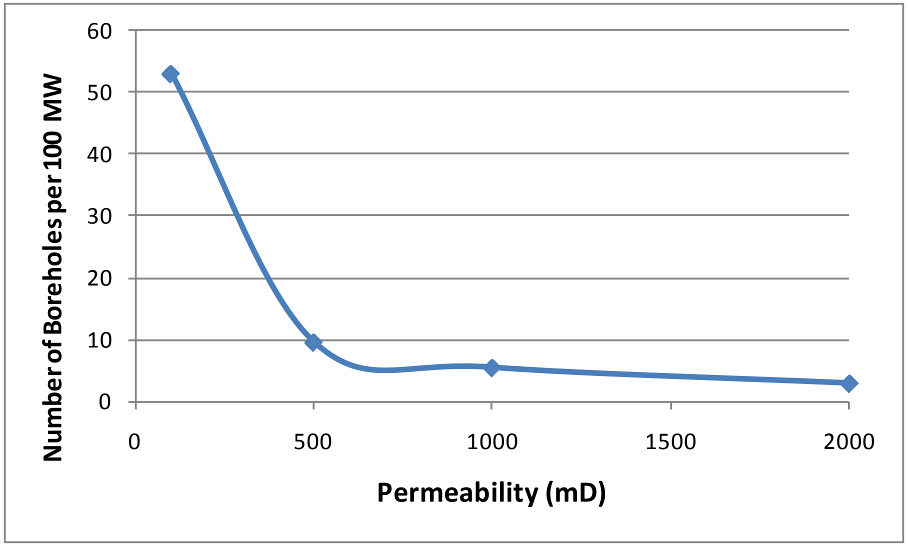

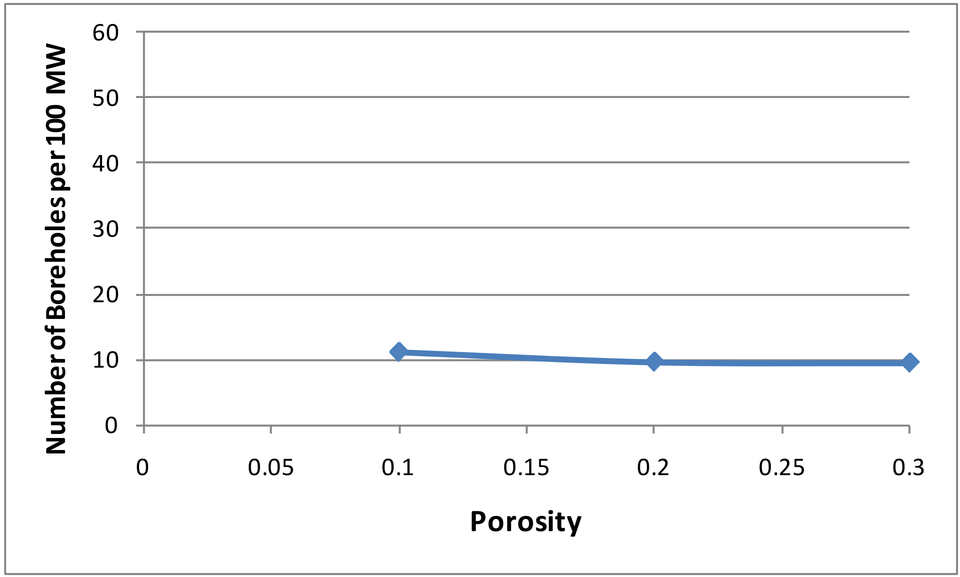

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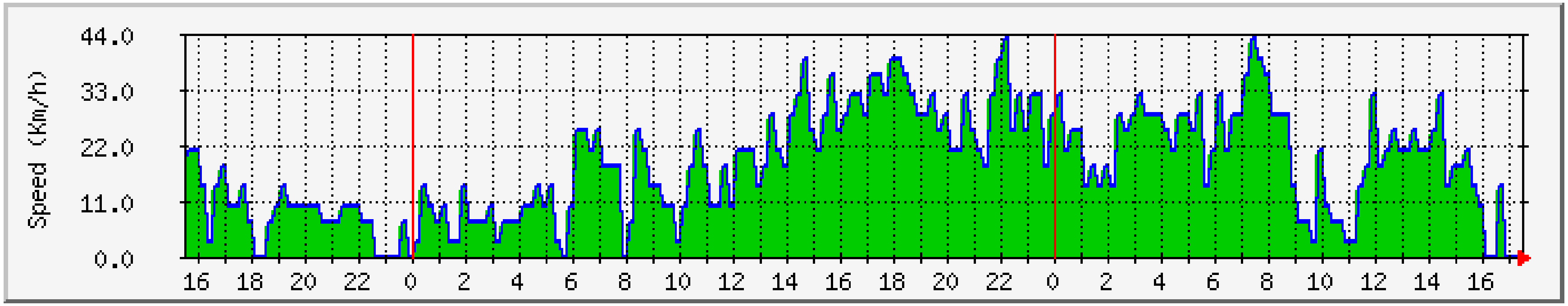
Material Degradation (T-M-C-H effects) Due to Cyclic Loading

Geomechanics Research Department

Experimental Deformation of Salt in Cyclic Loading

SJ Bauer and ST Broome

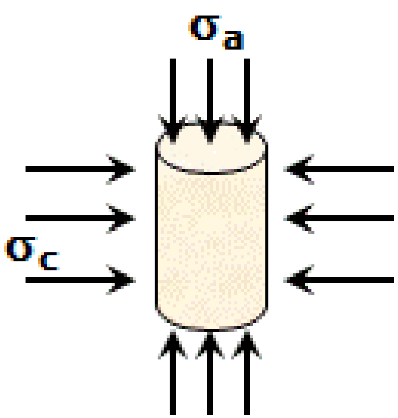


Hourly fluctuations in wind speed could translate to frequent pressurization/depressurizations of salt caverns

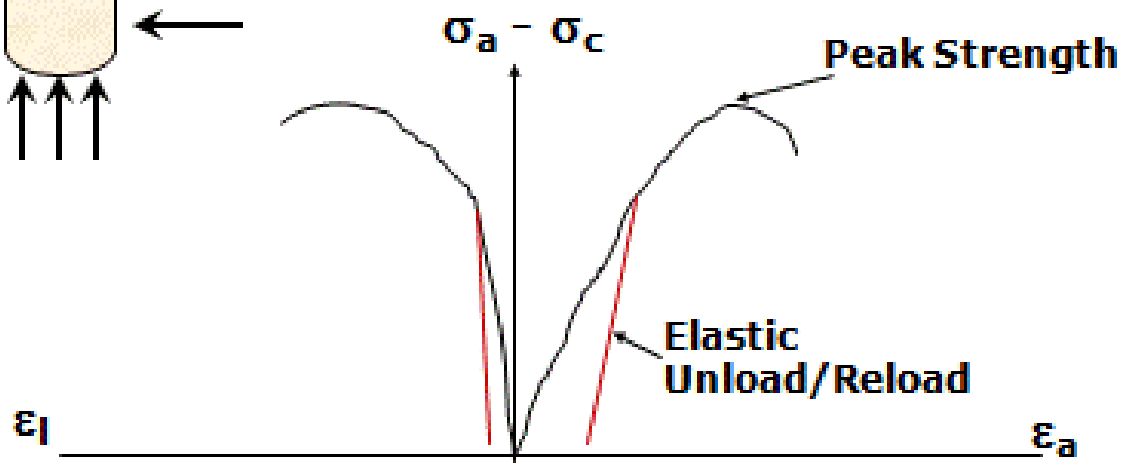
Experimental Deformation of Salt in Cyclic Loading

Geomechanics Research Department

Quasi-Static Loading



- Apply constant σ_c
- Increase σ_a until specimen fails
- Measure strains



Dilatant behavior of salt determined from quasi-static tests and stress states for this study

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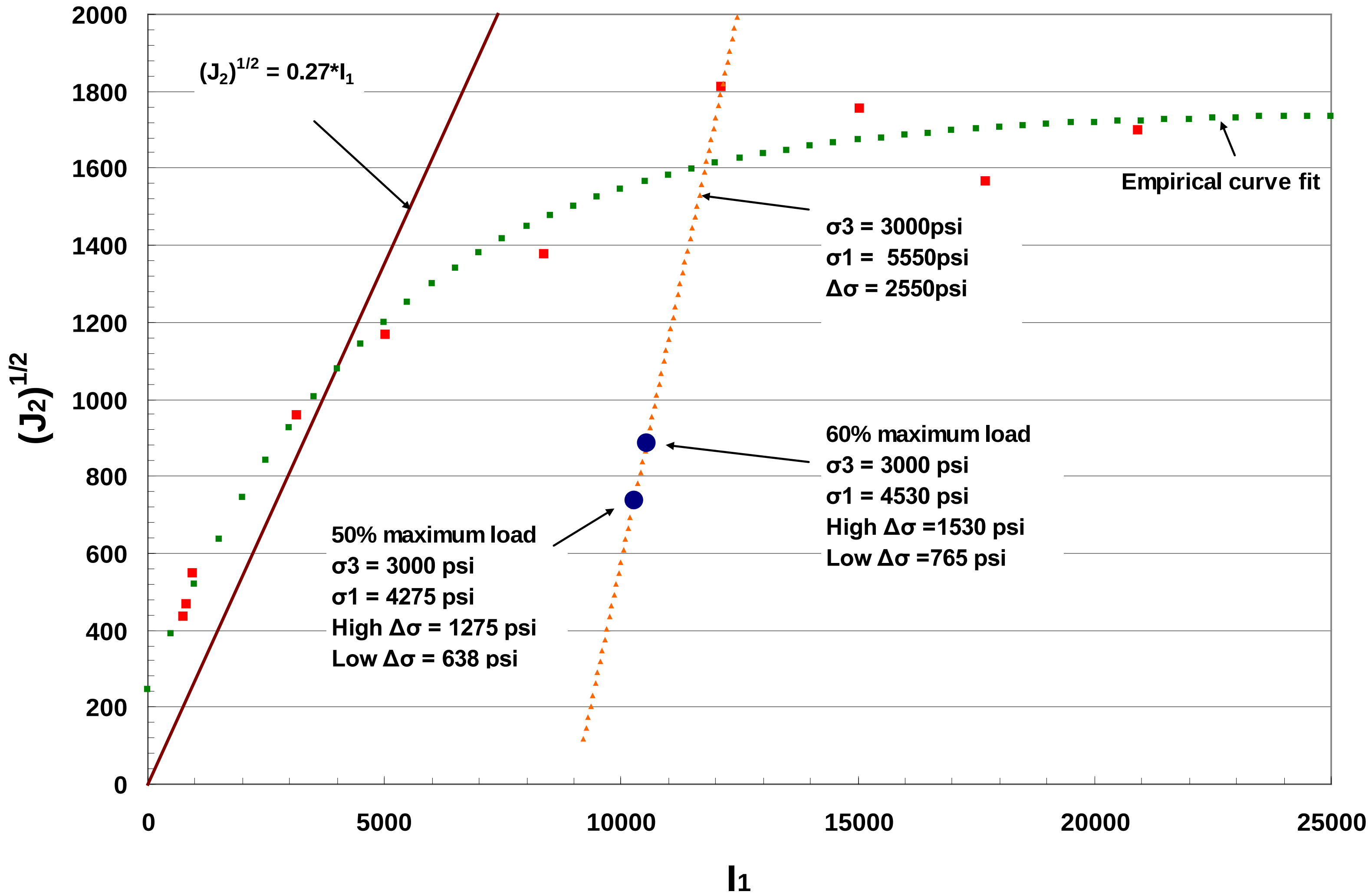

Test assembly

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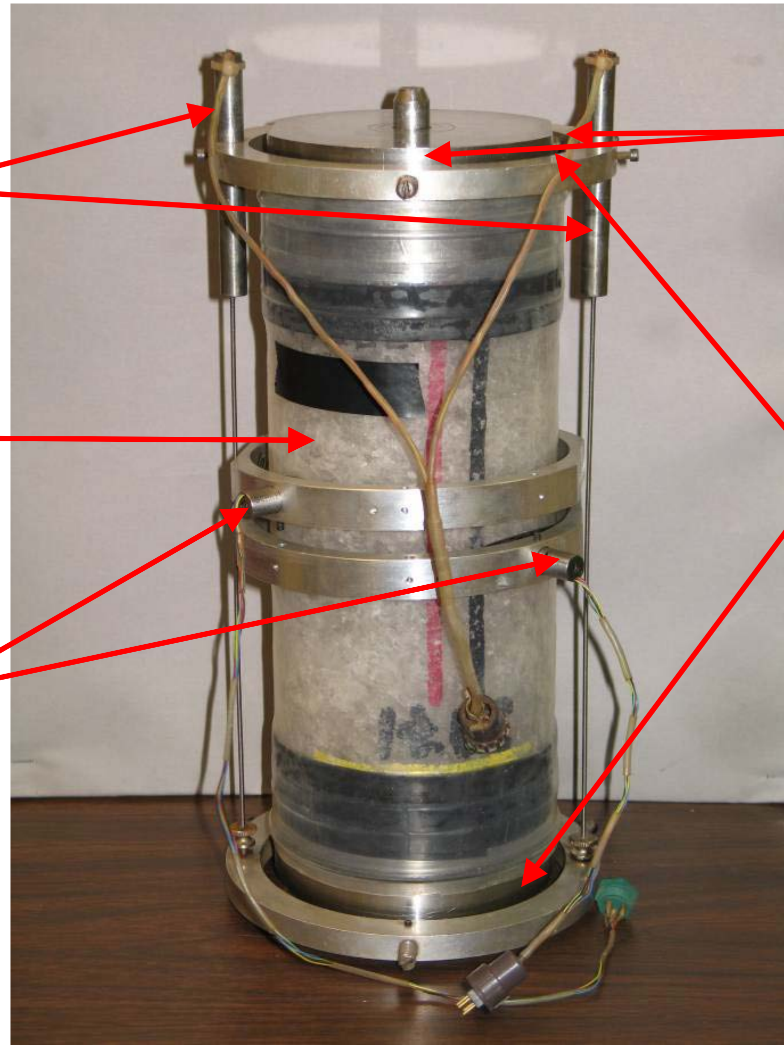
Axial LVDT's

AE pin location

Heat shrink jacket

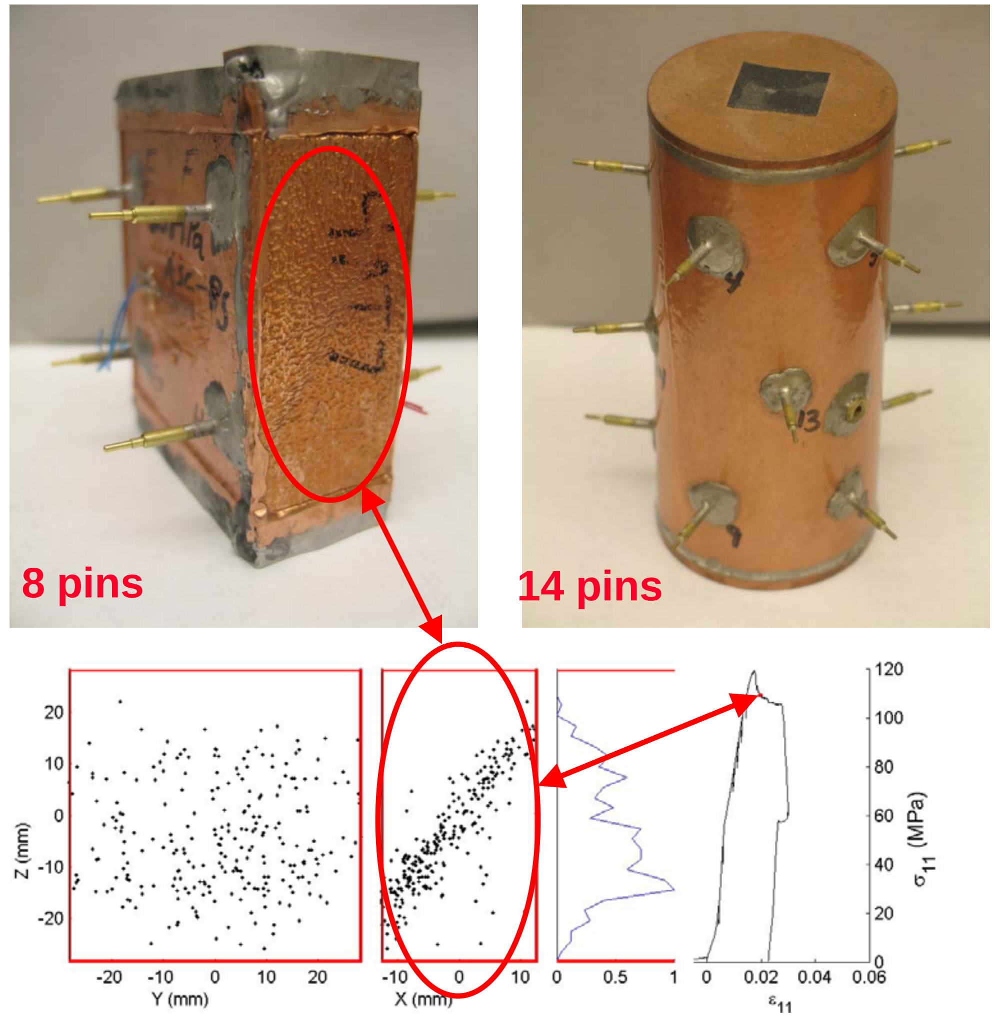


Sample end caps

Radial LVDT's

Acoustic Emissions System

- **Sample rates up to 25 MHz**
- **Typically acquire 3000 samples/event**
- **Tailor a discriminator to only sample events of a given criteria**
- **60 dB amplifier**
- **Location of events is possible with many pins**



Differential stress versus axial strain, Test 3.

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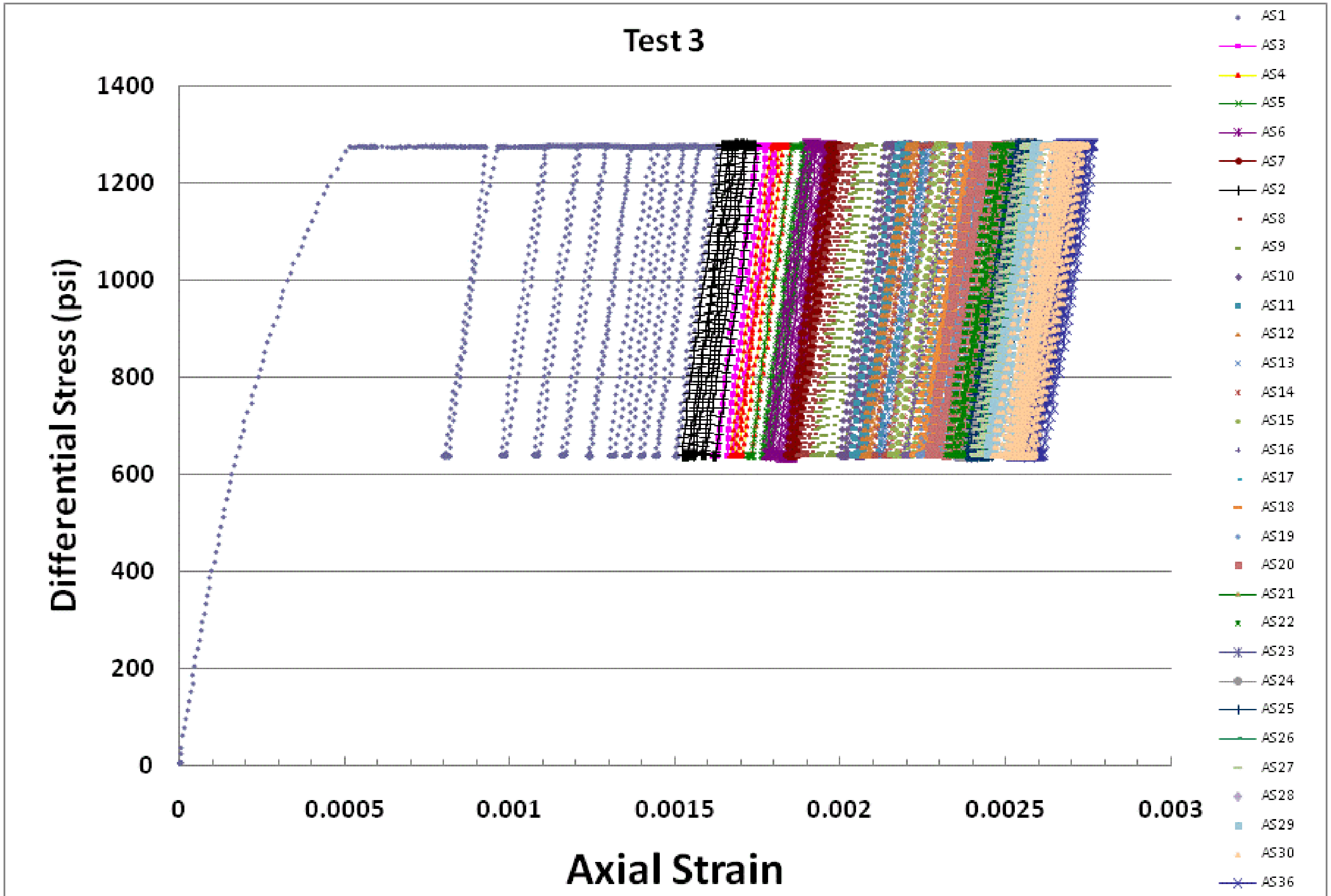

Test data

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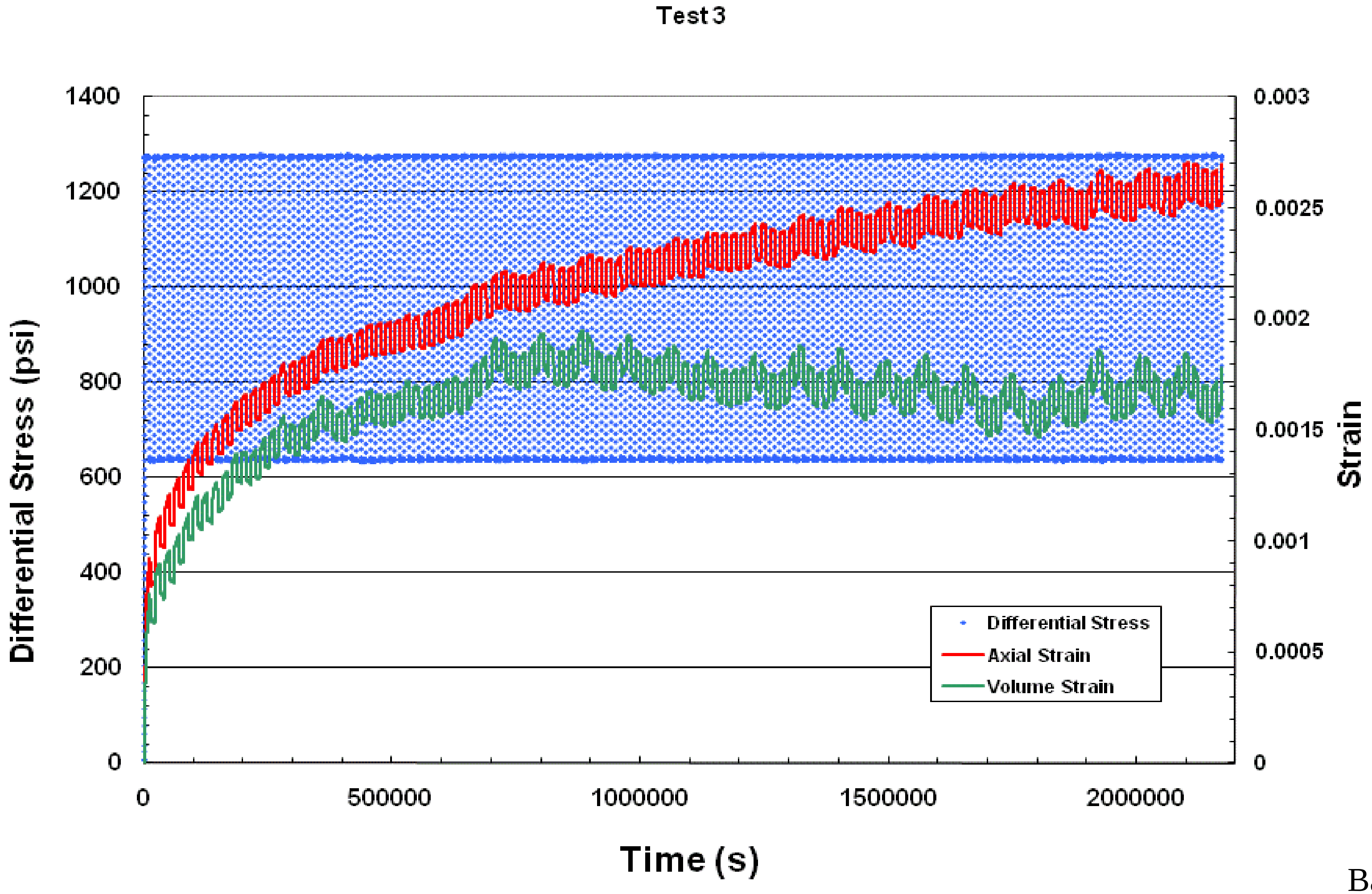
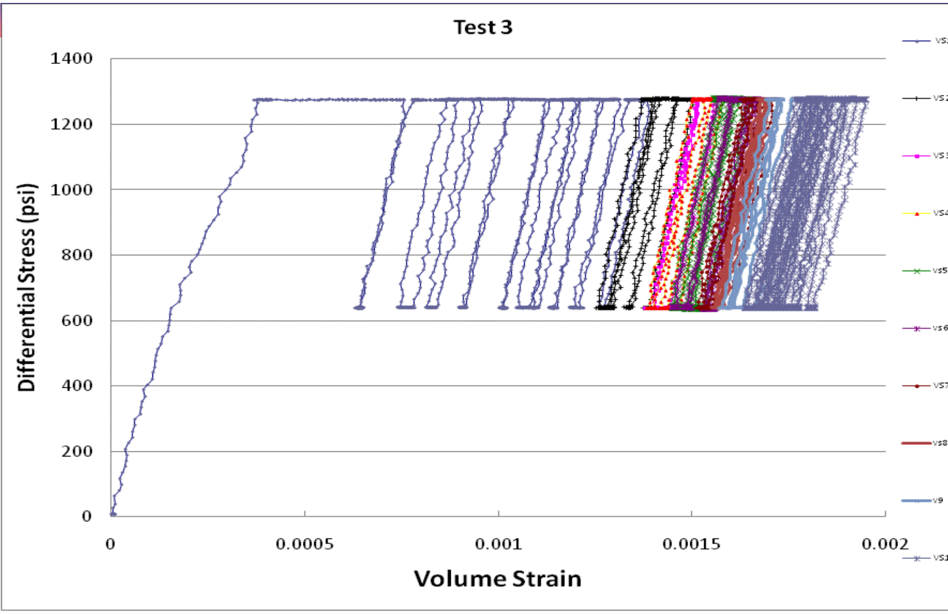
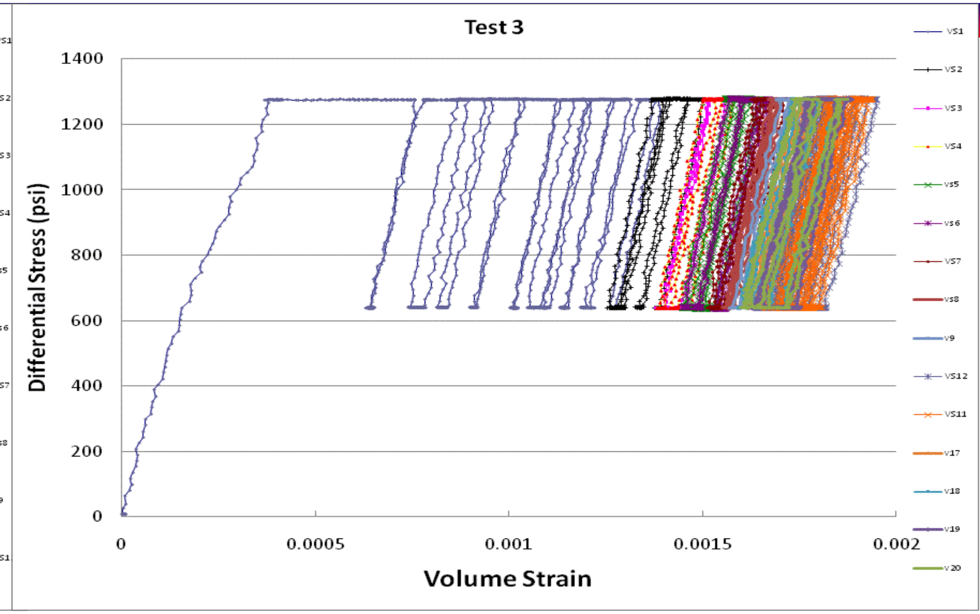
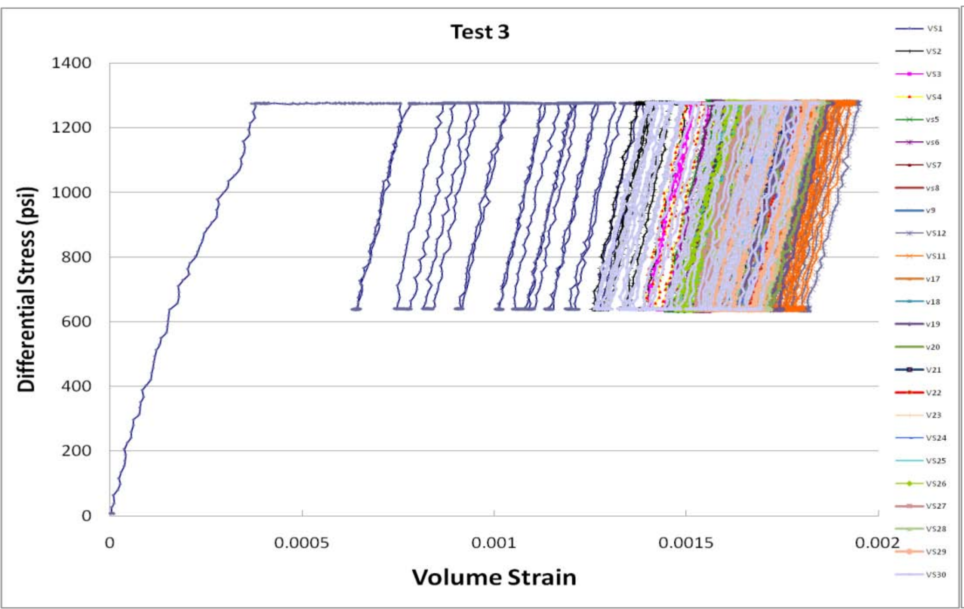
Differential stress, axial and volume strain versus time, Test 3.

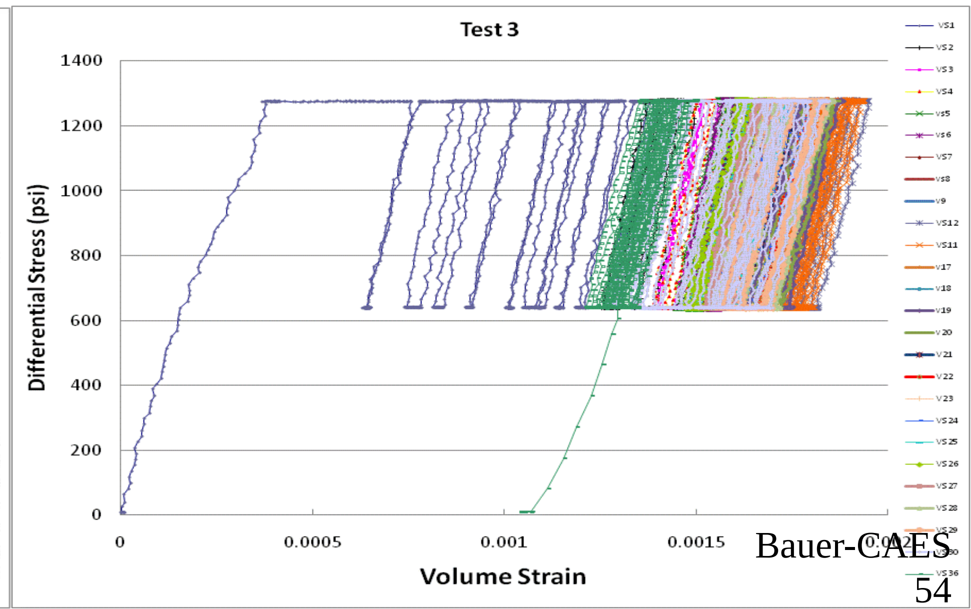


Differential stress versus volume strain, Test 3

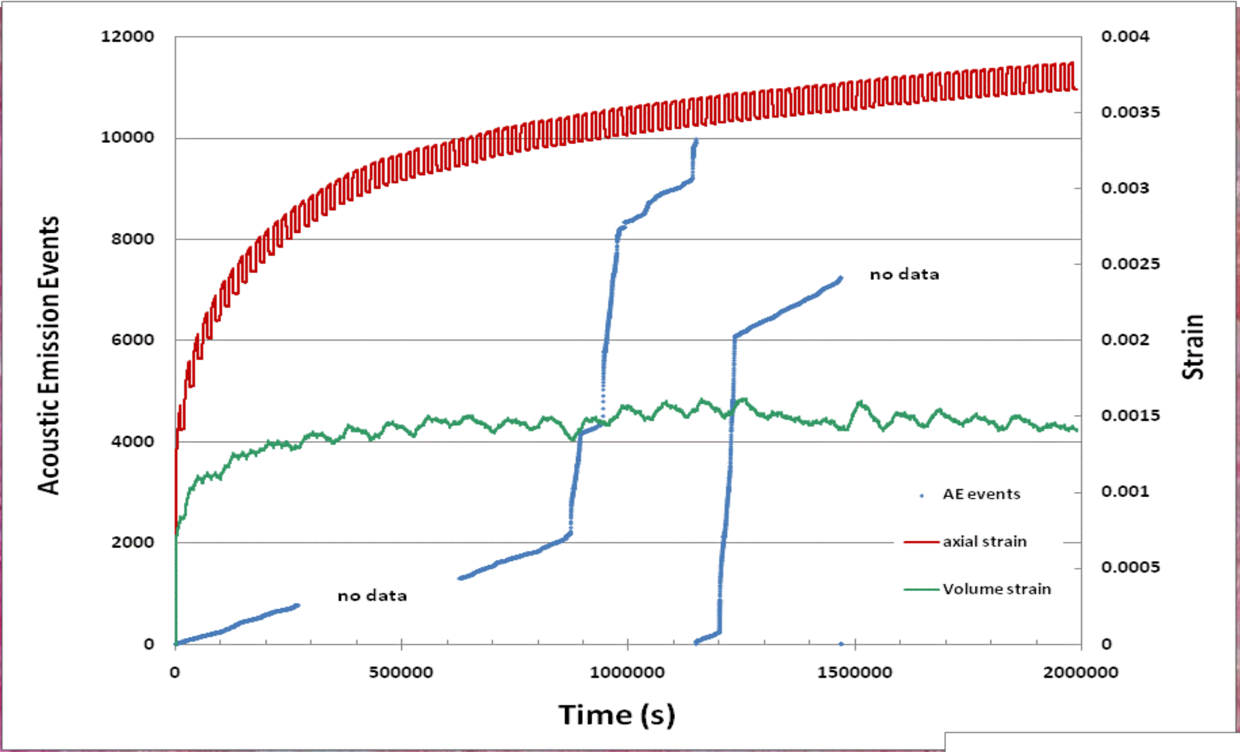






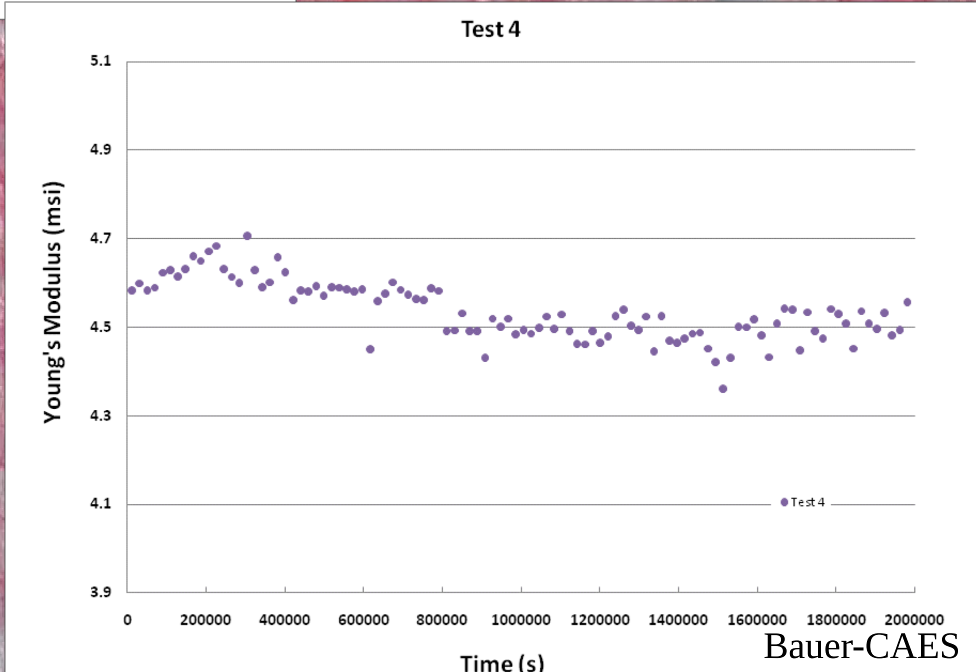


Bauer-CAES



Acoustic emission events and strain versus test time.

Young's Modulus versus test time



Concluding Comments

- Preliminary cyclic tests completed on salt
- Change in volume strain observed
- Young’s Modulus changes observed
- Acoustic Emissions detected
- Cracks observed in thick sections
- Results consistent with previous work
- Implication that cyclic loading caused cracking at low differential stresses


thanks
Questions?