Latest Developments in Drilling and Cementing R&D

SPE Webinar – August 16, 2016

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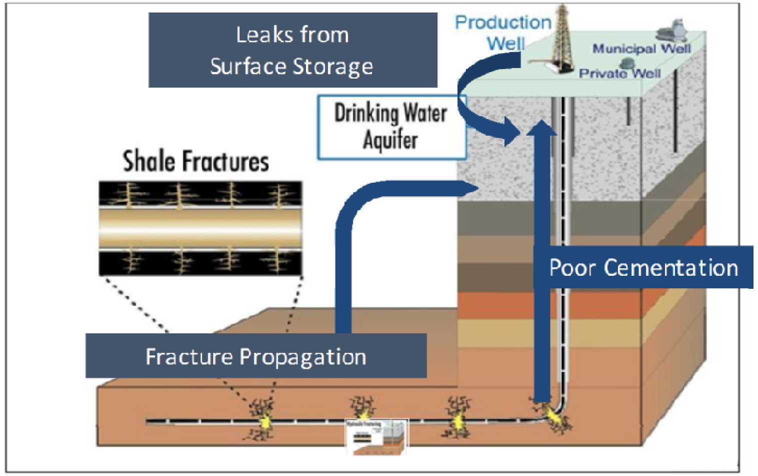
Presentation Outline

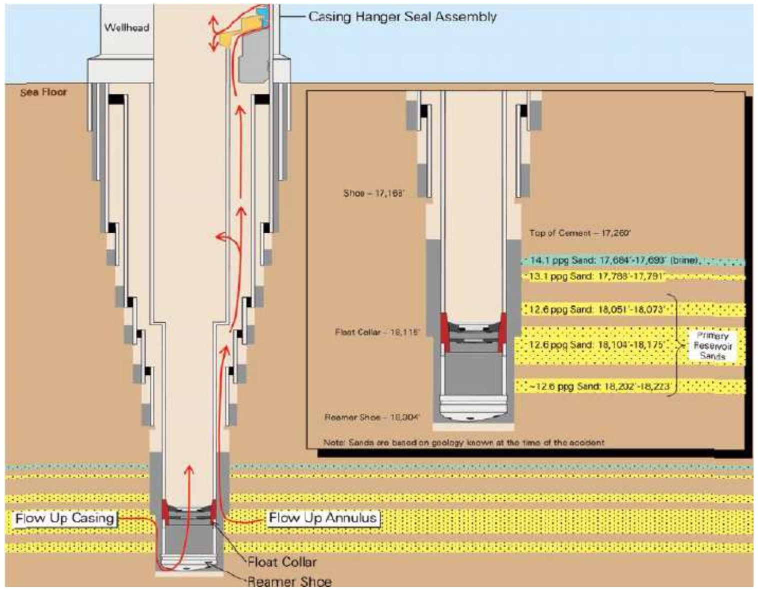
- **Cementing / Zonal Isolation / Well Abandonment**
  - Real-time cement monitoring with fiber optics
  - SBM/OBM consolidation with geopolymers
- **Drilling Fluids & Wellbore Strengthening**
  - Wellbore strengthening: Conventional & Thermal
  - High-performance WBMs & rock mechanics testing
- **Drilling Automation**
  - Automated fluid rheology measurement
  - Multi-phase flow simulation / automated well control / MPD control

Fiber Optic Cementing Sensors - 1

- Novel technology to address deepwater and unconventional zonal isolation concerns
- Actively monitor cement placement, cement hardening, cement fracturing/cracking and invasion by hydrocarbons in the cement sheet to verify cement quality and assure zonal isolation
- University of Texas at Austin: fiber-optic sensors in cement sheath, building on existing DAS & DTS fiber-optic monitoring technology



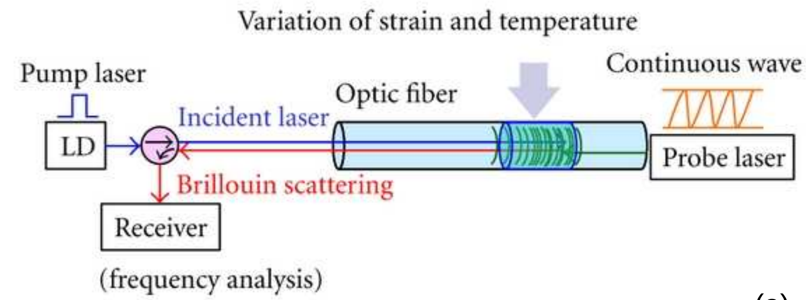
Source: Michael Holgate



Source: Deepwater Horizon Study Group

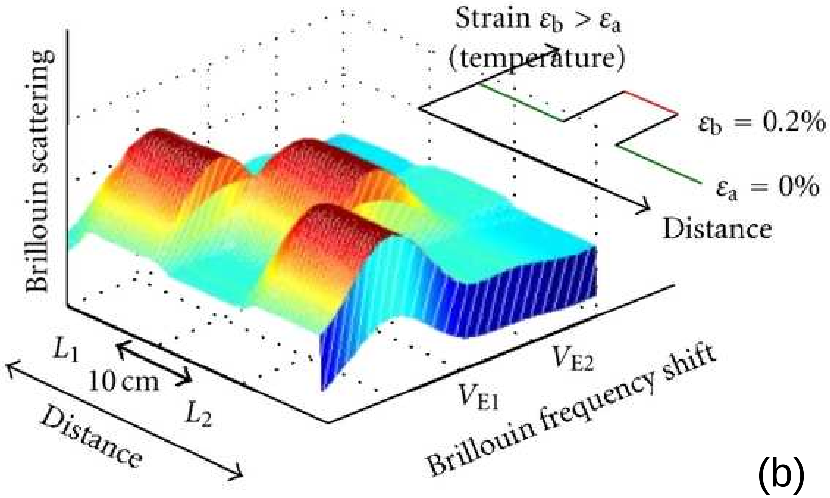
Fiber Optic Cementing Sensors - 2

- Distributed Temperature and Strain Sensing (DTSS) system (Neubrex)
  - Pre-Pump-Pulse Brillouin Optical Time-Domain Analysis (PPP-BOTDA)
  - Tunable Wavelength Coherent Optical Time Domain Reflectometry (TW-COTDR)
  - Based on Brillouin and Rayleigh back-scattering methods
- Measuring frequency shifts and amplitude modification due to temperature and strain effects in cement
- Extra-ordinary resolution (2 cm for cable of several km long) without the need for fiber gratings, using conventional comms cable



(a)

Source: Zhang & Wu, 2012



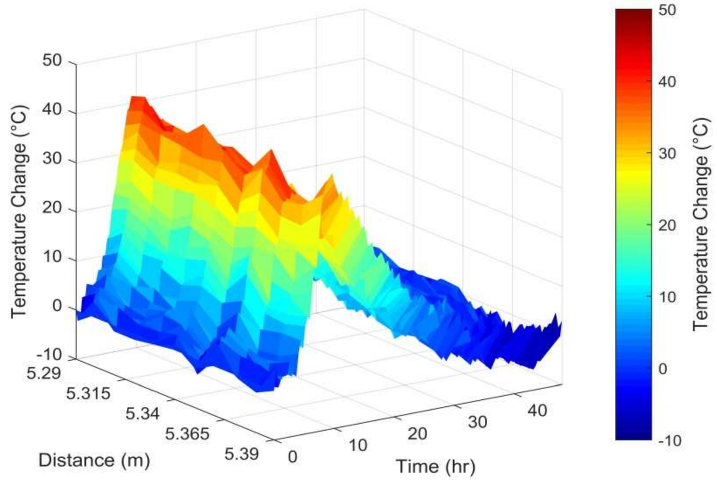
(b)

SPE 180329 & SPE 181429

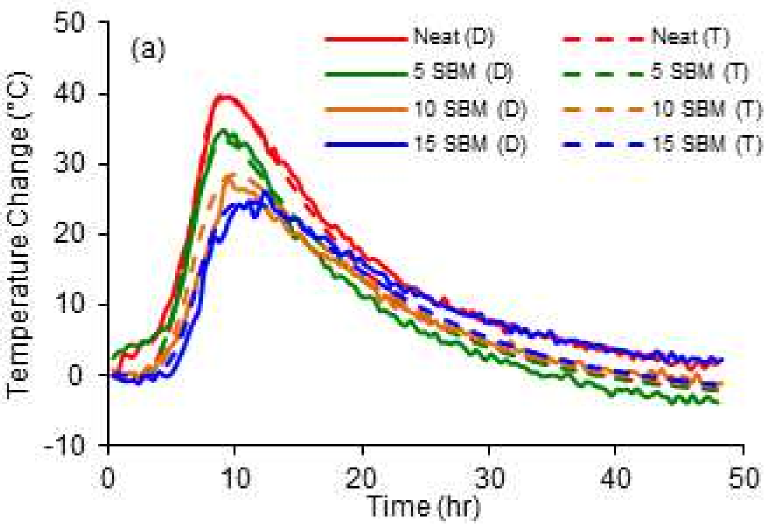
Fiber Optic Cementing Sensors - 3

- When cement sets, it reacts exothermically (i.e. releases heat)
  - Temperature and strain effect can be directly monitored using fiber optics
  - Can be used directly to monitor top of cement (TOC) and presence/ absence of cement behind casing
  - Will identify contamination of cement (lower exotherm)

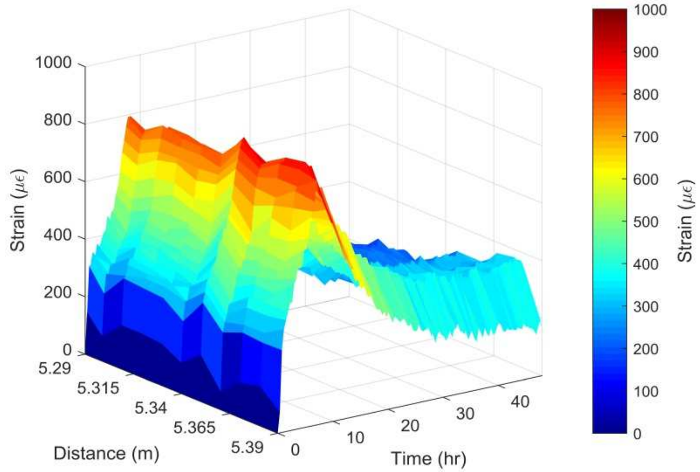
SPE 180329 & SPE 181429



Fiber-recorded temperature during cement set



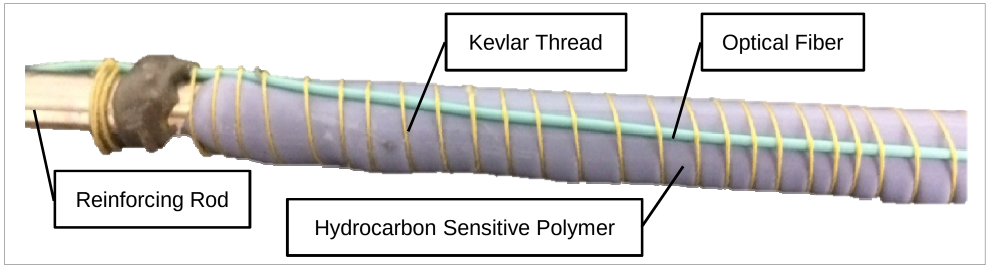
Effect of SBM contamination on cement exotherm



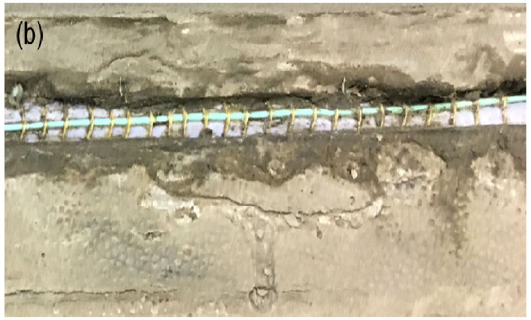
Fiber-recorded strain during cement set

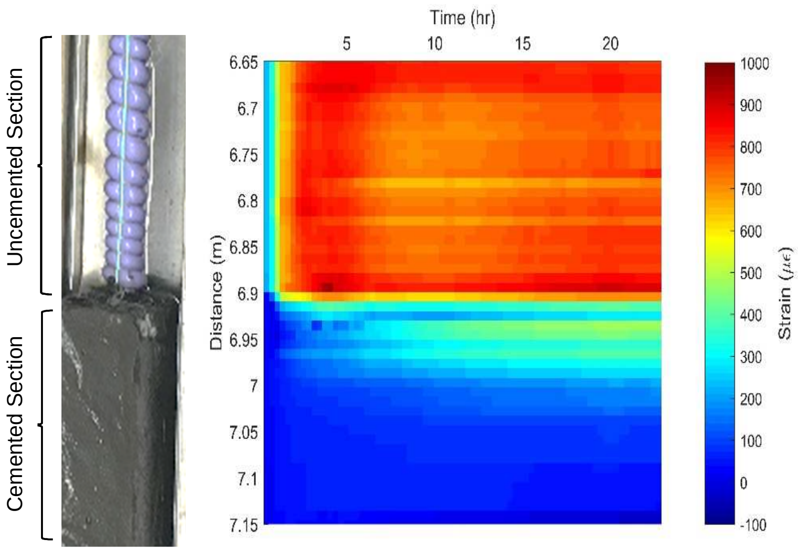
Fiber Optic Cementing Sensors - 4

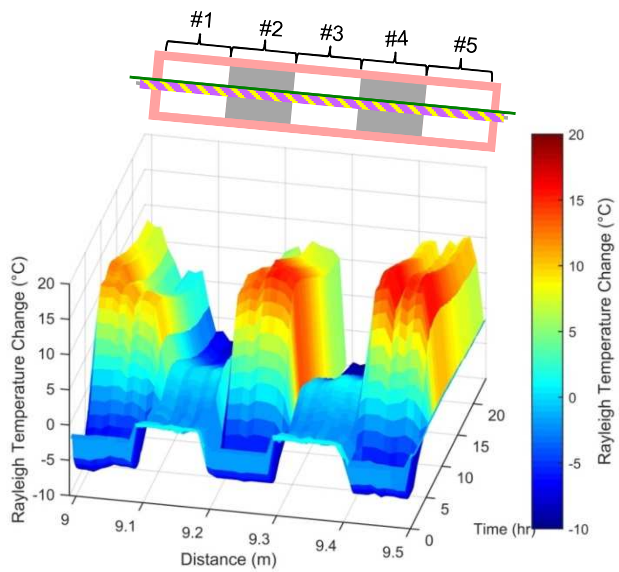
- Fiber optic technology is enhanced to detect invasion of hydrocarbons in cement sheath
- A hydrocarbon-sensitive polymer surrounding the fiber swells when contacted by hydrocarbon gas or oil, imparting strain on the fiber that is detected
  - To detect flaws, cracks, fractures, voids and channels in the cement



Sources: SPE 180329-MS
SPE 181429-MS

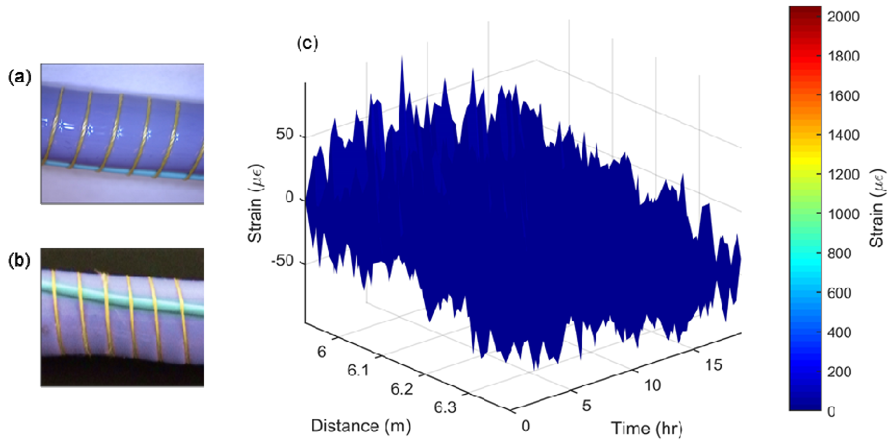




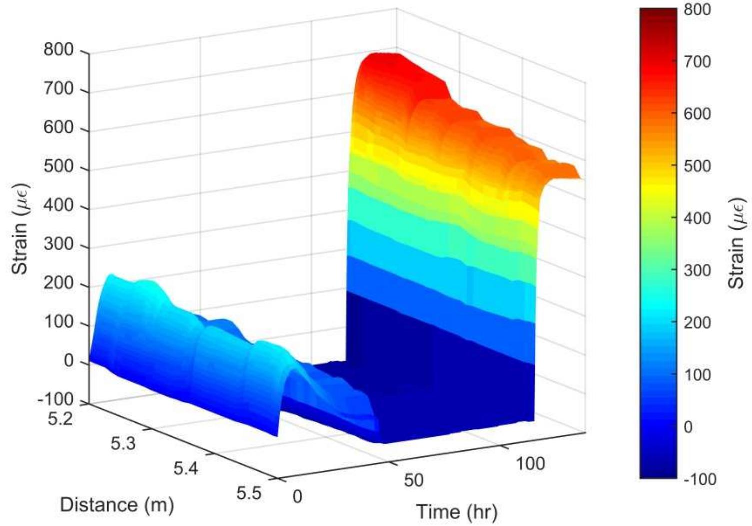


Fiber Optic Cementing Sensors - 5

- Merits of fiber-optic system:
  - Selectively detects only natural hydrocarbons, does not react with (synthetic) mud, spacers, brine etc.
  - Deployed outside of casing, similar to current DAS/DTS technologies
  - Continuous, real-time measurement is possible, for the entire life of the well, without need for wellbore re-entry
  - **Direct monitoring of a primary barrier!**
- Currently developing field-deployable cable, looking for partnering and field-trial opportunities
- Part of the sophisticated sensor work that is carried out in the **RAPID** (**R**ig **A**utomation and **P**erformance **I**mprovement in **D**rilling) consortium



Negligible strain response to brine

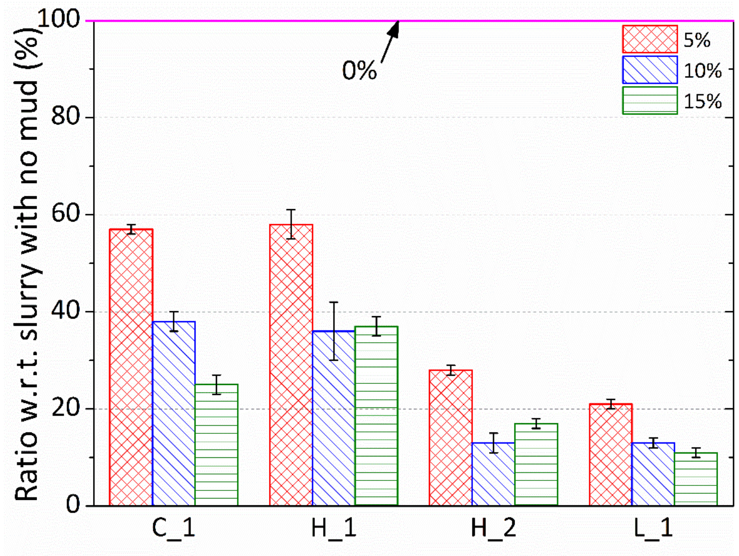


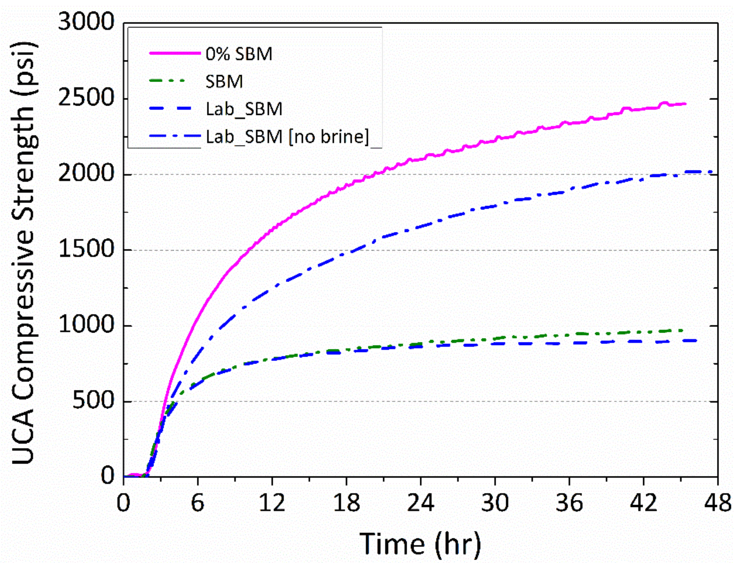
Fiber response during simulated cement displacement

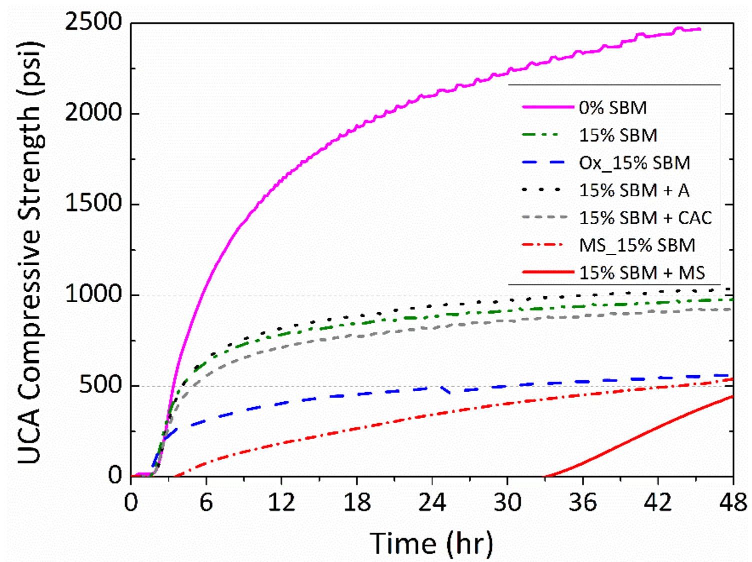
SPE 180329 & SPE 181429

Geopolymer Cement - 1

- Portland cement is very sensitive to contamination by SBM/OBM
- Particular concern for deepwater cementations and long ERD / horizontal OBM displacements
- Additional contamination effects from spacer fluids, etc.



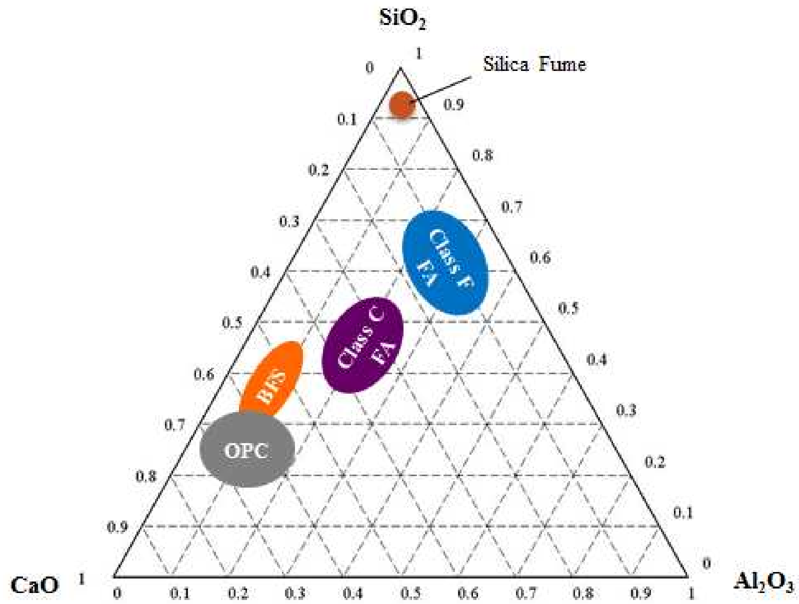




Contamination of class C, H and Lightweight Portland cement, SPE 170325

Geopolymer Cement - 2

- Not really a “polymer” but an alkali activated material (AAM) such as fly ash
- Geopolymers: introduced in 1970’s, used extensively in civil engineering
- Portland = Calcium Silicate
  Geopolymer = Alumino Silicate
- Negligible CO_2 emission during manufacturing compared to Portland!



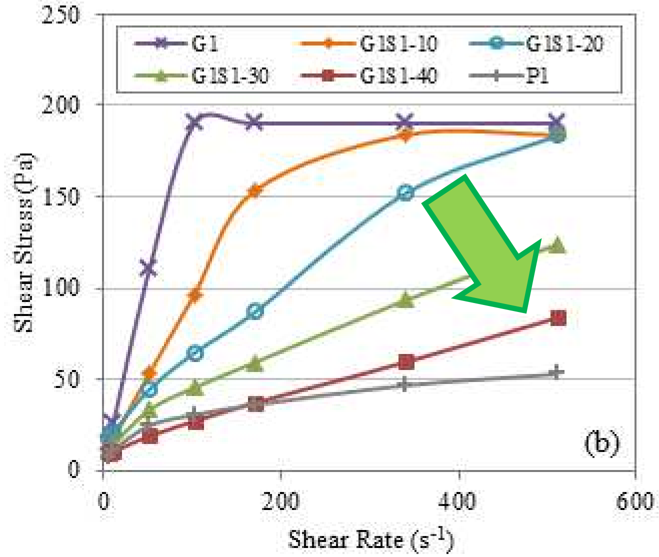
Aluminosilicate

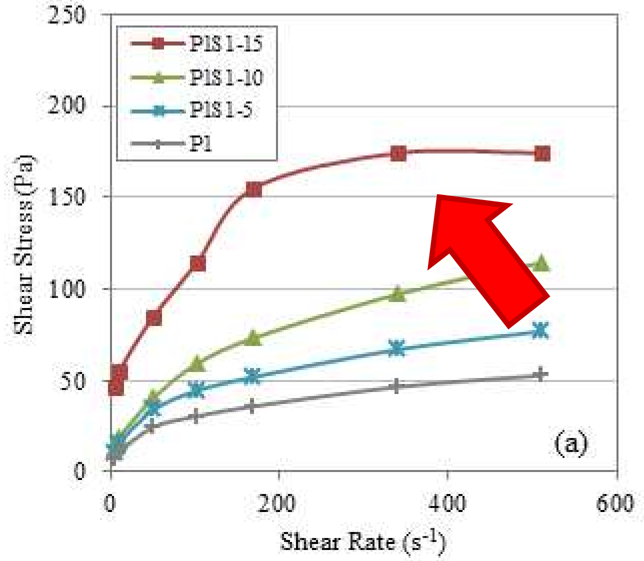
Alkaline Activator

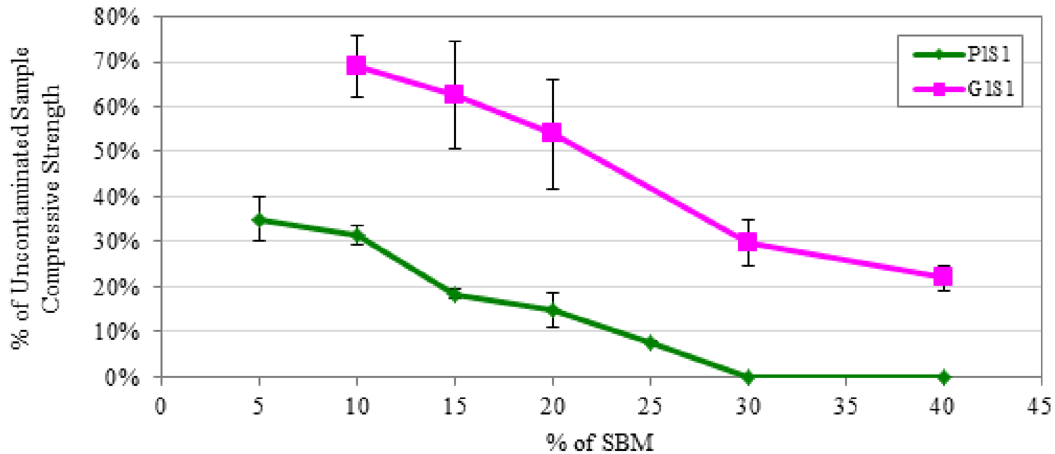
Geopolymer

Geopolymer Cement - 3

- Neat geopolymer cement can be poured (for road bases), but unfortunately not pumpable
- Discoveries & inventions:
  - Geopolymers have elevated OBM/SBM contamination resistance
  - OBM/SBM contamination lowers viscosity and makes geopolymers pumpable
  - Geopolymers can solidify and consolidate OBM/SBM
  - Technology can be used for primary cementation, lost circulation treatment, and waste consolidation!
- By contrast, Portland becomes unpumpable during SBM contamination

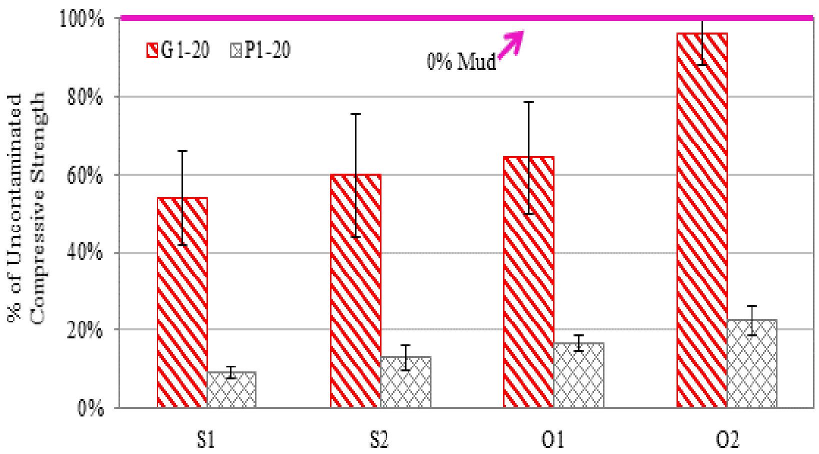






Geopolymer Cement - 4

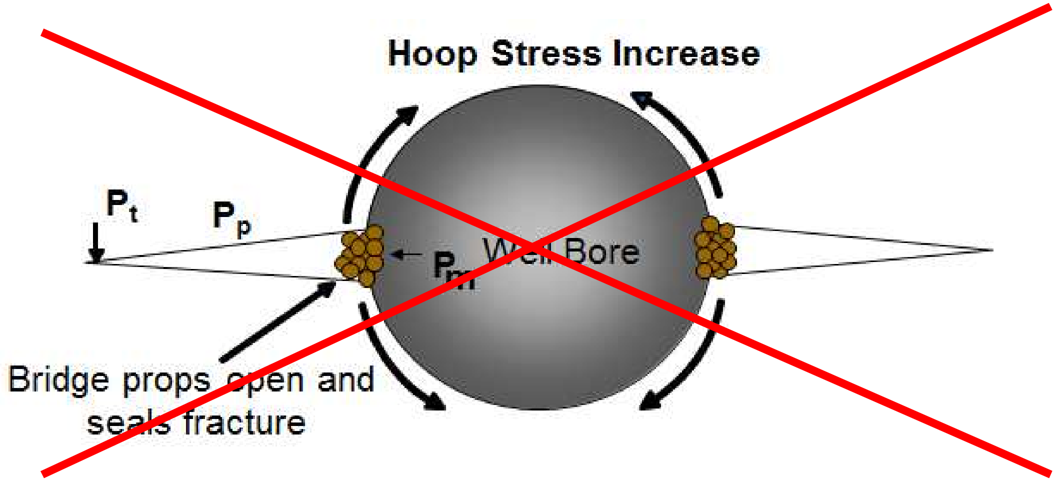
- Geopolymers appear to be superior alternatives to Portland cement for:
  - Lost circulation control (SBM contamination resistance, tunable strength)
  - Well abandonments
  - Primary cementations
- Current work revolves around additive development and formulating field-deployable systems



Geoploymer-consolidated OBM, 900 psi cube strength after 24 hours, SPE 180325

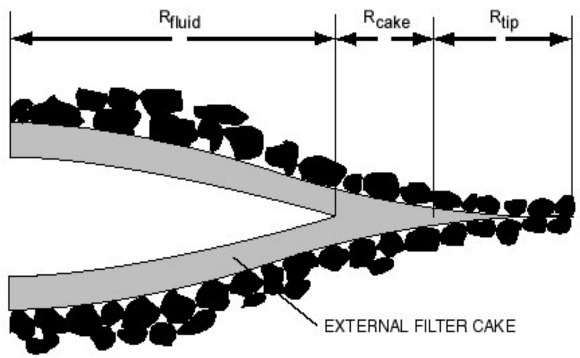
Wellbore Strengthening

- Thoroughly invalidated the idea of enhancing near-wellbore stress as explanation for wellbore strengthening (WBS)
  - Stress Caging and Fracture Closure Stress not supported by experimental data & field evidence
- Instead, WBS is due to elevated fracture propagation pressure through resistance from bridging particles

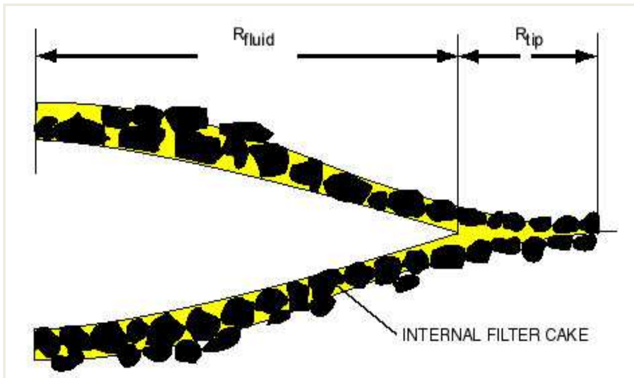


After SPE 90493; IADC/SPE 87130

Fracture propagation in WBM:
Full pressure shielded from tip by filter cake



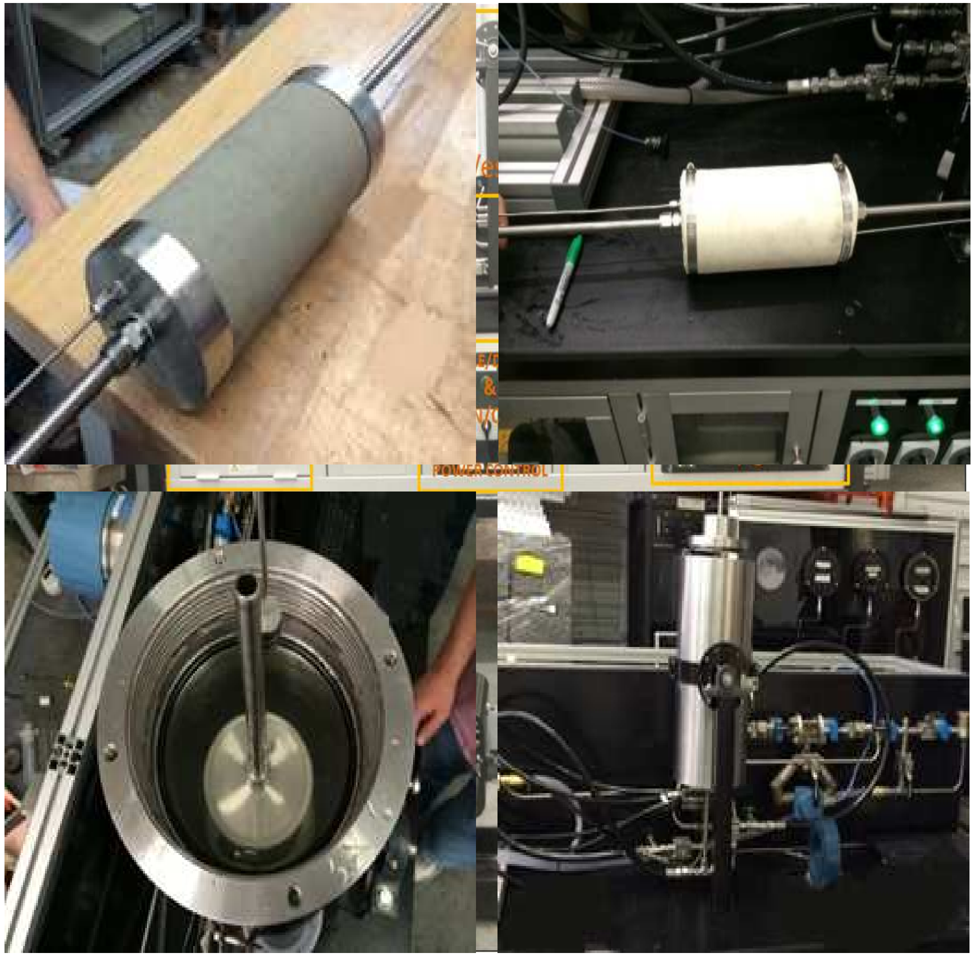
Fracture propagation in OBM/SBM:
Full pressure essentially at fracture tip.



After SPE 20409 , 22581 & DEA 13

UT MudFrac Experimental Equipment

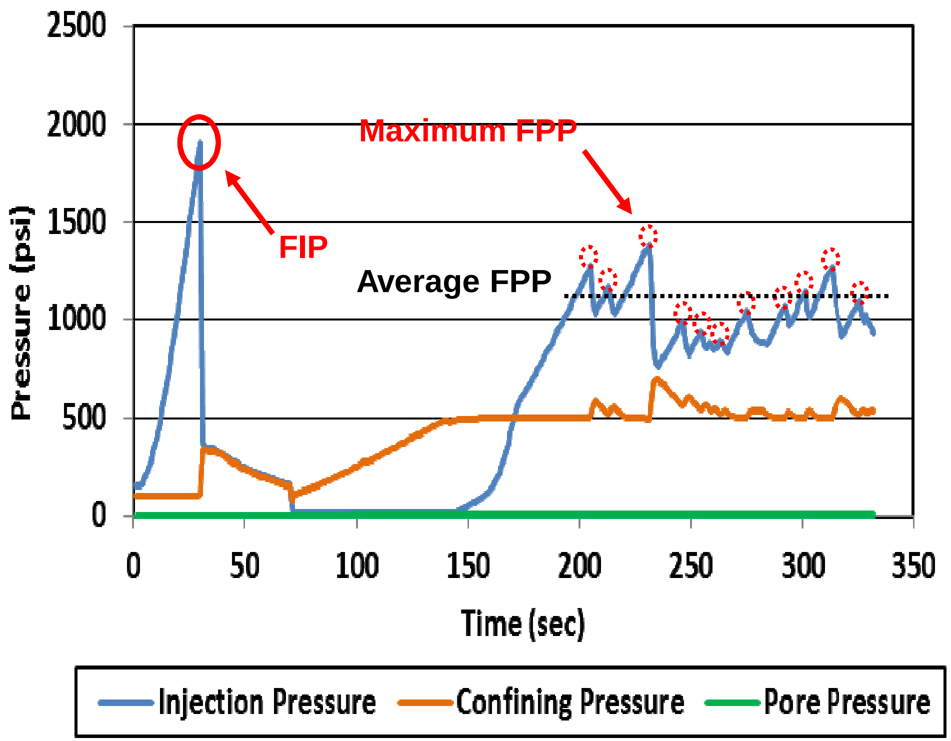
- The UT MudFrac set up is a state-of-the-art dual flow-loop/pressure-intensifying system for fracturing experiments under confinement
- Cylindrical rock samples of 4 inches diameter x 6 inches long are used (9/16" borehole)
- The sample is isolated using steel end-caps in the axial direction and a rubber sleeve in the radial direction
- The UT MudFrac System applies isostatic stress and pore pressure to the sample



SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

Fracture Initiation & Propagation

- Fracture Initiation Pressure (FIP) is marked in MudFrac experiments by a distinct peak in the injection pressure, followed by a sudden drop in the injection pressure and a simultaneous jump in confining pressure.
- Fracture Propagation Pressure (FPP) is distinguished by an injection pressure ramp up to a local maximum.
- FPP is best characterized by taking the average of injection pressure local maxima.

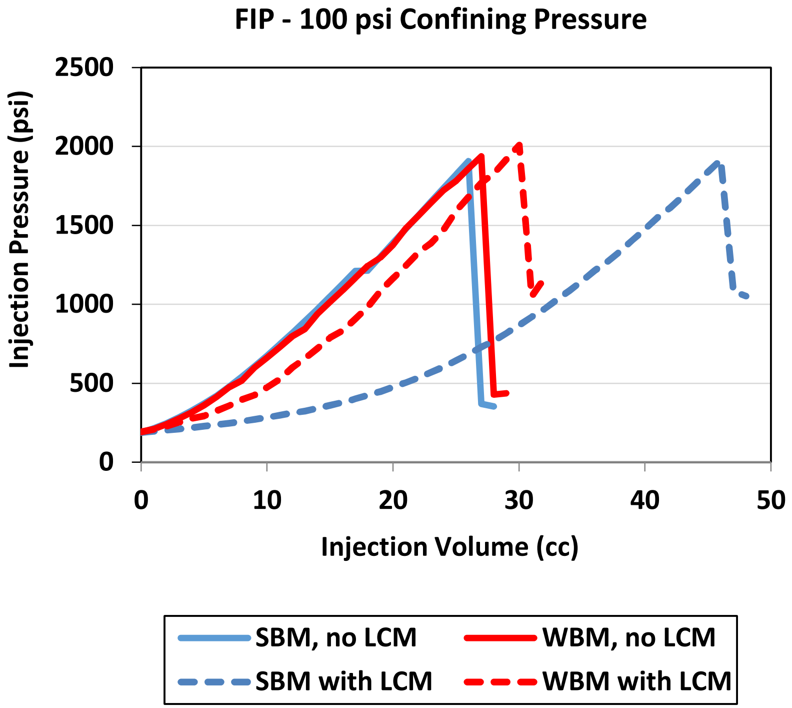


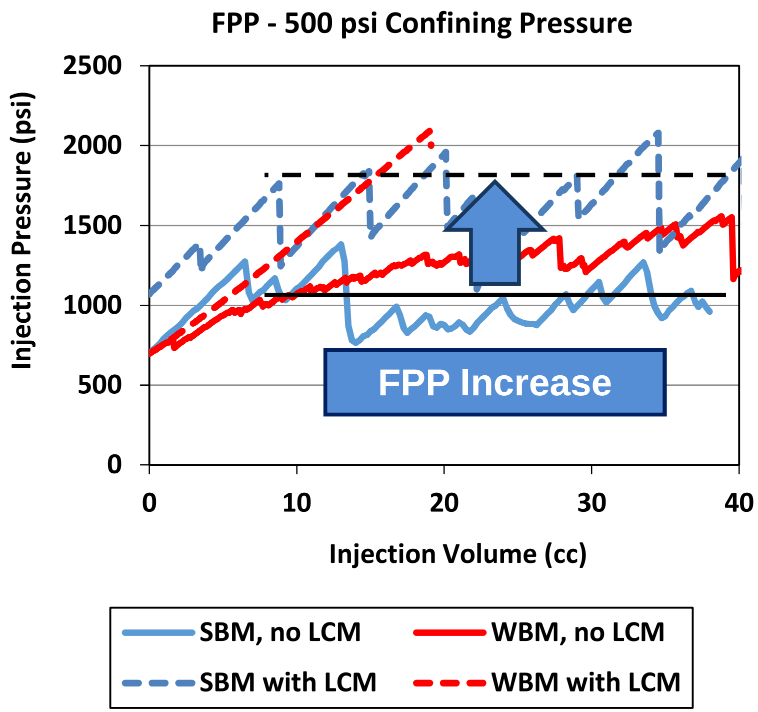
SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

Validation Experiments

- FIP is independent of drilling fluid formulation.
- No augmentation of the near wellbore tangential stress (hoop stress) is observed by adding LCM to the mud.

- The mud formulation have a significant effect on FPP.
- FPP increases significantly (>50%) by adding the proper LCM.

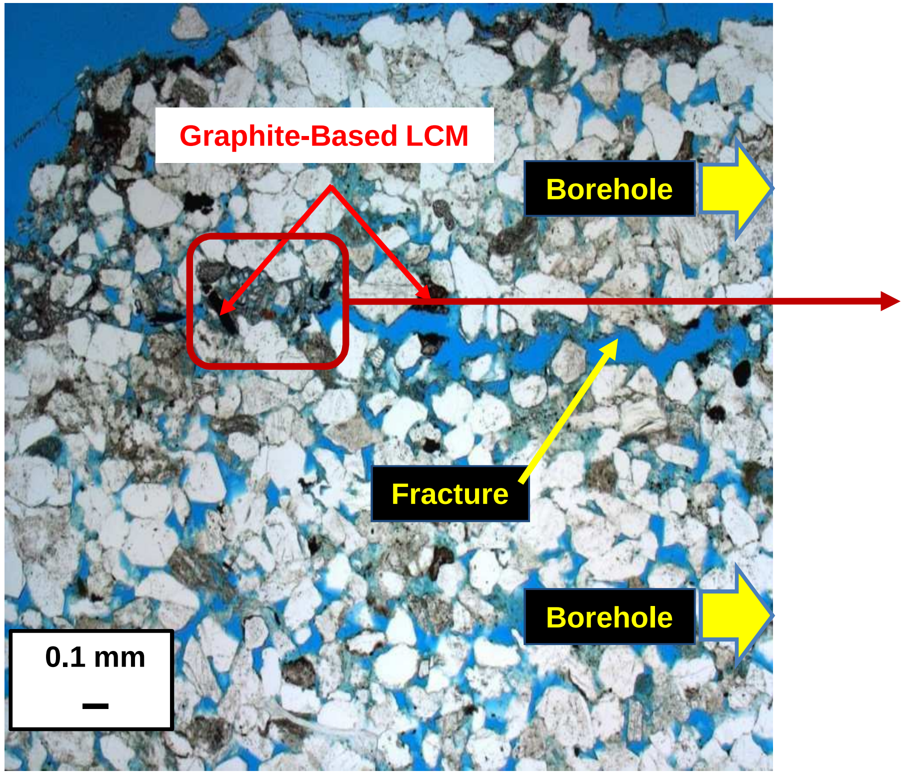


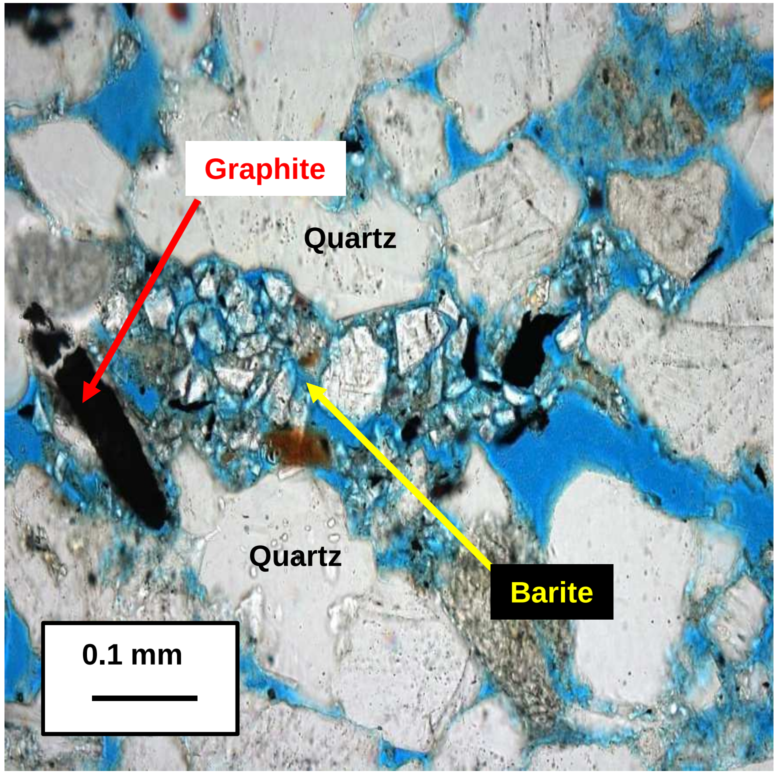


SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

Thin-Section Analysis

- Petrographic imaging indicates that the seals are formed in the close vicinity of the fracture-tip, **not** at the borehole face.

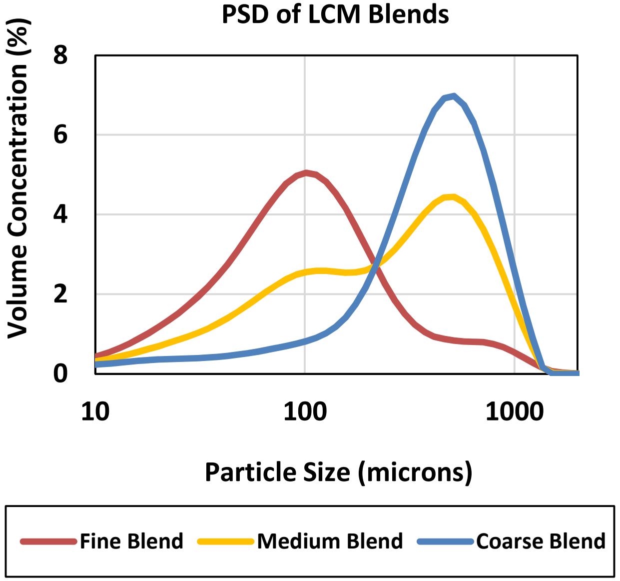




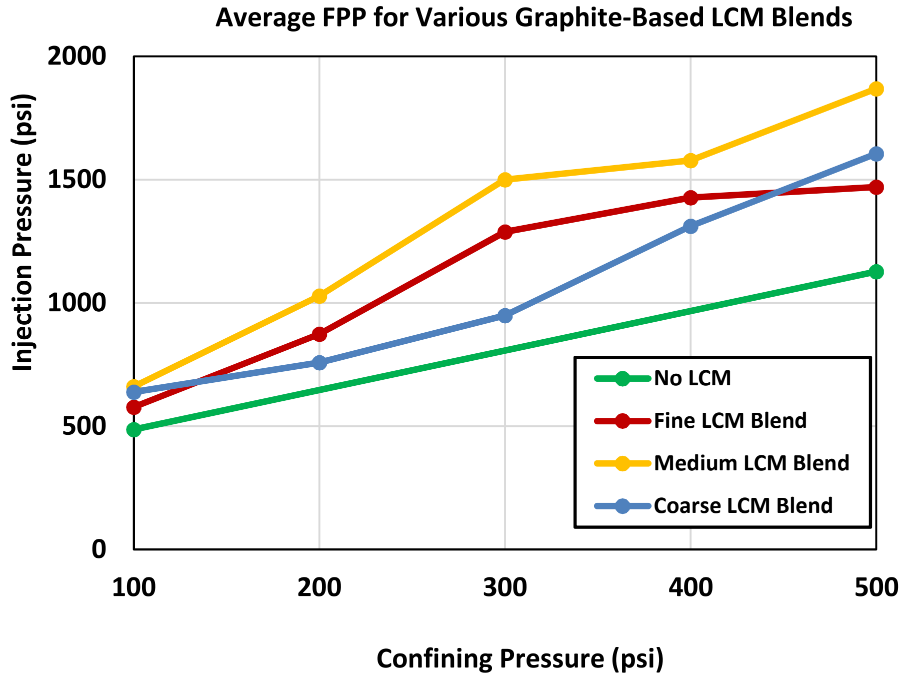
SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

Optimum LCM PSD

- A fine and a coarse grade were tested individually, and they were also combined to form a “medium” bi-modal grade.
- There is an optimum PSD which maximizes the strengthening effect.
- The optimum LCM has a distinct bi-modal PSD (tri-modal with weighting agent).



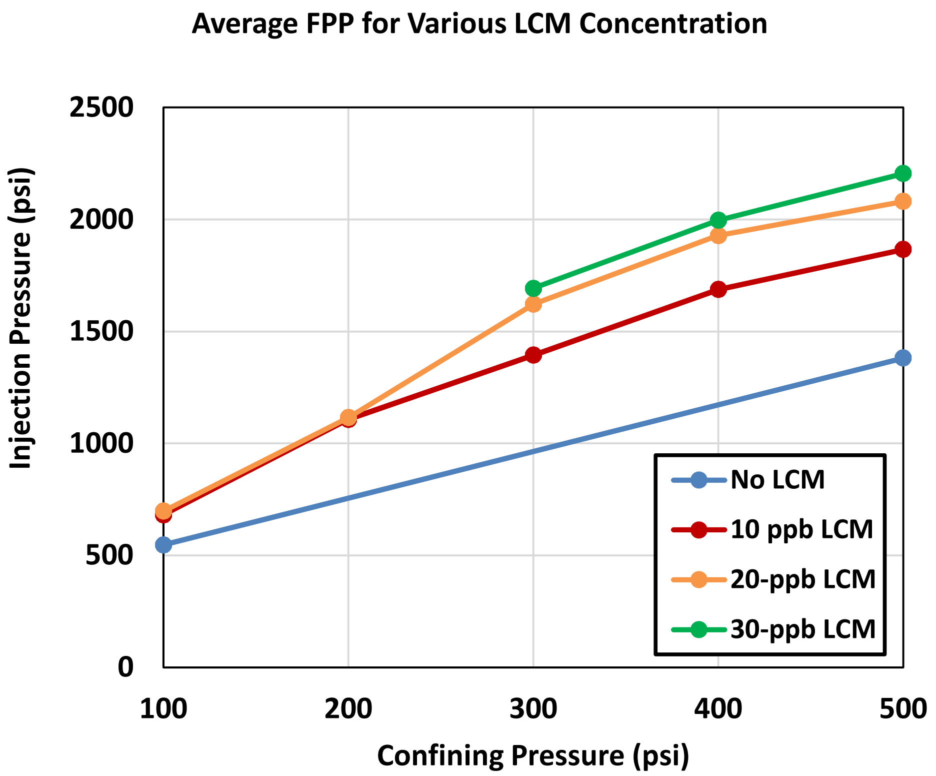
LCM Blend	Fine	Medium	Coarse
Median Size d_{50} (µm)	90	217	393



SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

Optimum LCM Concentration

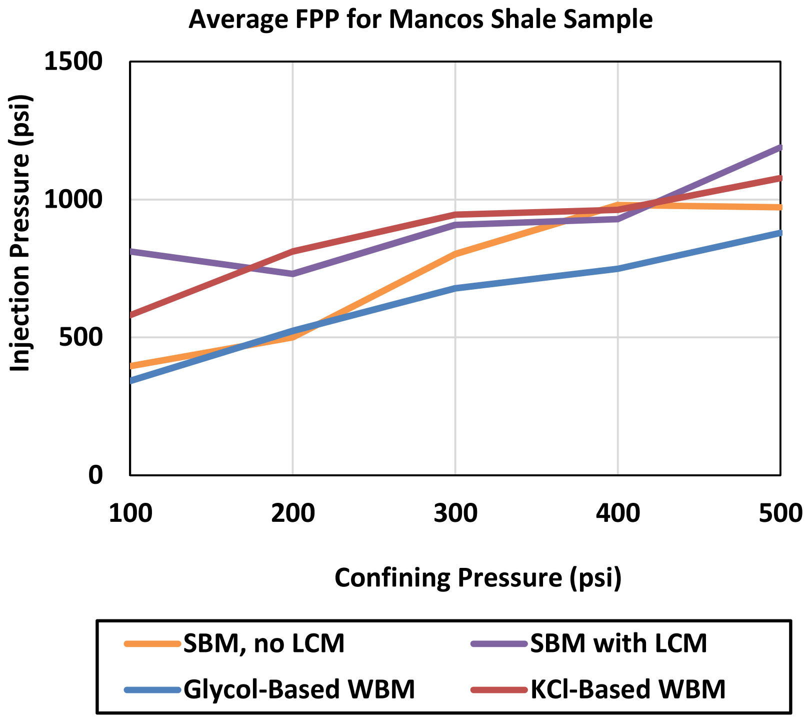
- Increasing the LCM concentration results in significantly higher FPP
- Beyond a certain concentration (i.e. 20 ppb for Berea sandstone), no significant further increase in FPP was observed (for Berea sandstone fractured with 12 ppg mud)
- The optimum LCM concentration may vary with change in mud density and/or rock type

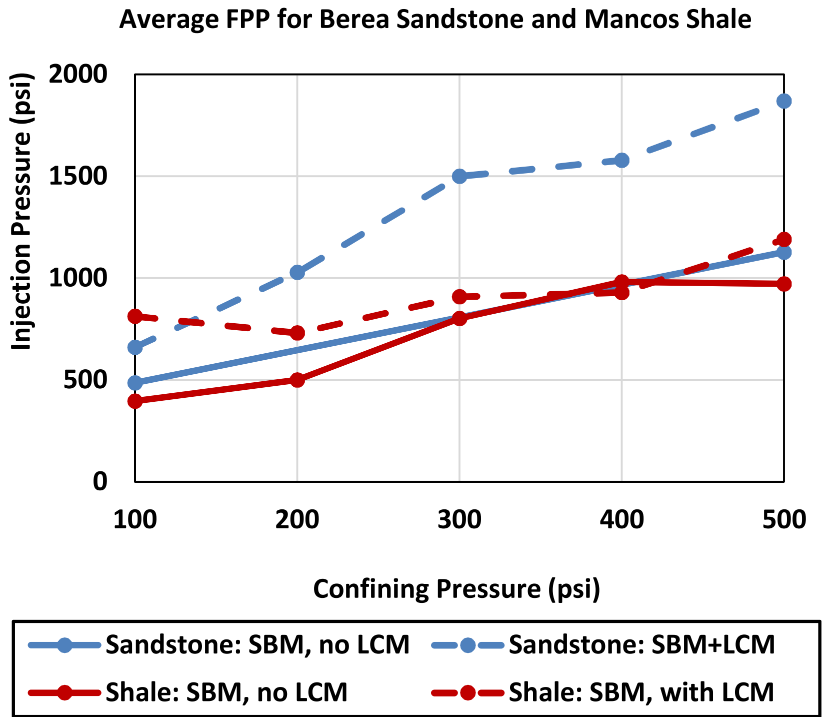


SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

Shale Fracturing Experiments

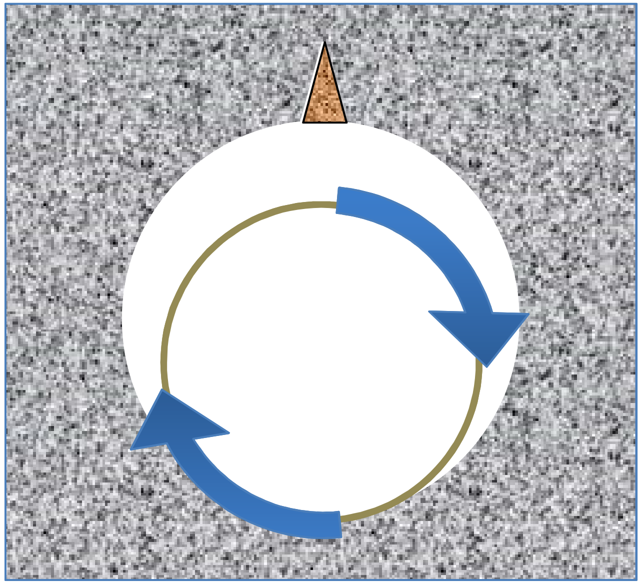
- Four shale samples were tested using two SBMs (with and without LCM) and two WBMs (Glycol- and KCl-based).
- Unlike sandstone samples, adding LCM to the drilling fluid had only minor effects on FPP enhancement in shale samples.





SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

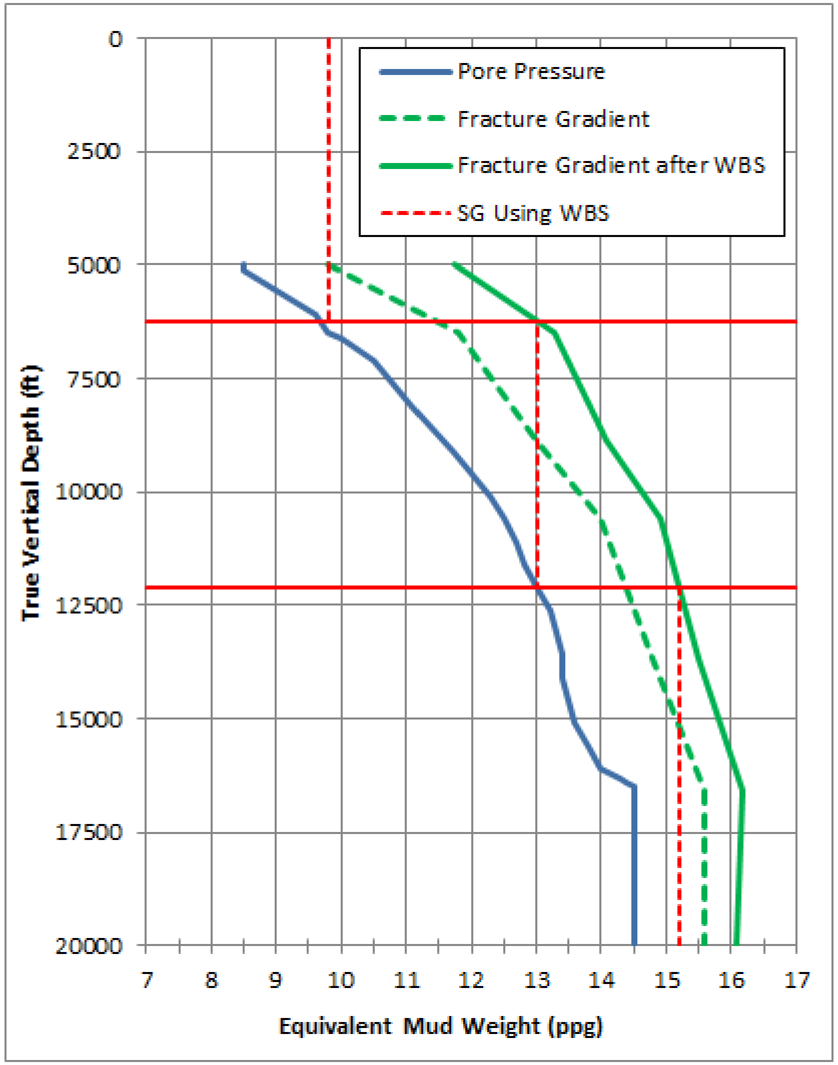
“Casing Smear” Explanation



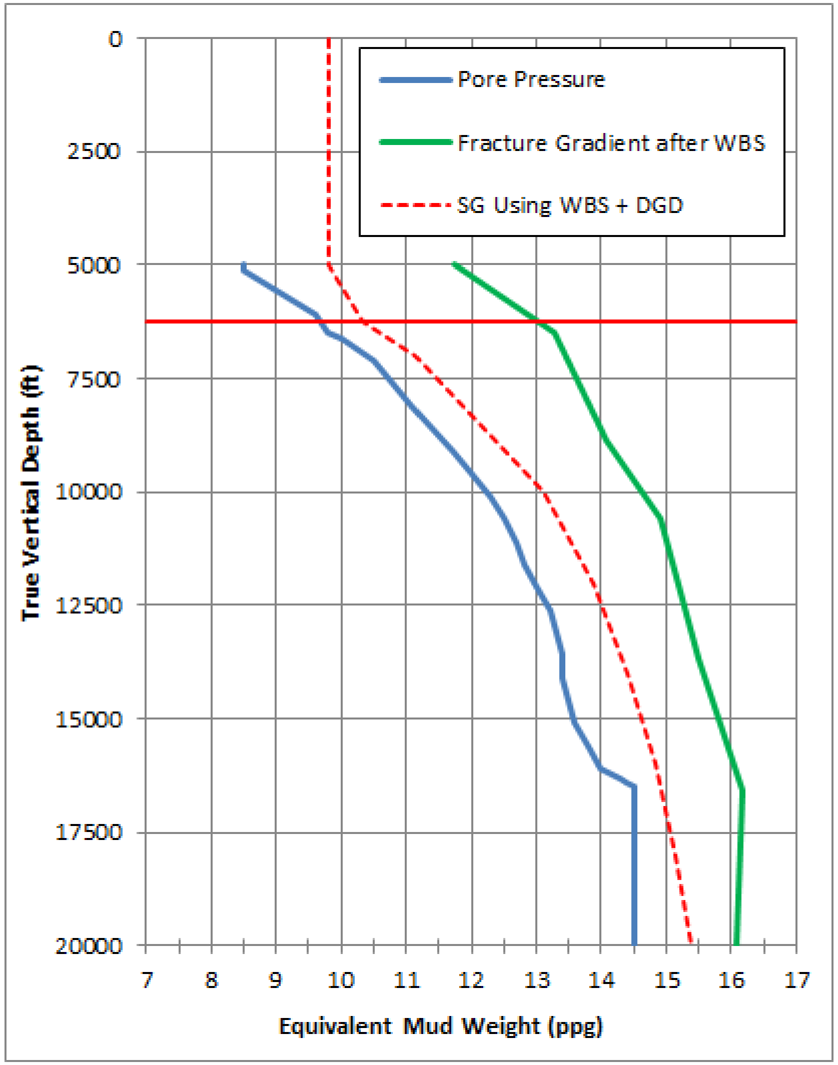
- Casing effectively grinds cuttings to small size
- Broad particle size distribution in the mud, supplemented with (coarse) LCM
- Any time a fracture initiates…..
- ……it quickly gets plugged with particles from the mud……….
- ……which raises the FPP……….
- and prevents further losses
- The CWD - WBS process is so effective because it is continuous, protects formations continuously, and does not allow fractures to grow to large(r) size
- The open hole LOT data tells the whole story, no further assumptions need to be made to explain the strengthening effect

SPE 168041; SPE 180341; SPE 180467; ARMA 16-694; SPE 180315

DGD and Wellbore Strengthening

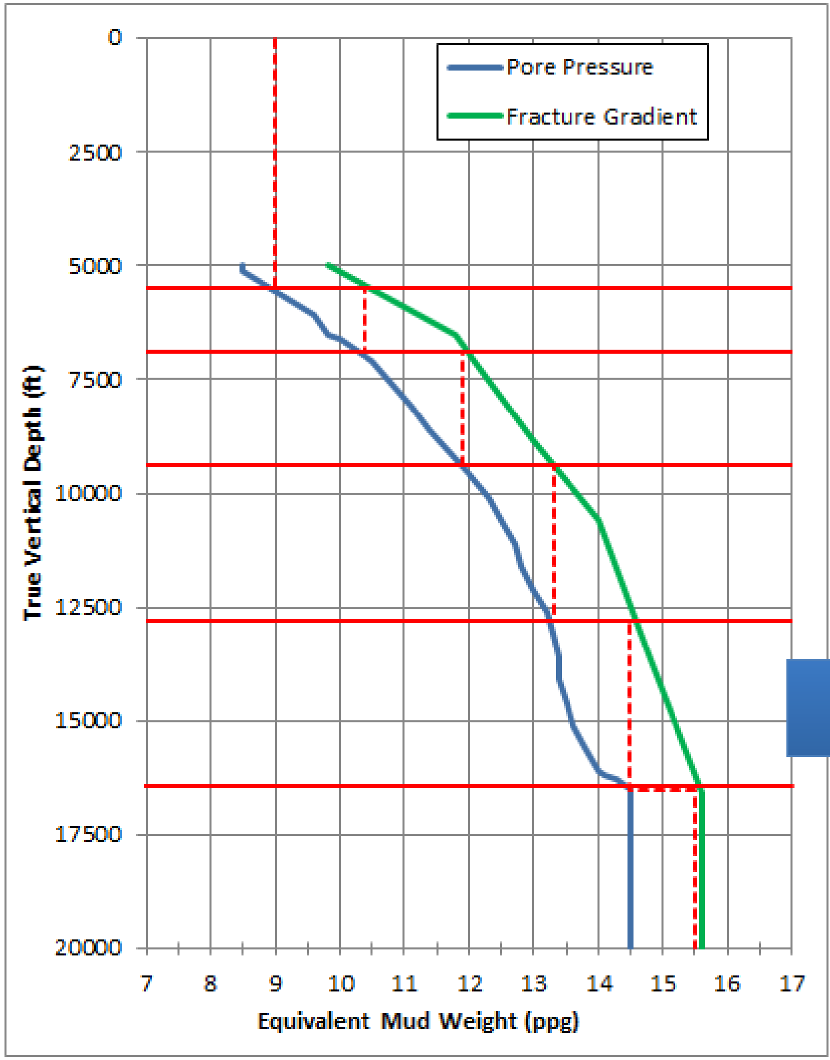


3 casing strings WBS

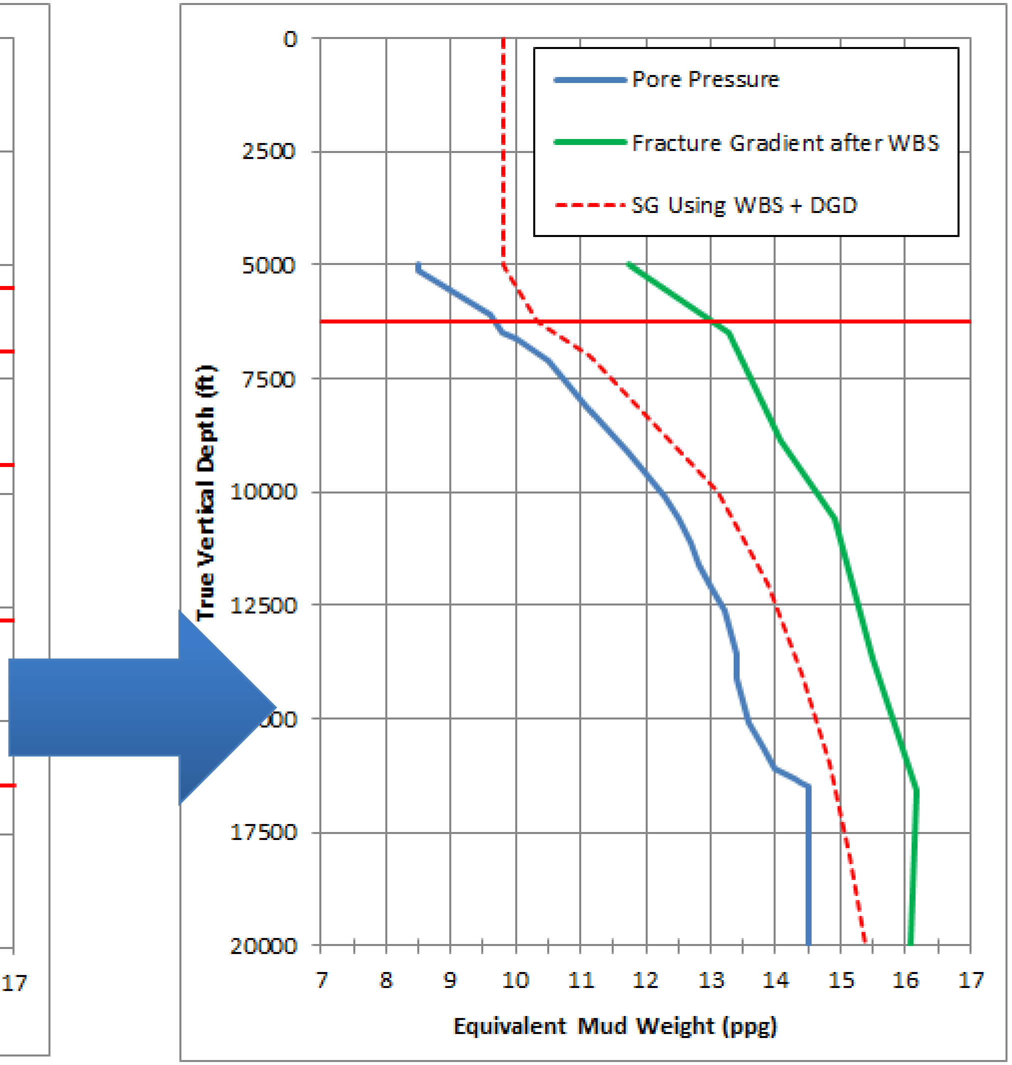


2 casing strings WBS + DGD

A Radical Change in Casing Point Selection



6 casing strings conventional



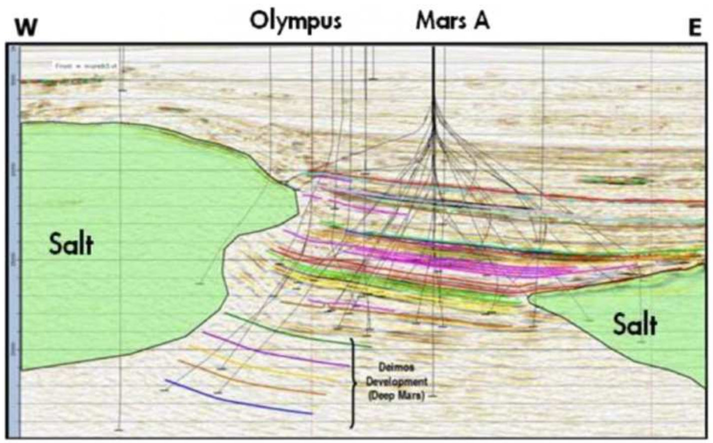
2 casing strings WBS + DGD

Thermal Wellbore Strengthening

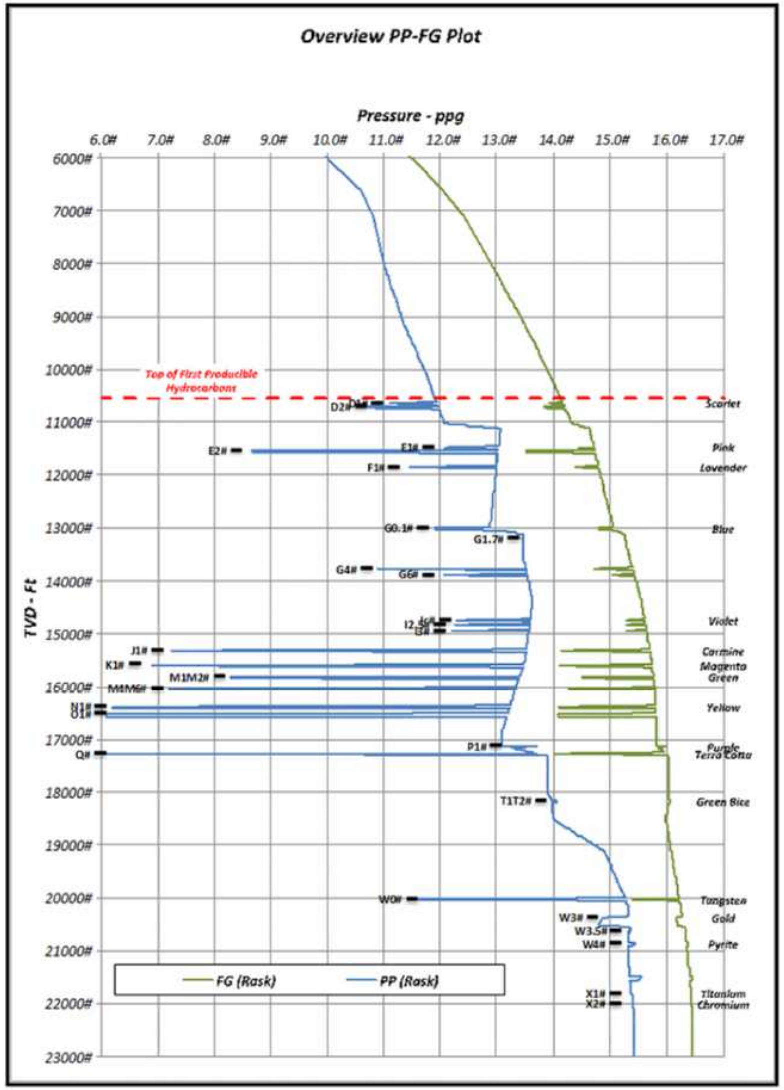
- Thermal effects have an effect on near-wellbore stress state
  - Cooling can cause lost circulation
  - Heating may elevate fracture initiation pressure by elevating thermal stress:

$$\boldsymbol{\sigma}_{\boldsymbol{\theta\theta}}^{\Delta T} = \boldsymbol{\alpha}_t \mathbf{E}\Delta\mathbf{T}/(\mathbf{1}-\boldsymbol{\nu})$$

- Thermal WBS may be used to negotiate narrow drilling margins, particularly during cementing in deepwater wells

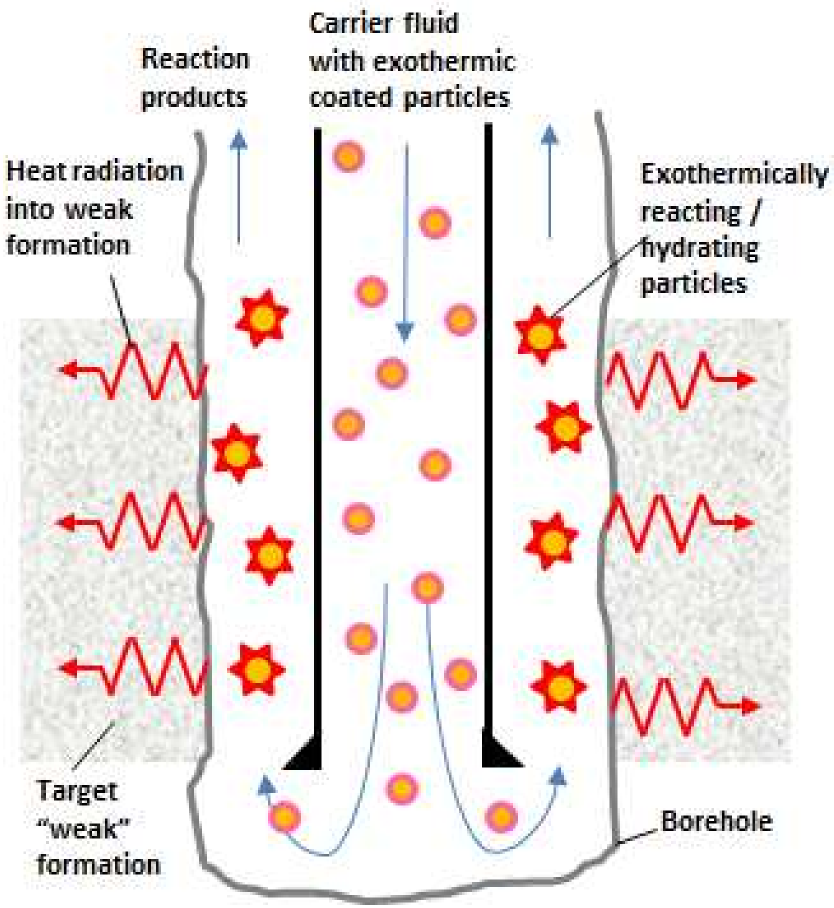


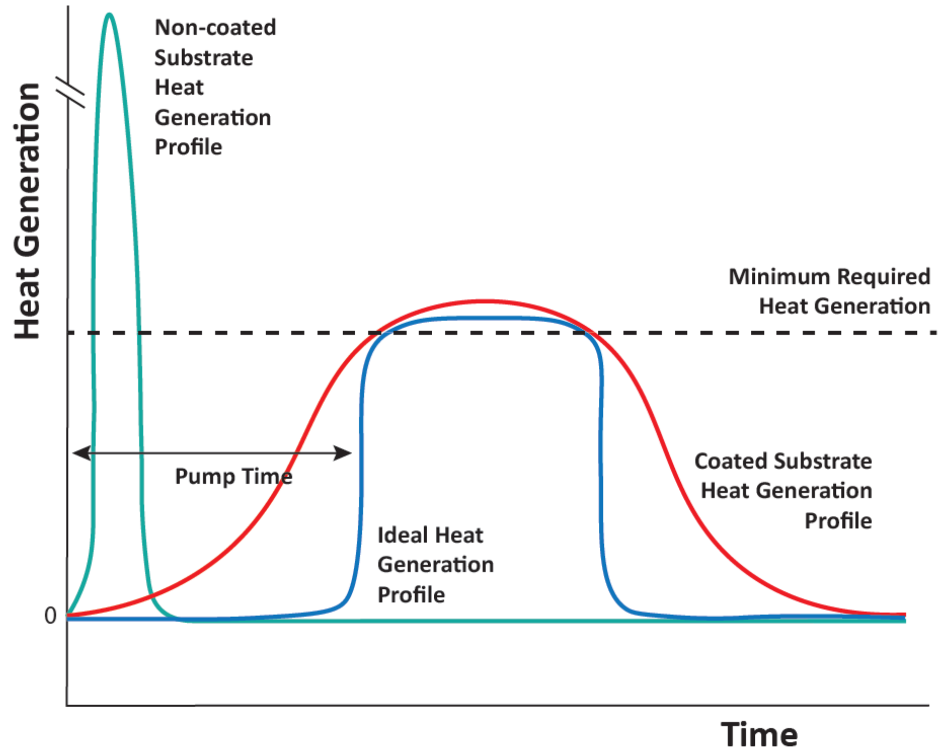
Source: OTC 25437



Source: SPE 170977

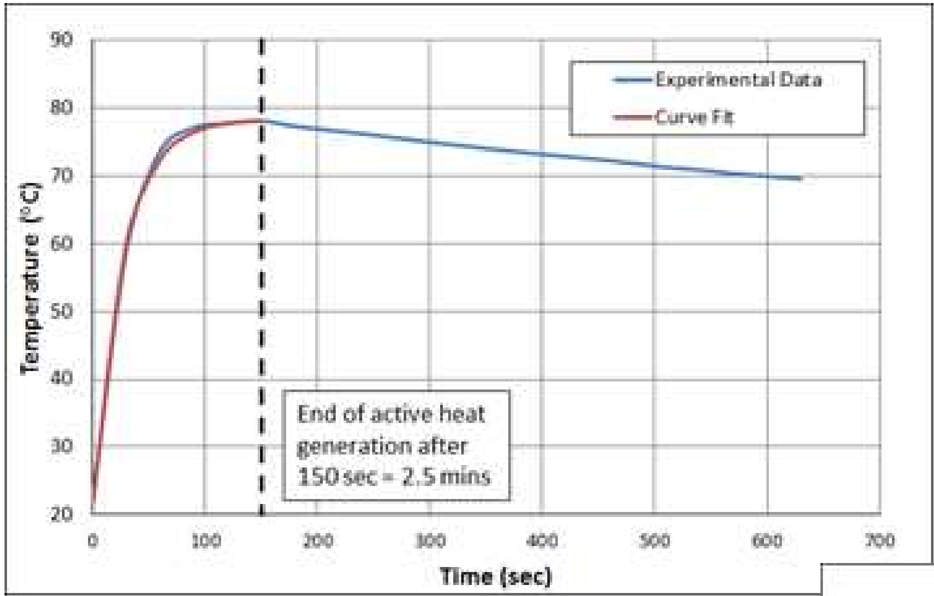
TWBS Principle



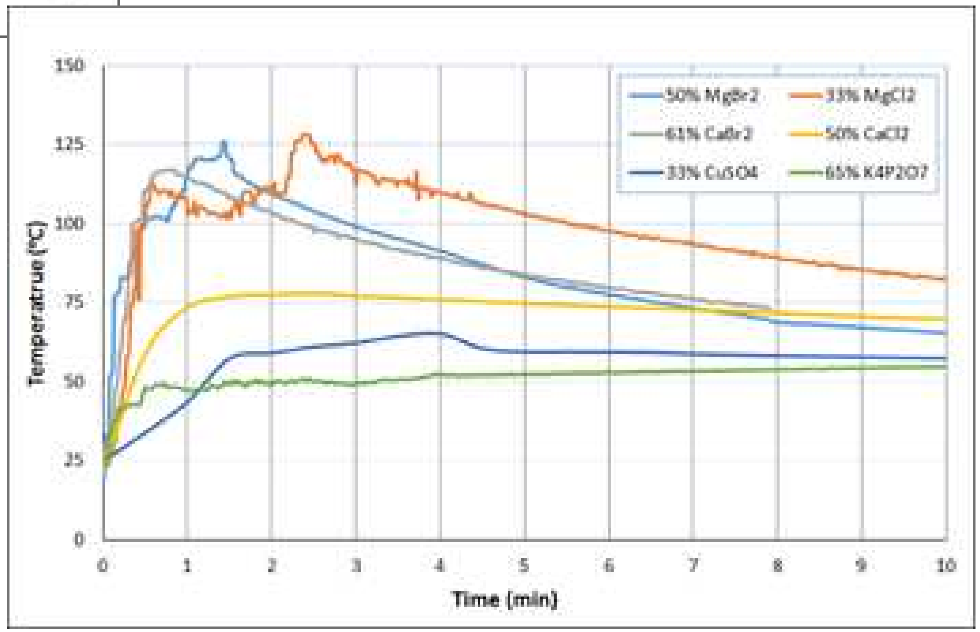


SPE 180315

TWBS Method - 1

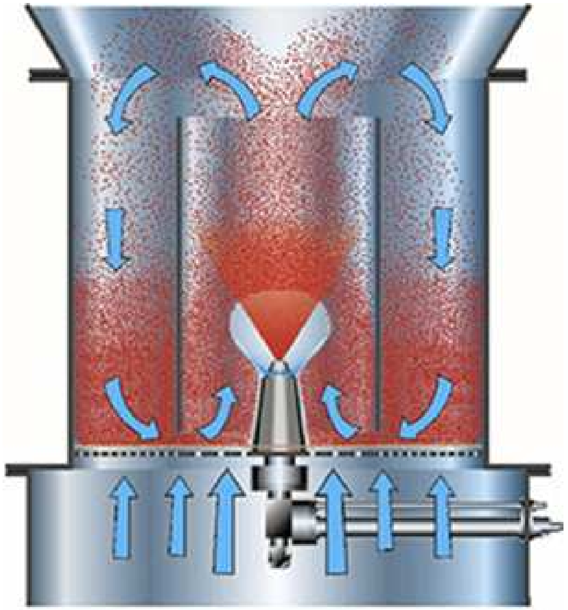


Examples of strong exothermal reactions (notably for $MgCl_2$, $MgBr_2$, $CaCl_2$, $CaBr_2$) and how data is processed to quantify heat release and enthalpy for various materials

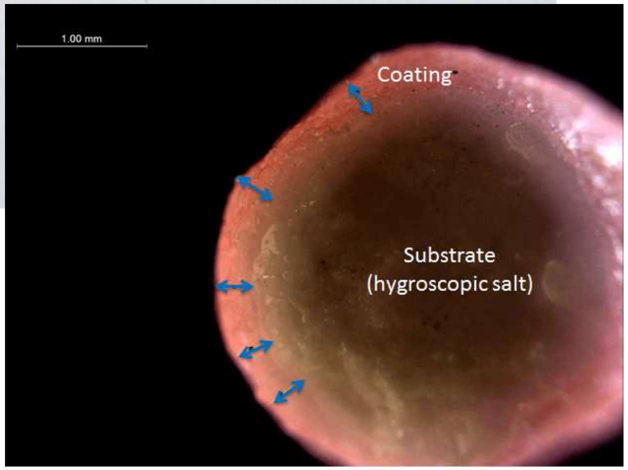


SPE 180315

TWBS Method - 2



Coating allows for reaction delay, similar to delayed-release medications

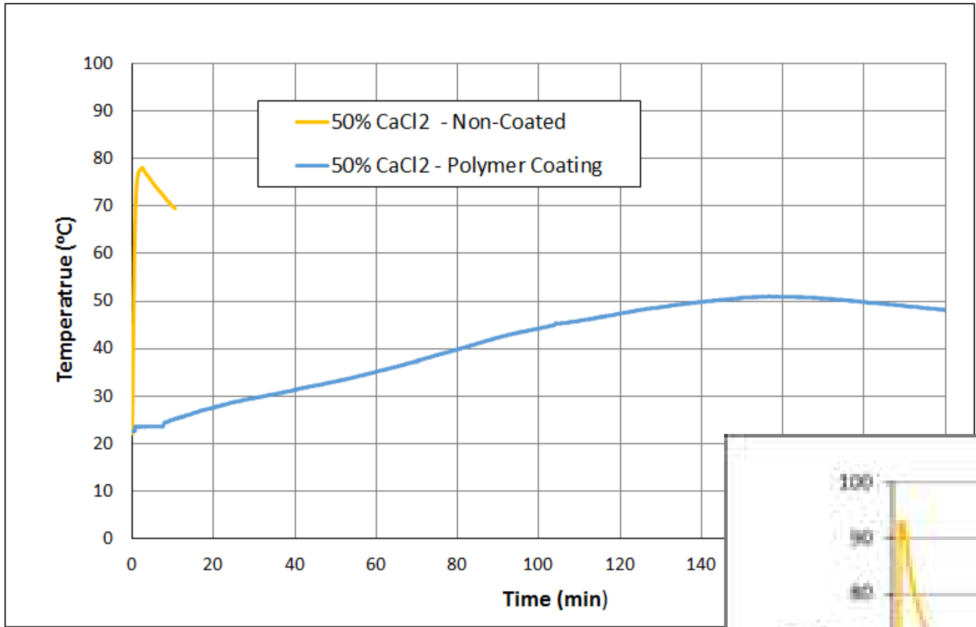


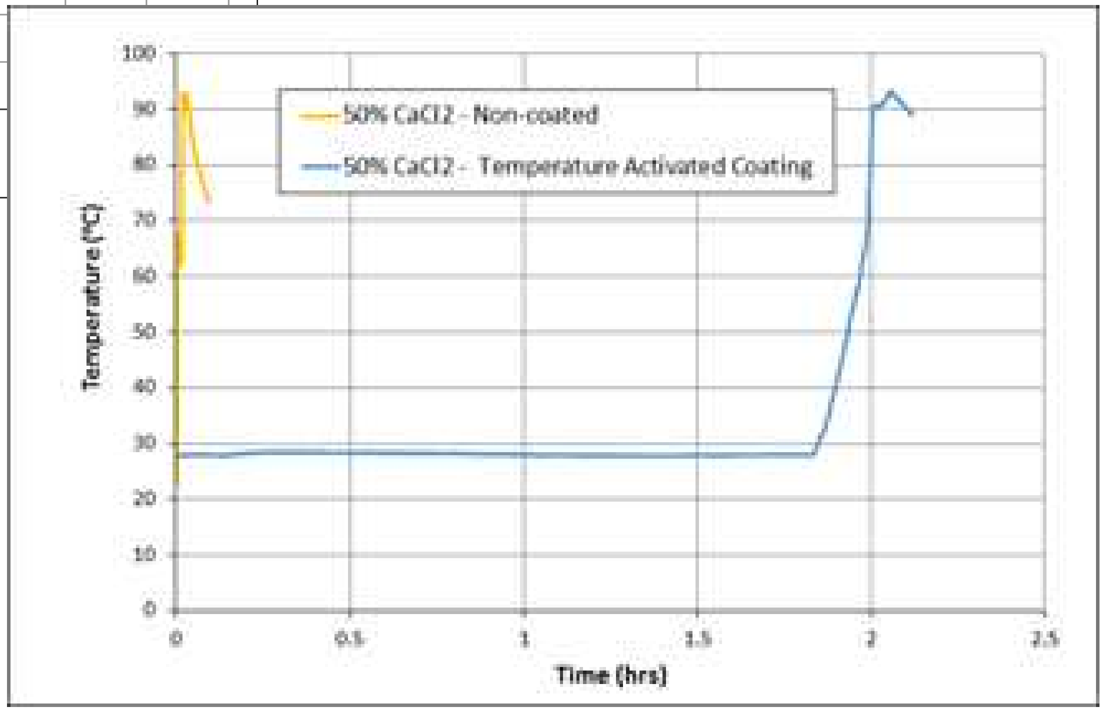
200 μm thickness

SPE 180315

TWBS Method - 3

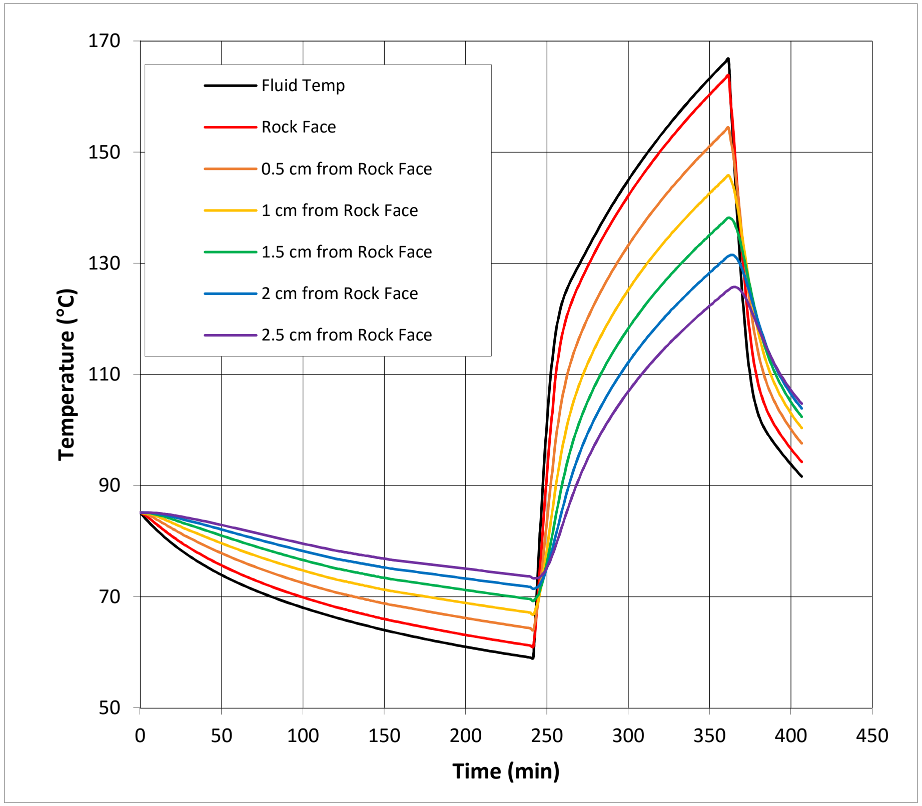
Examples of delayed exothermal reaction in order to achieve sufficient pump time to circulate reacting materials in place





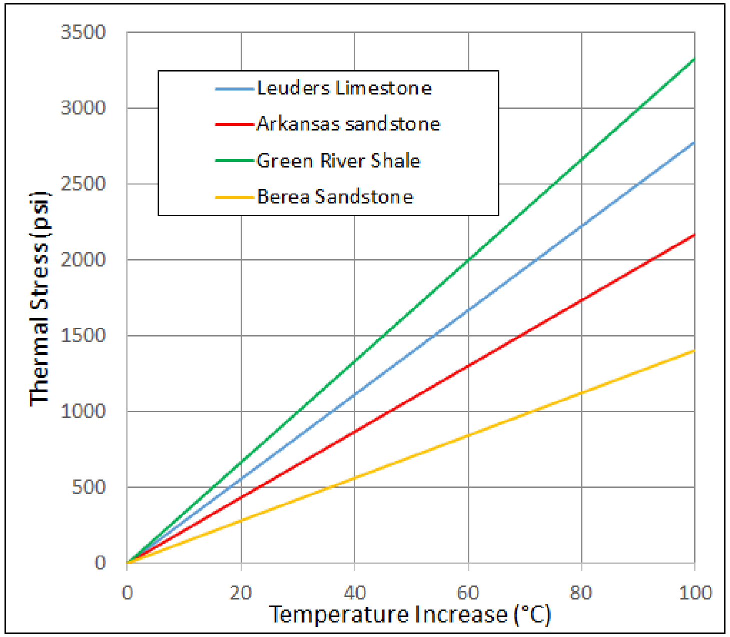
SPE 180315

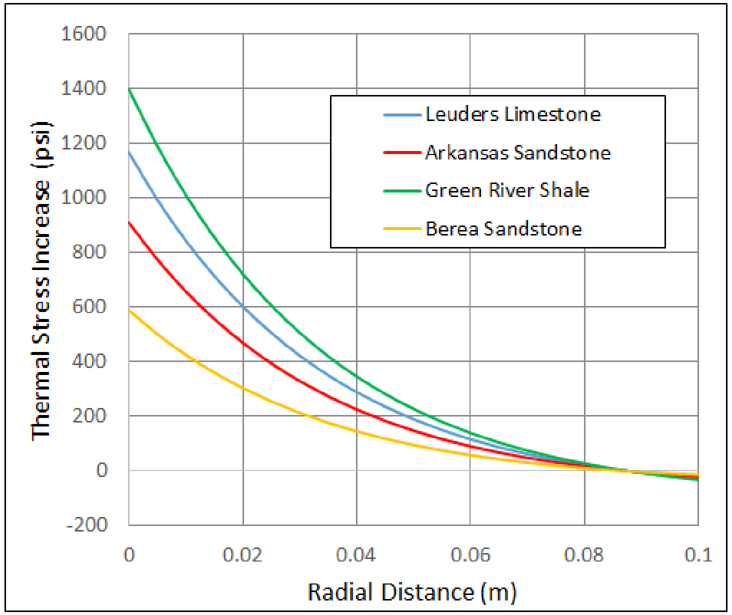
TWBS "Texas Heat Wave" Modeling



Modeling results of new thermal model

SPE 180315





Pro’s & Con’s of OBM / SBM

Advantages of OBM/SBM

- High ROP, reduced bit-balling
- Excellent shale inhibition
- Excellent wellbore stability / gauge hole
- Thermal stability
- High lubricity, lower torque
- Low fluid loss
- Reduced differential sticking
- High solids tolerance
- Good coring / salt drilling fluid
- Low corrosion

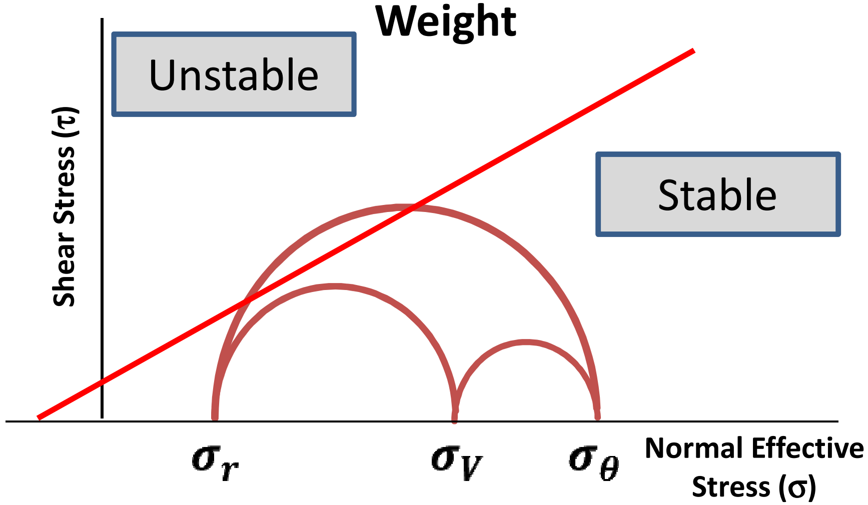
Disadvantages of OBM/SBM

- High per barrel cost
- Electical / resistivity log difficulties
- Oil emulsion blocks in gas sands
- Prone to severe lost circulation
- Poor cement bonds possible
- Gas kick detection more difficult
- Difficulty fingerprinting HC's
- Messy work environment
- High waste disposal cost
- Fumes / fire hazard

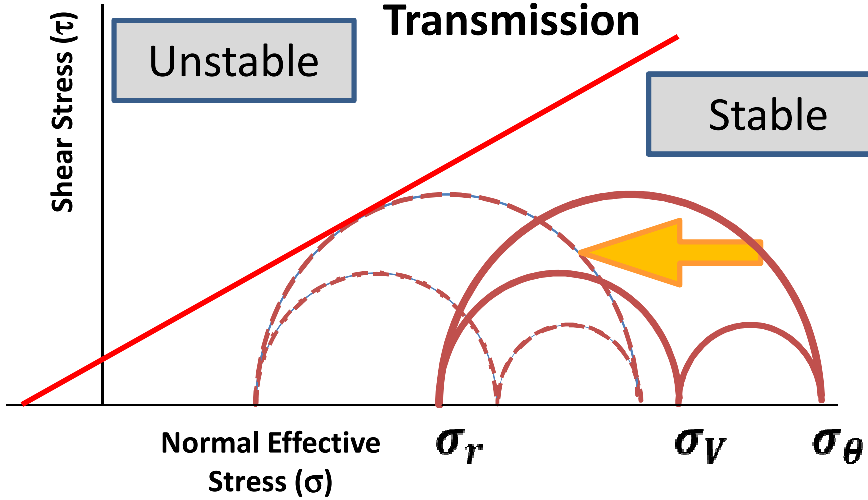
High Performance WBM

- Cuttings- and borehole stability **ARE NOT** the same thing!
- **They require very different tests**
- Leading cause of shale borehole instability is **inappropriate mud weight**, causing immediate wellbore cavings & failures
- Time-delayed shale borehole instability is caused by **mud pressure transmission**, increasing pore pressure, reducing effective stresses

Instability through Inappropriate Mud Weight



Instability through Mud Pressure Transmission

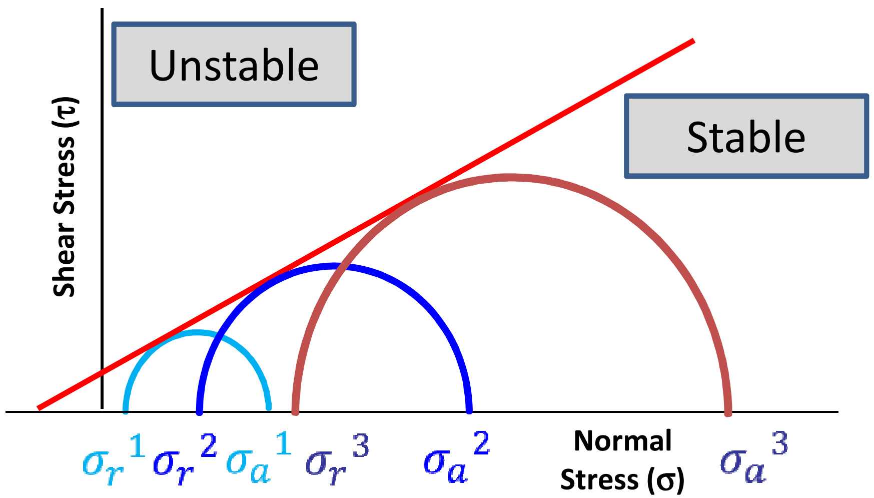


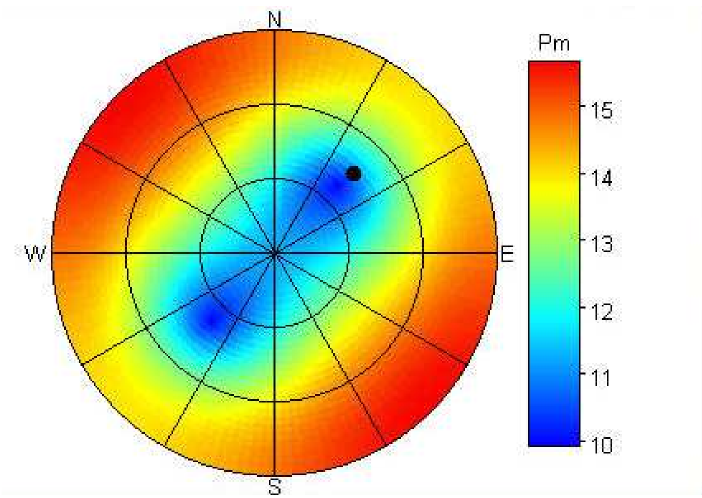
SPE 173138; AADE -16-FTCE-77

Triaxial Failure Test

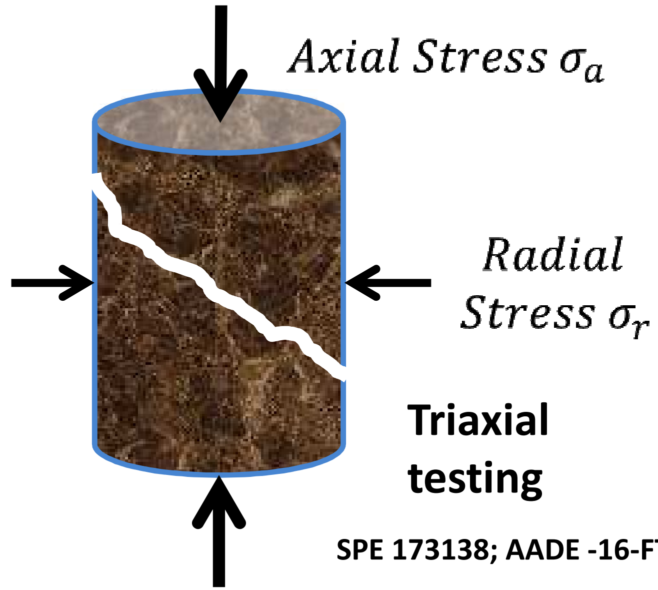
- Triaxial test under radial confinement of core samples, ramping axial stress to failure to map failure envelope
- Can be carried out with drained or undrained pore pressure
- Crucial to determining optimum mud weight requirement for shale borehole stability

Mapping the shale failure envelope





Mud Weight as a function of deviation and azimuth

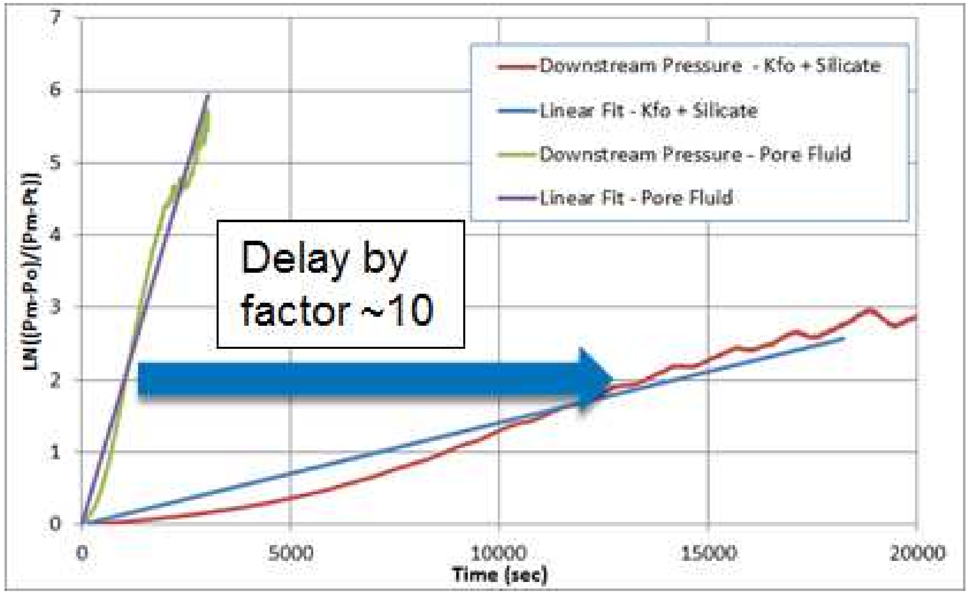


Triaxial testing

SPE 173138; AADE -16-FTCE-77

Pressure Transmission Test

- PT = main time-delayed shale failure mechanism
- Measure PT in shale (pore pressure elevation and effective stress reduction -> failure) for pore fluid and drilling fluids
- Ratio of PT rates between pore fluid and mud characterizes a delay factor that correlates with increase in trouble-free open hole time



PT test apparatus

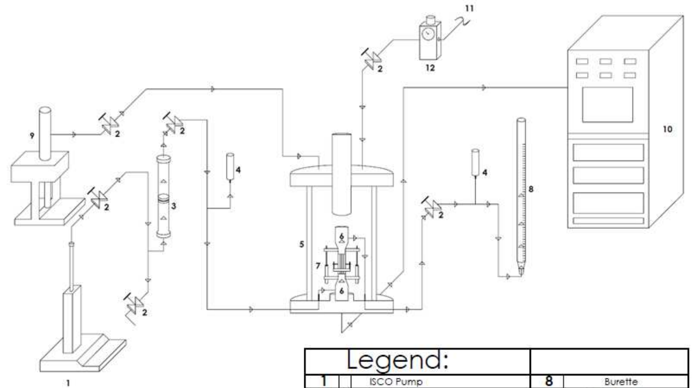
PT results for pore fluid and test mud, with high delay factor

SPE 173138; AADE -16-FTCE-77

Thick Walled Cylinder Test - 1

- Modified TWC = "poor-boy" DSC
- Cylindrical core samples: 1" diameter, 2" length, 1/3" borehole
- Confined at (downhole) stress (and temperature)
- Pore pressure applied
- Shale exposed to circulating drilling fluid in the borehole at overbalance for 12 – 24 hours
- Confining stress is ramped up until failure occurs (end of test)
- Failure indicated by sudden increase in volumetric strain
- Final confining stress = strength of shale sample after fluid exposure, reflecting shale-fluid compatibility

Modified TWC test equipment & schematic



Legend:		
1	ISCO Pump	8	Burette
2	Needle Valve	9	Confining Pump
3	Transfer Vessel	10	Data-Acquisition Unit
4	Pressure Transducer	11	Air Supply line
5	Pressure vessel	12	Air Pressure Regulator
6	End Caps		
7	TWC Sample Radial & Axial Strain Measurment		

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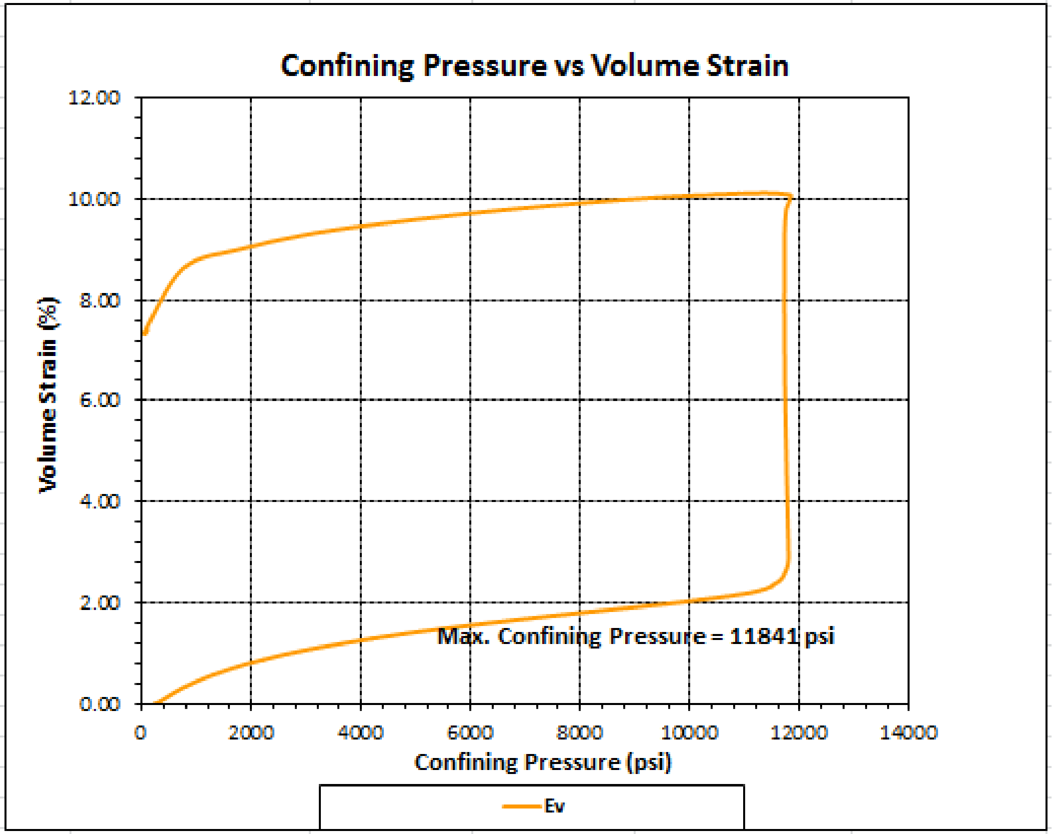
Thick Walled Cylinder Test - 2



Volumetric strain behavior as a function of confining pressure, with failure occurring at 11,841 psi for Mancos shale

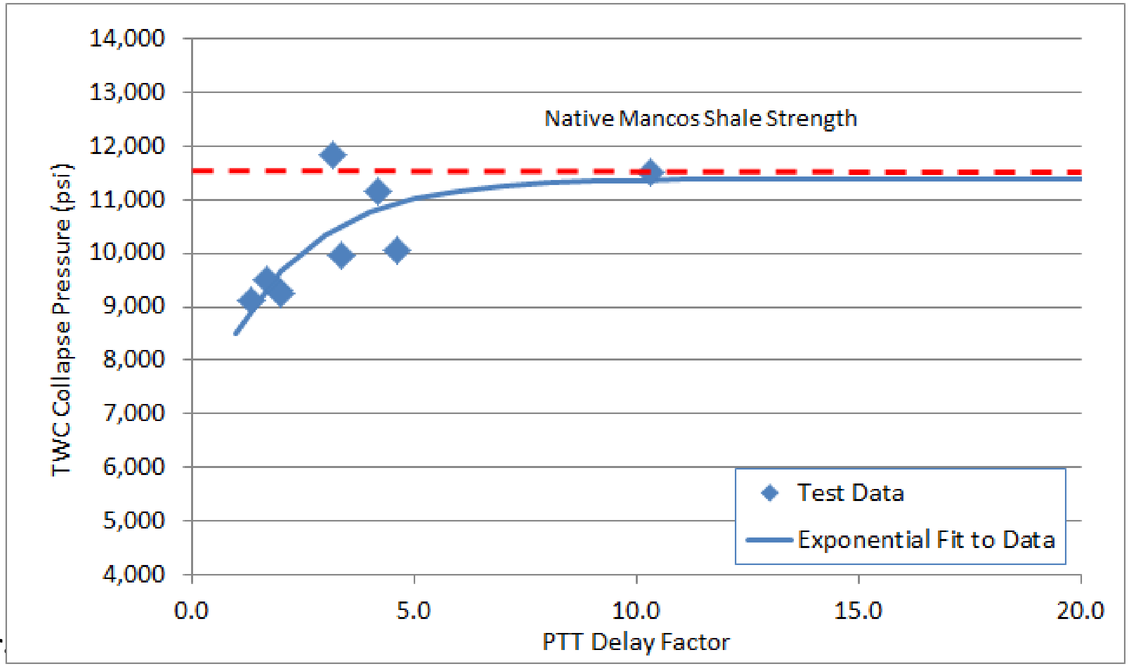
Pictures of shale samples before coring the borehole (top); before TWC testing (middle); after TWC testing (bottom)

SPE 173138; AADE -16-FTCE-77

Experimental HP-WBM Results

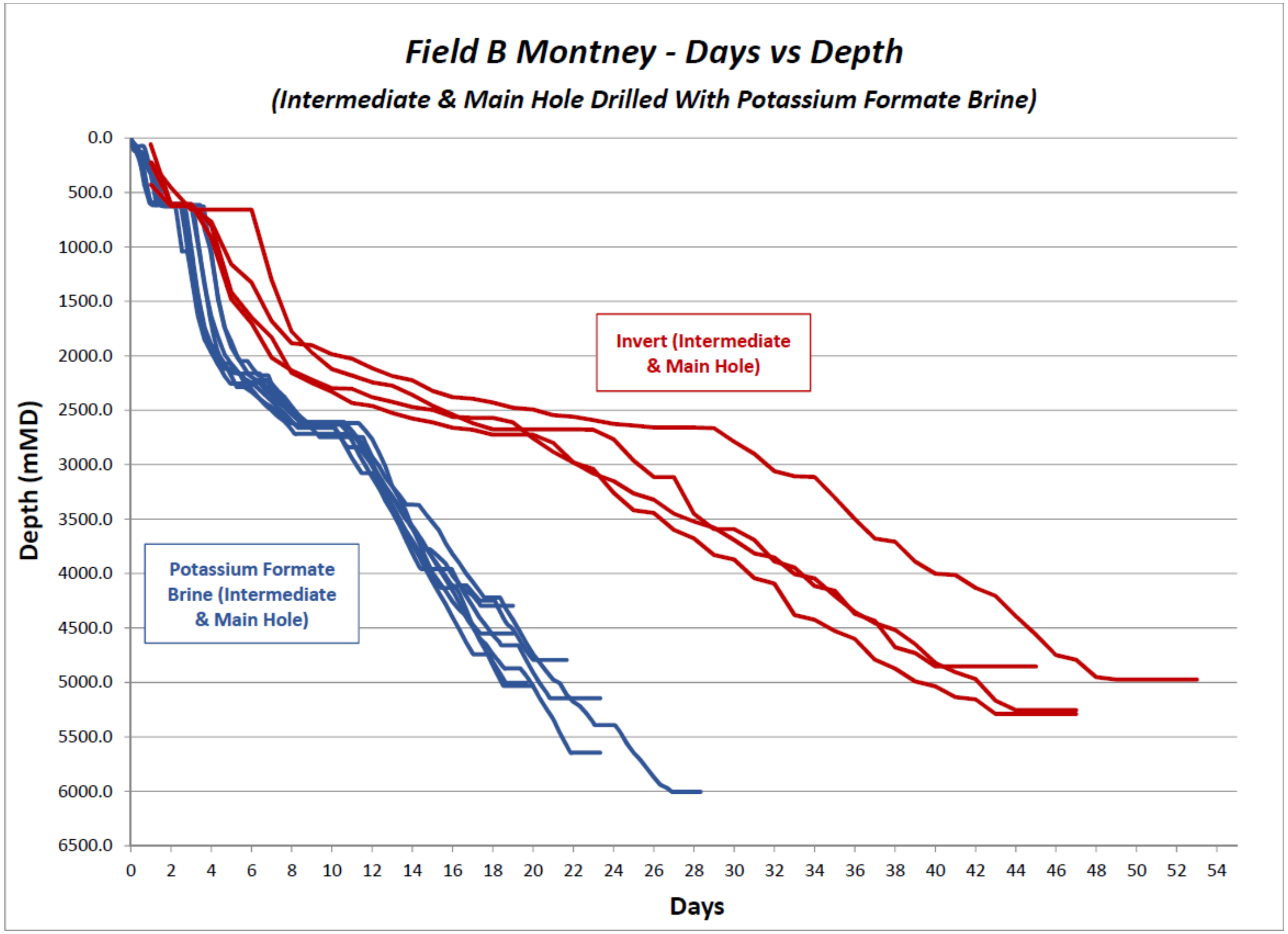
- Series of new HP-WBM fluids screened with PTT and TWC tests on Mancos shale
  - Potassium/Cesium/Mixed formate fluids + membrane builders
  - Nano-particle fluids
  - Compared to commercial HP-WBM & OBM systems

Fluid Type	PTT Delay Factor	TWC Collapse Pressure (psi)
NP1	3.2	11,841
KFo + Silicate	10.3	11,521
KFo + Polyglycol	4.2	11,149
HP-WBM1	4.6	10,055
OBM	3.4	9,953
KFo + Polyglycerol	4.5	9,503
HP-WBM2	2.0	9,321
NP2	2.0	9,240
NP3	1.3	9,108



- Excellent correlation between PTT delay factors and TWC collapse pressure values
- Confirms PT as dominant mechanism for time-delayed shale failure

Faster Shale Drilling: Canada Shale Drilling Performance



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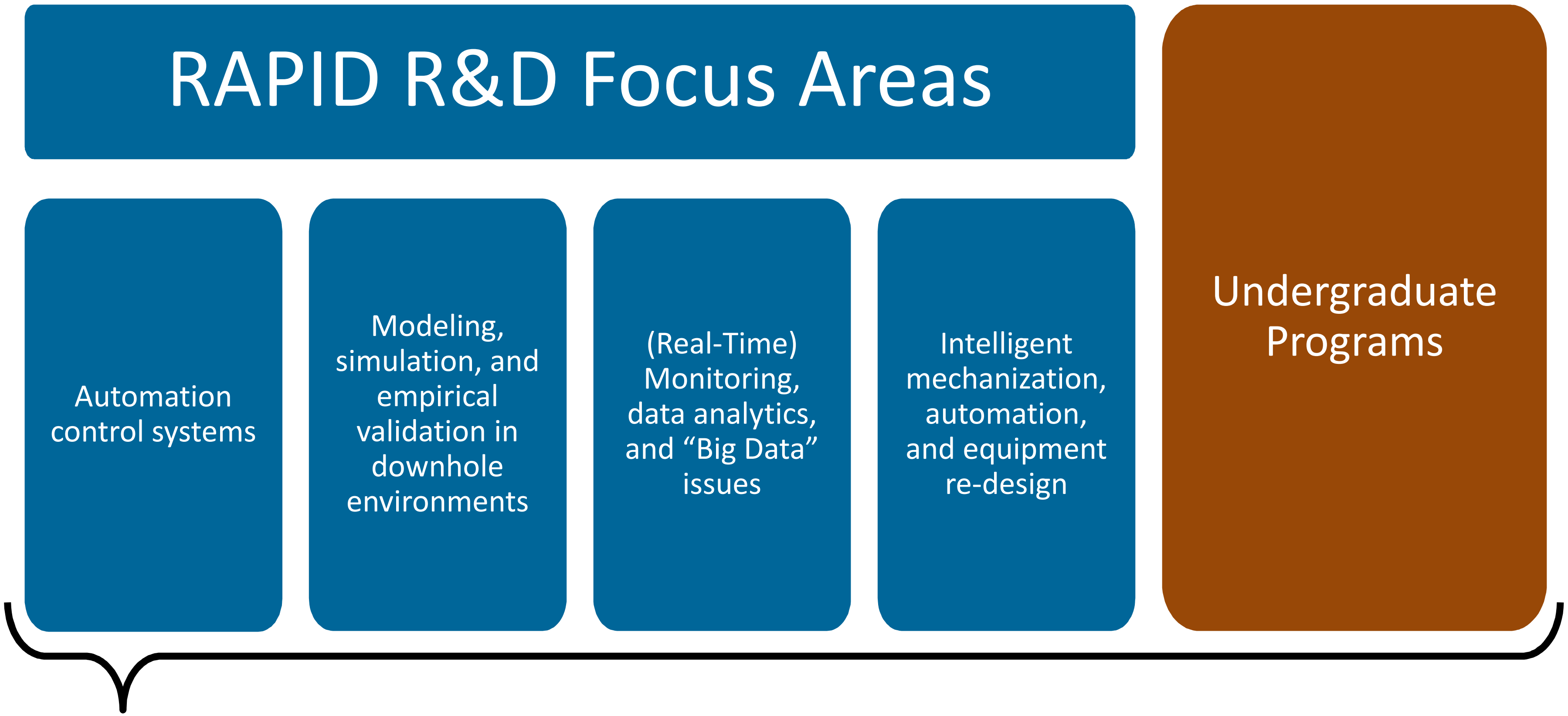
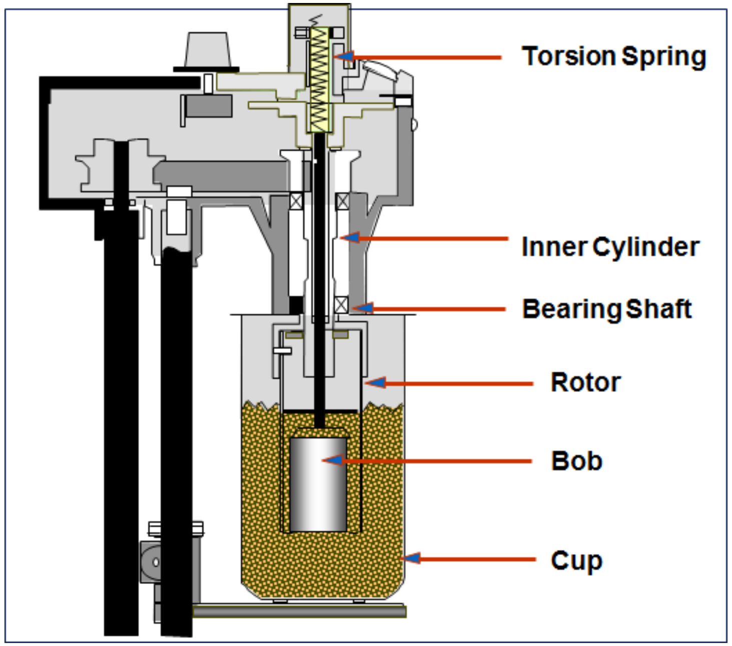
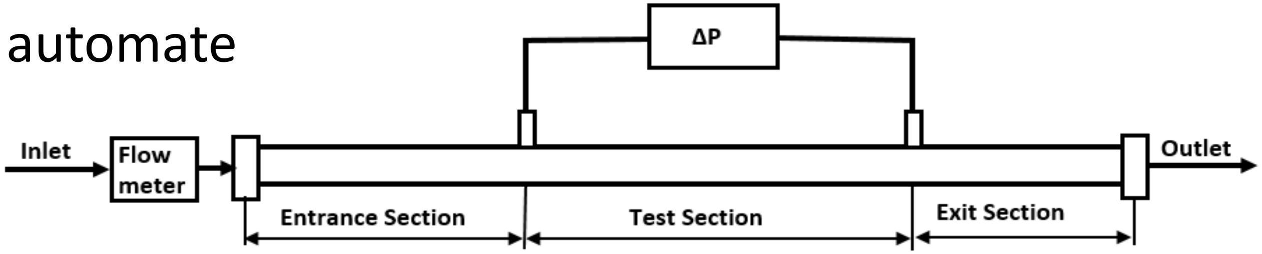


- Maintain a “minimum effort” in all identified focus areas and viable undergraduate programs.
- Funds beyond baseline efforts (including baseline projects in all focus areas) will largely be guided by feedback from RAPID members
- The Program Director will prioritize efforts to deliver a balance of short-term benefits and longer terms research efforts.

Drilling Fluid Automation - 1

- API standard method to measure viscosity is by rotational viscometer
  - Hard to automate
  - "Dishwashing Robot"
- Alternative method is by using pipe viscometer
  - Much easier to automate and control
  - "Dishwasher"
  - Alternative to API standard

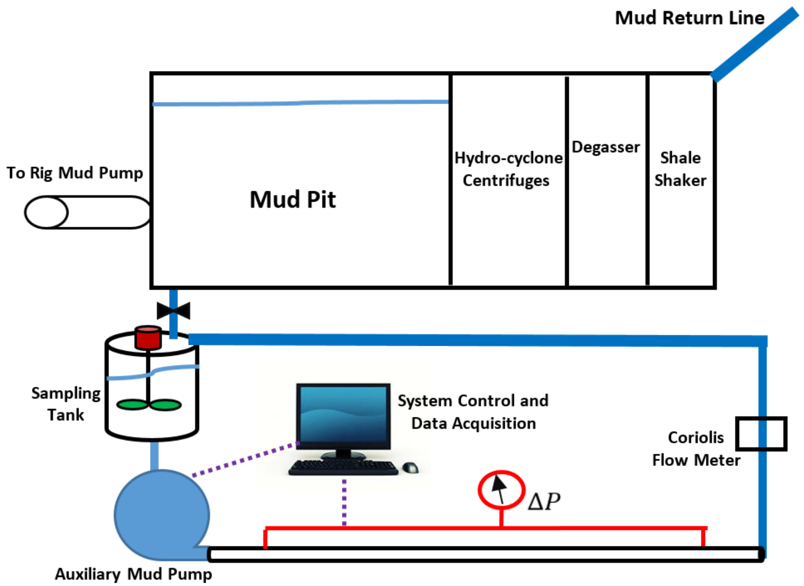


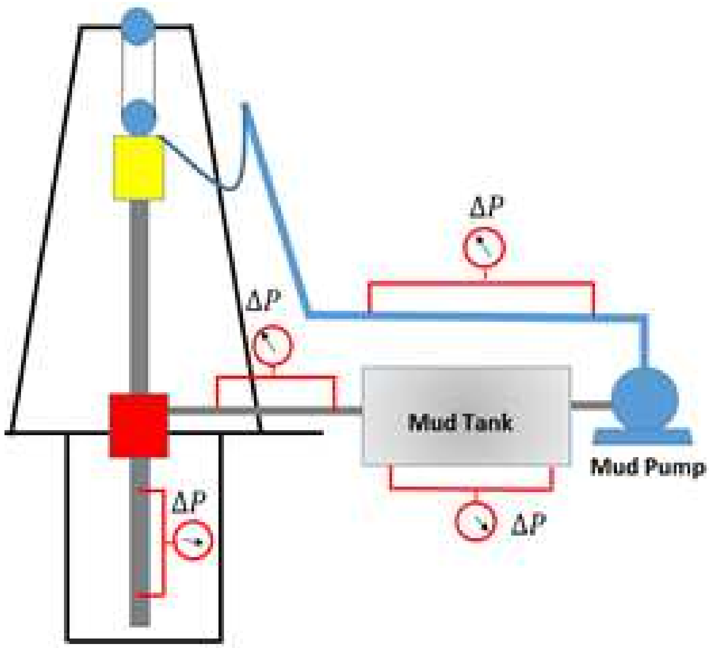


SPE 173085; SPE 180331

Drilling Fluid Automation - 2

- Pipe viscometer can be deployed at the rigsite in a variety of ways, both on surface AND downhole

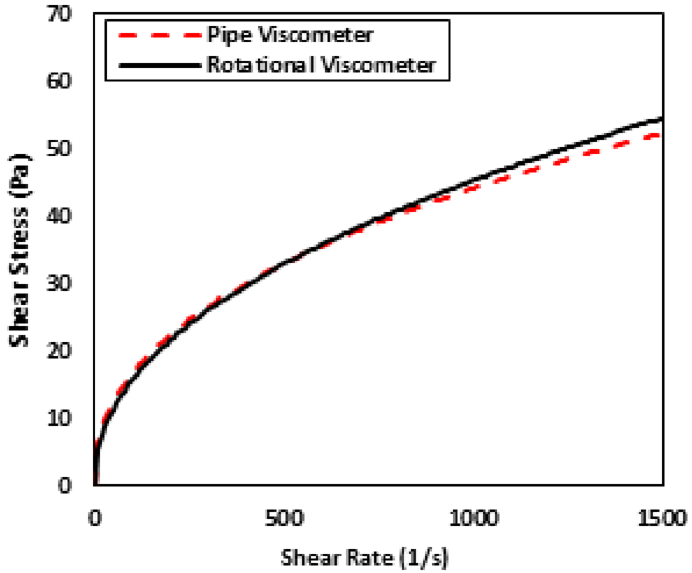


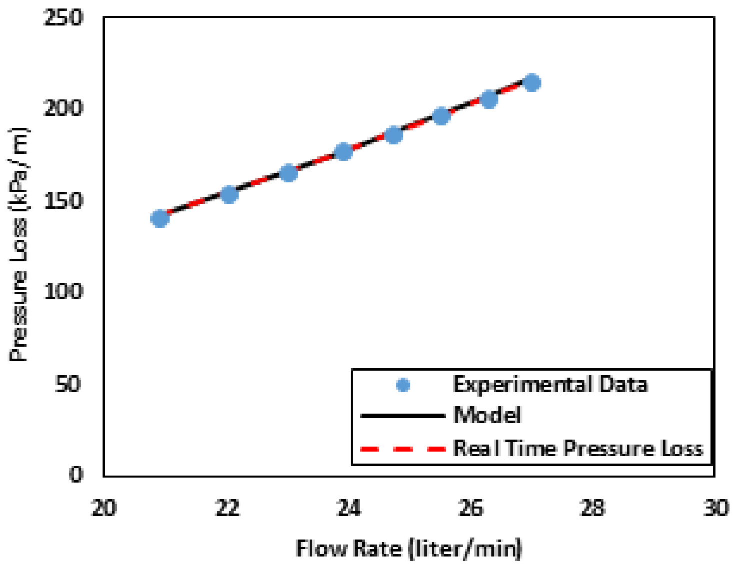


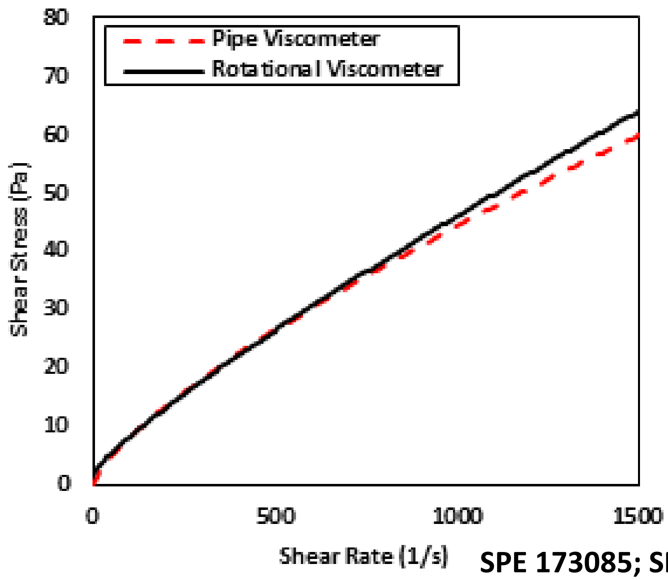
SPE 173085; SPE 180331

Drilling Fluid Automation - 3

- Fully automated pipe viscometer currently operational at UT Austin
- Delivers real-time, continuous viscosity measurement that is identical to rotational viscometer results
- NO manual labor involved, all mud changes recorded in real-time!
- Can also measure real-time friction coefficients





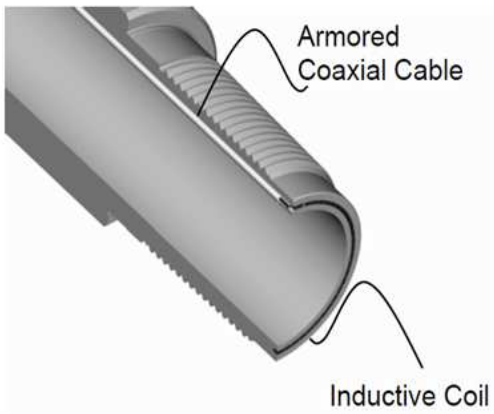


SPE 173085; SPE 180331

Drilling Fluid Automation - 4

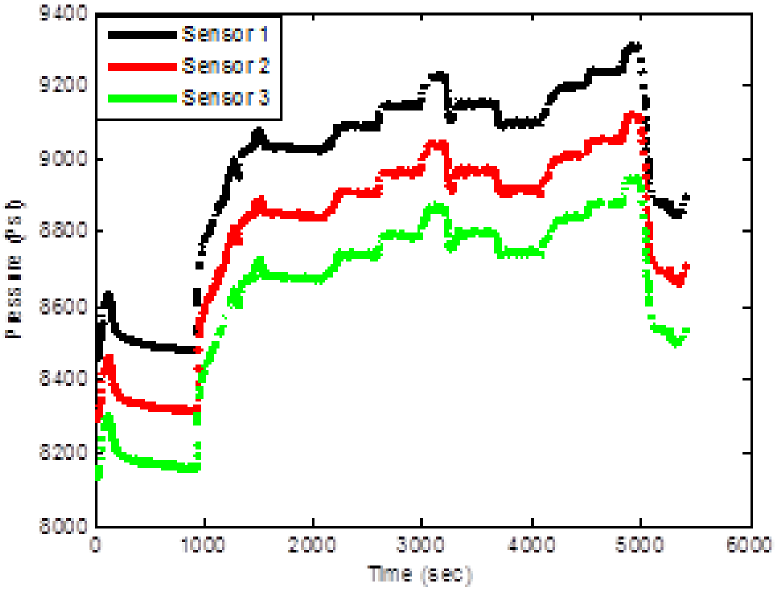
Downhole measurement:

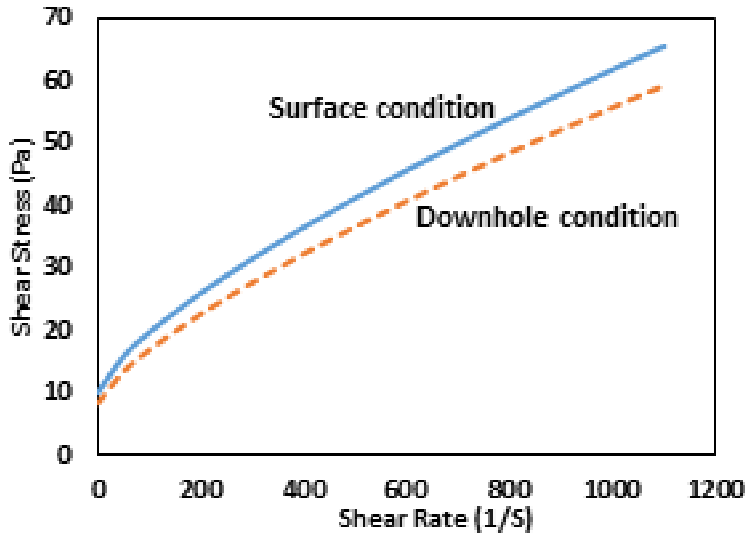
- The well itself can be used as a pipe viscometer using distributed pressure measurement, obtained from wired pipe (or other suitable MWD technique)
- Pressure drops between sensor locations can be used to construct rheogram, from which viscosity can be determined
- Mud viscosity is obtained in real-time at downhole pressure and temperature



Source: Reeves et al. (2005)

Amplification Joint



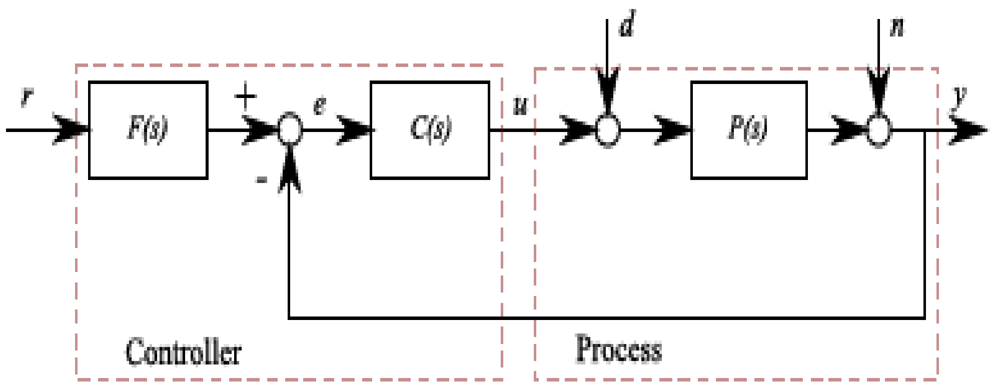


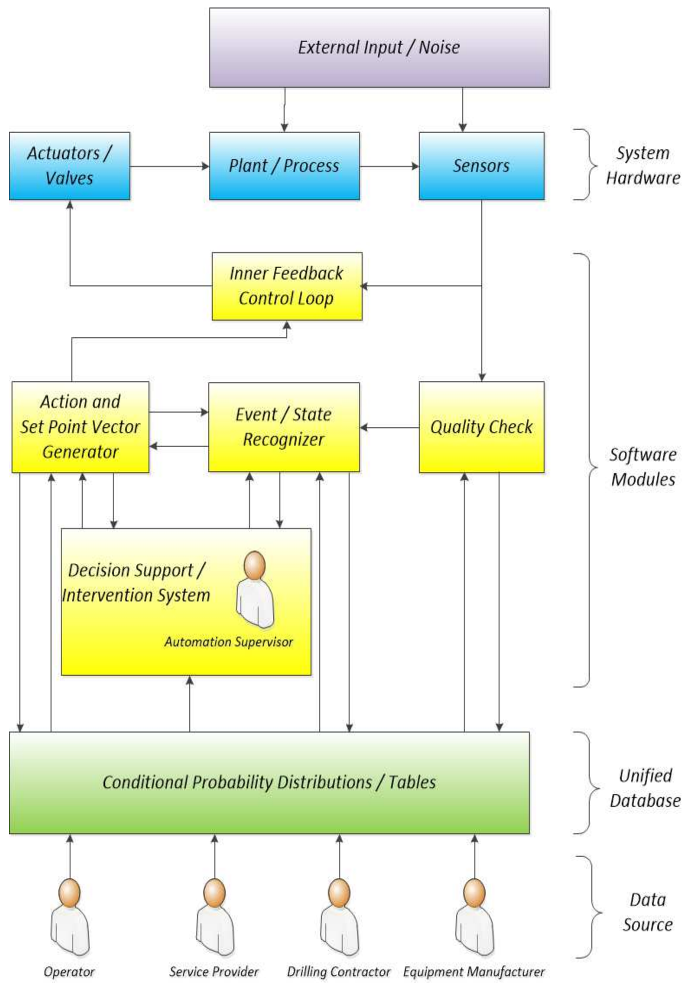
SPE 173085; SPE 180331

Automated MPD Control - 1

Research Objectives

- Develop reduced-order models for single and multi-phase dynamics in MPD wells.
- Design robust control systems for automated MPD
- Integrate with previous work on data quality and automated pattern recognition.



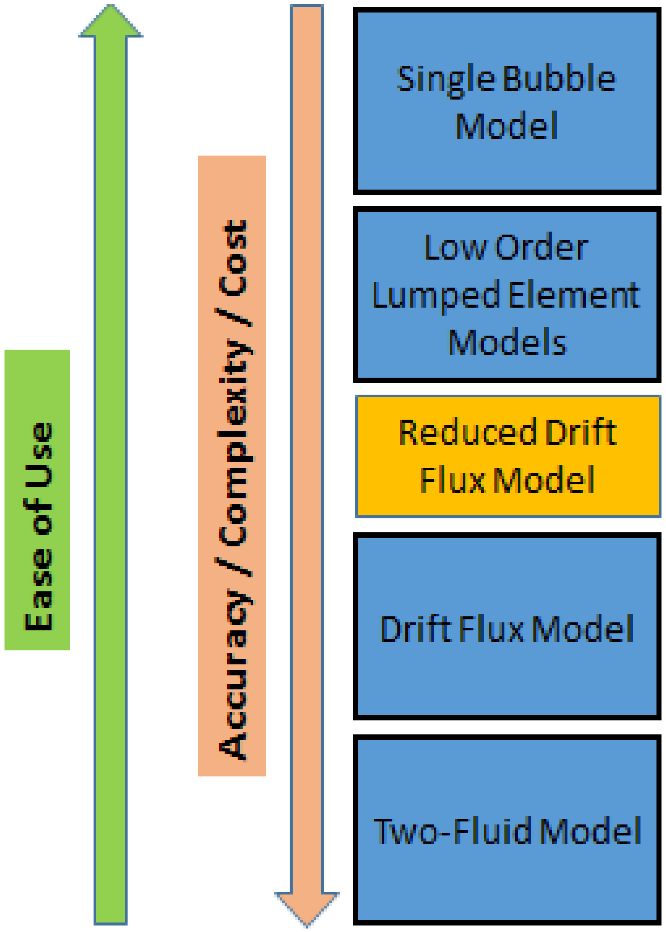


IPTC 18481; SPE 181672

Automated MPD Control - 2

Accomplishments to Date

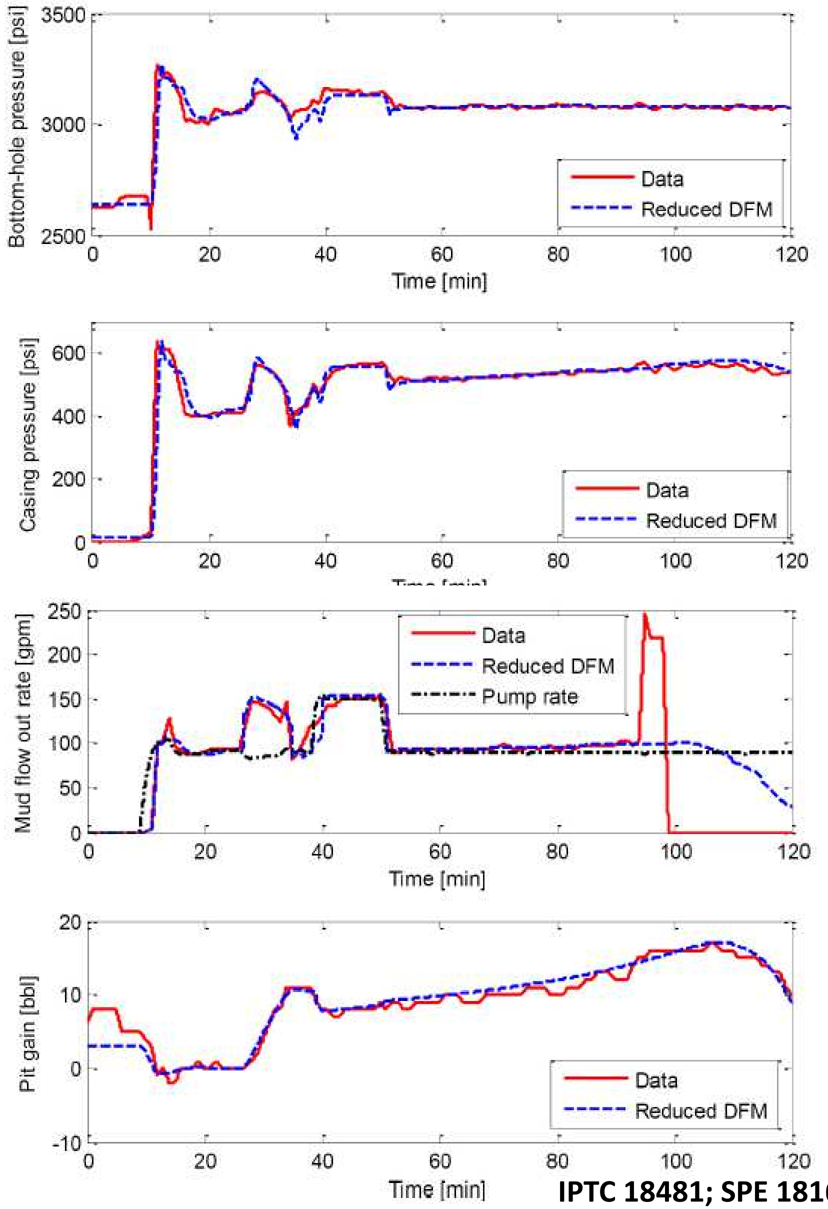
- Developed a simplified transient two-phase model for automatic well control in MPD.
- Model validated using OLGA simulation and experimental data →Paper IPTC-18481.
- Demonstrated potential application for model-based estimation and control algorithms →Paper ASME DSCC2015-9791.
- Developed state-of-the-art multi-phase flow model for simulation →Paper SPE 181672



Automated MPD Control - 3

Ongoing Activity

- Explore different control designs and evaluate robustness and performance for field deployment.
- Incorporate logic for event detection and estimation of faulty sensor readings.
- Test controllers in MPD well control simulations (OLGA/UT's Drift Flux Model) with uncertain system parameters, disturbances, sensor/ process faults.



IPTC 18481; SPE 181672

Acknowledgments

Sponsors

- Baker Hughes
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  - ExxonMobil
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  - Sinopec
  - Hess
  - Baker Hughes
  - NOV
  - Pason

Collaborators

- Pradeep Ashok
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- Maggie Chen
- Bez Hoxha
- Ali Karimi Vajargah
- Ramya Nair
- Mitch Prior
- Tesse Smitherman
- Behçet Açikmeşe (Washington State)
- Current and former graduate students, visiting scientists at UT Austin

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