COLLEGE OF EARTH RESOURCE SCIENCES & ENGINEERING
COLORADO SCHOOL OF MINES

Petroleum Engineering Department

Faculty Research & Lab Facilities

Spring 2017

Petroleum Engineering @ Mines

- Mines Facts
  - o Located in Golden, Colorado – foothills of the Rockies
  - o 4364 undergraduate students, 1157 graduate students (Spring enrollment 2017)
- Petroleum engineering
  - o 20 tenured / tenure track / research / teaching faculty
  - o $5 M in research funding in FY 16
  - o Active research projects in
    - Carbonate reservoir characterization
    - Enhanced oil recovery
    - Unconventional oil and gas
    - Hydraulic fracturing
    - Pore-scale physics and flow
    - CO_2 sequestration
    - Geothermal
    - Drilling

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

PE Research / Teaching Faculty

- Hazim Abass (habass@mines.edu)
- Linda Battalora (lbattalo@mines.edu)
- Rosmer Brito (rmbrito@mines.edu)
- Elio Dean (eldean@mines.edu)
- Alfred (Bill) Eustes (aeustes@mines.edu)
- Mansur Ermila (mermila@mines.edu)
- William Fleckenstein (wflecken@mines.edu)
- Ramona Graves (rgraves@mines.edu)
- Hossein Kazemi (hkazemi@mines.edu)
- Carrie McClelland (cmcclell@mines.edu)
- Mark Miller (mmiller@mines.edu
- Jennifer Miskimins (jmiskimi@mines.edu)
- Erdal Ozkan (eozkan@mines.edu)
- Manika Prasad (mprasad@mines.edu)
- Jorge Sampaio (jsampaio@mines.edu)
- Azra Tutuncu (atutuncu@mines.edu)
- Philip Winterfeld (pwinterf@mines.edu)
- Yu-Shu Wu (ywu@mines.edu)
- Xiaolong Yin (xyin@mines.edu)
- Luis Zerpa (lzerpa@mines.edu)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

PE Research Centers and Institutions

- **CEMMC** – Center for Earth, Materials, Mechanics, and Characterization (Graves / Miskimins)
- **MCERS** – Marathon Center of Excellence for Reservoir Studies (Kazemi / Ozkan)
- **UNGI** – Unconventional Natural Gas and Oil Institute (Tutuncu)
- **FAST** – Fracturing, Acidizing, Stimulation Technology (Miskimins)
- **OCLASSH** – Physics of Organics, Carbonates, Clays, Sands, and Shales (Prasad)
- **EMG** – Energy Modeling Group (Wu)
- **UREP** – Unconventional Reservoir Engineering Project (Ozkan/Yin)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

PE Faculty and Research Areas

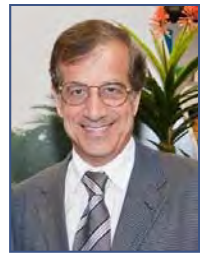
- Hazim Abass – Hydraulic fracturing research
- Rosmer Brito – Midstream, Production System Design and Optimization
- Alfred Eustes – Drilling for petroleum & non-petroleum
- Will Fleckenstein – Drilling and hydraulic fracturing
- Ramona Graves – Reservoir Characterization and CEMMC
- Hossein Kazemi – IOR/EOR, reservoir studies at MCERS
- Jennifer Miskimins – Stimulation and FAST consortium
- Erdal Ozkan – Well testing / MCERS / Unconventional reservoir engineering
- Manika Prasad – Petrophysics of Organics, Clay, Sand, and Shale
- Jorge Sampaio – Drilling and engineering modeling and simulation
- Azra Tutuncu – Geomechanics and unconventional gas and oil institute
- Philip Winterfeld – Numerical simulation, flow and transport phenomena in porous media
- Yu-Shu Wu – CO_2-EOR, CO_2 sequestration, geothermal, hydrology
- Xiaolong Yin – Pore-scale physics and flow, suspension, phase behavior
- Luis Zerpa – EOR, reservoir, flow assurance, gas hydrate in nature

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Hazim Abass

Professor & Research Director

- Education
  - o BS in Petroleum Engineering, U. of Baghdad, 1977
  - o MS in Petroleum Engineering, CSM, 1984
  - o PhD in Petroleum Engineering, CSM, 1988



- Experience:
  - o NPO, Kirkuk, Iraq, 1977-1980
  - o Halliburton, Duncan, OK, USA, 1988-1995
  - o PDVSA, Los Teqes, Venezuela, 1996-2001
  - o Saudi Aramco, Dharan, Saudi Arabia, 2001-2014
  - o CSM, Golden, CO, USA, 2014-present

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Awards

- o The 2015 recipient of the Int'l SPE/AIME Honorary Membership
- o The 2012 SPE Int'l Award- Completion Optimizations and technology
- o The 2012 SPE Middle East Regional award- Completion Optimizations and Technology
- o The 2009 SPE International Award- Distinguished Member
- o The 2008 SPE Middle East Regional award- production operations
- o SPE Distinguished Lecturer for the 2011/2012 season, "The use and misuse of applied rock mechanics in petroleum engineering."

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Philosophy

Once Einstein was asked why he was so smart; his reply was "It's not that I'm so smart, it's just that I stay with problems longer". This philosophy was key for me to earn many US granted patents and I preach it to my mentees and students all the time. It is really the power of persistence when dealing with a problem. Persistency in researching a technical challenge eventually leads to a simple and most of the time elegant solution.

Research requires multidisciplinary approach. I believe combining what seems disparate technical disciplines is vital to solve challenges in Petroleum Engineering.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus

- Applied geomechanics in petroleum engineering
- Pioneered advanced techniques related to oriented perforation, fracturing horizontal wells, fracturing coalbed methane, FrackPacking, wellbore stability, gas hydrate, and water coning.
- Current interest is fundamental research related to improving well productivity from tight reservoirs (sandstone, carbonate and shale). New techniques are being developed to modify rock properties such as capillarity, interfacial tension, dissolving cementation materials and inducing shearing effect of microfractures.
- Research innovative technologies in waterless fracturing

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

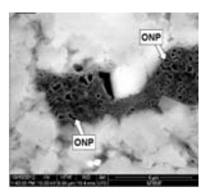
Research Focus

- Hydraulic fracturing in unconventional reservoirs
  - Optimization of hydraulic fracturing of shale gas reservoir
  - KOGAS

- Recent grads/theses topics:
  - Di Zhang: Stress-dependent fracture conductivity of propped fractures in the stimulated reservoir volume of hydraulically fractured shale well. (MSc)
  - Zhou Zhou: The impact of capillary imbibition and osmosis during hydraulic fracturing of shale formations. (Ph.D.)
  - Qi Cui: Permeability degradation of tight reservoirs and its impact on long-term production. (Ph.D.)

Current Projects/Research

Fundamentals: How does gas flow from matrix, fractures, Kerogen to wellbore? A combination of: desorption, diffusion, advection, slippage, osmosis, ……stress sensitivity, fracture closure, poromechanics,

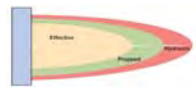


Outcrop block testing: available outcrops, well testing, generating fracture network, dual-well fracturing, fracturing fluids

Current Projects/Research

Physical Modeling: Fracturing fluid transport through wellbore, perforations, fractures

Mathematical Modeling: Fracture propagation, reservoir simulation, near wellbore phenomena, multi-well fracturing



Pilot/Yard Testing: Outcrop testing, mineback observation, large scale yard testing

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Dr. Rosmer M. Brito

- Assistant Professor, Petroleum Engineering Department, Colorado School of Mines
- Previous to CSM, Production Engineer JV Shell & PDVSA (Venezuela), and Research Scientist Intern ExxonMobil URC
- B.S. (2007) in Petroleum Engineering from the University of Zulia
- M.S. (2012) and Ph.D. in Petroleum Engineering (2015) from the University of Tulsa
- SPE and ALRDC member

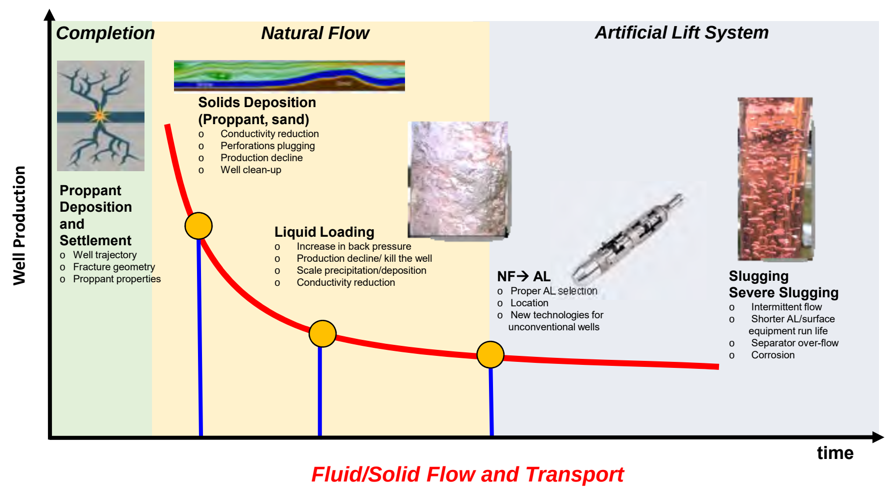
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus

- **Erratic Production Conditions in Wells and Pipelines**
  - Liquid loading
  - Terrain slugging
  - Severe slugging
- **Artificial Lift Systems Performance Evaluation**
- **Production System Design and Optimization**
  - Transient vs. steady-state simulations
- **Solid Deposition and Settlement**
  - Solid transport in wells and pipelines
  - Well-Fracture Interaction
- **Liquid-gas and Liquid-Liquid Separation**

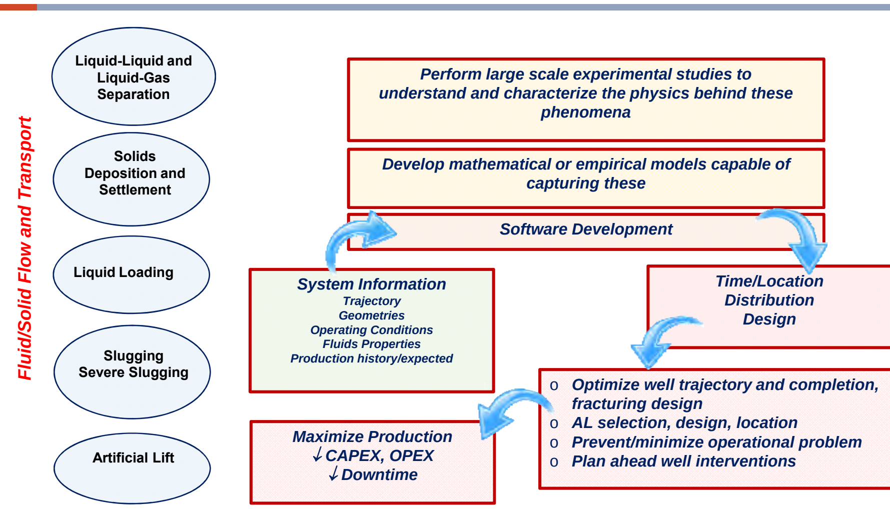
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Production Optimization Projects (POP) Proposal

- **Introduction**
  - CSM POP Consortium will be a joint industry/university research consortium with the objective to carry out research in all the areas of **integral production optimization of oil and gas production systems.**
  - POP will be focused on the development of modeling and experimental research that can be directly applied to the integral optimization of production systems all the way from the perforations to the wellhead, multiphase flow surface facilities, and midstream operations.
  - An engaged partnership with industry is essential to the success of the consortium, and future industry members are encouraged to provide direct input and guidance during the execution of the projects.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Production Optimization Projects (POP) Proposal

- Staff
  - Principal Investigator
    - Dr. Rosmer Brito
  - Students
    - Ayush Rastogi (PhD)
    - Daniel Croce (PhD)
    - Jagmit Singh (Master of Science)
    - Ted Rutkowsky (Master of Science)
    - Ayowole Ogunleye (Master of Science)
    - Logan Salewski (Undergraduate)
    - Maxat Toktarov (Undergraduate)

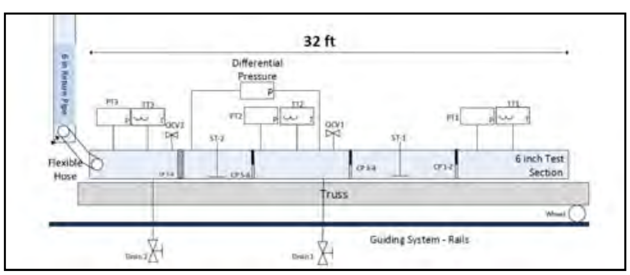
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Current Projects

- **Project 1:** GALLOP New Artificial Lift Method Development and Testing for Horizontal Gas Well Applications
  - o **Objective:** Investigate the performance of the GALLOP artificial lift system through experimental and modeling studies
    - Validate its functionality compared to other existing artificial lift systems
    - Extrapolate the experimental results to field conditions using mechanistic modeling
    - Identify key improvement opportunities in the GALLOP design and operation
  - o **Students:** Daniel Croce and Maxat Toktarov

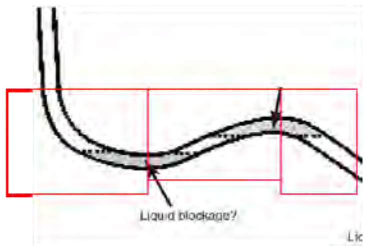
Current Projects

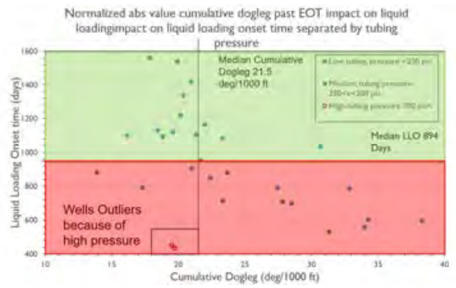
- **Project 2:** Liquid Loading Evaluation in Large Pipe Diameter and Three-Phase Flow System
  - o **Objective:** Carry out an experimental study to determine the effect of large diameter (6" in order to simulate casing) and three phase flow on the onset of liquid loading
  - o **Student:** Ayush Rastogi



Current Projects

- **Project 3:** Modeling and Statistical Analysis to Determine Undulation and Tortuosity Effect on Liquid Accumulation
  - **Objective:** Examine effect of wellbore trajectory and operating conditions on time liquid loading is detected on the surface based on transient modeling and field data
  - **Students:** Ayowole Ogunleye and Logan Salewski

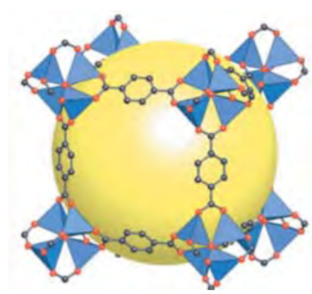




Current Projects

- **Project 4:** Pipeline Methane Leak Sensor Development Using Metal-organic Frameworks

MOFs are made by linking inorganic and organic units by reticular synthesis. More than 20,000 MOFs have been developed to store high densities of methane (CH_4), and new advances have led to MOFs with volumetric CH_4 uptake around 230 cc(STP)/cc at 35 bar and 270 cc(STP)/cc at 65 bar, which meets volumetric targets set by the DOE. The potential to use MOFs to develop systems to capture, store and detect CH_4 at wellheads reducing leaked and flared gas.



Objective: Develop and evaluate a system to detect and store methane at the wellhead using MOFs at expected pipeline pressure, temperature and flow rate conditions.
Student: Ted Rutkowsky

Alfred William (Bill) Eustes III

Ph.D., P.E. Colorado

- Early life
  - Born in Florida, raised in the southeastern US and on USAF bases
  - Graduate of Ben Eielson High School (Alaska), 1974
- Education
  - BS ME, Louisiana Tech University, 1978
  - MS ME, University of Colorado, Boulder, 1989
  - Ph.D. PE, Colorado School of Mines, 1996
- Employment
  - Colorado School of Mines (1996 - Now)
    - Associate Professor
  - ARCO Oil and Gas Company (1978 - 1987) (Hobbs, Midland, Tulsa, Tyler, Enid)
    - Senior Drilling Engineer
    - Senior Production/Facilities Engineer
  - Consultant
    - BP Alaska
    - Sklar Exploration
    - Fleckenstein, Eustes, and Associates
    - Bureau of Reclamation
    - Chemical Safety Board

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Other Things About Me

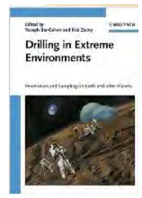
- Society of Petroleum Engineers
  - Distinguished Lecturer 2013 – 2014
  - Education and Accreditation Chair 2011 – 2013
- ASME IPTI - Petroleum Division
  - Executive Committee 2001 – 2007
  - Chair of the Division 2007
- NSF Technical Advisor
  - Ice Coring and Drilling 2000 – 2016
  - Ice Drilling Program Office 2014 – now
- NASA
  - Planetary/Lunar/Asteroid drilling operations, 1999 – now
  - Astrobiology project reviewer 2005 – 2006
- American Association of Drilling Engineers
  - Student chapter faculty advisor since 1996
- Geothermal Resources Council
- American Geophysical Union
- International Association of Drilling Contractors
- Pi Epsilon Tau

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Recent Books

- SPE Drilling Engineering Textbook
  - o Drilling fluids chapter
  - o Drilling problems chapter

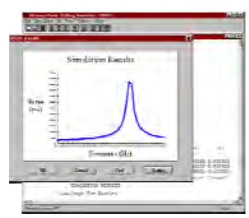
- Drilling in Extreme Environments
  - o Ground drilling and excavation chapter

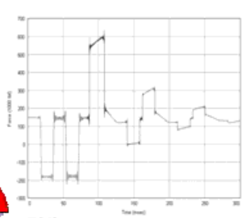


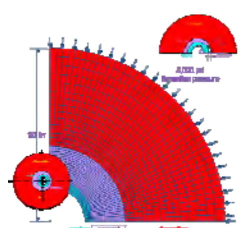
- SPE Petroleum Engineering Handbook
  - o General engineering chapter on vibrations

Past Drilling Research Projects

- Hanford Project
  - o Resonant Sonic Drilling Simulator
- Cougar Tool Project
  - o Jarring Wave Propagation
- DOE/BLM/USFS
  - o Directional Drilling in the Rocky Mountains
  - o Geothermal Drilling Risk Analysis
- Casing/Cement/Formation Finite Element
  - o Collapse and Burst analysis
- OMV
  - o Benchmarking Drilling Operations
- Vaca Muerta Consortium - Argentina
  - o Pore Pressure Prediction
- Unconventional Natural Gas and Oil Institute
  - o Analysis of Real-Time Operational Drilling Parameters and Reservoir Characterization

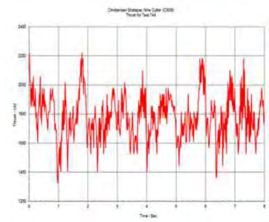


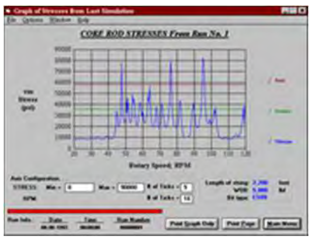


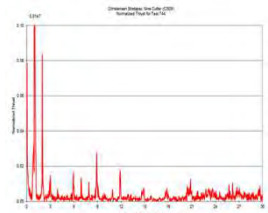


Yucca Mountain Project

- Vibratory Core Rod Simulator
- Deviation Control Simulator
- PDC Core Bit Frequency Analysis
- Air Coring and Drilling Simulator
- Fuzzy Logic Controller



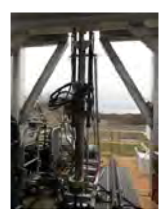




NSF - Ice Drilling Program Office

- Support National Science Foundation polar drilling and coring program
    - In cooperation with Dr. Fleckenstein
- Review of US ice coring operations
- Developed specifications on next generation ice core rig – The Deep Ice Sheet Core rig (DISCdrill) for Antarctic service
- ICECUBE (Amundsen-Scott South Pole Station)
- Developed specifications for Rapid Access Ice Drill (RAID)
- Represented US in Russian Lake Vostok penetration
- On NSF Tiger Team for Replicate Ice Coring
- Member Technical Advisory Board for Ice Design and Drilling Operations (IDDO) for fifteen years
- Subject Matter Expert for Agile Sub-ice Geologic Drill (ASIG)
- Industrial Liaison for Ice Drilling Program Office since 2014

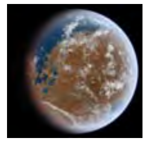


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

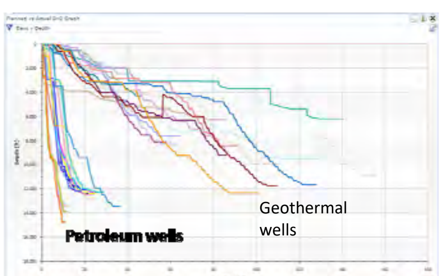
NASA - Jet Propulsion Laboratory

- Planetary/Lunar/Asteroid Drill Systems
- In-situ resource acquisition
  - Drilling state of the art review
  - Power requirements
  - Martian rock mechanics
- Prototype bit testing
- Penetrometer testing under extreme cold
  - At the National Ice Core Laboratory
- Minimum mass flowrate determination
- Autonomous drilling operations



DOE - Petroleum Practices Technology Transfer

- In cooperation with the National Renewable Energy Laboratory – reviewing geothermal drilling operations analysis in light of oil and gas drilling efficiency gains

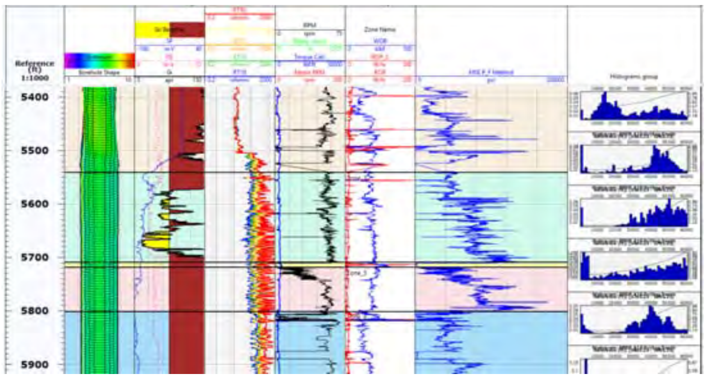


Days versus Depth

- Determined six primary areas for opportunity to improve geothermal economics:
  - Lost circulation
  - Rig and equipment selection
  - Rate-of-penetration (ROP)
  - Efficient and consistent drilling program
  - Effective time management
  - Cementing

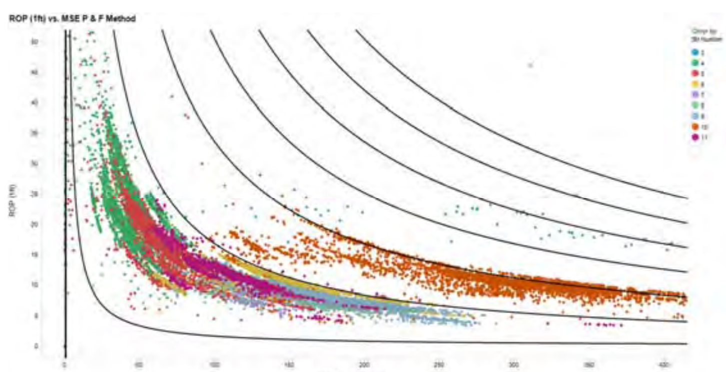
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Detailed Drilling Operations Analysis



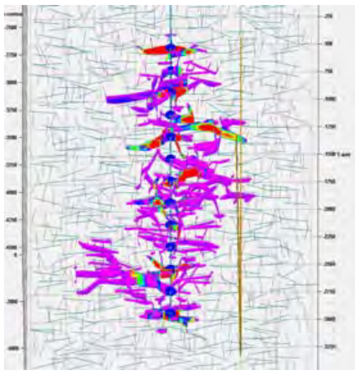
Used real time drilling operational data for efficiency analysis

Detailed Drilling ROP vs MSE Analysis

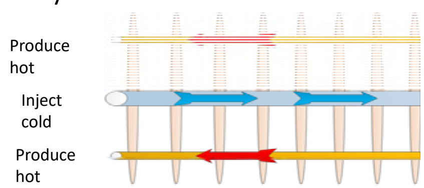


Drilling power output for a given bit and formation. The orange bit (1) is a PDC, the others are tricones.

DOE - Horizontal Geothermal Completions



- In cooperation with the National Renewable Energy Laboratory – A feasibility analysis of using multiple horizontal wells and stimulation to build an Enhanced Geothermal System

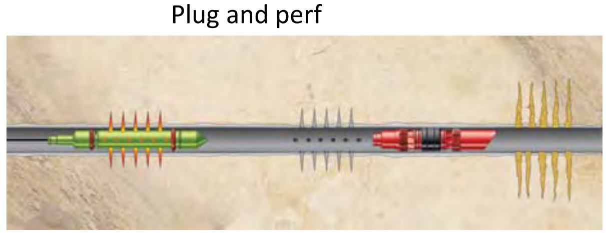


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Proposed Stage Isolation Techniques

These are common procedures for oil and gas wells; but, they are rare for geothermal completions

Plug and perf



Packer and port

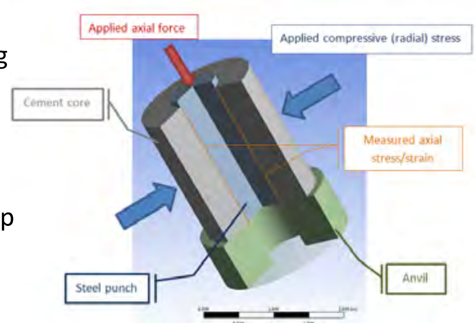
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

NSF - Sustainable Research Network

- Routes to Sustainability for Natural Gas Development and Water and Air Resources in the Rocky Mountain Region
- Two studies were undertaken by CSM PEGN
  - o Wellbore Integrity Modeling for common drilling operations
  - o Probability and Severity of Events for wells in the four active oil and gas Colorado Basins

Wellbore Integrity Modeling

- A finite element study to determine the formation, cement, and steel casing integrity under common drilling operations such as pressure integrity testing.
- Results indicate some slight debonding at the casing shoe; but, no significant debonding up the casing.
- Wellbore integrity is maintained, as long as it was completed correctly!



Well Categories / Piceance Basin Failure Probability

Category	Barriers	Independent Failure Events	Description	Risk Level
1	1	3	Shallow Surface Casing Top of Production Casing Cement Below Over-Pressured Hydrocarbon Reservoir	High
2	1	3	Shallow Surface Casing Top of Production Casing Cement Below Under-Pressured Hydrocarbon Reservoir	
3	2	3	Shallow Surface Casing Top of Production Casing Cement Above Top of Gas	
4	2	3	Shallow Surface Casing Top of Production Casing Cement Above Surface Casing Shoe	
5	3	3	Deep Surface Casing Top of Production Casing Cement Below Under-Pressured Hydrocarbon Reservoir	
6	3	3	Deep Surface Casing Top of Production Casing Cement Above Top of Gas	
7	4	3	Deep Surface Casing Top of Production Casing Cement Above Surface Casing Shoe	

Wells in all basins in Colorado were categorized by construction process. This includes determining the number of well control barriers in place. The categories allowed for the pinpointing of potential issues with specific types of well bore construction processes.

PICEANCE GARFIELD COUNTY WELLS

	ORIGINAL WELL COUNT	CATASTROPHIC BARRIER FAILURES	CATASTROPHIC FAILURE %
CATEGORY 1	0	0	0.00%
CATEGORY 2	48	0	0.00%
CATEGORY 3	145	2	1.38%
CATEGORY 4	589	0	0.00%
CATEGORY 5	1,769	2	0.11%
CATEGORY 6	5,293	4	0.08%
CATEGORY 7	1,862	1	0.05%
CATEGORY 8	80	0	0.00%
CATEGORY 9	90	0	0.00%
CATEGORY 10	0	0	0.00%
CATEGORY 11	105	0	0.00%
CATEGORY 12	1	0	0.00%
TOTAL	10,802	9	0.08%
D&A	196		
TOTAL WELLS	10,998		

The historical probability of catastrophic wellbore failure in the Piceance Basin is 8 out of 10,000 wells.

Raton and San Juan Basin Failure Probability

RATON BASIN WELLS

	ORIGINAL WELL COUNT	CATASTROPHIC BARRIER FAILURES	CATASTROPHIC FAILURE %
CATEGORY 1	0	0	0.00%
CATEGORY 2	23	1	4.35%
CATEGORY 3	4	0	0.00%
CATEGORY 4	65	0	0.00%
CATEGORY 5	399	0	0.00%
CATEGORY 6	52	0	0.00%
CATEGORY 7	2,800	2	0.07%
CATEGORY 8	7	0	0.00%
CATEGORY 9	0	0	0.00%
CATEGORY 10	30	0	0.00%
CATEGORY 11	25	0	0.00%
CATEGORY 12	0	0	0.00%
TOTAL	3,359	3	0.09%
D&A	188		
TOTAL WELLS	3,547		

The historical probability of catastrophic wellbore failure in the Raton Basin is 9 out of 10,000 wells.

SAN JUAN BASIN WELLS

	ORIGINAL WELL COUNT	CATASTROPHIC BARRIER FAILURES	CATASTROPHIC BARRIER FAILURE %
CATEGORY 1	0	0	0.00%
CATEGORY 2	11	1	9.09%
CATEGORY 3	15	0	0.00%
CATEGORY 4	71	0	0.00%
CATEGORY 5	54	1	1.85%
CATEGORY 6	345	0	0.00%
CATEGORY 7	2,577	0	0.00%
CATEGORY 8	64	0	0.00%
CATEGORY 9	17	0	0.00%
CATEGORY 10	148	0	0.00%
CATEGORY 11	427	0	0.00%
CATEGORY 12	0	0	0.00%
TOTAL	3,881	2	0.05%
D&A	305		
TOTAL WELLS	4,186		

The historical probability of catastrophic wellbore failure in the San Juan Basin is 5 out of 10,000 wells.

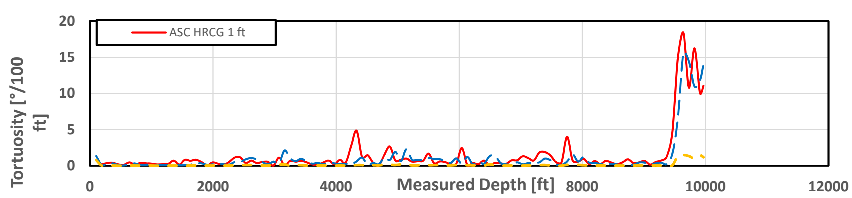
Wattenberg Field Failure Probability

VERTICAL AND DEVIATED WELLS										
	ORIGINAL WELL COUNT	POTENTIAL BARRIER FAILURES	POTENTIAL BARRIER FAILURE %	CATASTROPHIC BARRIER FAILURES	CATASTROPHIC BARRIER FAILURE %	AVG COMPLETION DATE	P&A WELL COUNT	CURRENT WELL COUNT	ORIGINAL AVG SURFACE CASING DEPTH (FT)	ORIGINAL AVG TOP OF PRODUCTION CEMENT (FT)
CATEGORY 1	166	100	60.24%	3	1.81%	1979	57	15	253	7,334
CATEGORY 2	621	219	35.27%	5	0.81%	1983	138	301	306	6,566
CATEGORY 3	46	16	34.78%	1	2.17%	1987	14	31	321	4,008
CATEGORY 4	7	0	0.00%	0	0.00%	1982	1	15	222	125
CATEGORY 5	8,789	77	0.88%	1	0.01%	1995	782	6,140	559	6,111
CATEGORY 6	5,433	6	0.11%	0	0.00%	2007	105	7,181	712	2,816
CATEGORY 7	1,766	0	0.00%	0	0.00%	2009	8	2,040	719	534
TOTAL	**16,828**	**418**	**2.48%**	**10**	**0.06%**		**1,105**	**15,723**		
D&A	**147**									

The historical probability of catastrophic wellbore failure in the Wattenberg Field is 6 out of 10,000 wells.

3D Survey and Torque and Drag Analysis

- Understanding and modeling wellbore tortuosity and rugosity allows us to model wellbore trajectory in three dimensions.
- We have developed an Advanced Spline Model that shows good agreement with high resolution surveys.
- This is input into soft and stiff string axial and torsional frictional models for a more accurate torque and drag output.
- With this, wells can be extended further by mitigating stuck pipe issues.



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Apache Drill

- New Rig
  - o Sandvik DE130 Rig unit
  - o 3" Core rod (drill pipe)
  - o Pump/fluid system
  - o Bits/core bit and wireline retrievable barrel
- Plans include
  - o Integrating rig operations sensors
  - o Mechanization of rig
  - o Adding teleoperations features
  - o Developing automation algorithms and implementation

A Real World Drilling Rig for students to have a first hand experience drilling a real well.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Drilling Simulators

Drilling Systems DS5000

CS Inc DWPS-22UL

New drilling simulators for improved understanding of real world drilling problems and solutions.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

William W. Fleckenstein

Ph.D., P.E. (CA #1666)

- Education
  - 1986 – BS Petroleum Engineering, Colorado School of Mines
  - 1988 – ME Petroleum Engineering, Colorado School of Mines
  - 2000 – Ph.D. Petroleum Engineering, Colorado School of Mines
- Academic Experience
  - PE Interim Department Head – 2012-2014
- Industry Experience
  - Roughneck and Roustabout
  - Operator's Representative – Drilling, Completion and Workovers
  - Engineer – Drilling, Completion, and Workover Design
  - Field Area and Development Engineer
  - Founder – FracOptimal, LLC
  - Intellectual Property consulting
  - Chairman of Board - $1.3 Billion in Asset Credit Union

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Philosophy

My research is devoted to engineering research that solves critical problems, with an emphasis on drilling and completions. My focus is research projects that develop tangible technologies, yield intellectual property, and ultimately, commercial benefits.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Collaborations (International & Domestic)

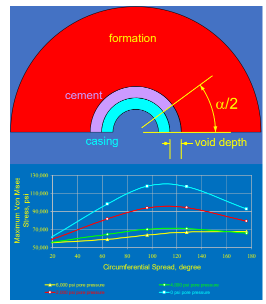
- Led the CSM effort to collaborate with the Kuwait Petroleum Corporation and Booz (PwC) to design a world class research center in Kuwait, including contract negotiations.
  - Facilitated workshops to determine challenges for research objectives
  - Facilitated the design of a research "Roadmap" to address those challenges, including coordinating inter-disciplinary research project design.
- Training programs with REPSOL, Encana, Devon
- Initial Program design with the Halliburton Fellows program
- AirWaterGas National Science Foundation Sustainability Research Network – Co-PI.
- Former Advisory Board Member – Ice Coring

PERFORM

- Production Enhancement Research FORuM
- The emphasis of PERFORM is to address problems with solutions that have a practical application.
- The overriding aim of PERFORM is to develop technology with practical field applications by performing research developed somewhat on the model of biotech university research.
- Not all research will generate useful technology and truly feasible solutions, but all projects will try and some will succeed.

Wellbore Stress Modeling Project Publications

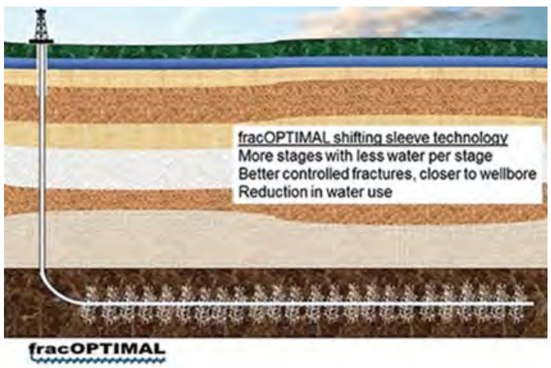
- Fleckenstein, W.W., Eustes, A.W., Rodriguez, W. J., Berger, A., Sanchez, F. J.: “Borehole Stresses in Cemented Wellbores”, Exploration & Production – Volume 10 Issue 2, (October 2012), 27-31
- Fleckenstein, W.W., Eustes, A.W., Rodriguez, W. J., Berger, A., Sanchez, F. J.: “Cemented Casing: The True Stress Picture”, AADE-05-NTCE-14, American Association of Drilling Engineers Annual Conference, Dallas, Texas, April 5-7, 2005
- Berger, A., Fleckenstein, W.W., Eustes, A.W., and Tronhauser, G.: “Effect of Eccentricity, Voids, Cement Channels, and Pore Pressure Decline on Collapse Resistance of Casing,”, SPE 90045, Society of Petroleum Engineers Annual Technical Conference and Exhibit, Houston, Texas, September 26–29, 2004
- Rodriguez, W. J., Fleckenstein, W. W., Eustes, A. W., “Simulation of Collapse Loads on Cemented Casing”, Journal of Petroleum Technology, (August 2004): 59-60
- Rodriguez, W. J., Fleckenstein, W. W., Eustes, A. W., “Simulation of Collapse Loads on Cemented Casing Using Finite Element Analysis”, SPE 84566, Society of Petroleum Engineers Annual Technical Conference and Exhibit, Denver, Colorado, October 5-8, 2003.
- Fleckenstein, W. W., Eustes, A. W., et al., “Burst-Induced Stresses in Cemented Wellbores.” SPE Drilling & Completion (June 2001): 74-80.

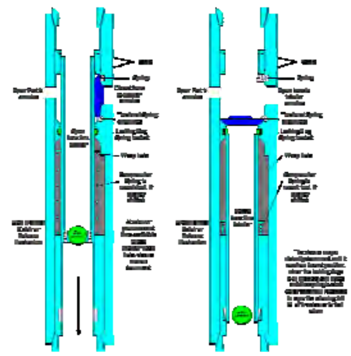


Intellectual Property Development

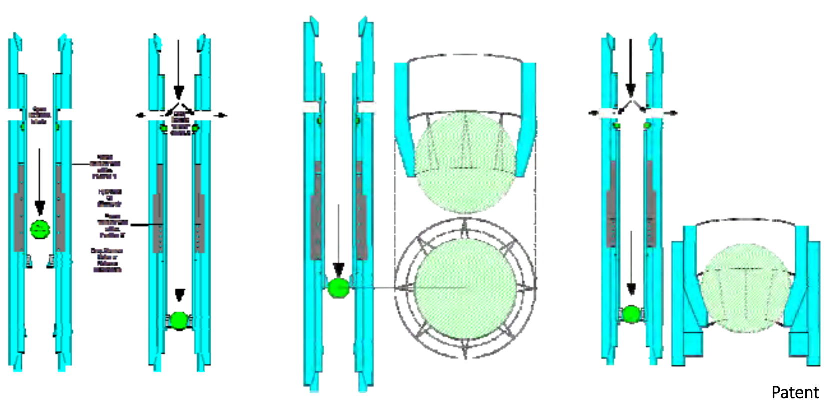
- Patents
  - o Downhole Tools and Methods for Selectively Accessing a Tubular Annulus of a Wellbore (US 8,991,502 B2) – Basis of Startup “FracOPTIMAL” – sold development option to major service company.
- Pending Patent Applications
  - o Method and Apparatus for Accessing a Tubular Annulus of a Wellbore
  - o Method and Apparatus for Testing a Tubular Annular Seal
  - o Method and Apparatus for to Rotate Subsurface Wellbore Casing

CSM Start Up - fracOPTIMAL





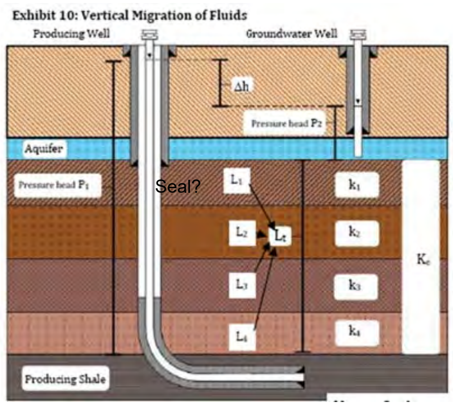
FracOPTIMAL2



Patent Pending

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Annular Casing Seal Test Apparatus and Method

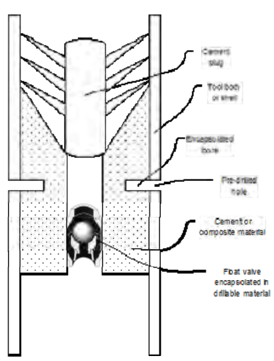


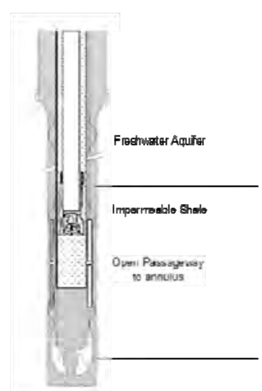
- The invention provides an apparatus and method to test the annular seal of a casing string positioned within a wellbore.
- The cement seal between a surface casing string and a wellbore is tested to assure there is no contamination of groundwater.

Patent Pending

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Annular Casing Seal Test Apparatus and Method



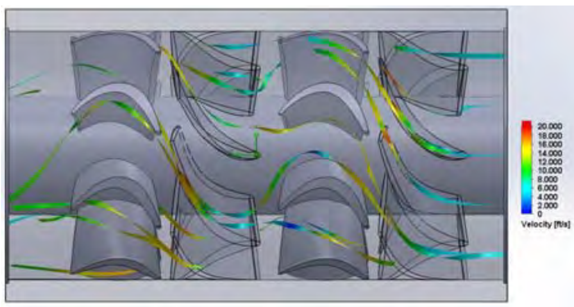


Patent Pending

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

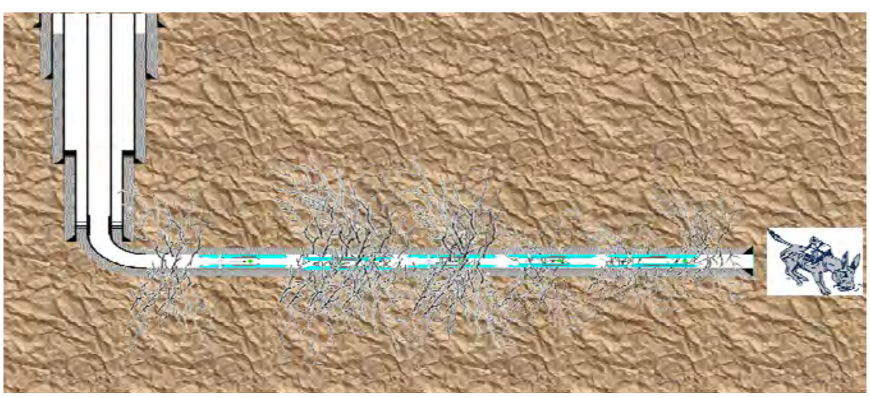
Method and Apparatus to Rotate Subsurface Casing

- Embodiments of the present invention are generally related to a method and apparatus for subterranean wellbores, and in particular, to a method and apparatus for rotating a subsurface tubular string, such as a casing section, without rotation at the surface.



Patent Pending

FracOPTIMAL2 Refrac System



Dr. Ramona M. Graves

Dean

College of Earth Resource Sciences and Engineering

&

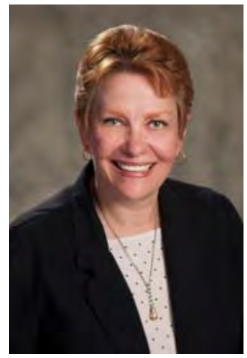
Petroleum Engineering Professor

rgraves@mines.edu

Colorado School of Mines

Petroleum Engineering Department

Golden, Colorado 80401 USA



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

College of Earth Resource Sciences and Engineering

CERSE is a unique College that combines earth science, engineering, economics, business, and social science.

Economic and Business

Geology and Geological Engineering

Geophysics

Liberal Arts and International Studies

Mining Engineering

Petroleum Engineering

The Colorado Geological Survey

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

My Philosophy

In order for us to stay a top quality program

…we must keep faculty - they are committed to both research and teaching.

… we have to have quality graduate students.

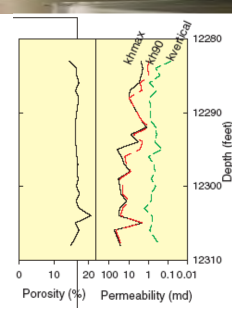
… we must create an integrated graduate environment of scholarship, professionalism, and become a graduate "community".

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Interest – Reservoir Characterization

Illite

ROCKS



Kaolinite

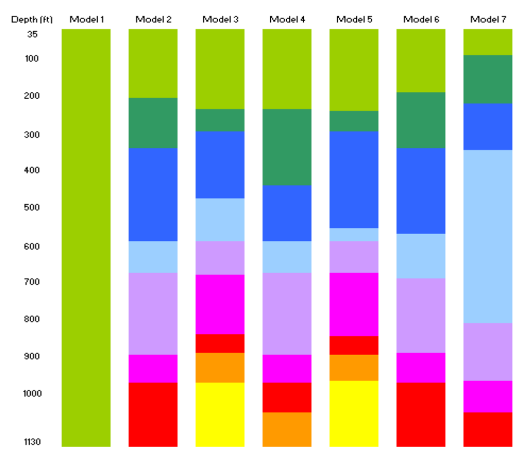
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Example (1) Research Projects

SENSITIVITY STUDY OF FLOW UNIT DEFINITION
BY USE OF RESERVOIR SIMULATION
by
Anne-Kristine Stolz

SPE 84277

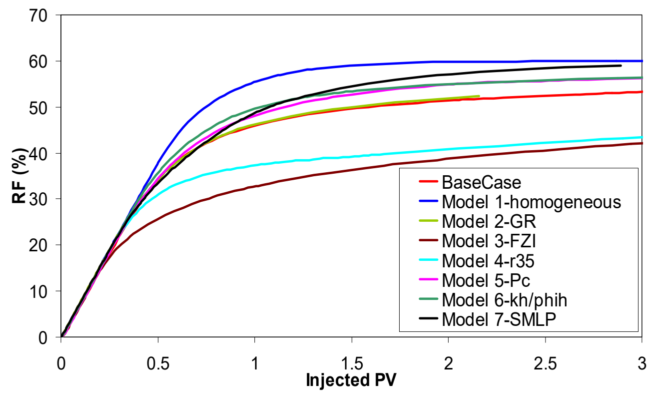
Example Flow Units



Model 1- *homogeneous*
Model 2- *GR*
Model 3-*FZI*
Model 4-*r35*
Model 5-*Pc*
Model 6-*kh/ϕh*
Model 7-*SMLP*

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Results



Recovery Factor versus Injected Pore Volume

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Conclusions

- Numerical simulation is important to confirm the flow unit assignment of a reservoir, in order to avoid inaccurate prediction of flow performance.
- Results of the numerical simulation are a strong function of geologic model→ flow unit definition method.
- Best correlation for a reservoir has to be established individually, based on data available.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Example (2) Research Projects

DETERMINING THE BENEFITS OF
APPLYING *"STARWARS "* LASER TECHNOLOGY
FOR DRILLING AND COMPLETING
OIL AND GAS WELLS

Special thanks to former students
Darien O'Brien, Samih Batarsh, Bailo Suliman, Zane Gordon, Kristina Loop

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

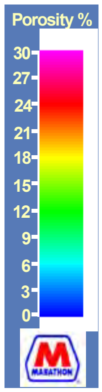
Quote

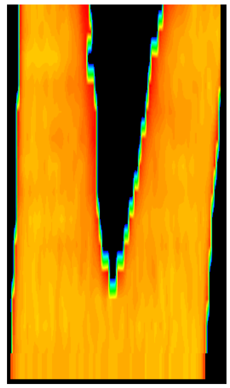
"Drill for oil? You mean drill into the ground to try and find oil? You're crazy."

-- said to Col. Drake when he tried to enlist support for his project to drill for oil in 1859.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Berea Sandstone CT Scan





Sample ID: OBG3
Duration: 5.2 seconds
Power: 6.2 kilowatts
Continuous Beam
Orientation: Horizontal
Penetration: 1.6 inches
COIL Laser

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Example (3) Research Projects

Porosity and Permeability Changes in Lased Rocks Calculated Using Fractal Fragmentation Theory

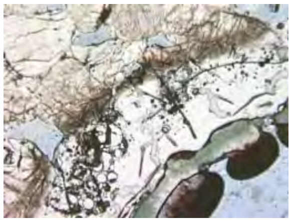
by
Bailo Suliman

CIPC 2004
Calgary, Canada

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

What is a Fractal?

- Originates from the Latin word *factus* which means to break
- Collection of examples linked by a common point of view
- Method for describing the inherent irregularity of natural objects
- Fractal Theory applies to artificially fragmented rock
- Fractal dimension is a relative measure of complexity (the greater the number, the more complex structure)



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Fractal Permeability Model

(Flow Equations)

Hagen-Poiseuille equation for flow rate though one straight capillary of diameter D:

$$q = \frac{\pi * D^4 * \Delta P}{128 * L_t * \mu}$$

Darcy's equation for flow rate though a tortuous path:

$$q = \frac{k * A * \Delta P}{L_t * \mu}$$

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Fractal Permeability Model
(Combined Equation)

Permeability equation in porous medium:

$$k = \frac{\mu L_0 Q}{\Delta PA} = \frac{\pi * L_0^{1-D_T} * D_P}{128 * A * (3 + D_T - D_P)} * D_{max}^{3+D_T}$$

Where: D_p = Pore size fractal dimension
D_{max} = Maximum capillary diameter
L_T = tortuous length
L_o = straight length
D = diameter of average capillary
D_T = tortuosity fractal dimension

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Overview

- **Multidisciplinary Reservoir Characterization**
- **Laser/Rock Interaction**
- **Energy and Energy Engineering**

In general, any topic which helps us better understand reservoirs!

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Hossein Kazemi

Professor, Chesebro' Distinguished Chair in Petroleum Engineering

- Education
  - PhD University of Texas-Austin, 1963
  - BS University of Texas-Austin, 1961
- Professional Experience & Affiliations
  - Colorado School of Mines, 1981
  - Marathon Oil Technology Center, 1969
  - Sinclair Research, 1963
  - Society of Petroleum Engineers, 1959
  - National Academy of Engineering
  - SPE Honorary and Distinguished Member
  - Co-Director, Marathon Center of Excellence for Reservoir Studies (MCERS)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus

- **Research Summary/Overview**

  Pore-scale Physics, mathematical modeling, fractured reservoir engineering, and enhanced oil recovery in conventional and unconventional reservoirs

- **Research Philosophy**

  Greater appreciation for the use of science and engineering fundamentals in solving engineering problems

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Marathon Center of Excellence for Reservoir Studies

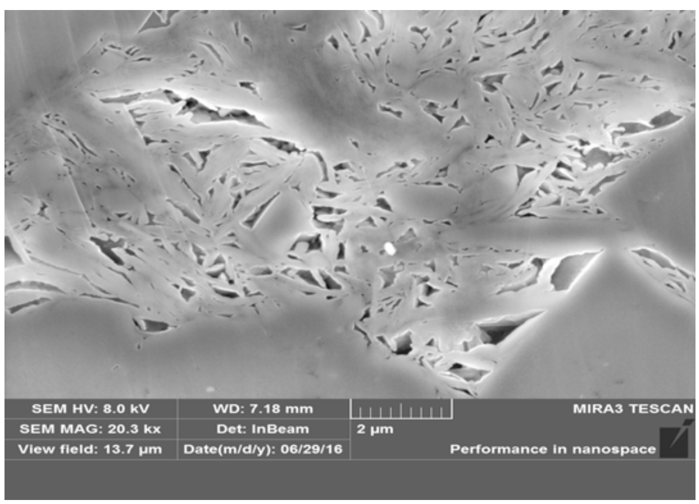
- Promotes excellence in application of science and engineering to reservoir problems.
- The center has produced around $17,000,000 for research ever since its establishment in 2004 with initial funding from Marathon Oil Corporation.
- Professors Ozkan (Co-Director), Chu, Yin and Zerpa are also associated with the center.
- Recent graduates include Najeeb Alharthy (Gas injection EOR in shale reservoirs), Perapon Fakcharoenphol (Geomechanics and low-salinity imbibition), Ali Al-Sumaiti (Double-displacement EOR in fractured reservoirs) and Basak Kurtoglu (Reservoir characterization and EOR in Bakken).

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Pore Scale Physics

FE-SEM Image of Angular Pores in a Middle Bakken Core

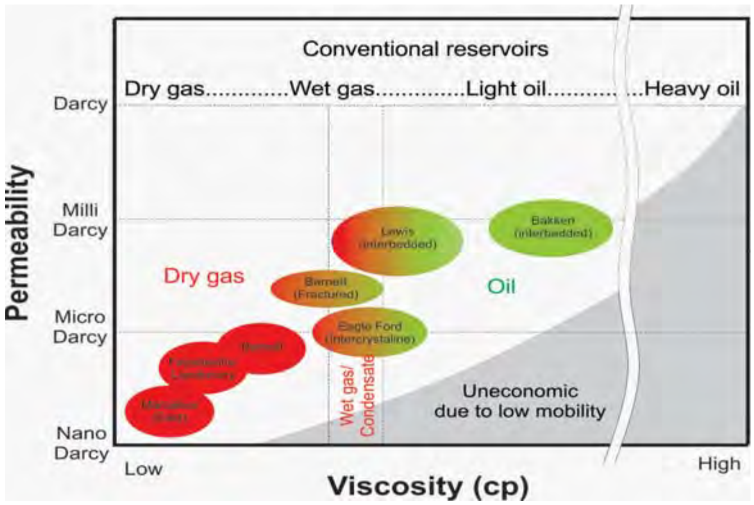
(Somayeh Karimi, SPE 185095, 2017)



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Unconventional Reservoirs

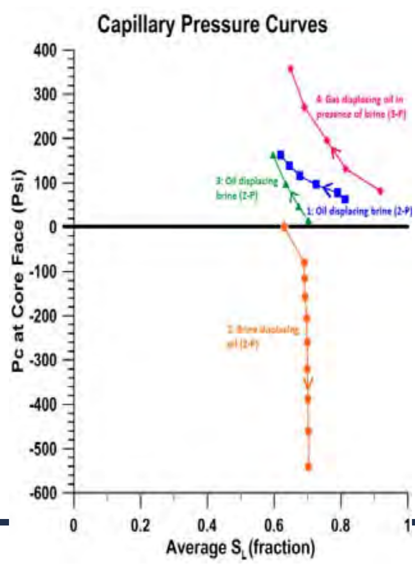
(modified from Bohacs et al., 2013)



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Centrifuge Measurement in a Bakken Core

(Somayeh Karimi, CSM, 2015)



Mobile saturation window to WF
~ 10 %

Mobile saturation window to GF
~ 30 %

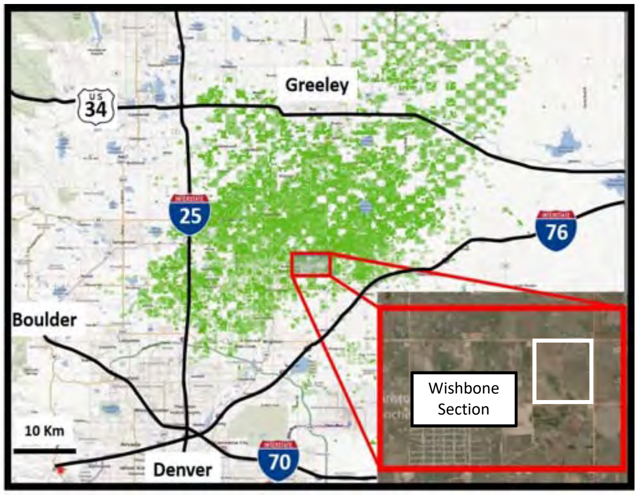
Residual oil saturation to water
~ 29.7%

Irreducible water saturation
~ 62%

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Unconventional Production in DJ Basin

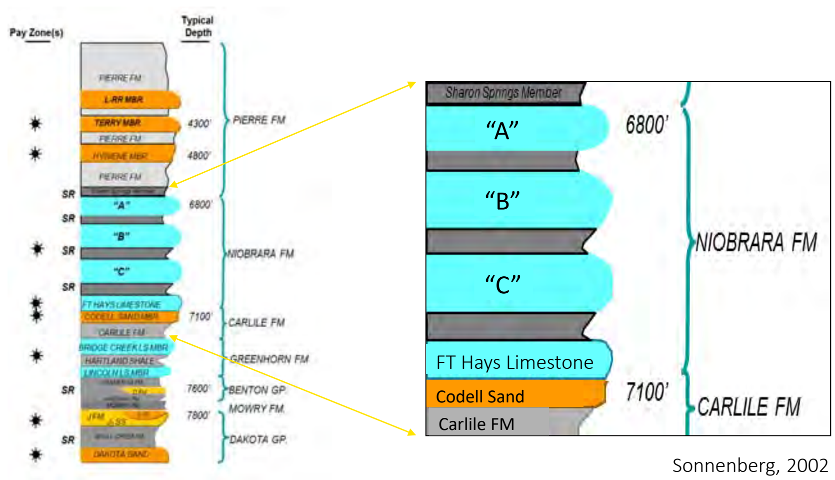
Yanrui Ning, RCP, 2016



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Stratigraphic Column - DJ Basin

Yanrui Ning, RCP, 2016

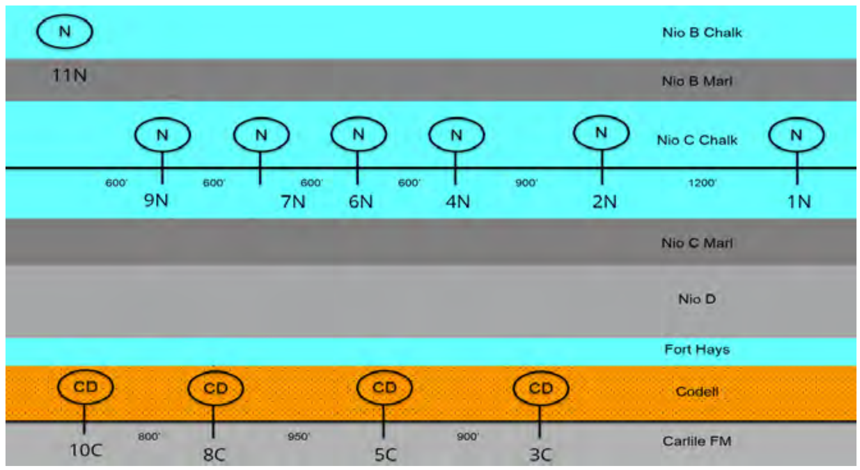


Sonnenberg, 2002

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Eleven Horizontal Wells in Wishbone

Yanrui Ning, RCP, 2016

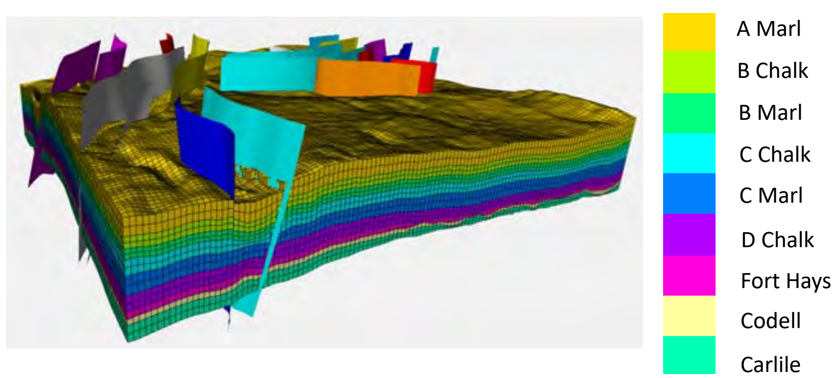


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Geo-cellular Model of a DJ Basin Reservoir

Yanrui Ning, RCP, 2016

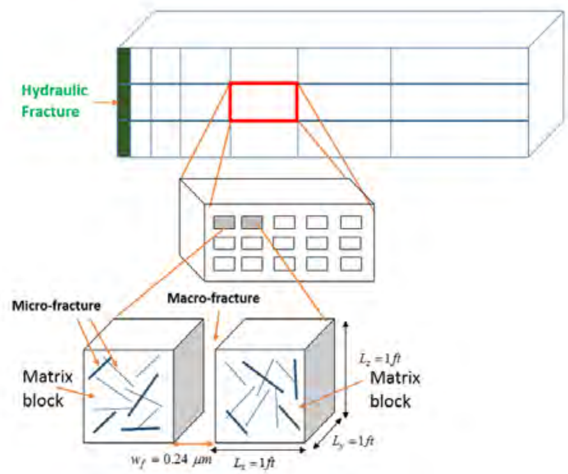
- 4 square miles
- 19 faults



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Flow and Rock Deformation in NFR

Erdinc Eker, RCP, 2016



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Modeling Flow and Rock Deformation in NFR

Erdinc Eker, RCP, 2016

$$\nabla \cdot \left[\frac{k_{f,eff}}{\mu} \left(\nabla p_f - \gamma_{fl} \nabla D \right) \right] - \tau + \hat{q} = \frac{1}{M_f} \frac{\partial p_f}{\partial t} - \frac{\partial \varepsilon_v}{\partial t}$$

Porosity Update

$$\phi_f = \phi_{f,sim} = \left[\phi_f^{init} + \left(e^{-\alpha_f \varepsilon_v} - 1 \right) \right]$$

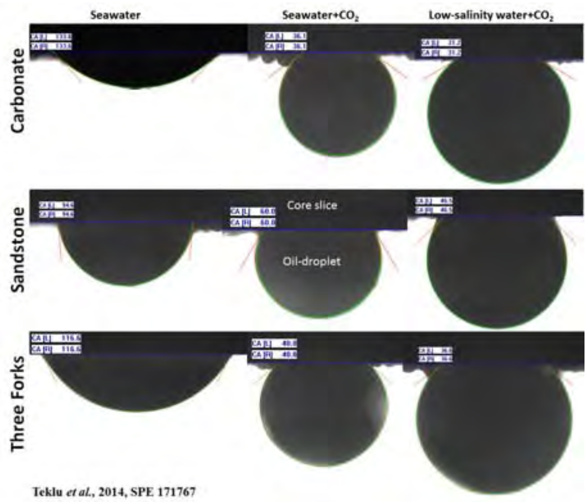
$$\phi_f = \phi_{f,true} = 1 - \left(1 - \phi_f^{init} \right) e^{\alpha_f \varepsilon_v}$$

Permeability Update

$$\frac{k_{f,eff}}{k_{f,eff}^{init}} = \left(\frac{\phi_{f,true}}{\phi_f^{init}} \right)^3$$

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

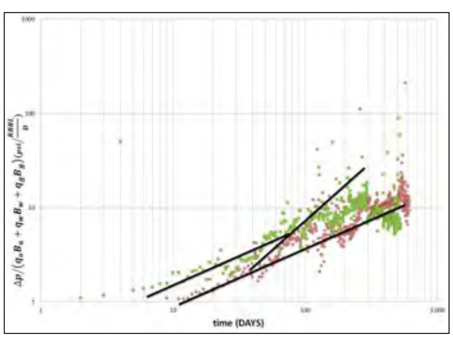
Wettability and Contact Angle Modification for EOR (Teklu et al., 2014, SPE 171767)

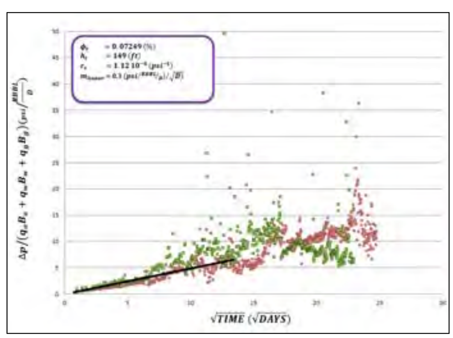


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Multiphase Rate Transient Analysis

Eagle Ford (Ilkay Eker, 2015, CSM)

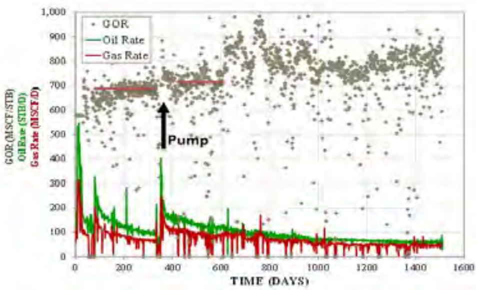


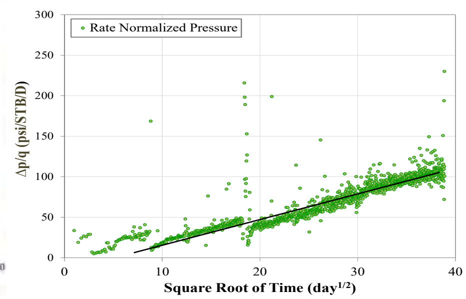


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Multiphase Rate Transient Analysis

Bakken in Bailey Field (Ilkay Eker, 2015, CSM)

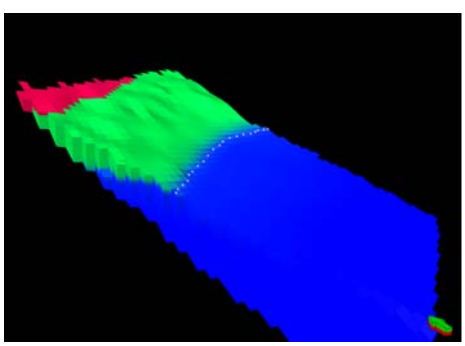


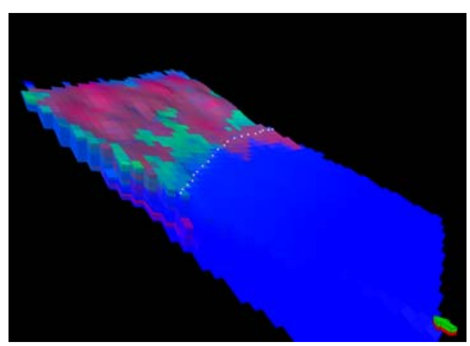


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

DELHI FIELD CONTINUOUS CO_2EOR

Tingting Chen, PhD candidate in Civil and Environmental Engineering, Collaborative Research, Reservoir Characterization Project (RCP), Geophysics





Initial field fluid saturations | **2015 CO2 saturation**

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Jennifer L. Miskimins, P.E.

Associate Professor/Assistant Department Head

- Education
  - B.S. Petroleum Engineering, Montana College of Mineral Science & Technology
  - M.S. Petroleum Engineering, Colorado School of Mines
  - Ph.D. Petroleum Engineering, Colorado School of Mines
- Academic experience
  - Colorado School of Mines, 2002 – Current
- Industry experience
  - Marathon Oil Company, 1990 – 1998
  - Barree & Associates, 2013 – 2016

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Jennifer L. Miskimins, P.E.

Associate Professor/Assistant Department Head

- Professional activities and service
  - Registered Professional Engineer (CO #36193)
  - Member SPE, AAPG, RMAG
  - Member of 2017 SPE Hydraulic Fracturing Technology Conference Committee and 2017 UrTEC Conference Committee
  - Two-time SPE Distinguished Lecturer 2010-2011 and 2013-2014
  - Awarded the 2014 SPE International Completions Optimization and Technology Award
  - Currently serving on the SPE International Board of Directors as the Technical Director for Completions

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus

- My research focuses on stimulation and completions, specifically in unconventional reservoirs. The efficiency of the completions in these reservoir systems is of prime interest. How do the completions interact with the reservoir? How do they impact production? How can they be improved to maximize NPV and recovery?
- In addition to completions/stimulation, I am interested in multidisciplinary integration both from a research and a teaching standpoint.

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus

- Proppant transport in complex fracture systems
- Proppant transport in horizontal wellbores
- DAS/DTS data integration with stimulation
- Water hammer stage signatures
- HPHT non-Darcy flow in proppants
- Conductivity degradation
- Stage spacing optimization/stress-shadowing impacts
- Multistage horizontal well fracture initiation efficiency
- Re-fracturing

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

FAST Consortium

- Director of the Fracturing, Acidizing, Stimulation Technology (*FAST*) Consortium
- Joint industry-academia research consortium started in 2004
- Mission
  - o Perform *practical* research in the area of oil and gas well stimulation with an emphasis on:
    - Direct application
    - Timely application
    - Production improvement
  - o Provide an opportunity for graduate students to work on industry-sponsored projects

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

FAST Consortium

- 40 students involved/graduated
  - o 12 Ph.D.
  - o 18 M.S.
  - o 3 M.E.
  - o 7 B.S.
- +40 industry publications
- http://petroleum.mines.edu/research/fast/index.html

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

CEMMC

- Co-Director of the Center for Earth Materials, Mechanics and Characterization
- Fosters research in both “hard rock” and “soft rock” applications
- Encourages interdisciplinary communications between the associated disciplines
- Participating departments include Petroleum Engineering, Geophysical Engineering, Geology and Geological Engineering, Physics, and the Department of Math and Computer Sciences.
- http://petroleum.mines.edu/research/cemmc/

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Dr. Erdal Ozkan
Department Head of Petroleum Engineering
Director, UREPP; Co-Director, MCERS

- **Education**
  - o PhD, Petroleum Engineering, University of Tulsa (1988)
  - o MS, Petroleum Engineering, Istanbul Technical University (1982)
  - o BS, Petroleum Engineering, Istanbul Technical University (1980)
- **Professional Experience**
  - o Department Head of Petroleum Engineering (since 2015)
  - o Faculty at CSM (since 1998)
  - o Director, Unconventional Reservoir Engineering Project (UREP) (since 2012)
  - o Co-Director, Marathon Center of Excellence for Reservoir (MCERS) (since 2005)
- **Affiliations & Awards**
  - o SPE
    - —Recipient of the SPE Lester C. Uren (2013) and Formation Evaluation (2007) Awards.
    - —SPE Distinguished Lecturer on shale-gas reservoirs in 2011 - 2012
  - o ASME
  - o SIAM

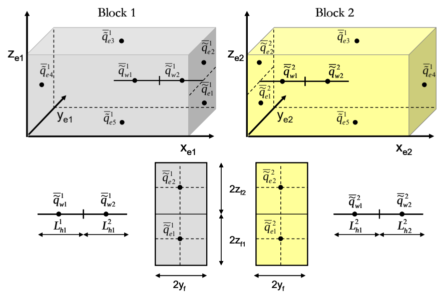
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Interests

- o Modeling Unsteady Flow in Porous Media,
- o Unconventional Reservoirs
- o Pressure- and Rate-Transient Analysis,
- o Horizontal Well Technology

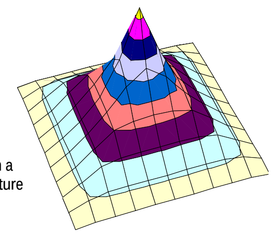
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Modeling Unsteady Flow in Porous Media

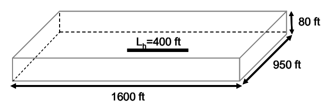


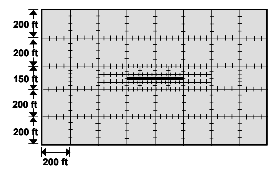
Semi-analytical simulation

Pressure profile in a horizontal well fracture

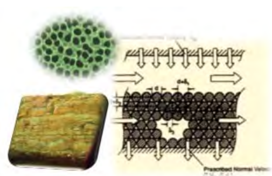


Horizontal well in a heterogeneous reservoir

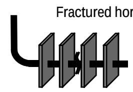


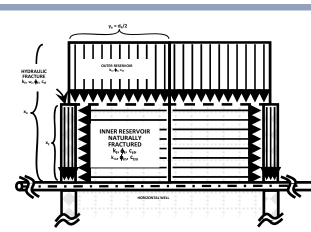


Unconventional Gas and Oil



Fractured horizontal wells





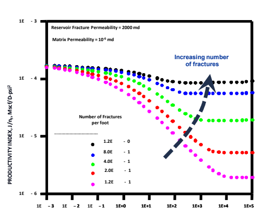
Unconventional flow regimes in shale matrix

- Slip flow
- Microfractures
- Coupling flow at the matrix-fracture interface

Trilinear flow model for fractured horizontal wells in shale

- Multiple hydraulic fractures
- Stimulated reservoir volume

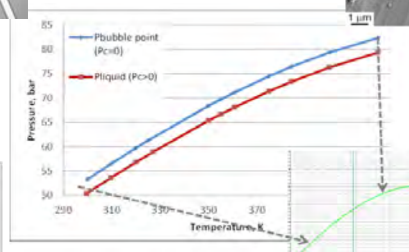
Gas storage in shale

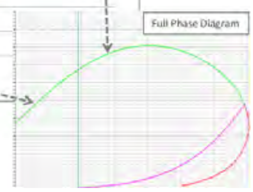


Productivity of fracture horizontal wells in shale

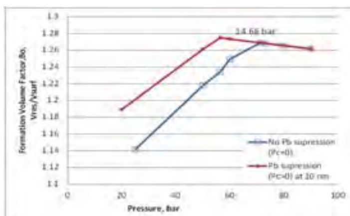
Phase Behavior in Nano-porous Media

Nanofluidics experiments





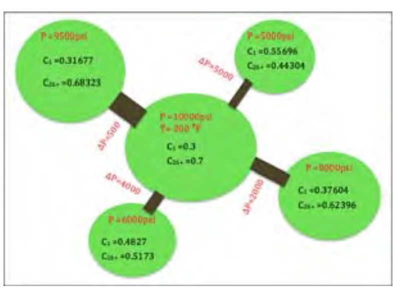
Bubble-point suppression
in confinement



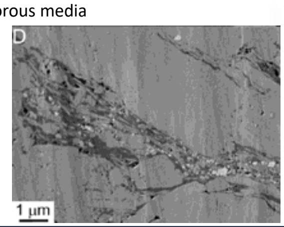
Formation Volume Factor
in tight formation

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

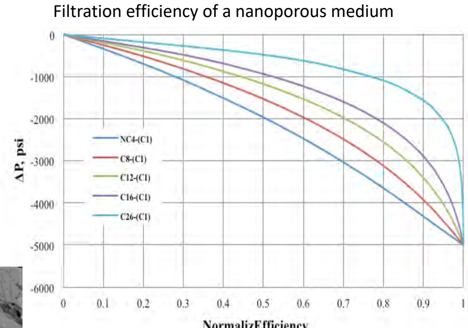
Flow in Nano-porous Media



Filtration in nanoporous media

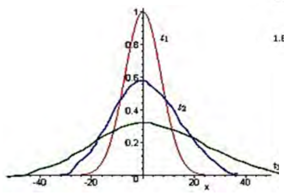


Filtration efficiency of a nanoporous medium

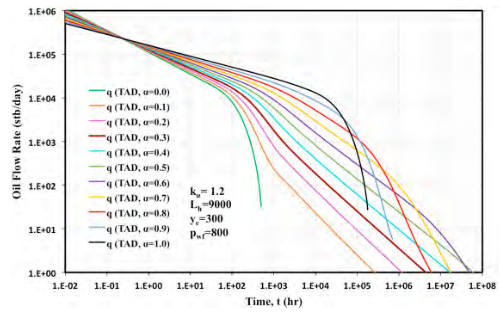


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Anomalous Diffusion in Tight Fractured Media



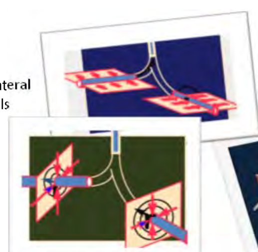
Brownian motion and normal diffusion



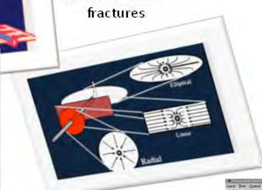
Rate decline under anomalous diffusion

Horizontal, Multilateral, and Fractured Wells Well and Reservoir Performance Prediction

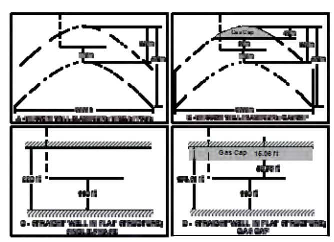
Multilateral wells



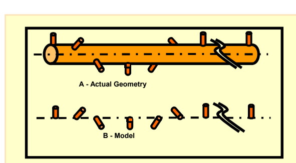
Horizontal-well fractures

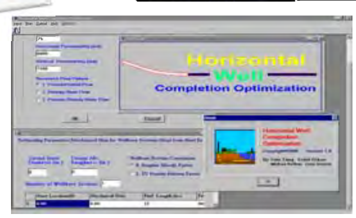


Horizontal wells in anticlines



Perforated horizontal wells

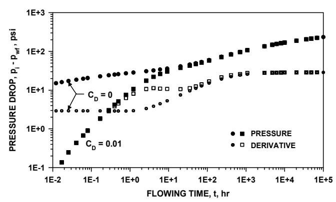




Horizontal-well completion optimization

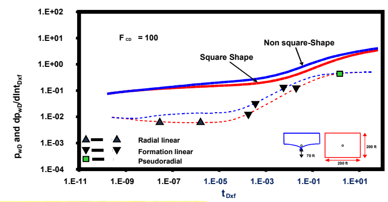
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Pressure-Transient Analysis

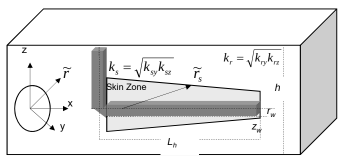


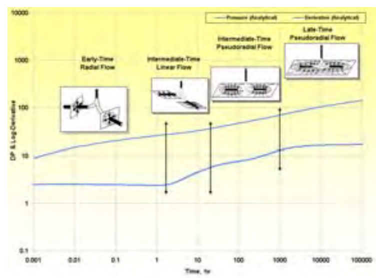
Horizontal-well PTA

Fractured horizontal well PTA



Horizontal-well skin effect





Multilateral-well PTA

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Dr. Azra N. Tutuncu

UNGI

Harry D. Campbell Chair, Professor, Director - UNGI

- Education
  - PhD, Petroleum Engineering, University of Texas
  - MS, Petroleum Engineering, University of Texas
  - MS, Geophysics, Stanford University
  - BS, Geophysical Engineering, Istanbul Technical University
- Professional Experience
  - Research Faculty
    - University of Texas at Austin, Petroleum Engineering Department
    - Stanford University
  - Oil Industry Technical and Leadership Assignments
    - Shell Exploration and Production, Shell International EP
    - Shell Unconventional Resources
  - Colorado School of Mines, Petroleum Engineering Department

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Dr. Azra N. Tutuncu

UNGI

Harry D. Campbell Chair, Professor, Director - UNGI

- Professional Affiliations
  - SEG Research Committee Vice Chair
  - Founder and Faculty Advisor, CSM ARMA Student Chapter
  - Chair, ARMA Induced Seismicity Committee
  - Former President, Exec. Board Member, American Rock Mechanics Association (ARMA)
  - Licensed Professional Engineer and Professional Geoscientist in the state of Texas
  - Associate Editor, Journal of Natural Gas Science and Engineering
  - SPE, SEG, ARMA Editorial Review Committee Member
  - SEG North America Affairs Committee (RAC)
  - AGI Environmental Geoscience Advisory Committee
  - ISRM Underground Research Laboratory Committee US Representative
  - 30 Year Club Member SEG, 30 Year Club Member SPE
  - Member of Pi Epsilon Tau and Sigma Xi Honor Societies

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

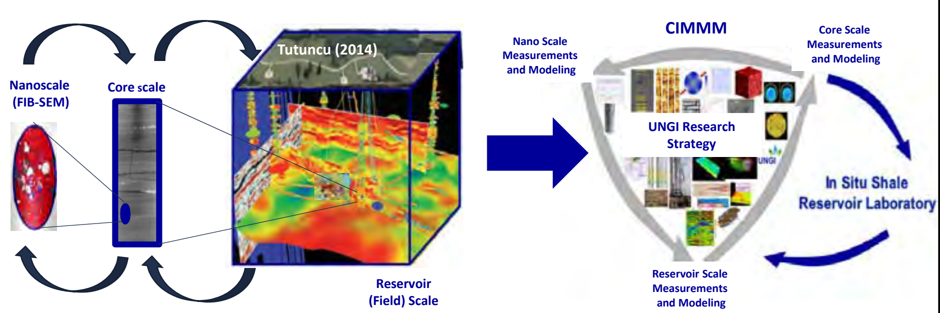
Research Focus

- Coupled Geomechanics, Acoustic, Petrophysics, Fluid Flow Measurements and Modeling
  - Multiscale coupled deformation, failure, wave velocity, complex resistivity, permeability and geochemistry measurements under triaxial/true triaxial in situ stress, elevated pore pressure/temperature states, rock-fluid interactions/fluid compatibility, drilling and fracturing fluid formulation, proppant selection, hydraulic fracturing design and optimization, production efficiency
  - Integrated complex naturally fractured reservoir and hydraulic fracturing model development and case studies utilizing in-house developed and modified commercial simulators coupling rock-fluid interactions and geomechanics into the simulations
- Integrated Real Time Reservoir Characterization, Well and Field Integrity
  - Lifecycle monitoring of deformation, acoustic and flow properties in unconventional resources, deepwater, HPHT and geothermal applications
  - Impacts of hydraulic fracturing, production, CO_2 sequestration, EOR and waste disposal operations on well and seal integrity, compaction, subsidence, sanding, geohazard risk assessment (DTS, DTP, DAS, microseismic,… monitoring integration)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

UNGI Research Strategy and CIMMM Consortia

Coupled Integrated Multiscale Measurements and Modeling



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

UNGI Research and Development

Industry, Academia and Government Collaboration

UNGI

- Research Consortia
  - US Unconventional Resources Consortium (UNGI CIMMM US URC)
  - International Unconventional Resources Consortium (UNGI CIMMM IURC)
  - Geothermal Resources Consortium (UNGI-GRC)
  - Deepwater Well Integrity Project (DWIP)
- Technical Unconventional Training for Professionals (US and International)
- Training for Regulators/Policy Makers and Associated Research
  - TOPCORP Regulator Training (State and Federal Regulators, Industry)
  - UNGI- UGTEP Collaborative Program (International Regulators/Department of State)
  - Induced Seismicity and Environmental Challenges Research
- IOGCC, State Oil and Gas Commissions, USGS, BLM, NETL, EPA, GWPA, SPE, SEG, ARMA partnership in research and training, public engagement

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

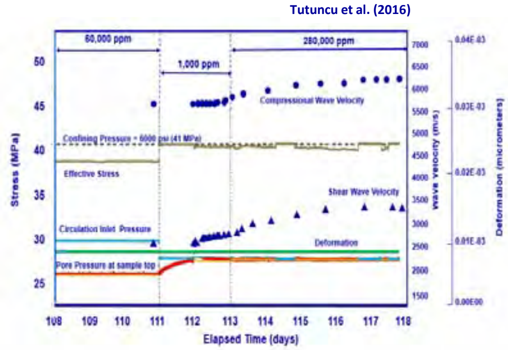
UNGI Experimental Capabilities (I)

UNGI

Pore Pressure Penetration - Coupled Geomechanics and Flow Measurements and Modeling

- Unique coupled experimental assemblies for simultaneous ultrasonic, 100 KHz, permeability, resistivity and deformation measurements for reservoir characterization, drilling/fracturing fluids interactions with the formation and optimization studies
- True triaxial coupled measurements using cylindrical samples (utilizing novel fluid pressure) on loan to UNGI
- Real Time Micro-CT during coupled measurements*
- 400 and 2 MHz NMR measurements

Tutuncu et al. (2016)



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

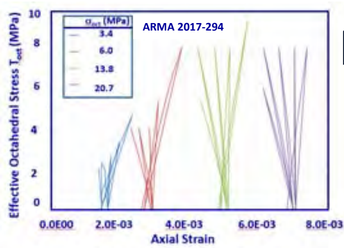
UNGI Experimental Capabilities (II)

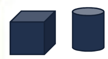
True Triaxial Cell Assembly – Patent Pending
On Loan from Geomechanics Engineering & Research to UNGI

UNGI

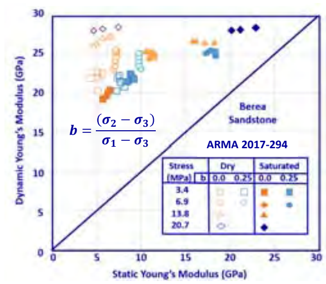
- Novel poly-axial cell using cylindrical and cubic samples (utilizing fluid pressure, not plate driven) with simultaneous ultrasonic, 100 KHz, permeability, resistivity and deformation/failure measurements
- Classical triaxial measurement sample sizes

Baizhanov, Katsuki and Tutuncu et al. (2017)





1”
1.5”
2"



b: relative magnitude of σ_2 in relation to σ_1 and σ_3, < b <1

b = 0 triaxial compression (σ_2=σ_3); b = 1 triaxial extension (σ_2=σ_1)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

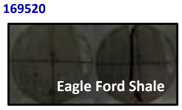
CIMMM US URC

Effect of NF and Calcite-Filling on Failure

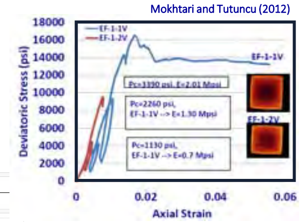
UNGI

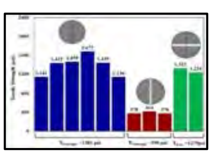
Tensile Strength of Calcite Filled Fractures is almost one third of the matrix

SPE 169520

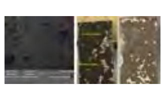


Mokhtari and Tutuncu (2012)

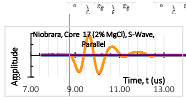


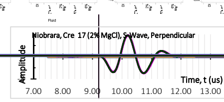


Proppant-fluid interactions and associated geomechanical and geochemical changes

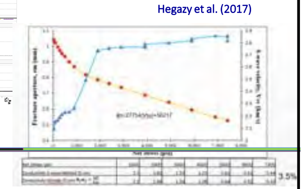


Iriarte et al. (2017)





Hegazy et al. (2017)

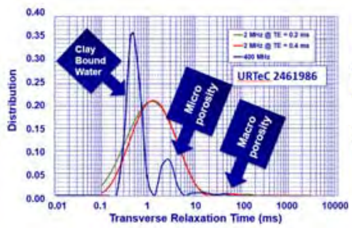


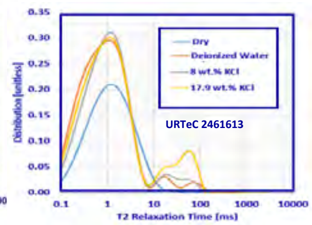
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

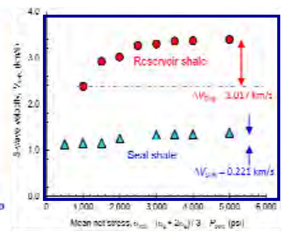
Novel UNGI Experimental Capabilities (III)

NMR Field Strength for Pore Fluid Characterization and Anisotropic Permeability

UNGI







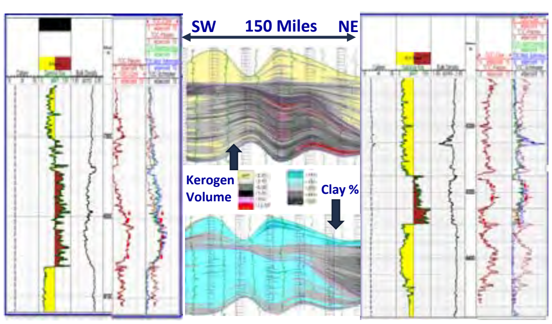
- Low-field NMR (2 MHz) indicates incremental porosity in “larger” pore space
- High-field (400 MHz) NMR provides detailed information in “smaller” pore space
  - Function of salinity
  - Change in capillary pressure
  - Diffusion coefficient

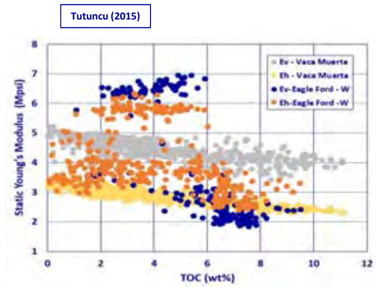
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

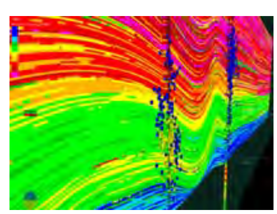
TOC – Logs and Core/Cutting Measurements

Natural and Hydraulic Fracture Effect on Failure and Production

UNGI





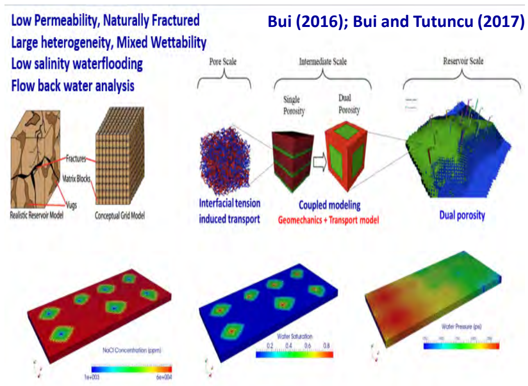


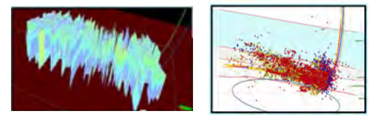
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

CIMMM US URC

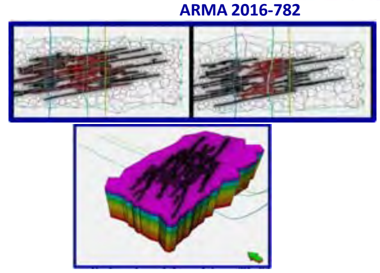
Multi-Scale Coupled Modeling with Rock-Fluid Interactions

Bui (2016); Bui and Tutuncu (2017)





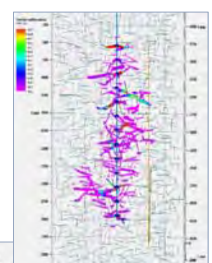
ARMA 2016-782

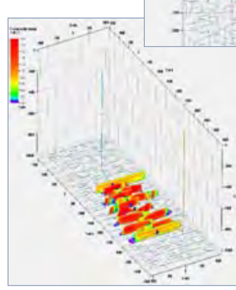


UNGI Geothermal Resources Project

Reservoir and Fracture Characterization for EGS

- Determine full characteristics of the geothermal reservoir (NF) for potential EGS application (sedimentary and/or granitic)
- Sensitivity analysis using key parameters in optimizing EGS design (stress anisotropy, fluid viscosity, pump rate, pump volume, proppant concentration, DFN spacing, orientation,…?)
- Use local oil and gas, water and other offset geothermal well data for geothermal area characterization using statistical analysis of the microseismic, geomechanics, seismic, EM, and log data from field and laboratory
- Conduct numerical analysis for various scenarios of injection and production to determine the injection induced seismicity potential in specific interest areas and resulting substantial environmental risk in the area of interest



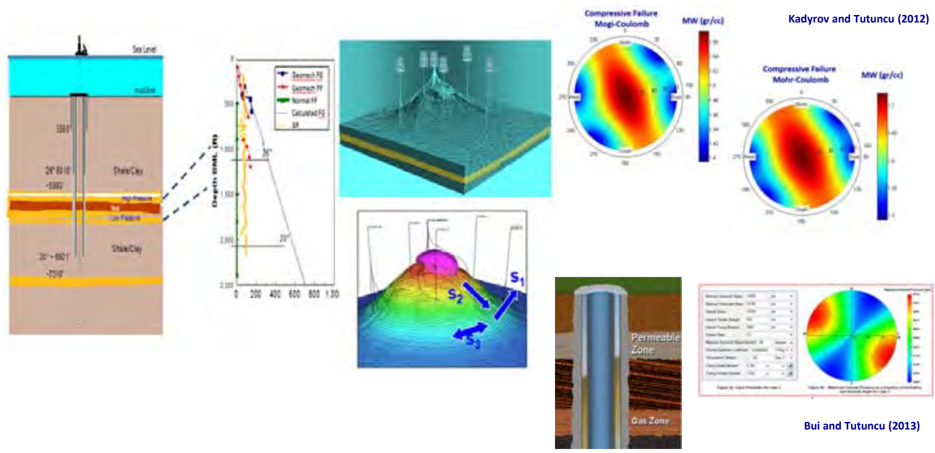


PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Deepwater Well Integrity Project (DWIP)

UNGI

PP/FG Determination, Wellpath Optimization, Fluid Formulation, Cement Integrity



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

UNGI Sponsors and Collaborators

UNGI

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

UNGI Faculty and Staff

(60+ Faculty)

- Hazim Abass
- Donna Anderson
- Brian Asbury
- Linda Battalora
- Tom Bratton
- Robert Benson
- Rosmer Brito
- Binh Bui
- Tzahi Cath
- John Curtis
- Kadri Dagdelen
- Tom Davis
- Elio Dean
- Mansur Ermila
- Alfred W. Eustes
- Linda Figueroa
- William Fleckenstein
- Ramona Graves
- Vaughan Griffith
- Marte Gutierrez
- Wendy Harrison
- Daisuke Katsuki
- Hossein Kazemi
- Carolyn Koh
- Yaoguo Li
- Nigel Middleton
- Ning Lu

Joe Chen, Al Sami, Denise Winn-Bower, Terri Snyder, Debra Marrufo, Rachel McDonald

- **Carrie McClelland**
- Mark Miller
- Jennifer Miskimins
- Paul Morgan
- Junko Munakata-Marr
- Priscilla Nelson
- Ugur Ozbay
- Erdal Ozkan
- Piret Plink-Bjorklund
- John Poate
- Jorge Sampio
- Rick Sarg
- Paul Sava
- Kathleen Smits
- Steve Sonnenberg
- Ali Tura
- Azra Nur Tutuncu
- Whitney Trainor-Guitton
- Ilya Tsvankin
- Craig van Kirk
- Robert Weimer
- Michael Wells
- Yu-Shu Wu
- David Wu
- Yuan Yang
- Xiaolong Yin
- Terry Young
- Lesli Wood
- Luis Zerpa

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

UNGI Recent Alumni

(2015-2016)

- Binh Bui, PhD, Spring 2016, A Multi-physics Model for Enhanced Oil Recovery in Liquid-rich Unconventional Reservoirs (Tutuncu)
- Anton Deben Padin, Spring 2016, PhD, Experimental and Theoretical Study of Water and Solute Transport Mechanisms in Organic-Rich Carbonate Mudrocks (Tutuncu)
- Jingmei Huang, MS, Spring 2016, Pore-scale Simulation of Multiphase Flows Using Lattice Boltzmann Method: Developments And Applications (Yin)
- Nishant Kamath, PhD, Spring 2016, Full Waveform-Inversion in 2D VTI Media (Tsvankin)
- Andrew J. Rixon, MS, Spring 2016, Real Time Triaxial Resistivity and Pore Pressure Penetration Measurements for Measuring Saturation and Electrical Property Alterations Under Stress (Tutuncu)
- Sebastian Ramiro Ramirez, MS, Spring 2016, Petrographic and Petrophysical Characterization of Eagle Ford Shale in La Salle and Gonzales Counties, Gulf Coast Region, Texas (Sonnenberg)
- Benjamin Zeidman, Summer 2016, PhD, Monte Carlo Simulations of Phase Distribution in Porous Materials (D. Wu)
- Aidil Adham, MS, Summer 2016, Geomechanics Model for Wellbore Stability Analyses in Field "X" North Sumatra Basin (Tutuncu)
- Ali Albinali, PhD, Summer 2016, Anomalous Diffusion Analytical Solution for Fractured Nano-Porous Reservoirs (Ozkan)
- Xiexiaomeng (Jack) Hu, MS, Summer 2016, A Coupled Geomechanics and Flow Modeling Study for Multistage Hydraulic Fracturing of Horizontal Wells in Enhanced Geothermal Systems Applications (Tutuncu)
- Theerapat Suppachoknirun, Summer 2016, MS, Evaluation of Multi-Stage Hydraulic Fracturing Techniques Using Unconventional Fracture Model for Production Optimization in Naturally Fractured Reservoirs (Tutuncu)
- Bekdar Baizhanov, MS, Fall 2016, An Experimental Study of True-Triaxial Stress Induced Deformation and Permeability Anisotropy (Tutuncu)
- Najeeb Alharthy, Spring 2015, PhD, Compositional Modeling of Multiphase Flow and Enhanced Oil Recovery Prospects in Liquid-Rich Unconventional Reservoirs (Kazemi)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

UNGI Recent Alumni

(2014-2015)

- Jennifer Curnow, Spring 2015, MS, Coupled Geomechanics and Fluid Flow Model for Production Optimization in Naturally Fractured Shale Reservoirs (Tutuncu)
- Andrew Dietrich, Spring 2015, MS, The Impact of Organic Matter on Geomechanics and Anisotropy in the Vaca Muerta Shale (Tutuncu)
- Mehdi Mokhtari, Spring 2015, PhD, Characterization of Anisotropy in Organic-Rich Shales: Shear and Tensile Failures, Wave Velocity and Permeability (Tutuncu)
- Tan Ngo, Spring 2015, MS, Shale Gas Reservoir Estimates Based on Experimental Adsorption Data (Pini – Graves)
- Tadesse Teklu, Spring 2015, PhD, Experimental and Numerical Study of Carbon Dioxide Injection Enhanced Oil Recovery in Low-Permeability Reservoirs (Graves and Al-Sumati)
- Abdelraof Almulhim, MS, Spring 2014, Fluid Flow Modeling in Multi-Stage Hydraulic Fracturing Patterns for Production Optimization in Shale Reservoirs (Tutuncu)
- Luke Frash, PhD, December 2014, Laboratory Investigation of Hydraulic Fracture Stimulation in Anisotropic Porous Media (Gutierrez)
- John Calvin Hood, MS, Fall 2014, Acoustic monitoring of hydraulic stimulation in granites (Gutierrez)
- Alex Gibson, MS, Spring 2014, Paleoenvironmental analysis and reservoir characterization of the Late Cretaceous Eagle Ford Formation in Frio County, Texas USA (Sonnenberg)
- Talgat Kosset, MS, Spring 2014, Wellbore Integrity Analysis for Wellpath Optimization and Drilling Risks Reduction: The Vaca Muerta Formation, The Neuquen Basin (Tutuncu)
- Chris McCullagh, MS, Spring 2014, Application of Distributed Temperature Sensing (DTS) in Hydraulic Fracture Stimulation (Tutuncu)
- Lei Wang, PhD, December 2014, Simulation of Slip Flow & Phase Change in Nanopores (Yin)
- Maxwell Willis, MS, Spring 2014, Upscaling Anisotropic Geomechanical Properties Using Backus Averaging and Petrophysical Clusters in the Vaca Muerta Formation (Tutuncu)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Yu-Shu Wu

Professor

- **Education**
  - PhD, Reservoir Engineering, U. of California at Berkeley
  - MS, Reservoir Engineering, U. of California at Berkeley
  - MS, Petroleum Engineering, Southwest Petroleum U.
  - BS (Eqv.), Petroleum Engineering, Northeast Petroleum U.
- **Professional Experience & Affiliations**
  - Professor, Petroleum Engineering, Colorado School of Mines (2008-current)
  - Staff geological scientist, Lawrence Berkeley National Laboratory, Berkeley, CA, 1995-2008
  - Hydrogeologist, HydroGeoLogic, Inc., Herndon, VA,1990-1995
  - Petroleum Engineer, Research Inst. of Petroleum Exploration and Development (RIPED), Beijing, China, 1982-1985

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Research Focus and Interest

- Unconventional reservoir flow dynamics and simulation
- CO_2-EOR and geosequestration
- IOR/EOR approaches in low-permeability petroleum reservoirs
- Simulation of coupled thermal-hydrological-mechanical-chemical (THMC) processes in reservoirs
- Fractured reservoir modeling studies
- Geothermal reservoir simulation and enhanced geothermal systems (EGS)
- Coupled process models for hydraulic fracturing and oil/gas production
- Hydraulic and rock fracturing simulation

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

EMG Research Team

FOUNDATION CMG

EMG's Mission: Develop state-of-the-art reservoir modeling technology and advanced simulation tools for research, teaching, and field application in the area of subsurface energy and natural resources, and environmental science and engineering.

Research Projects:

- Unconventional gas and oil reservoir simulation (funded by US DOE, Sinopec, UNGI, and CNPC-USA)
- Optimization of hydraulic fracture design/operation and tight gas production (funded by CNPC-USA)
- CO2 geosequestration (funded by US DOE) and CO2 EOR (funded by PetroChina)
- Geothermal reservoir (EGS) modeling (funded by US DOE)
- Capillary pressure and non-Darcy flow in shales (funded by Halliburton)
- Optimization of multi-staged hydraulic fracturing and gas production (funded by CNPC-USA)
- Cryogenic fracturing technology (funded by US DOE/RPSEA)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Reservoir Simulators Developed at EMG

- Shale gas reservoir simulator: **SUNGAS**
- Tight oil reservoir simulator: **MSFLOW_COMP**
- CO2 geosequestration: **TOUGH2_CSM**
- Geothermal reservoir (EGS) simulators: **TOUGH2_EGS, CSM_EGS**
- Fracturing model and software: **CSMFrac**

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Impacting Research Outcome

- **Development of conceptual and mathematic models as well as numerical approaches for fully-coupled geomechanics-reservoir flow processes (**e.g., THMC, etc.**)**
- **Enhancement of fractured reservoir simulation**
- **Lab and modeling studies of cryogenic fracturing technology**
- **Modeling and experimenting fracturing processes in** (1) hydraulic fracturing operation and (2) high-pressure CO_2 injection operation
- **Publications in past 5 years:**
  - 35 peer-reviewed journal papers (e.g., "Simulation of Coupled Thermal/Hydrological/Mechanical Phenomena in Porous Media," *SPE Journal*, June. 2016)
  - One book/4 book chapters (e.g., "*Multiphase Fluid Flow in Porous and Fractured Reservoirs*," First Edition, Elsevier, Pages: 418, 2015)
  - 37 SPE papers (e.g., "Effect of Large Capillary Pressure on Fluid Flow and Transport in Stress-sensitive Tight Oil Reservoirs," SPE-175074, ATCE, 2015)

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Roster of EMG

Faculty: Dr. Yu-Shu Wu, Professor; Dr. Philip H. Winterfeld, Research Associate professor; Dr. Xiaolong Yin, Associate professor

Postdoc Research Fellows: Dr. Lei Wang; Dr. Zhaoqin Huang

Current PhD Students: Cong Wang; Shihao Wang, Xiangyu Yu; Bowen Yao; Ye Tian; Nasser Aljishi; Thanh Nguyen; Haojun Xie

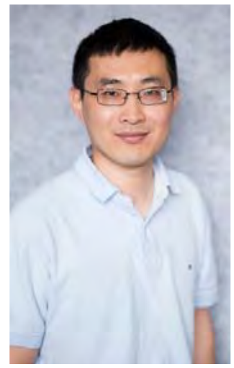
Recent PhD Grads/Theses Topics:

- Nicolas Farah, PhD., "Flow Modelling in Low Permeability Unconventional reservoirs," 2016
- Yi Xiong, PhD., "Development of a Compositional Model Fully Coupled with Geomechanics and Its Application to Tight Oil Reservoir Simulation," 2015
- Perapon Fakcharoenphol , PhD., "A Coupled Flow and Geomechanics Model for Enhanced Oil and Gas Recovery in Shale Formations," 2013
- Ronglei Zhang, PhD., "Numerical Simulation of Thermal-Hydrological-Mechanical-Chemical Processes during CO2 Geological Sequestration," 2013
- Ajab Al-Otaibi, Ph.D., "Pressure Transient Behavior of Vertical Wells Accounting For Non-Darcy Flow in Porous and Fractured Reservoirs," 2010

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Xiaolong Yin

Associate Professor



- Education
  - PhD, Chemical Engineering, Cornell University
  - MS, Mechanical Engineering, Lehigh University
  - BS, Mechanics, Peking University
- Professional Experience & Affiliations
  - Associate Professor, Colorado School of Mines, 2015 – current
  - Assistant Professor, Colorado School of Mines, 2009 – 2015
  - Postdoc Researcher, Princeton University, 2006-2008
  - Associate Editor, SPE Journal
  - Member of SPE, AIChE, APS

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Focus – Fluid Dynamics and Fluid Properties

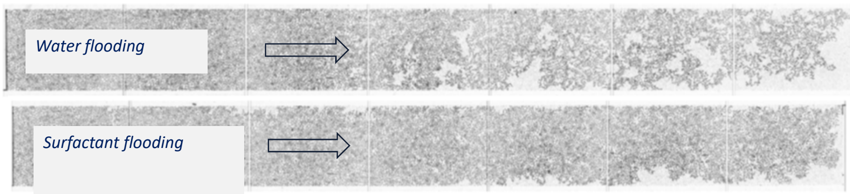
- Research Directions
  - Computational and experimental multiphase fluid dynamics
  - Phase behavior of petroleum systems
- Current Projects
  - Multiphase flow in porous media
  - Particle transport in porous media
  - Petroleum fluids phase behavior
  - Nano-scale flows
  - Particulate flows
- Current Students
  - 8 PhDs, 1 MS, 2 undergraduates

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

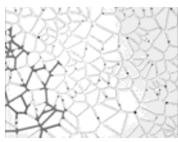
Multiphase Flows in Porous Media

Microfluidic Porous Media Models

Surfactant enhanced water flooding

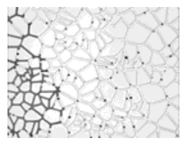


Geometry with pore size distribution: Surfactant increases the displacement efficiency



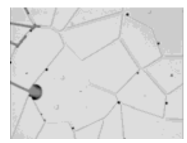
Homogeneous texture

Water flooding



Homogeneous texture

Surfactant flooding

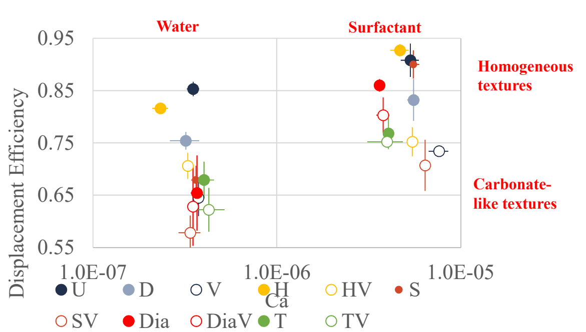


Carbonate-like texture

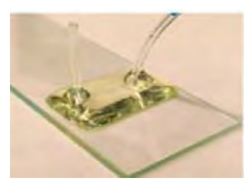
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Surfactant EOR in Microfluidic Porous Media Models

Effect of capillary number and geometric complexity

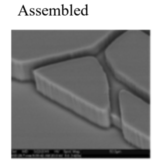


Collaborator: Keith B. Neeves (ChemE, CSM)



Assembled

SEM image

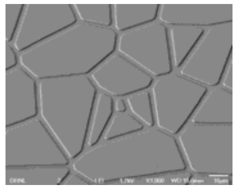


Wu et al., Lab Chip, 2012
Xu et al., Phys. Fluids, 2014
Yang et al., Langmuir, 2016
Kenzhekhanov, MS thesis, 2016

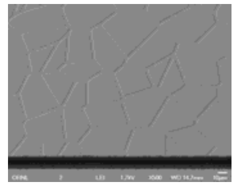
PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Nanofluidic Porous Media Analogs

Flow, displacement, and phase behavior in nanopores

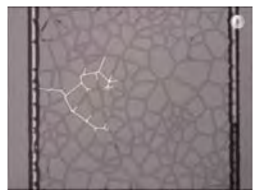


300 nm network



30 nm network

Collaborators: Keith B. Neeves (ChemE, CSM)
Erdal Ozkan (PE, CSM)
Yu-Shu Wu (PE, CSM)



Visualization of N_2-water displacement in 100 nm pore network

Wu et al., Lab Chip, 2013
Wu et al., SPE J., 2014
He et al., J. Petro. Sci. Eng., 2015

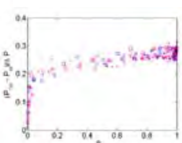
Flow and Transport in Porous Media
Numerical Simulations

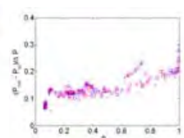
Yong et al., Sci. China Chem. 2011
Newman and Yin, SPE J., 2013
Yong et al., Chinese J. Chem. Eng., 2013
Yong et al., Comput. Math. Appl., 2014
Xiao and Yin, Comput. Math. Appl., 2016

Single- and multiphase lattice Boltzmann models

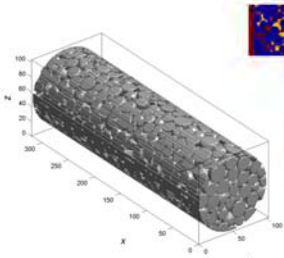
Saturation field

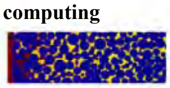
Pressure field





High-performance computing

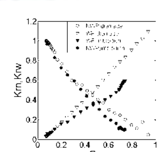




Saturation field

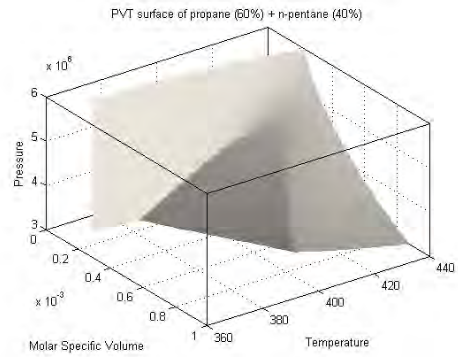
Pressure field

Capillary pressure and relative permeability curves



PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Fluid Properties and Phase Behavior



- PVT of petroleum fluids
- Interfacial tension and wetting
- Phase behavior in nanopores
- Brine-CO_2-oil equilibrium
- Gas dissolution and diffusion in heavy oils

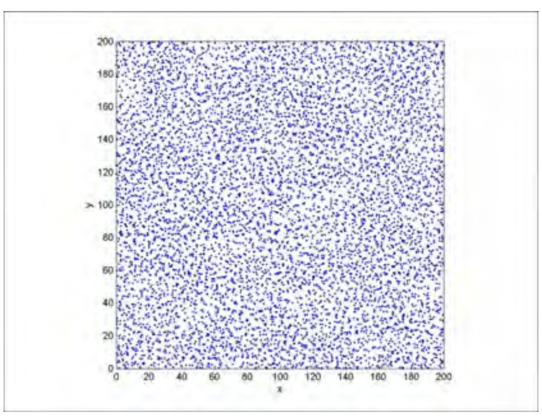
Collaborators: Erdal Ozkan (PE, CSM)
Hossein Kazemi (PE, CSM)

Teklu et al., SPE Res. Eval. Eng., 2014
Wang et al., SPE J., 2016

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Particulate Flows

Numerical Simulation



- Heat and mass transfer in suspensions
- Flow instability in gas-solid flows
- Simulation and modeling of proppant transport in narrow fractures

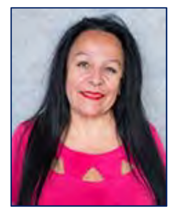
Collaborators: Christine Hrenya (ChemE, CU Boulder)

Metzger et al., J. Fluid Mech., 2013
Yin et al., J. Fluid Mech., 2013
Li et al., AIChE J., 2014
Souzy et al., Phys. Fluids, 2015
Garzó et al., Phys. Rev. E, 2016

PETROLEUM ENGINEERING
COLORADO SCHOOL OF MINES

Acknowledgements

- Supporting Staff
  - Ms. Kayla Boster
  - Ms. Rachel McDonald
  - Ms. Debra Marrufo
  - Ms. Denise Winn-Bower
  - Ms. Theresa Snyder
  - Mr. Al Sami
  - Mr. Joe Chen




Laboratory Facilities and Instruments Available for Research

1st Edition, January 2017

Somayeh Karimi, PhD Candidate

Ilkay Eker, PhD Candidate

and

Petroleum Engineering Faculty

Table of Contents

Preface

The purpose of this booklet is to inform the Petroleum Engineering Department faculty and students with a list of the laboratory facilities and equipment available for research in PE department and other CSM departments. A brief description of each instrument and a photo of the instrument is presented. Furthermore, we intend to promote experimental research in the department.

Please contact Joe Chen (jychen@mines.edu) for assistance in coordinating use of the devices.

Core Lab CMS™-300 Core Measurement System

The CMS™-300 Core Measurement System is an automated unsteady state, pressure decay, permeability and porosity measurement instrument. The instrument can be used to conduct measurements under confining stress to simulate reservoir conditions. Measurements can be conducted on cylindrical cores with 1 or 1.5” diameter and 0.75 to 3.12” length. Helium and Nitrogen are used to conduct the measurements.

The following is a partial list of parameters that can be determined with the instrument:

1- Porosity
2- Permeability
3- Klinkenberg permeability

Figure 1: Core Lab CMS™-300 Core Measurement System (image adapted from catalog)

Core Lab PDPK™-400

The PDPK™-400 Pressure-Decay Profile Permeameter is a pressure decay system that is used to determine core permeability and heterogeneity. The instrument can be used to measurement permeability in x and y direction on a core as long as 3 meters. Cleaned and dried core slabs as well as whole cores can be used in measurements. The range of rock permeability for reliable measurements is 0.001 mD to greater than 30 D.

Figure 2: Core Lab PDPK™-400, Pressure-Decay Profile Permeameter (image adapted from catalog)

Gas Adsorption

The gas adsorption system is used to determine adsorption isotherms of different solvents on source rocks such as shales and coal bed methane. Zeolite 13x, an aluminum silicate or ceramic material which is a strong adsorbent, may be used for demonstration purposes. The system is manually operated and consists of high accuracy pressure gauges, two stainless steel open cylinder cells, stainless steel lines and high pressure needle valves all rated to 3500 psi. The two cylinders are referred to as the dosing cell and the uptake cell. The system is also designed to fit wholly into a temperature water bath allowing for temperature regulation during an experiment. Ultimately, the gas storage capacity of the samples can be determined at different pressures through material balance calculations.

The combination of the dosing cell volume, uptake cell volume, valve and the line volumes represent the system volume. For high pressure experiments, minimum sample cell cylinders volumes (available from Swagelok) are able to withstand pressures up to 3000 psi is 150 cc. In this case, a large amount of sample is required to reduce the system volume to sample ratio. Generally, subtle reduction in the amount adsorbed by the adsorbent material is experienced when system volume is lowered. Optimum ratios for the dosing cell and uptake cell have to be determined prior to experiment.

Figure 3: Gas Adsorption System

Micromeritics ASAP 2020™

This Micromeritics ASAP 2020™ is a gas adsorption instrument designed for core samples with very small pore sizes that range between 3 to 200 nanometers. It is mostly useful to measure the pore sizes of unconventional reservoir rocks. It has two outgassing and one analysis ports. Depending on the pore sizes, each sample measurement can take from a few hours (only surface area) to a few days (nanometer-sized pores in organic matter). The samples are measured in their powder form, and the gases that can be used for this instrument are Argon, N_2, Hexane, CO_2, and Water Vapor. The samples are first outgassed for 24 hours at 200 °C under vacuum condition while flowing inert gas through the sample to remove any contaminant gas. Then, the sample is subjected to increasing partial pressures to obtain a full isotherm. The following is a list of parameters which can be measured using ASAP 2020™:

1. Specific Surface Area
2. Isotherm – Adsorption & Desorption
3. Pore Size Distribution
4. Total Pore Volume
5. Average Pore Size

Figure 4: Micromeritics ASAP 2020™

Quadrasorb EVO/ SI

The Quadrasorb EVO/ SI is a versatile gas adsorption instrument designed for high throughput. With four independent analysis stations it is capable of analyzing four samples simultaneously. Quadrasorb EVO/ SI is available in a KR/MP configuration, which is equipped with a turbomolecular pump and 10-torr or 1-torr pressure transducer for measuring low surface area samples with krypton and microporous samples with nitrogen or argon. The following is a partial list of important parameters which can be determined from Quadrasorb Adsorption experiments:

1- Specific Surface Area
2- Isotherm – Adsorption & Desorption
3- Pore Size Distribution
4- Total Pore Volume
5- Average Pore Size

Flovacdegasser is used in conjunction with the QUADRASORB EVO/ SI for outgassing at vacuum condition purposes.

Figure 5: QUADRASORB EVO/ SI (image adapted from user manual)

Low Frequency Velocity Measurements

The technique used to determine elastic properties at low frequencies consists of a stress/strain system that deforms the rock at a frequency range of 1 to 2000 Hz. Measurements can be conducted at different confining and pore pressure stages to simulate reservoir conditions. Additionally we can control temperature of the pressure vessel (0 – 100 °C). Besides measuring low frequency velocities we are also able to perform ultrasonic (1 MHz) velocity measurements.

The following is a partial list of parameters that can be determined using the set up:

1- Young's modulus
2- Poisson's ratio
3- Bulk modulus
4- Shear modulus
5- Compressional and shear wave velocities
6- Attenuation

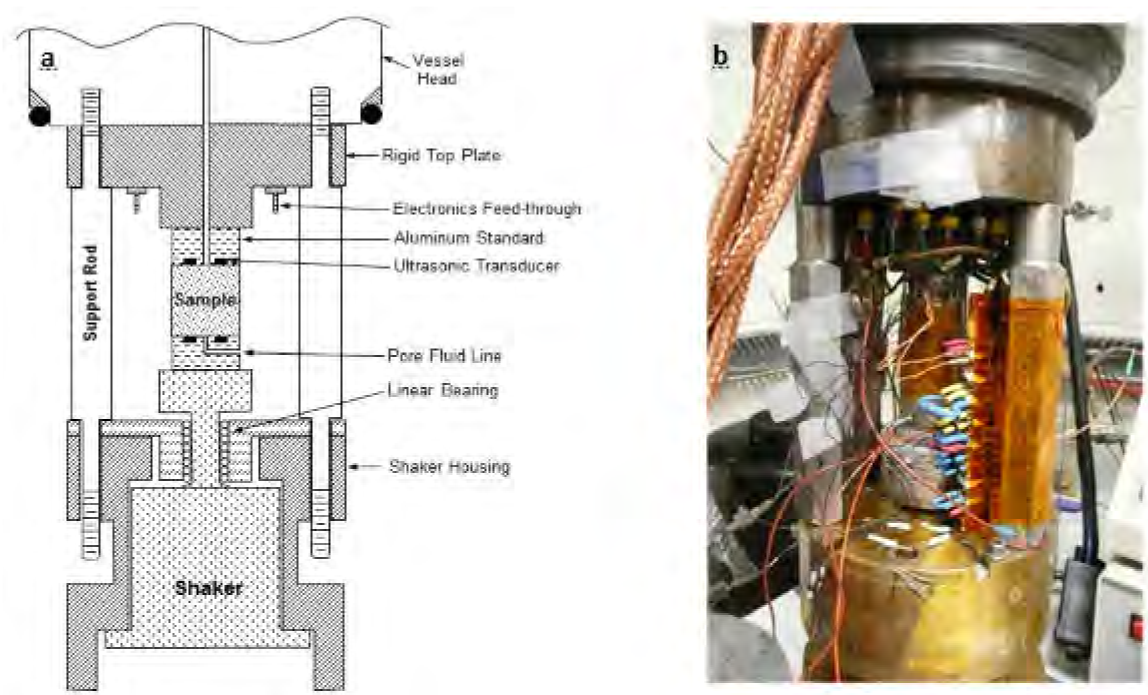


Figure 6: (a) Schematic of the low frequency measurement assembly. For seismic frequencies, strains are measured on both the sample and aluminum standard. Ultrasonic transducers permit wave propagation measurement near 1 MHz. Fluid lines permit control and exchange of pore fluids independent of confining pressure, (b) Photograph of completed measurement assembly

NER AutoLab 1500

AutoLab 1500 is a servo-hydraulic operated system for biaxial measurements with software-controlled arbitrary stress paths on rock specimens up to 50.8 mm (2.0 in) in diameter at in-situ stress conditions with pore pressure and temperature controls. The high pressure biaxial system consists of a pressure vessel with an internal piston for differential stress and servo-hydraulic intensifiers for differential stress, confining and pore pressure. This instrument allows us to make measurements at reservoir pressures up to 69 MPa (10,000 psi) and temperatures up to 120˚C (248˚F).

The key features of the instrument are the following:

- Servo-hydraulic control of confining pressure, pore pressure, flow rate, strain rate, and force.
- Control of stresses and temperatures at reservoir conditions.
- Pore pressure intensifier compatible with water, brine, oil, and gas (including CO2).
- AutoLab software for system data acquisition and reduction.
- Integrated electronics console for servo-amplifiers and signal conditioning.

A list of the parameters measured using NER Autolab 1500 are as following:

1. Compressional and shear wave velocities
2. Electrical resistivity
3. Permeability

Figure 7: NER AutoLab 1500

XRadia MicroXCT-400

The micro X-ray CT (computed tomography) machine provides high resolution 3D images of samples with up to 2 ʻʻ in diameter. The weight of the sample must be less than 15 kg. Image resolution of up to 1 µm can be achieved. Four different lenses allow us to cover a varying field of view size and a variable resolution. It is a non-destructive method to explore the internal structure of samples which might be unobservable with conventional 2D techniques, such as SEM.

The instrument chamber can house a pressure cell for studying in-situ change in internal microstructure with application of pore and confining pressures up to 2500 psi as well as a temperature controls between -5 °C to 50 °C. The following is a list of parameters that can be measured using the instrument:

1. Rock microstructure for oil and gas exploration
2. In situ measurement during imaging (e. g. ultrasonic velocities)
3. Semiconductor packaging development and failure analysis
4. Life-science research
5. Advanced material characterization

Figure 8: XRadia MicroXCT 400 (image adapted from catalog)

Microfluidic and Nanofluidic Porous Media Analogues

Microfluidics and nanofluidics are technologies developed to control and manipulate fluids at micro- and nanoscale. Using micro- and nanofabrication, pores of controlled dimensions, surface properties, and complexities can be made on silicon or polymer substrates to facilitate direct visualization and fundamental studies of fluid flow through porous media. Microfluidic porous media analogues (µPMA) are primarily polymer based and the pore size ranges from a few micrometers to hundreds of micrometers. Nanofluidic porous media analogues (nPMA) are built by bonding silicon to pyrex, and the channels have critical dimensions in the range of tens to hundreds of nanometers. These devices are being used to study enhanced oil recovery, phase behavior, and nano-scale single- and multiphase flows in unconventional reservoirs.

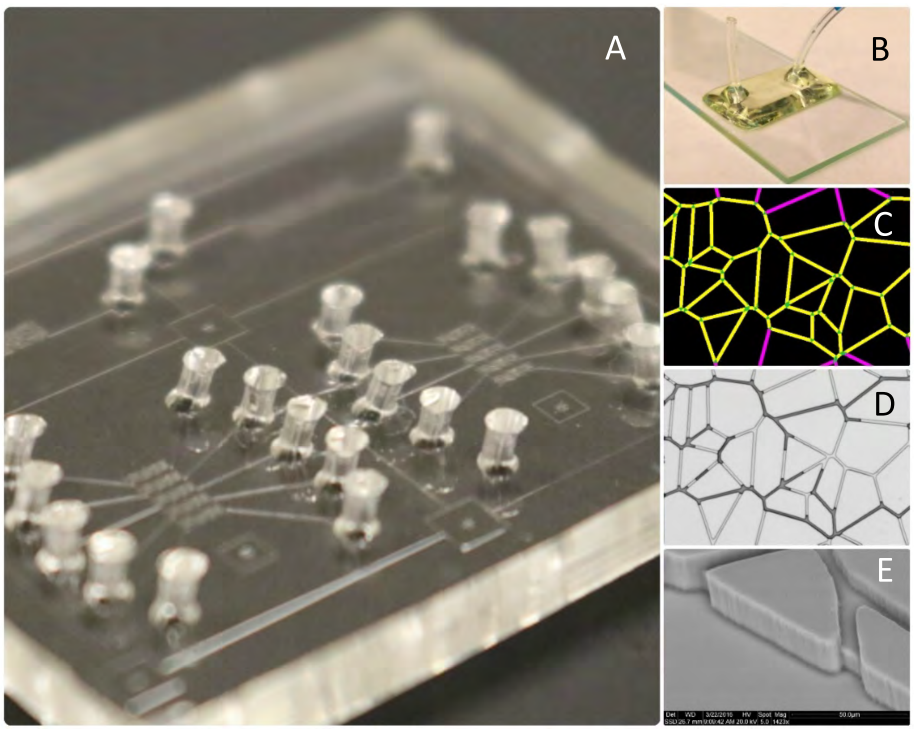


Figure 9: A – µPMA "chips" being prepared on a master substrate; B – A fully assembled µPMA; C – A section of pore network etched onto µPMA; D – Water flooding pattern in the same section; E – SEM image of channels in a µPMA

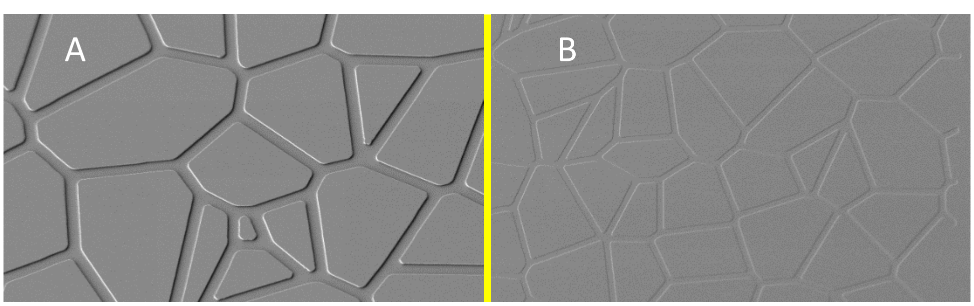


Figure 10: Pore networks on nPMA. A – 300 nm channels; B – 30 nm channels

Slim Tube System

The Slim Tube is equipped with a temperature controlling enclosure, with both 60' and 10' 1/4" slim tubes (60' for lighter oils, 10' for v. heavy oils), a constant pressure backpressure system, a constant volume positive displacement pump and the "cannon" the large SS tube that pressurizes the gas to the desired pressure and utilizes water to displace the gas into the slim tube at a constant rate, constant pressure, and constant temperature. Minimum miscibility pressure of liquid hydrocarbon and gases such as N2, Co2, and hydrocarbon gases are measured using the slim tube.

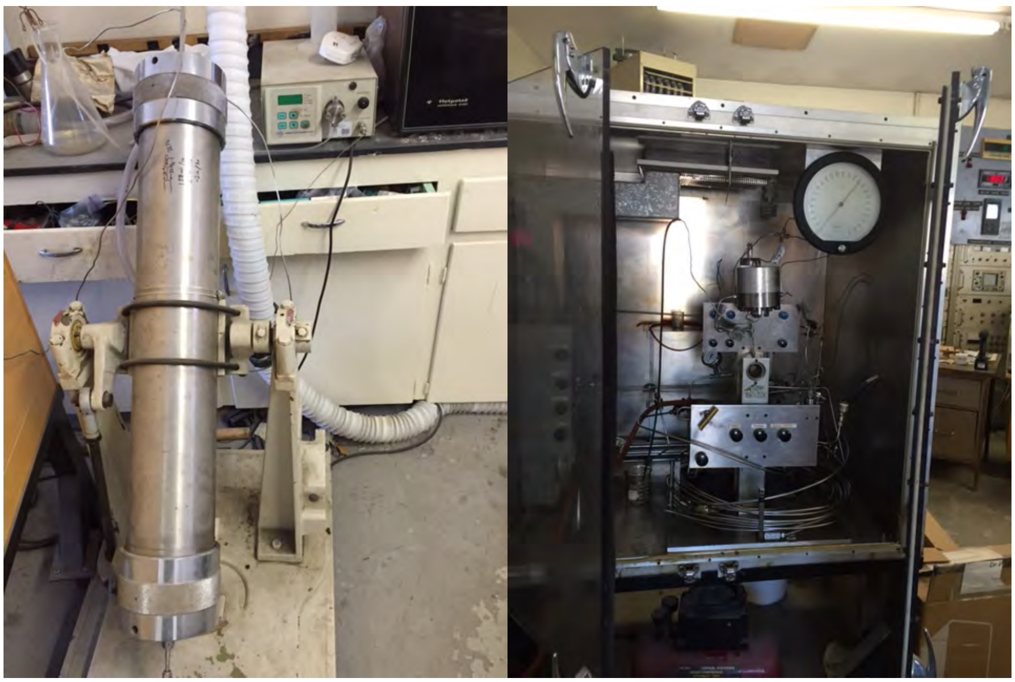


Figure 11: Slim Tube System

Core Lab PVT SYSTEM 400/1000

This PVT system can operate at reservoir pressure and temperature conditions up to a maximum of 14,500 psi and 400° F. The PVT cell is equipped with a camera that provides full visual observation of PVT experiments. We use the PVT cell to characterize reservoir fluid (oil and gas) systems, and to determine the effect of different gases (such as N2, CO2 and pure hydrocarbon components) on the reservoir oil behavior. The following is a partial list of important parameters which can be determined from PVT experiments:

1- Bubble point pressure
2- Dew point pressure
3- Gas oil ratio
4- Formation volume factor
5- Oil and gas compositions

We must use auxiliary instruments such as a gasometer, gas chromatograph (GC), and densitometer in conjunction with PVT cell experiments.

Figure 12: Core Lab PVT System 400/1000 (Core Lab catalog)

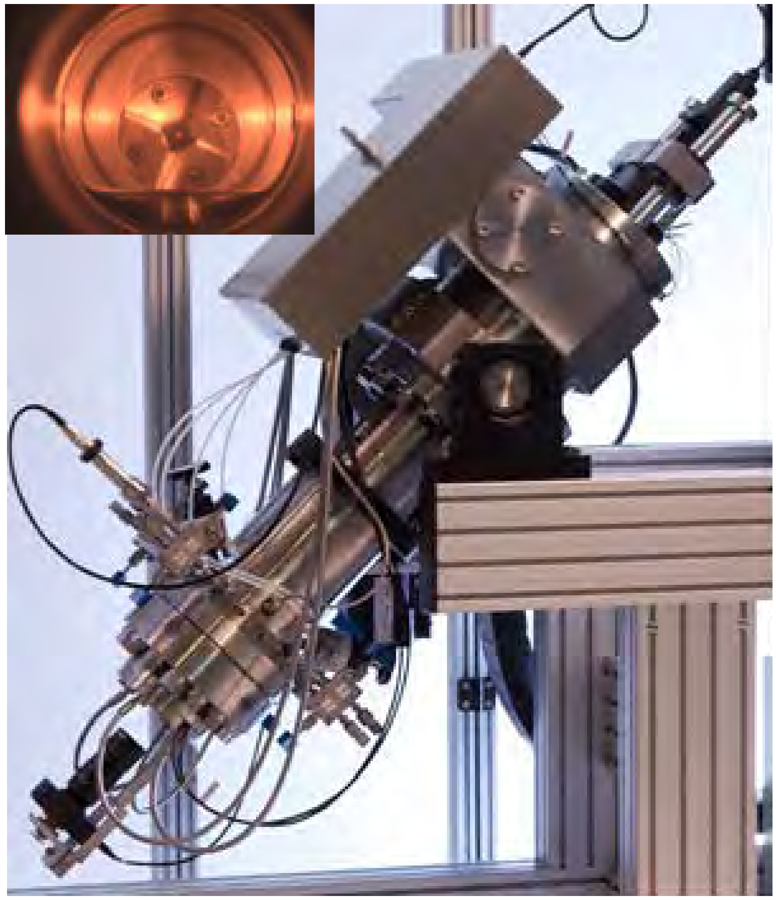


Figure 13: PVT cell at 45 ° from horizontal to capture condensate accumulation, and a view of the cell interior on the top left corner (modified from Core Lab catalog)

DBR Gasometer

A sample of a live oil (or gas) sample from the PVT cell is transferred to the gasometer. Then it is slowly flashed to the ambient conditions to measure the resulting gas and liquid volumes for GC analysis. The measured volume is used to determine GOR. The gasometer cylinder capacity can increase up to 10 liters at ambient pressure and temperature conditions.

Figure 14: DBR Gasometer

Anton Paar DMA 4200 M Densitometer

The densitometer is an automated instrument used to measure oil density at different pressure and temperature conditions. The range of operating temperature for our densitometer is -10° C to 200° C. The pressure of the sample can be up to 500 bar (~ 7200 psi). The sample volume required for measurements is 2 cc.

Figure 15: Anton Paar DMA 4200 M Densitometer

KRüSS Spinning Drop Tensiometer SITE100

The spinning drop tensiometer is an instrument to measure very low IFTs of the oil-water systems in the range of 10 to 10^{-6} mN/m. Such systems generally contain surface active agents. The spinning speed of the capillary tube can go up to 15,000 rpm for measurements. We can decrease or increase temperature using a recirculating bath. The temperature for measurements can vary in the range of -20° C to 200° C.

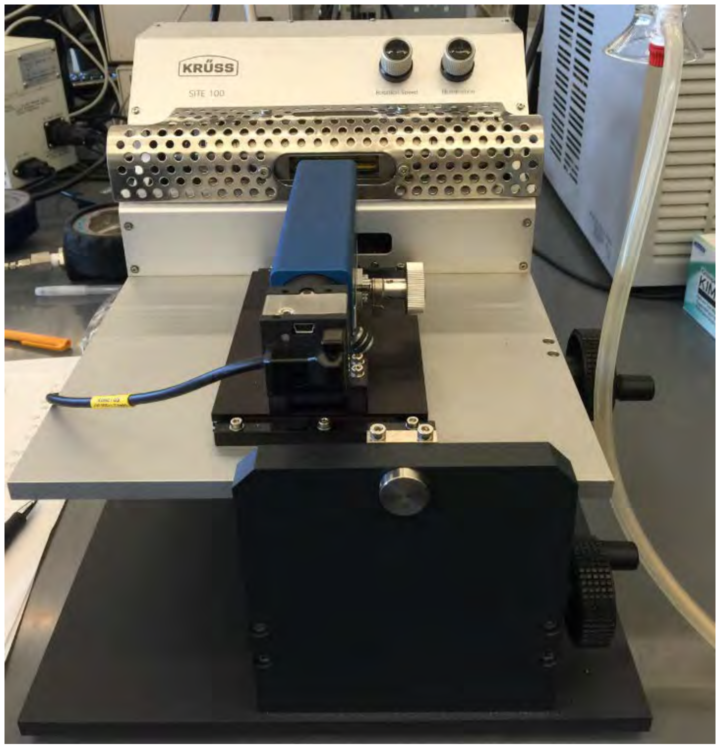


Figure 16: KRüSS Spinning Drop Tensiometer SITE100

Fluid Measurement System (FMS)

The fluid measurement system (FMS) is used to measure acoustic velocities in fluids at reservoir pressure and temperature conditions up to a maximum of 20,000 psi and 200° C. The FMS cell is equipped with a computer that provides full control and data acquisition of the FMS experiments. We use FMS to characterize reservoir fluid (brine, oil, and gas) systems, and to determine the effect of different gases (such as methane, N_2, CO_2 and pure hydrocarbon components) on reservoir oil behavior. The following is a partial list of important parameters which can be determined from FMS experiments:

1- Fluid velocity under pressure change
2- Fluid velocity under temperature change
3- Fluid permeability

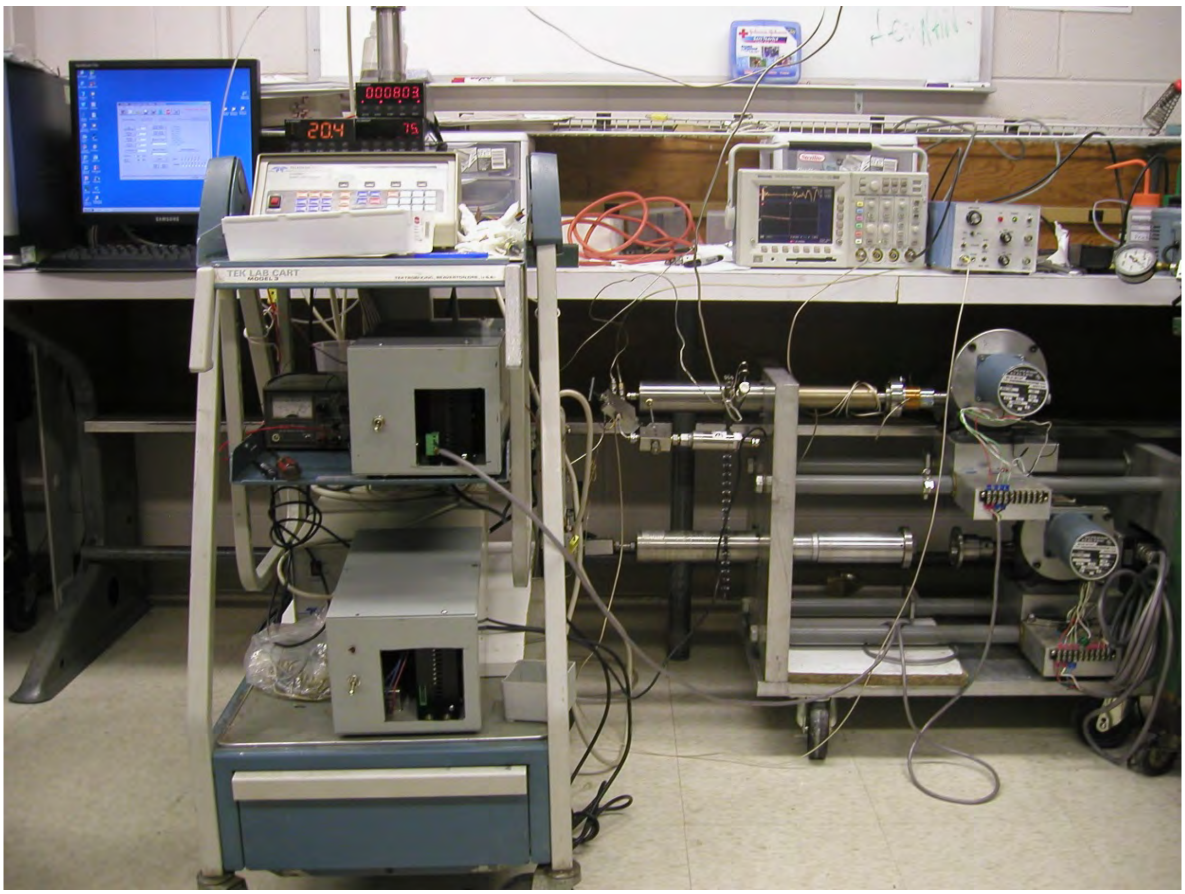


Figure 17: Fluid Measurement System (FMS)

Core Lab ACES-200 Automated Centrifuge System

This high speed centrifuge system is capable of spinning cores at different rotational speeds (maximum practical speed is 13,000 rpm). The temperature can also be increased from the ambient temperature to the reservoir temperature. The centrifuge can use conventional (high porosity-high permeability) core plugs as well as unconventional (low porosity-low permeability) core plugs. The centrifuge is equipped with a high resolution camera which makes it possible to measure small produced fluid volumes from cores. Using rotor PIR 16.5, experiments on three core plugs can be conducted simultaneously. The core plugs dimensions should be maximum 1.5” diameter and up to 2” length.

We have used the centrifuge to determine the wettability related properties of the oil-water and gas-liquid flow in cores. Gravity drainage (or, the fluid replacement concept) is the major outcome of the centrifuge experiments. Specifically, the following is a partial list of important parameters that can be determined with the centrifuge:

1- Drainage and imbibition capillary pressure curves for oil-water and gas-liquid systems
2- Relative permeability end-points
3- Oil recovery by gravity drainage
4- Pore size distribution
5- Wettability

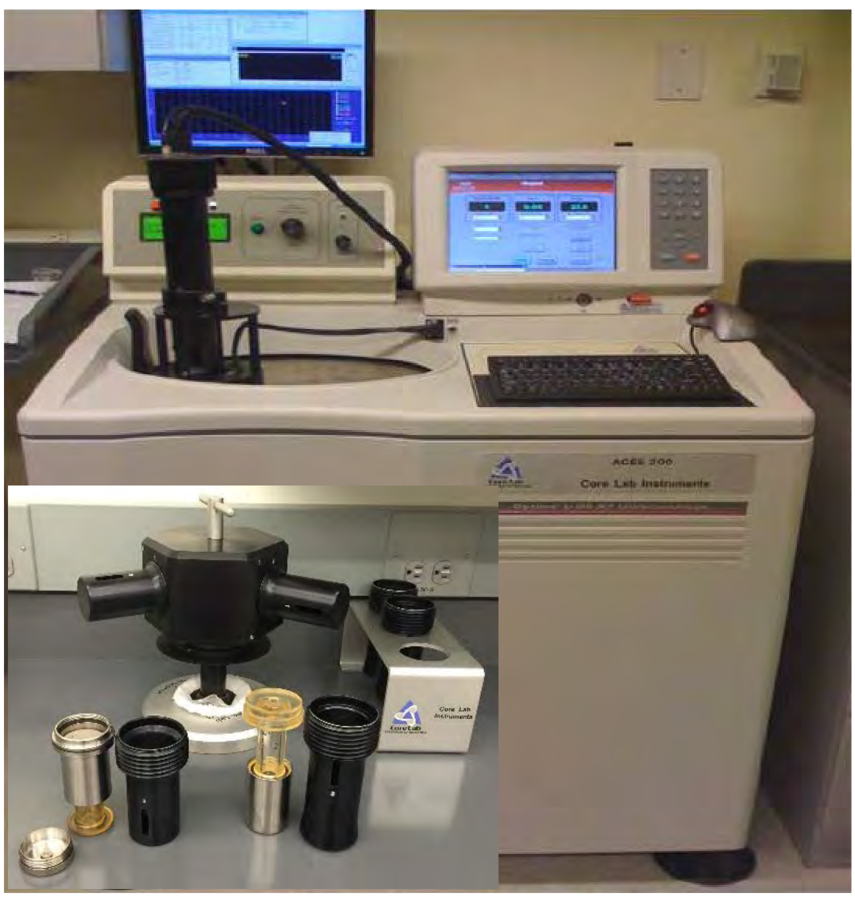


Figure 18: Core Lab ACES-200 Automated Centrifuge System

Mass-Based Spontaneous Imbibition Device

The mass-based spontaneous imbibition experimental setup is used to measure fluid mass produced in spontaneous imbibition experiments. The equipment can be used to study fluid-rock interaction at room conditions. Various salinity brines, oil, dilute acid, and surfactant are some of the fluids used to study fluid-rock interactions in spontaneous imbibition experiments. Moreover, rock samples such as carbonate, sandstone, or shales with quantity as low as of 5 gm up to 200 gm are used in spontaneous imbibition experiments.

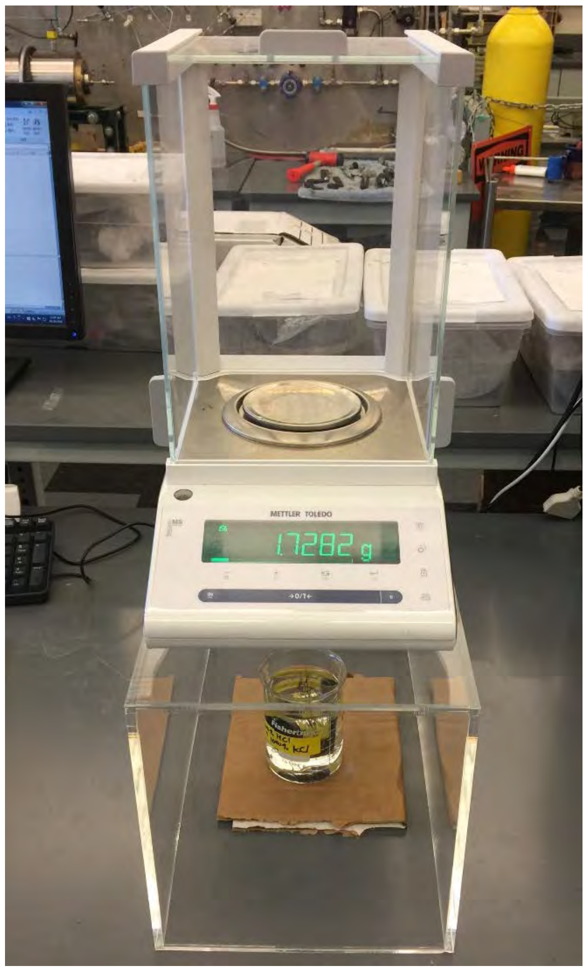


Figure 19: Mass-based spontaneous imbibition device

Chandler Formation Response Tester (FRT) 6100 Core Flooding System

There are two core flooding systems at PE research laboratory facilities. One of the core flooding systems is used in the reservoir characterization laboratory for reservoir engineering studies. The core flooding apparatus is used to determine core properties and the oil recoveries using water displacing oil or N_2 and CO_2 displacing oil-water mixture. In addition, different salinity brines and surfactant and polymer solutions can be used in core flooding experiments. The second core flooding system in the formation stimulation laboratory is used for stimulation and formation damage studies.

Our core flooding systems can operate at reservoir pressure and temperature conditions up to a maximum of 5,500 psi injection pressure, up to a maximum of 6,000 psi confining pressure, and 300° F temperature. The core plugs dimensions used in experiments are 1 and 1.5” diameter and up to 12” in length.

The following is a partial list of the parameters that can be determined from core flooding experiments:

1- Absolute permeability
2- Relative permeability
3- Oil recovery

Figure 20: Chandler Formation Response Tester (FRT) 6100 Core Flooding System

Linear Core Flooding System for Formation Damage Studies

The core holder is used to study formation damage at reservoir pressure conditions with a confining pressure of up to 6000 psi, and pore pressure up to 5500 psi. It operates at room temperature at this point; however, it can be upgraded to reservoir temperature condition. Nitrogen gas is used as pore pressure fluid (helium or argon gas can also be used). We are capable of using cores with up to 4” in diameter and 12” in length.

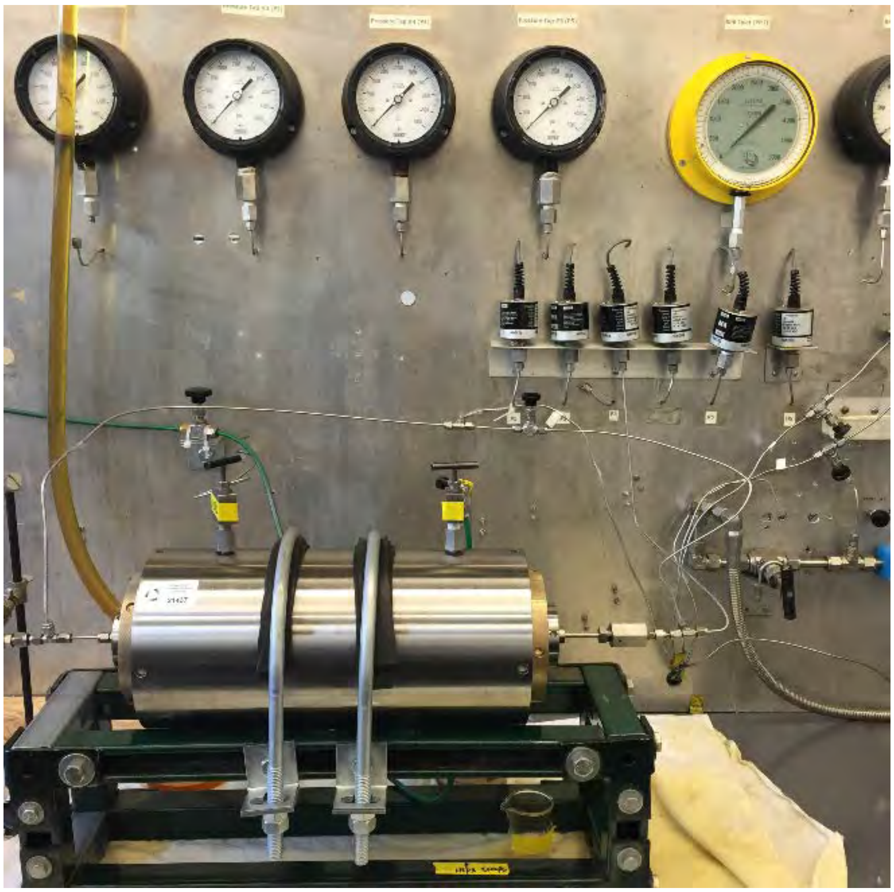


Figure 21: Linear core holder unit

KRüSS Drop Shape Analyzer DSA100

Our DSA100 unit is an automated instrument which gives us the capability to measure contact angle as well as liquid surface tension and calculates IFT. The contact angle is measured between two fluids (usually formation/synthetic brine and oil) and a polished solid surface such as rock. In addition, using the Minidosing MS PD-E1700, we can measure the parameters at pressure and temperature conditions up to maximum 10,000 Psi and 180° C.

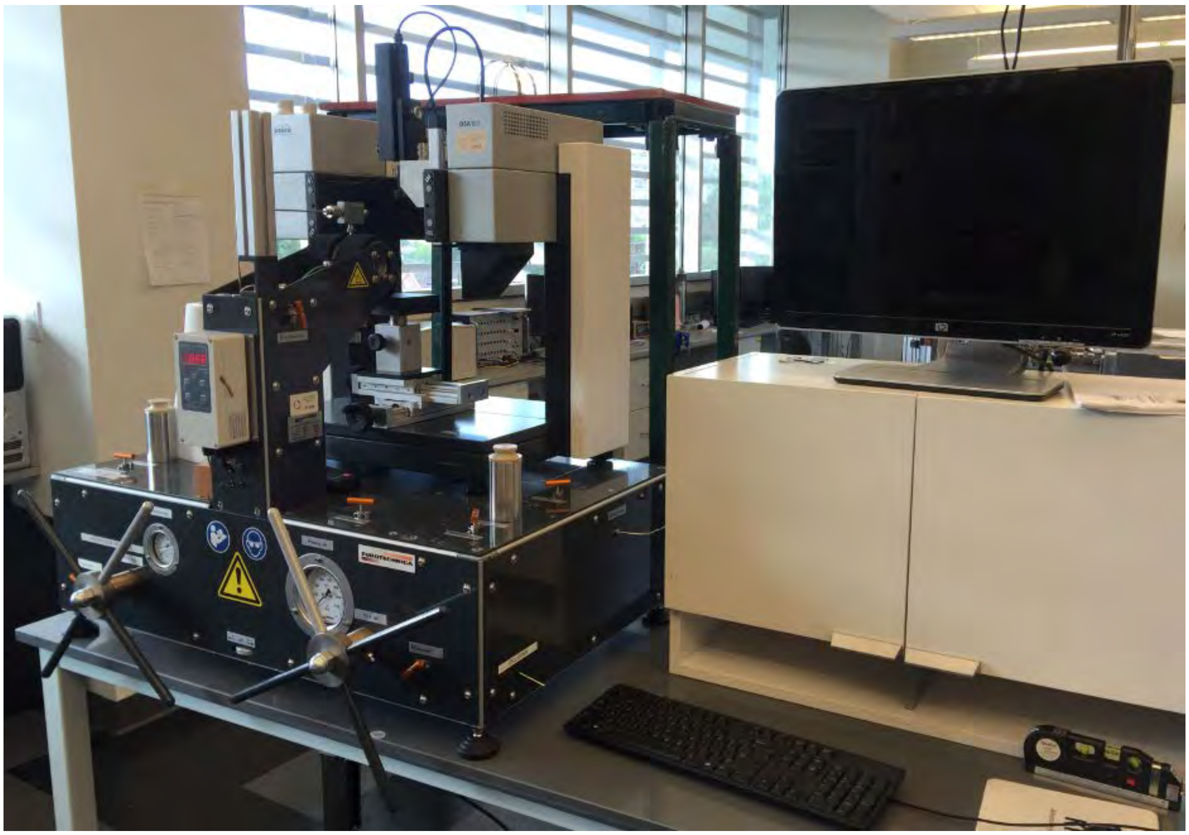


Figure 22: KRüSS Drop Shape Analyzer DSA100

The Spectral Induced Polarization (SIP) Resistivity Measuring Instrument

The SIP resistivity measuring instrument measures the real and imaginary components of resistance for brine-saturated porous rocks in the frequency range of 1 mHz to 45 KHz.

The following is a partial list of the important parameters which can be determined from SIP experiments:

1- Resistivity
2- Tortuosity

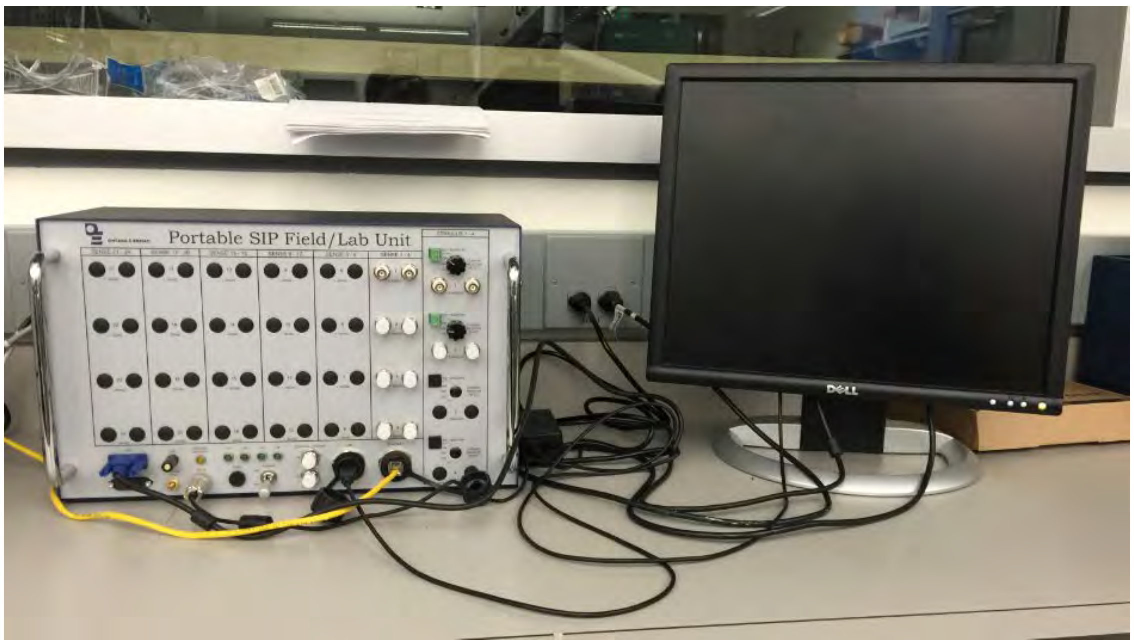


Figure 23: Resistivity Measuring Instrument

Impedance Analyzer – Keysight E4990A

This Impedance Analyzer is a complex resistivity measurement used for bench top measurements in a range of frequencies (20Hz to 120MHz). The analyzing probe can be used for samples with a maximum length of 11mm and variable diameters. The following is a partial list of important parameters which can be determined from these experiments:

1- Conductivity
2- Permittivity

We use auxiliary instruments, for example Refractometer, to measure fluid conductivity if the sample analyzed is saturated.

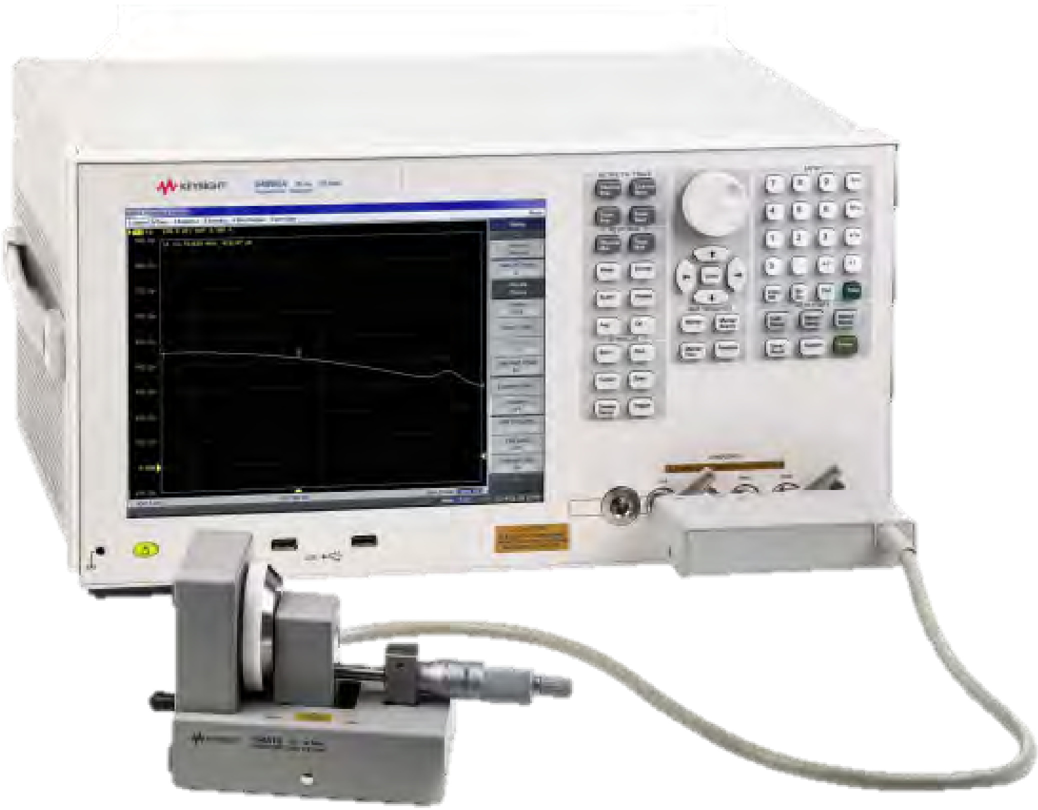


Figure 24: Impedance Analyzer (Keysight manual)

Network Analyzer – Keysight ENA Series

This Network Analyzer is a complex resistivity measurement used for bench top measurements in a range of frequencies (300 kHz to 20 GHz). The analyzing probe can be used for any sample; the only specification is the need for a flat polish surface, to allow full contact with the sample and reliable measurements. The following is a partial list of important parameters which can be determined from these experiments:

1- Conductivity
2- Permittivity

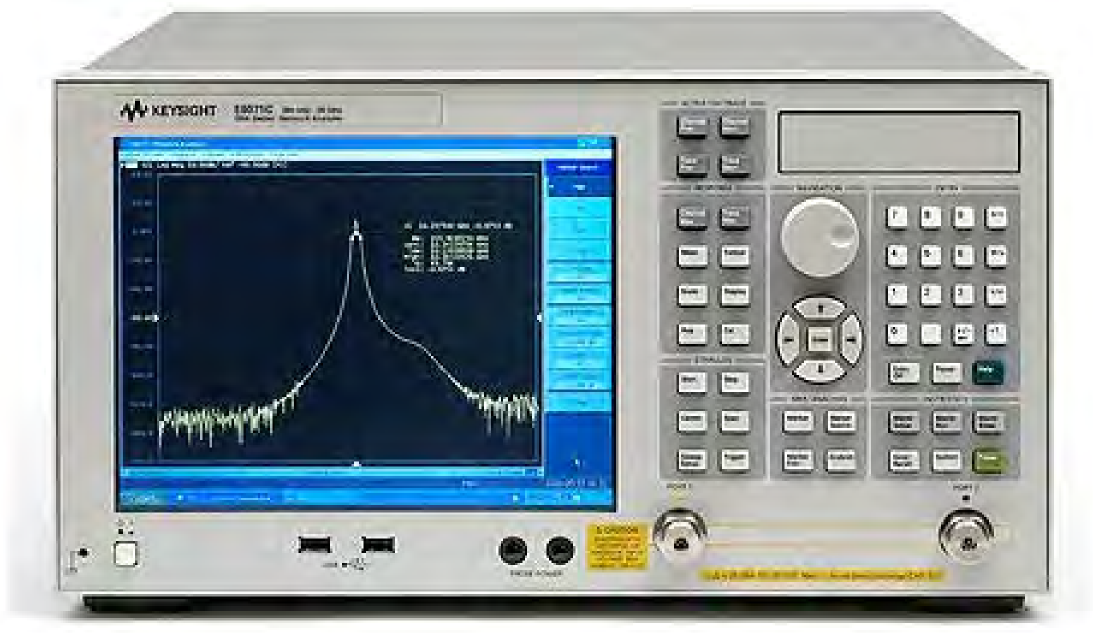


Figure 25: Network Analyzer (Keysight manual)

Anisotropic Acoustic–Electrical Joint Measurement System

We use the system to characterize the geophysical rock properties and anisotropy, and to determine the effect of pressure and fluids on reservoir rock physics parameters. Specifically, the joint anisotropic acoustic-electrical measurement system is used to measure P- and S-wave velocities and complex electrical conductivity as functions of angle simultaneously on rock samples at various confining and pore pressure stages up to 4000 psi. The following is a list of parameters measured using the instrument:

1- Compressional and shear wave velocities and their anisotropies
2- Formation elastic properties and stiffness tensor
3- Acoustic attenuation and attenuation tensor
4- Complex electrical conductivity and conductivity tensor

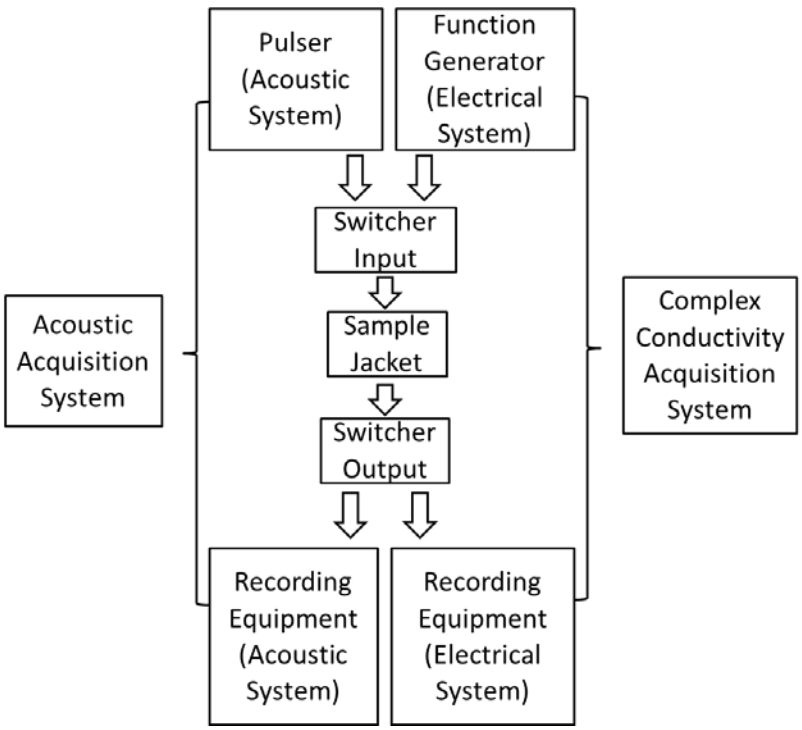


Figure 26: Schematic of anisotropic acoustic – electrical joint measurement system

In the acoustic acquisition system, the pulser initiates a pulse signal to the acoustic transducers and trigger signal to oscilloscope isochronously, while the recording equipment, or oscilloscope (Tektronix TDS 3014C), receives signals from acoustic transducers and trigger signals from the pulser in different channels, and displays the wave amplitudes as a function of time.

The complex conductivity acquisition system mainly consists of the Spectral Induced Polarization (SIP) system, which comprises a four-channel acquisition array and nominal frequency range of 1 mHz to 45 kHz.

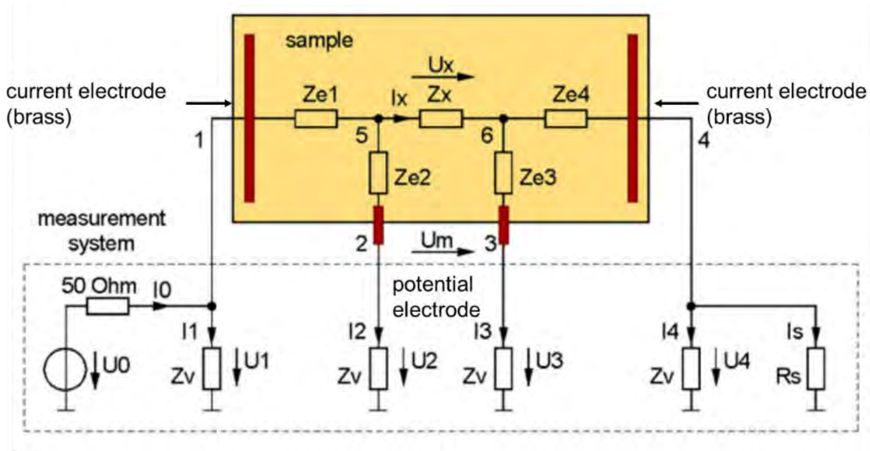


Figure 27: Electrode array and circuit simplified diagram of SIP system. 1 and 4 represent current electrodes, 2 and 3 represent potential electrodes. (Adapted from Zimmermann et al., 2008)

Magritek® Low-Field 2-MHz NMR

This Nuclear Magnetic Resonance (NMR) system operates a frequency of 2MHz and a magnetic field strength of 0.05T. For saturated porous media such as rocks and soils, the NMR response of this system is dependent on the size of the pore space as well as the hydrogen index of the saturating fluid. This non-destructive measurement leaves the core completely intact, while detecting hydrogen nuclei contained in the pore space through alternating magnetic fields. This allows for pore space properties to be determined without alteration of the core or pore space environment. Additional information about interstitial fluids and core mineralogy can be determined with some NMR methods. The following is a partial list of important parameters which can be determined from NMR experiments:

1- Pore Size Distribution
2- Porosity
3- Permeability
4- Fluid Viscosity
5- Oil and Gas Compositions

These results are commonly used in conjunction with nitrogen adsorption and resistivity studies for a complete analysis of pore-space in both laboratory and downhole logging applications.

Figure 28: 2-MHZ Magritek NMR laboratory setup for core analysis (Magritek website)

UNGI Coupled True Triaxial Core Measurement Assembly

The true triaxial measurement assembly is a unique experimental apparatus loaned to UNGI Geomechanics Research Laboratory by Dr. Ali Mese of Geomechanics Engineering and Research, PLLC. Cylindrical core samples are used in the apparatus under true triaxial stress conditions with capability of three independent principal stress magnitude application with elevated pore pressure.

The apparatus is designed to use cylindrical core samples of 2" in diameter with varying lengths with the two independent orthogonal stress magnitudes in the horizontal plane loaded with fluid pressure. The stress magnitudes applied are limited to the pressure capacities of the ISCO hydraulic syringe pumps with 0.001 psi precision. Pumps with capability of 20,000 psi, 10,000 psi and 7,500 psi are currently utilized in the true triaxial measurement assembly to implement the three principal stress magnitudes and pore pressure, respectively. The stress magnitudes can be increased using different pumps with higher pressure capacity and/or placing the standalone sample cell into the MTS load frame at the UNGI Geomechanics Laboratory if core samples needs to be tested at higher stress state. The entire assembly sits in an enclosed insulation box allowing precise temperature control with elevated temperature measurements.

The following is a list of the parameters we can determine using the instrument:

1- Compressional and shear wave velocities
2- Deformation
3- Resistivity
4- Permeability in three orthogonal directions
5- Differences between static and dynamic moduli
6- Permeability anisotropies as a function of stress

Figure 29: Coupled True Triaxial Core Measurement Assembly

UNGI Coupled Pore Pressure Penetration Apparatus (Triaxial Assembly)

The coupled pore pressure penetration assembly is a sample cell for core samples to be tested under triaxial stress state and was donated to UNGI Geomechanics Laboratory by Dr. Ali Mese of Geomechanics Engineering and Research, PLLC. The apparatus has been utilized for cylindrical core samples of 1.5” diameter with varying lengths to conduct coupled measurements of lateral and axial deformations, compressional and shear wave velocities, resistivity and permeability under triaxial stress state with confining and pore pressures up to 20,000 psi and 10,000 psi, respectively under controlled elevated temperatures up to 90˚C (within 0.03˚C precision) using an insulation box for the full assembly. The two hydraulic lines with a porous filter at the bottom cap allows circulation of any pore fluid at specific elevated pressure.

We can measure differential pressure at the top of the sample while different fluids are circulated at the bottom. The data used to study rock-fluid interaction and osmosis, while the data measured while circulation is happening within the sample is used for permeability and directional resistivity measurements.

Axial, confining, pore and circulation pressures as well as injection and back pressure systems are controlled by independently computerized ISCO syringe pumps with 7,500 psi to 20,000 psi capacities. The mixing of the pore fluid brines containing salts and/or chemical additives and the pressurizing hydraulic fluid (mineral oil or deionized water) is prevented in individual pumps as well as between the pressurizing fluid and the core sample for accurate measurements of true rock- pore fluid interactions. Real time monitoring of the pressure, deformation, resistivity and permeability is accomplished for the long duration of the experiments to capture the equilibrium state reached in shale/mudrock samples.

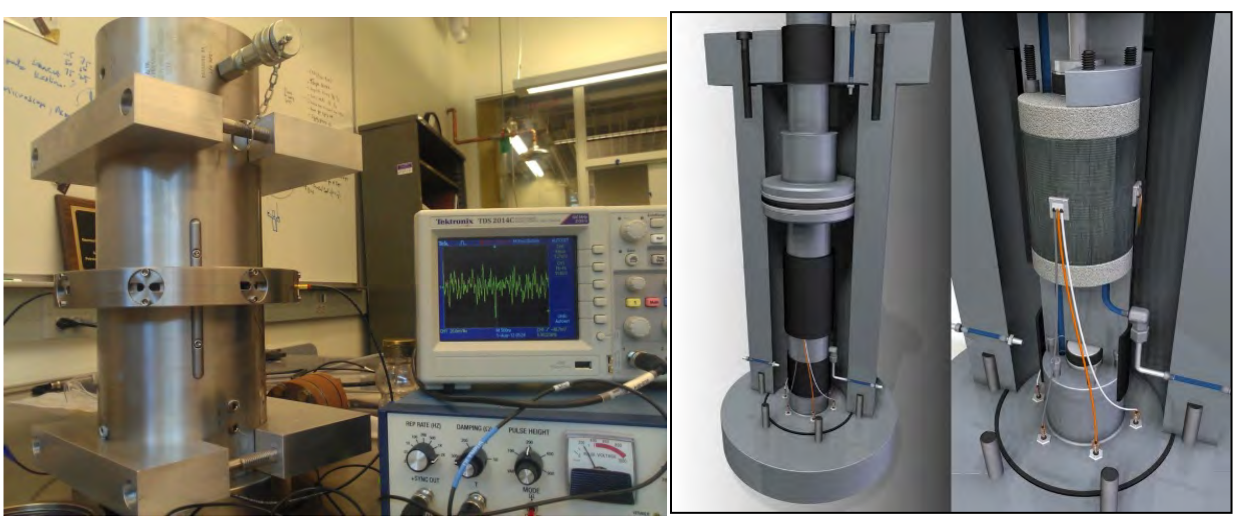


Figure 30: Coupled Pore Pressure Penetration Apparatus (Triaxial Assembly)

Research and Education Sandvik DE130 Diamond Core Drilling Rig

This rig is sponsored by Apache Corporation for research and education of the Mines Community. The Sandvik DE130 is a drilling unit for both surface and underground applications. It can drill in any orientation from horizontal and vertical and at depths of up to 1,200 m with the “N” rotary drive. It can be used to wireline core to 1,200m. The unit can push with 10,350 lbf and pull with 13,820 lbf. It is capable of a drilling torque of 137 to 619 ft-lbf. The hydraulic system has a maximum working pressure of 3,625 psi. The fluids system uses a FMC L1122 Triplex capable of 75.1 gpm at 1,000 psi.

Figure 31: Sandvik DE130 Diamond Drill Core

Figure 32: Mines' DE130 delivered on September 6, 2016

Hydraulic Fracturing System with Tri-axial Stress Loading

The hydraulic fracturing testing system, can be used to investigate fracture initiation and propagation in samples up to 8 inch × 8 inch × 8 inch with tri-axial stress conditions. The maximum stress loading that can be applied in x, y, and z directions are 4500, 4500, and 6000 psi, respectively. Temperature can be adjusted from the ambient condition to about 60 °C. The system is equipped with an ISCO pump to provide the injection fracturing pressure. The following is a partial list of parameters that are measured from experiments:

1- Pressure profile during injection
2- Temperature profile during injection
3- Rate of leak-off before and after fracturing
4- Acoustic wave propagation
5- Fracture pattern and fracture morphology

Figure 33: Hydraulic fracturing system with tri-axial stress loading

Proppant Transport in Horizontal Wellbores & Perforations

Our multiple cluster perforated horizontal wellbore is used to study proppant transport. The slurry is mixed in the tank, and run through the 30-foot long polycarbonate. Sand which exited through the perforation clusters are collected and analyzed to study proppant transport in multi-cluster perforated horizontal wellbores.

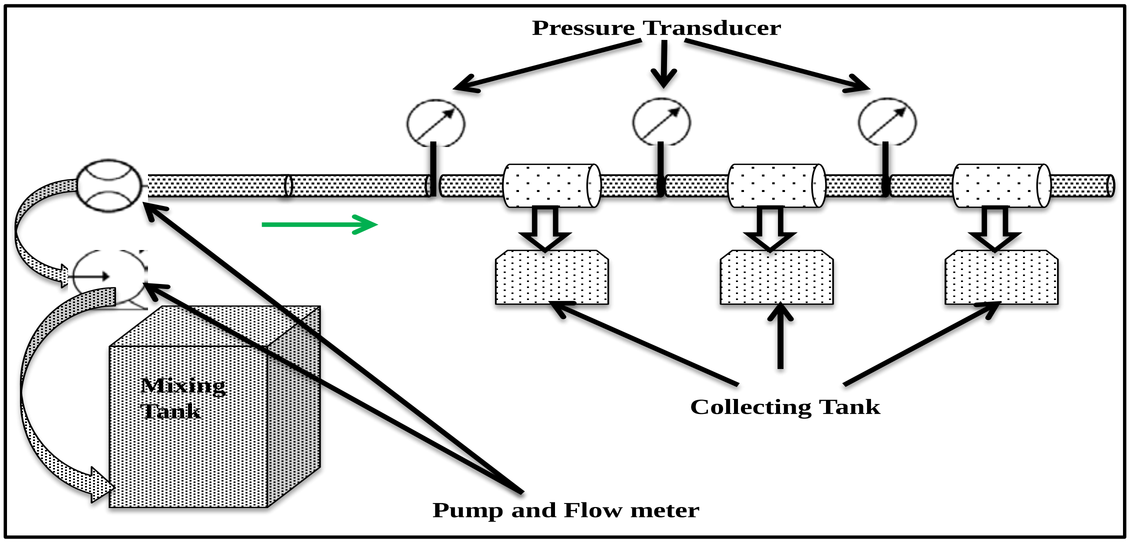


Figure 34: Schematic of proppant transport in horizontal wellbore experimental setup

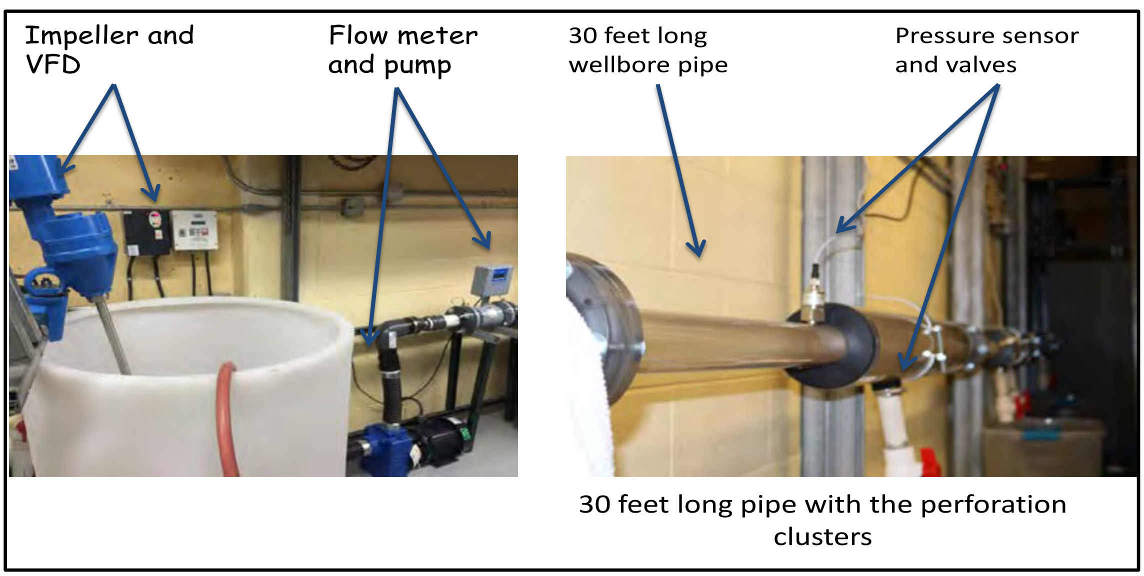


Figure 35: Images of proppant transport in horizontal wellbore experimental setup

Proppant Transport in Complex Fracture Network

We can study proppant transport in complex fracture systems. The experimental setup can be used to study proppant concentration and proppant transport behavior in each fracture network as well.

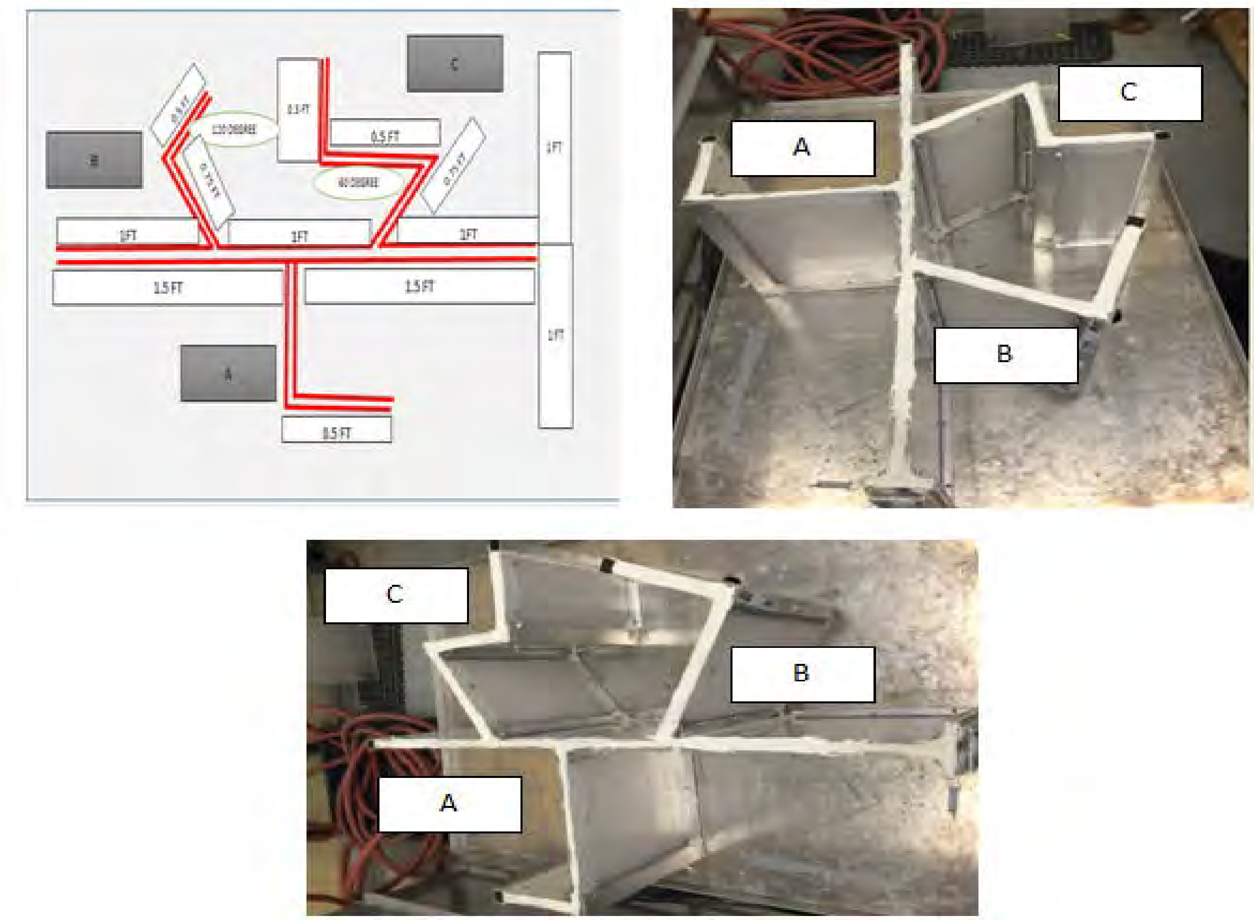


Figure 36: Schematic and images of experimental setup used to study proppant transport in a complex fracture system

Artificial Lift Experimental Facility

This experimental facility has been designed to test the performance and operation of new artificial lift equipment. The purpose of this device is to remove stagnated liquids from horizontal gas where low flow pressure and low flow rates (5 to 10 BPD approx.) are expected. The device prototype consists of a mandrel with two check valves that allow the injection of gas to remove stagnated liquids through a double tubing arrangement.

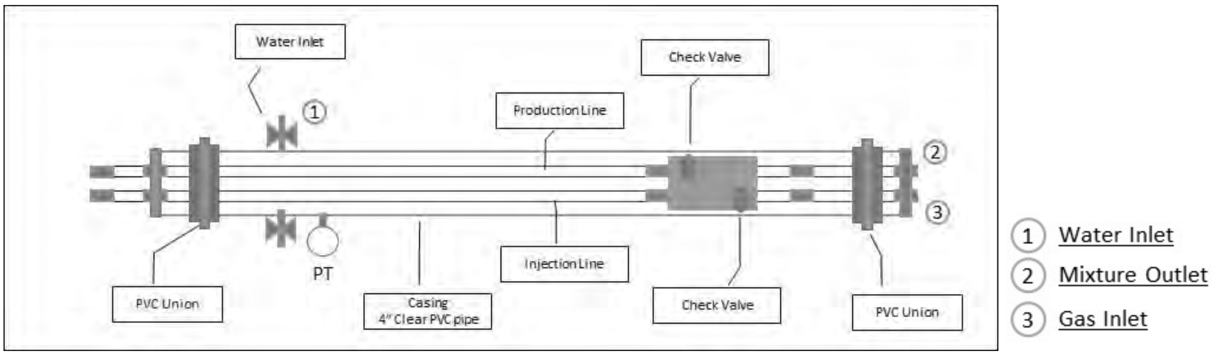


Figure 37: Gallop Installation Scheme

The mandrel is installed inside a 4’ ID casing which contains a water inlet valve that allows the entrance of low pressure liquids (less than 20 psi) form a continuous water supply line. As the liquid level reaches certain height within the casing, the mandrel allows the liquids to flow towards the tubing. Once the tubing is filled with water, compressed air from an external line is injected (between 30 and 60 psi of pressure) into one of the tubes, pushing the liquids along the horizontal section towards a 42’ long crystal PVC vertical line of ¾’ ID. This vertical section is followed by a recollection pipe which allows the injected gases out and measures the volume of liquids produced through a pressure transducer.

The designed instrumentation for the facility should allow us to measure the ratio of injected gas to recovered fluids. While continuous operation is done at 65 ^{o}F and under 60 psi, the facility has been designed to operate at up to 80 psi and up to 140 ^{o}F. Future modifications to the layout include the considerations for analyzing changes on the inclination of the horizontal section of the well.

Figure 38: Casing with Mandrel inserted

Figure 39: Top of the facility

The facility has been designed to recirculate the water inject/produced so to minimize the environmental footprint.

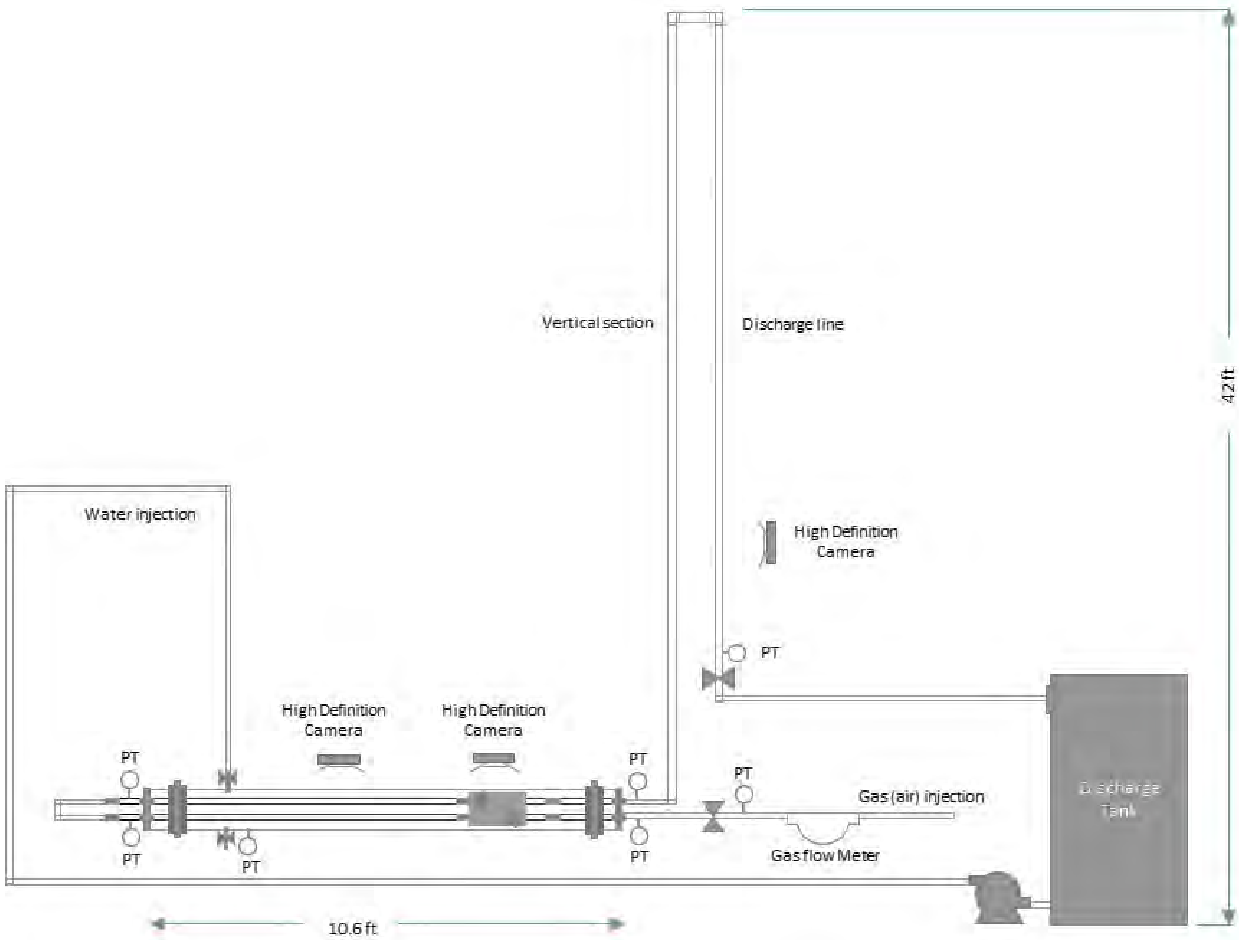


Figure 40: Schematic of the experimental test facility

Table 1: Fluids, operating conditions, and instrument

Fluids	Gas: Air Liquid: Tap water
Operating Conditions	• Pressure: 60 psi (Max 100 psi) • Temperature: Ambient (Max 140 F) • Gas flow rate (in): 0 to 0.03 MMSCFD (Superficial vel.: 0 to 95 ft/s) • Water flow rate (in): 0 to 11,314 BBPD (Superficial vel.: 0 to 150 ft/s)
Test Section	• Casing material: PVC • Casing dimensions: 4 in ID, 10.6 ft long • Production and injection lines: ¾ in ID. • Vertical section: Crystal PVC, ¾ in ID, 42 ft long • Pipes fitting and connections: Copper ¾-in ID

6-in. Flow Loop Experimental Facility

The facility operates with gas (Air), water (Tap Water) and oil (Low Viscosity Mineral Oil), and has been designed to study the effects of well trajectory on flow behavior in a test section, which is made of transparent acrylic pipe to observe the flow pattern along the flow loop. The inclination angle can be changed with a 3-ton capacity electric hoist. Based on the inclination angle, several well configurations can be simulated in this facility. Operating maximum pressure is 35 psi. The tests are conducted at ambient temperature. However, the operating conditions change depending on the project.

The experimental facility is designed to handle the following liquid and gas flow rates:

Table 2: Expected Flow Conditions

Fluid	Maximum Flow Rate	Minimum Flow Rate	Source
Tap Water	35 gpm	2.9 gpm	Water Tank + Electric Submergible Pump
Mineral Oil	35 gpm	2.9 gpm	Oil Tank + Progressive Cavity Pump
Air	1150 CFM	3.9 CFM	Air Blower

Test Section

Pipe Material: Acrylic
Diameter of Pipe: 6-in
Test Section: 32 ft
Inclination Angle: 0 – 90 degree
Maximum number of undulations: NA

Table 3: Instrumentation and Flow Characteristics

Measured Parameters	Instrumentation
Liquid Holdup	• Quick Closing Valves • Conductivity Probes
Flow Pattern	• Surveillance Cameras • High Speed Camera
Pressure Gradient	• Differential Pressure Transducer
Slug Flow Characterization (translational velocity, slug length and frequency)	• Conductivity Probes
Severe Slugging Characterization (Cycle duration, slug frequency and maximum expected pressure)	• Pressure Transducers

Facility Schematic: 6 in ID Flow Loop

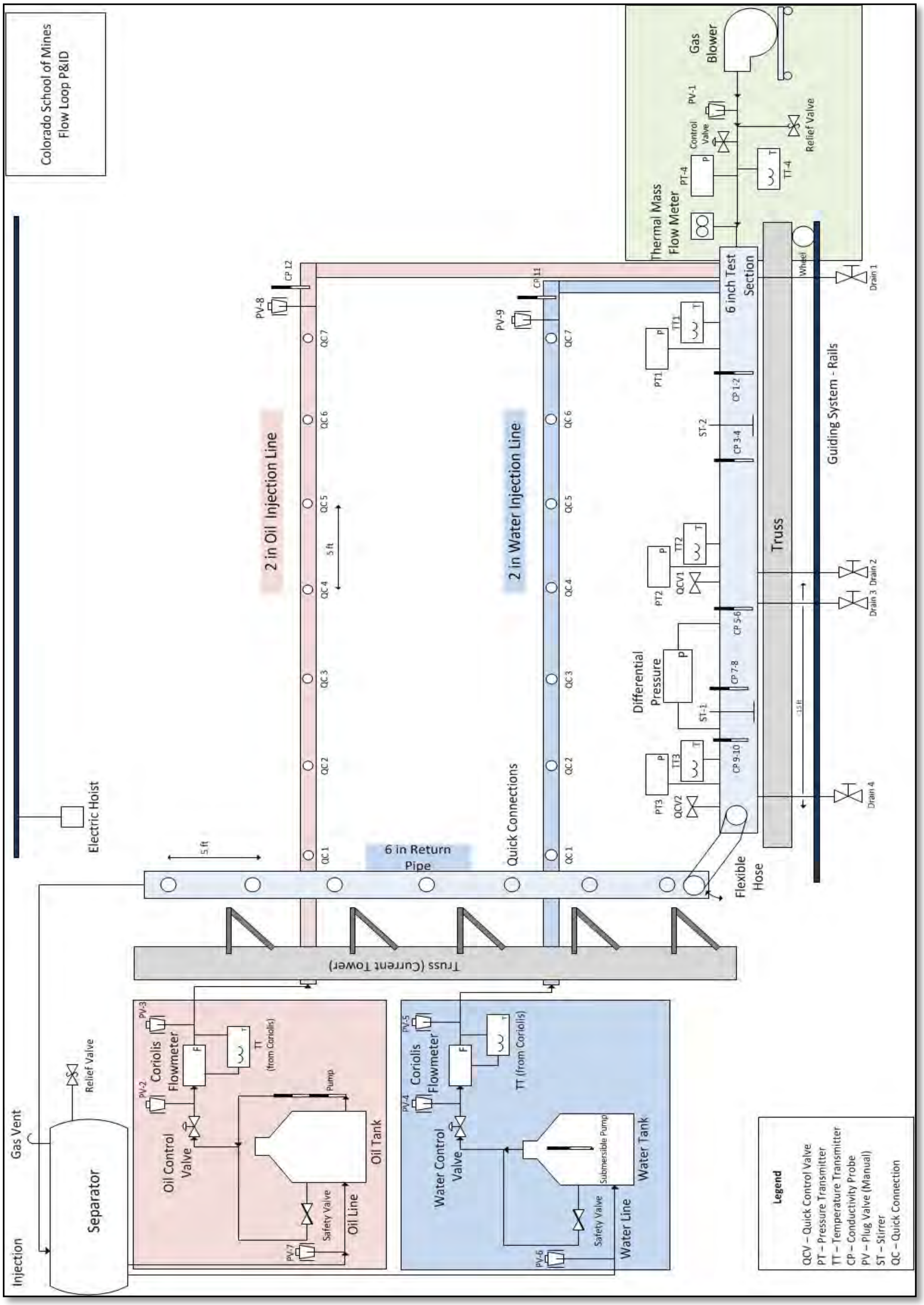


Figure 41: Schematic of 6 in ID flow loop

Laboratory Facilities and Instrument

Available for Research

Outside Petroleum Engineering Department

JEOL JSM-700F Field Emission Scanning Electron Microscope (FE-SEM)

The FE-SEM in the Electron Microscopy Laboratory in the Department of Metallurgical and Materials Engineering is a high resolution scanning electron microscope for nano analysis of structures and surface details. The instrument has a maximum resolution of 1.2 nm at 30kV.

The following parameters can be identified and analyzed using the FE-SEM on ion-milled samples:

1- Texture
2- Fabric
3- Morphology of the grains, matrix, and cement

Figure 42: Field Emission Scanning Electron Microspore (FE-SEM)

JEOL IB-0910CP Cross-Section Polisher

The JEOL cross-section polisher uses Argon ions to remove surface damage from a cut and grinds the surface of the specimen, creating a polished surface suitable for observation in a scanning electron microscope that is free of preparation artifacts.

Figure 43: The JEOL cross-section polisher

FEI QUANTA 600I Environmental Scanning Emission Microscope (E-SEM)

The E-SEM in the Electron Microscopy Laboratory in the Department of Metallurgical and Materials Engineering is a high performance instrument with three operating vacuum modes to accommodate a wide range of samples. The conventional mode is the High Vacuum Mode, which operates at up to 10^{-6} torr. The Low Vacuum Mode is used for imaging of non-conductive samples that cannot be coated with metal and the pressure specification for this mode ranges between 0.1 – 1.0 torr, using water vapor from a built-in water reservoir. The last mode is the Environmental Mode (E-SEM) where water vapor or auxiliary gas supplied by user can be used. The Environmental Mode operates between 1.0 – 10 torr. The E-SEM has a large chamber of 15" enabling the rotation of large specimens. The instrument also has a hot stage, with a temperature rating of 1500^{o}C.

The following parameters can be identified and analyzed from E-SEM:

1- Imaging of hydrated samples
2- Crystallization or phase transformation
3- Particles in suspensions
4- Tensile testing, with heating or cooling

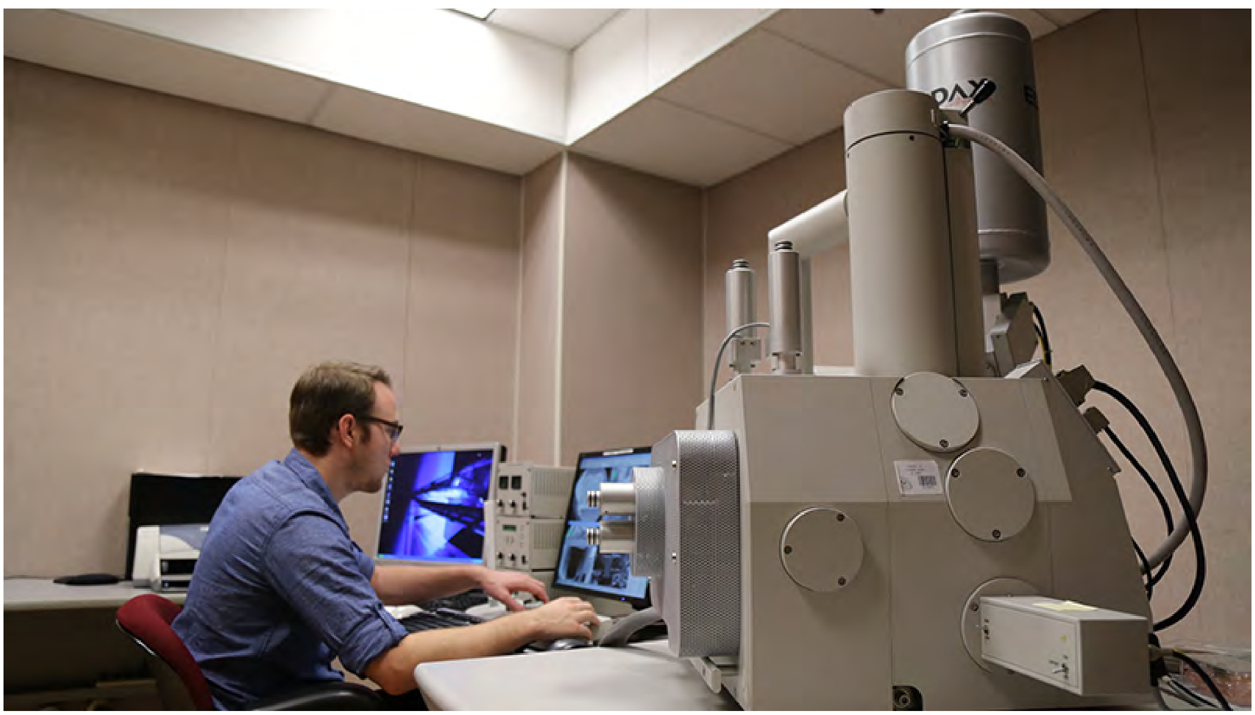


Figure 44: Environmental Scanning Emission Microspore (E-SEM)

TESCAN Integrated Mineral Analyzer (TIMA) and FEI QEMSCAN

Both TIMA and QEMSCAN instruments in Automated Mineralogy Laboratory in Geology & Geological Engineering Department is a fully automated SEM-based analysis system that provides quantitative mineralogical and textural data on the basis of automated point counting. The instrument contains a custom-built electron-beam platform equipped with four energy dispersive X-ray spectrometers (EDS) for mineral and compound identification within a wide range of sample types.

The software for each instrument allow for the automated stepping of the electron beam across samples at a user-defined pixel resolution (typically 1 – 40 micrometers). At each pixel, the system collects a backscatter electron (BSE) signal and an EDS spectrum. A mineral or phase identification is made on the basis of the BSE value and elemental intensities. Analysis was performed at an acceleration voltage of 25 kV and a specimen current of 5 nA for the QEMSCAN and a beam intensity of 14.5 for TIMA.

The analysis from these instruments provide quantitative mineralogical and textural data, false-color mineral maps, and robust statistical data which include

1. Highly accurate mineral (phase) abundance (i.e. modal abundance) maps
2. Element X-ray mapping
3. Particle and grain size
4. Particle and grain shape
5. Mineral associations
6. Lithotyping
7. Porosity quantification
8. Organic matter scans
9. Mineral (phase) liberation

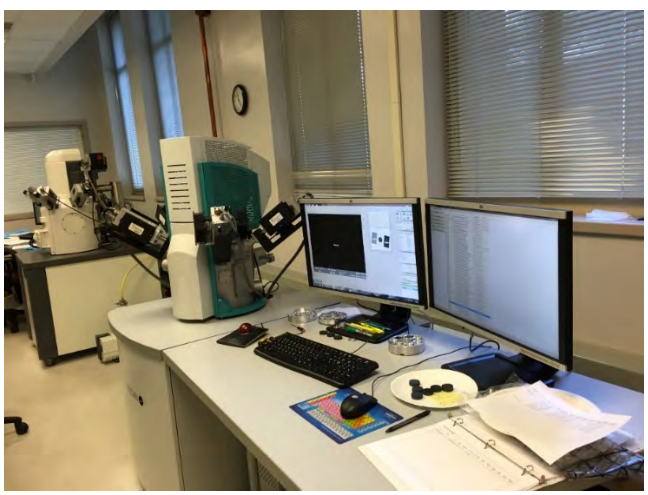


Figure 45: TIMA

TESCAN MIRA3 LMH Schottky Field Emission Electron Microscope (FE-SEM)

The FE-SEM in the Department of Geology and Geological Engineering is a state-of-the-art high resolution scanning electron microscope for nano analysis of structures and surface details. The SE detector has a maximum resolution of 1.2 nm at 30kV and 2.5 nm at 3 kV, and the In-Beam SE detector has a maximum resolution of 1 nm at 30kV.

We use secondary electron imaging for topography contrast study, backscatter electron imaging for phase contrast, and energy-dispersive X-ray spectroscopy for compositional analysis.

Figure 46: Field Emission Scanning Electron Microspore (FE-SEM image adapted from CSM website)

High-Field Nuclear Magnetic Resonance (NMR)

The state-of-the-art NMR instruments (JEOL 500MHz liquid state [Pulse Field Gradient – PFG] NMR and Bruker 400MHz solid state NMR) in the Chemistry Department can provide important information for structure characterization as well as molecular dynamics study. We have one 5 mm multinuclear double tuned liquid state NMR probe, two 4 mm multinuclear triple/double tuned Magic Angle Spinning Solid State NMR probes, and one diffusion probe (single axial DIFF 60) equipped with exchangeable 1H, 7Li and 13C coils.

The Chemistry Department has used both NMR instruments to study molecular structures, molecular interactions, and ion/molecule diffusivity. In Petroleum Engineering, we have used the instrument to measured self-diffusion coefficients for a couple of components.

Figure 47: 500MHz liquid-state (left image-adapted from CSM website) and 400 MHz solid-state NMR (right image-adapted from CSM website)