YPP Presentation

“Where We Came Up with Some of the Things We Do in Hydraulic Fracturing”

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Chair, SPE Queensland Section
Frac Topics to be Covered

- Fracturing equipment
- Bottomhole treating pressure analysis
- Hydraulic fracture models, modelling, and job scheduling
- Fracturing fluid history and selection
- Breaker history and selection
- Proppant selection and conductivity
- Evaluating post-treatment results
Fracturing Equipment then vs Now

- This is how it looks today on a Shale Gas frac
- Mechanically, the tanks pumps, blender and sand conveyage hasn’t changed since 1970’s
- Equipment setup and layout the same
- Communications, data processing, monitoring, equipment instrumentation, and “on-the-fly” mixing has improved significantly
- Now coiled-tubing is incorporated into many frac operations

Source: Halliburton website
Surface Treating Pressure Estimation
Closure Pressure Estimation

Source: Recent Advances in Hydraulic Fracturing, SPE 1989
# Hydraulic Fracture Modelling in the Early 1980’s

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A Rapid Method of Predicting Width and Extent of Hydraulically Induced Fractures</strong></td>
<td>Geertsma and de Klerk</td>
<td>SPE 2458-PA 1969</td>
</tr>
<tr>
<td><strong>On the Design of Vertical Hydraulic Fractures</strong></td>
<td>Daneshy</td>
<td>SPE 3654-PA 1973</td>
</tr>
<tr>
<td><strong>Fracturing Design Using Perfect Support Fluids for Selected Fracture Proppant Concentrations in Vertical Fractures</strong></td>
<td>Harrington and Hannah</td>
<td>SPE 5642-MS 1975</td>
</tr>
<tr>
<td><strong>On The Computation of The Three-dimensional Geometry Of Hydraulic Fractures</strong></td>
<td>Clifton and Abou-Sayed</td>
<td>SPE 7943-MS 1979</td>
</tr>
<tr>
<td><strong>Comprehensive Design Formulae For Hydraulic Fracturing</strong></td>
<td>Cleary</td>
<td>SPE 9259-MS 1980</td>
</tr>
</tbody>
</table>
Hydraulic Fracture Modelling in the Early 1980’s

Source: Recent Advances in Hydraulic Fracturing, SPE 1989
Frac Design and Bottomhole Treating Pressure Analysis in the Early-1980’s

Determination of Fracture Parameters From Fracturing Pressure Decline, Nolte, 8341-MS 1979

Interpretation of Fracturing Pressures Nolte and Smith, SPE 8297-PA 1981
Workflow of Bottomhole Treating Pressure Analysis in the Early-1980’s

Source: Recent Advances in Hydraulic Fracturing, SPE 1989
Hydraulic Fracture Modelling into the Mid- to Late-1980’s

A Practical Numerical Simulator for Three-Dimensional Fracture Propagation in Heterogeneous Media
Barree SPE12273-MS 1983

Three-Dimensional Simulation of Hydraulic Fracturing
Settari and Cleary SPE 10504-PA 1984

Design Formulae for 2-D and 3-D Vertical Hydraulic Fractures: Model Comparison and Parametric Studies
Meyer SPE 15240-MS 1986

Simulation of Hydraulic Fracturing in Low-Permeability Reservoirs
Settari and Price SPE 8939-PA 1984

The Engineering of Hydraulic Fractures-State of the Art and Technology of the Future
Cleary SPE 17260-PA 1988
Bottomhole Treating Pressure Analysis in the Mid- to Late-1980’s

The Real-Time Calculation of Accurate Bottomhole Fracturing Pressure From Surface Measurements Using Measured Pressures as a Base  Hannah, Harrington, and Lance, SPE 12062-MS 1983

Measurement of Width and Pressure in a Propagating Hydraulic Fracture  Warpinski, SPE 11648-PA 1985

Modified Fracture Pressure Decline Analysis Including Pressure-Dependent Leakoff  Castillo, SPE 16417-MS 1987

Application of Fracture Design Based on Pressure Analysis  Nolte, SPE 13393-PA 1988

Improvement of Hydraulic Fracture Predictions by Real-Time History Matching on Observed Pressures  Crockett, Willis & Cleary SPE 15264-PA, 1989
## Bottomhole Treating Pressure Analysis in the Early to Mid-1990’s

### Experimental and Modeling Evidence for Major Changes in Hydraulic Fracturing Design and Field Procedures
- **Cleary, Wright and Wright**
  - SPE 21494-MS 1991

### Major New Developments in Hydraulic Fracturing, with Documented Reductions in Job Costs and Increases in Normalized Production
- **Cleary, Doyle, Teng, Cipolla, Meehan, Massaras, and Wright**
  - SPE 28565-MS 1994

### Comparison Study of Hydraulic Fracturing Models 0x97 Test Case: GRI Staged Field Experiment No. 3 (includes associated paper 28158 )
- **Warpinski, Moschovidis, Parker and Abou-Sayed**
  - SPE 25890-PA 1994

### Microseismic Mapping of Hydraulic Fractures Using Multi-Level Wireline Receivers
- **Warpinski, Engler, Young, Peterson, Branagan, and Fix**
  - SPE 30507-MS 1995

### Determination of Pressure Dependent Leakoff and Its Effect on Fracture Geometry
- **Barree and Mukherjee**
  - SPE 36424-MS 1996
Bottomhole Treating Pressure Analysis in the Mid-1990’s

The Application of Hydraulic Fracturing Models in Conjunction with Tracer Surveys to Characterize and Optimize Fracture Treatments in the Brushy Canyon Formation, Southeastern New Mexico

Johnson and Woodroof, SPE 36470-MS 1996
Fully Integrated Analyses Emerging since Early-1990’s

Case Study of a Stimulation Experiment in a Fluvial, Tight-Sandstone Gas Reservoir (includes associated papers 23475 and 23567) Warpinski, Branagan, Sattler, Cipolla, Lorenz, and Thorne SPE 18258-PA 1990

Optimizing Horizontal Completion Techniques in the Barnett Shale Using Microseismic Fracture Mapping Fisher, Heinze, Harris, Davidson, Wright, and Dunn, SPE MS-90051, 2004

Closing the Gap: Fracture Half Length from Design, Buildup, and Production Analysis Barree, Cox, Gilbert and Dobson SPE 84491-PA 2005

Integrating Microseismic Mapping and Complex Fracture Modeling to Characterize Hydraulic Fracture Complexity Cipolla, Weng, Mack, Ganguly, Gu, Kresse, and Cohen, SPE 140185-MS 2011
Fluids

- **1980s**
  - Lightly gelled / slicked water and crosslink gelled were used 50:50 in 100% fluid fracs
  - Crosslinked gels were mostly Ti/Cr/Al crosslink, B crosslink diminishing
  - Push for temperature stability
  - Foams/Energized fluids were predominantly Nitrogen with some CO2
- **1990s**
  - Lightly gelled or slicked water to crosslink gelled was 25:75 in 100% fluid fracs
  - Crosslink gels were mostly Zr crosslink, B crosslink increasing, Less gellant
  - Foams/energized fluids were predominantly CO2 with some N2 in San Juan and Appalachian Basin
- **2000s**
  - Lightly gelled or slicked water to crosslink gelled was 65:35 in 100% fluid fracs
  - Crosslink gels were mostly B crosslink, Zr crosslink steady in HT areas
  - Foams/energized fluids minimal
Fracturing Fluids

Borates – High pH
Zirconates – Low or High pH

Source: Recent Advances in Hydraulic Fracturing, SPE 1989
# US Frac Fluids Progressing towards Minimising Additives

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Purpose</th>
<th>Family/Additives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrochloric Acid, Formic Acid, Acetic Acid</td>
<td>Helps dissolve minerals and initiate cracks in the rock</td>
<td>Acid, Low pH Adjusting Agent</td>
</tr>
<tr>
<td>Glutaraldehyde, Quaternary Ammonium Chloride, 'Tetrakis Hydroxymethyl-Phosphonium Sulfate</td>
<td>Eliminates bacteria in the water that produces corrosive by-products</td>
<td>Biocide</td>
</tr>
<tr>
<td>Ammonium Persulfate, Magnesium Peroxide</td>
<td>Allows a delayed break down of the gel</td>
<td>Breaker</td>
</tr>
<tr>
<td>Sodium Chloride, Calcium Chloride</td>
<td>Formulate or condition fluids or brine preparation</td>
<td>Salts</td>
</tr>
<tr>
<td>Choline Chloride, Tetramethyl ammonium chloride</td>
<td>Prevents clays from swelling or shifting</td>
<td>Clay Stabilizer</td>
</tr>
<tr>
<td>Isopropanol, Methanol, Ethylene Glycol</td>
<td>Product stabilizer and/or winterizing agent</td>
<td>Various</td>
</tr>
<tr>
<td>Ethanol, Methanol, petroleum distillate, hydrotreated light petroleum distillate</td>
<td>Carrier fluid for borate or zirconate crosslinker, friction reducers, etc.</td>
<td>Various</td>
</tr>
<tr>
<td>Borate Salts, Potassium Metaborate, Sodium Tetraborate, Boric Acid, Triethanolamine Zirconate</td>
<td>Carrier fluid for guar or guar-derivatized polymer</td>
<td>Crosslinker</td>
</tr>
<tr>
<td>Polyacrylamide</td>
<td>“Slicks” the water to minimize friction</td>
<td>Friction Reducer</td>
</tr>
<tr>
<td>Guar Gum, Derivatized Guar (HPG, CMG, CMHPG), Polysaccharide Blend</td>
<td>Thickens the water in order to suspend the sand and may be crosslinked</td>
<td>Gelling Agent</td>
</tr>
<tr>
<td>Citric Acid, Acetic Acid, Thioglycolic Acid, NTA, EDTA, Sodium Erythorbate</td>
<td>Prevents precipitation of metal oxides</td>
<td>Iron Control</td>
</tr>
<tr>
<td>Lauryl Sulfate, Isopropanol, Methanol, 2-Butoxyethanol, Turpenes</td>
<td>Used to prevent the formation of emulsions in the fracture fluid</td>
<td>Non-Emulsifier/Surfactant</td>
</tr>
<tr>
<td>Sodium Hydroxide, Potassium Hydroxide, Sodium Carbonate, Potassium Carbonate</td>
<td>Adjusts the pH of fluid for effectiveness of other components, such as crosslinkers</td>
<td>High pH Adjusting Agent</td>
</tr>
<tr>
<td>Copolymer of Acrylamide and Sodium Acrylate, Sodium Polycarboxylate, Phosphonic Acid Salt</td>
<td>Prevents scale deposits in the pipe</td>
<td>Scale Inhibitor</td>
</tr>
</tbody>
</table>

Source, //fracfocus.org/chemical-use/what-chemicals-are-used
Detailed Disclosure being Made by Australian Industry

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Fracking use</th>
<th>Common/household use example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Propanol</td>
<td>Complexor</td>
<td>Used as a solvent in the pharmaceutical industry</td>
</tr>
<tr>
<td>1,2-Butanediol</td>
<td>used to reduce surface tension to aid in gas flow</td>
<td>Used in whiteboard cleaners, liquid soaps, cosmetics and lacquers.</td>
</tr>
<tr>
<td>Acetic Acid</td>
<td>clue breaker</td>
<td>Gives vinegar its taste</td>
</tr>
<tr>
<td>Acrylic copolymer</td>
<td>Lubricant</td>
<td>Used as a soil repellent coating by the building industry</td>
</tr>
<tr>
<td>Ammonium persulfate</td>
<td>Crosslinker to increase viscosity</td>
<td>Used in hair bleaches, bleaching gels and glass cleaning products</td>
</tr>
<tr>
<td>Boric Acid</td>
<td>Crosslinker to increase viscosity</td>
<td>Used in antiseptics to treat cuts and fungal infections (athlete's foot)</td>
</tr>
<tr>
<td>Boric Oxide</td>
<td>Crosslinker to increase viscosity</td>
<td>Used to produce high strength alloys, glasses and ceramics</td>
</tr>
<tr>
<td>Carboxy-Methyl Hydroxy-Propyl Guar</td>
<td>Stabilizer (thickens fluid to help suspend sand)</td>
<td>Found in soft drinks, champagnes, and blood</td>
</tr>
<tr>
<td>Crystalline silica (chitosan)</td>
<td>Proppant (holds open fractures)</td>
<td>A more refined version of guar which is found in food products</td>
</tr>
<tr>
<td>Crystalline silica (quartz)</td>
<td>Proppant (holds open fractures)</td>
<td>Sand and gravel</td>
</tr>
<tr>
<td>Citric Acid</td>
<td>Citric acid</td>
<td>Contained in orange juice</td>
</tr>
<tr>
<td>Diassium Persulfate</td>
<td>Crosslinker to reduce viscosity (turns a gel into water)</td>
<td>Used in hair bleaches, bleaching gels and glass cleaning products</td>
</tr>
<tr>
<td>Disodium Octaborate Tetrahydrate</td>
<td>Crosslinker to increase viscosity</td>
<td>Used as a fertilizer</td>
</tr>
<tr>
<td>Gas oils (petroleum), hydrotreated light vacuum</td>
<td>Guar buffer</td>
<td>Baby oil, coolant or thermal fluid, wood conditioner</td>
</tr>
<tr>
<td>Guar</td>
<td>Guar buffer</td>
<td>Used to treat psoriasis, and as a flavouring, and to make sourdough and rye bread</td>
</tr>
<tr>
<td>Guar Gum</td>
<td>Guar buffer</td>
<td>Used to make jelly</td>
</tr>
<tr>
<td>Guanidine Base Enzyme with without Sodium Chloride</td>
<td>Guar buffer</td>
<td>Used as a food thickening agent</td>
</tr>
<tr>
<td>Hydrochloric Acid</td>
<td>Cleaning of the well bore prior to fracing</td>
<td>Citrus for food processing and coffee</td>
</tr>
<tr>
<td>Hydroxy-Ethyl Cellulose</td>
<td>Crosslinker to reduce viscosity (turns a gel into water)</td>
<td>Used to clean swimming pool filters</td>
</tr>
<tr>
<td>Hydroxy-Propyl Guar</td>
<td>Crosslinker to increase viscosity</td>
<td>Used as a placebo in medical trials</td>
</tr>
<tr>
<td>Magnesium silicate hydrate</td>
<td>Crosslinker to increase viscosity</td>
<td>Chemically identical to talcum powder</td>
</tr>
<tr>
<td>Methanol</td>
<td>Crosslinker to reduce viscosity (turns a gel into water)</td>
<td>A type of alcohol, can be used in wastewater treatment and as an alternative fuel</td>
</tr>
<tr>
<td>Mono Ethanol amine</td>
<td>Crosslinker to increase viscosity</td>
<td>Used in the manufacture of cosmetics, pharmaceuticals, and emulsifiers</td>
</tr>
<tr>
<td>Ethylene Glycol Monobutyl Ether</td>
<td>Crosslinker to increase viscosity</td>
<td>Used in household cleaners, fire fighting foam, and to degrease bowing pins and lances</td>
</tr>
<tr>
<td>Muriatic Acid</td>
<td>Crosslinker to increase viscosity</td>
<td>Used in household cleaners, fire fighting foam, and to degrease bowing pins and lances</td>
</tr>
<tr>
<td>Non-crystalline silica</td>
<td>Crosslinker to increase viscosity</td>
<td>Used to make glass</td>
</tr>
<tr>
<td>Poly (oxy-1,2-ethanediyl)</td>
<td>Crosslinker to increase viscosity</td>
<td>Hair treatments and shampoo</td>
</tr>
<tr>
<td>Polyacrylamidylammonium chloride</td>
<td>Clay inhibitor</td>
<td>Used in paper making, as an antiseptic and as a fire suppressant</td>
</tr>
<tr>
<td>Potassium Carbonate</td>
<td>Clay inhibitor</td>
<td>Used in waste water treatment</td>
</tr>
<tr>
<td>Potassium Chloride</td>
<td>Clay inhibitor</td>
<td>Provides the primary flavoring in salt and vinegar potato chips</td>
</tr>
<tr>
<td>Quaternary Polyamines</td>
<td>Clay inhibitor</td>
<td>A component in glass, pottery, and detergents</td>
</tr>
<tr>
<td>Sodium Acetate</td>
<td>pH buffer</td>
<td>Used in cooking</td>
</tr>
<tr>
<td>Sodium Borate</td>
<td>pH buffer</td>
<td>Used to neutralise acid</td>
</tr>
<tr>
<td>Sodium Bicarbonate</td>
<td>pH buffer</td>
<td></td>
</tr>
<tr>
<td>Sodium Carbonate (Soda Ash)</td>
<td>pH buffer</td>
<td></td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>pH buffer</td>
<td></td>
</tr>
<tr>
<td>Sodium Hypochlorite with Sodium Hydroxide</td>
<td>Antiseptic to eliminate bacteria in water</td>
<td></td>
</tr>
<tr>
<td>Sodium Persulfate</td>
<td>Antiseptic to eliminate bacteria in water</td>
<td></td>
</tr>
<tr>
<td>Sodium Sesquicarbonate/citric acid</td>
<td>Antiseptic to eliminate bacteria in water</td>
<td></td>
</tr>
<tr>
<td>Tetraethyl (hydromethyl) Phosphonium Sulfate</td>
<td>Antiseptic to eliminate bacteria in water</td>
<td></td>
</tr>
<tr>
<td>Tetramethyl ammonium chloride</td>
<td>Clay control</td>
<td></td>
</tr>
<tr>
<td>Terpolymer complex</td>
<td>Crosslinker to increase viscosity</td>
<td></td>
</tr>
</tbody>
</table>

Testing Fracturing Fluids

Frac Fluid Lab, Proptester Inc.

Fann 50 Rotational Viscometer, Fann Instrument Company

Mobile Testing Lab, Proptester Inc.

Frac Fluid Sample, Proptester Inc.
Ray's Location:

- 1980 Farmington NM (Mesa Verde/Dakota/Fruitland)
- 1981 Rocky Mtn Region
- 1982-1983 Williston Basin
- 1984-1987 Bryan Tx (Austin Chalk)
- 1988-1991 Mid Continent Region
- 1991-1993 Rocky Mtn Region
- 1993-1996 Farmington NM (Mesa Verde/Dakota/Fruitland)
- 1996-1997 Midland Texas
Fluid Trends vs Gas Price

Ray’s Location:
- 1980 Farmington NM (Mesa Verde/ Dakota/Fruitland)
- 1981 Rocky Mtn Region
- 1982-1983 Williston Basin
- 1984-1987 Bryan Tx (Austin Chalk)
- 1988-1991 Mid Continent Region
- 1991-1993 Rocky Mtn Region
- 1993-1996 Farmington NM (Mesa Verde/ Dakota/Fruitland)
- 1996-1997 Midland Texas
Breakers

- **1980s**
  - Oxidizing breakers
  - Heat (eliminate oxygen scavengers from fluids)

- **1990s**
  - Encapsulated breakers (*Encapsulated Breaker for Aqueous Polymeric Fluids* King, Gulbis, Hawkins, and Brannon, PETSOC 90-89 1990)
  - *Evaluation of the Breaker Concentrations Required To Improve the Permeability of Proppant Packs Damaged by Hydraulic Fracturing Fluids* Brannon and Pulsinelli SPE19402-MS 1990
  - Fluid based (*New, Delayed Borate-Crosslinked Fluid Provides Improved Fracture Conductivity in High-Temperature Applications*, Brannon and Ault SPE 22838-MS 1991)
  - Biotechnological Breakthrough Improves Performance of Moderate to High-Temperature Fracturing Applications Brannon SPE 28513-MS 1994
  - *Novel Oxidizing Breaker for High-Temperature Fracturing* Terracina, McCabe, Shuchart, and Walker, SPE 56278-PA 1999
Breaker Technology

- Oxidisers react on oxidisable sites (non-specific)
  - Side chains/linkages
  - Backbone
  - Solubility groups
- Enzyme Breakers (non-specific or specific)
  - Blends or polymer specific
  - Unlock the polymer side chains or backbone
    - 1970’s Cellulase and Mannase first used
    - Late-1990s Galactomannan specific enzymes developed
  - Can be grown in tolerant bacteria for high temp, high pH
Breakers

• 2000s
  – Anti-oxidants rarely used
  – Lowered gel loading systems
  – Trend to B crosslinked fluids
  – Combinations of oxidizing, delayed oxidizing, and enzyme breakers
  – Faster flowback
Proppants

• 1980
  – Sand
    • Brady or Brown
    • Ottawa or higher-strength sand
  – High strength alternatives (glass beads, walnut hulls, etc.)
  – Exxon used sintered bauxite, establishing patent

• 1980-1985
  – 75% Sand
    • 70% Brady or Brown Sand
    • 40% Ottawa Sand
  – 15% Curable or Pre-cured resin-coated sand
  – <10% Bauxite (deep hot wells with Exxon patent)

• 1985-1995
  – 60% Sand
  – 30-35% Intermediate Strength Proppants (Ceramics, Resin Coated)
  – Some Bauxite (Exxon patent still in effect for very deep, very hot)
Types of Proppants

- Frac Sand
- Resin Coated Sand
- Ceramic Proppant
- Sintered Bauxite
Early Proppant Conductivity Studies

Source: Recent Advances in Hydraulic Fracturing, SPE 1989
Early Proppant Conductivity Studies

Source: Recent Advances in Hydraulic Fracturing, SPE 1989
Proppants

- Circa 1995….the game changed forever
  - Moxa Arch Frontier Formation Development Success Through Increased Fracture Conductivity, Schubarth and Chabaud, SPE 28610-MS, 1994
  - Moxa Arch Frontier Formation Development Success Through Increased Fracture Conductivity – Part 2, Schubarth, Chabaud, and Penny SPE 30717-MS, 1995
  - Proppants? We Don't Need No Proppants, Mayerhofer, Richardson, Meehan, Oehler, Browning SPE 38611-MS, 1997
  - The Effect of Yield Stress on Fracture Fluid Cleanup, Britt and Nolte, SPE 38619, 1997
  - Non-Darcy and Multiphase Flow in Propped Fractures: Case Studies Illustrate the Dramatic Effect on Well Productivity, Vincent and Pearson SPE 54630-MS, 1999
Fracture Conductivity

Conductivity Test Cells – Proptester Inc.

SEM of proppant pack – Proptester Inc.

Resin coated sand with frac fluid 16,500 psi closure stress and 415ºF – Proptester Inc.
Proppants

• >1995
  – Rationalisation of multiphase, non-darcy effects
  – Better understanding of cyclic loading
  – Better understanding of breaker characteristics and cleanup mechanisms
  – Better understanding of proppant transport
  – Rationalisation of effective fracture length

• More alternatives today
  – Bauxite
  – Ceramic
  – Resin Coated Ceramic or Sand
  – Sand
  – Lightweight Proppants (wood/resing products, pvc-spheres)
  – Fibres
Early Fracture Evaluation

Source: Lee, Recent Advances in Hydraulic Fracturing, SPE 1989
Rate Transient Analysis for Fracture Evaluation

A Practical Model for Evaluating a Well Producing From a Tight Gas Formation  Crafton, Poundstone and Brown, 10841-MS 1982

Pressure Transient Behavior of a Finite Conductivity Fracture in Infinite-Acting and Bounded Reservoirs  Poe, Elbel and Blasingame, 28392-MS 1994

Oil and Gas Well Evaluation Using the Reciprocal Productivity Index Method,  Crafton, 37409-MS 1997

Career Topics/Areas to be Covered

• Gain varied experiences roles
  – Balance areas of expertise (e.g., well engineering, production technology, reservoir, etc.)

• Understand external factors that can influence your career and maintain flexibility to adjust
  – Oil price
  – Gas price
  – Activity

• Technology Streams
  – Develop technology streams to focus career development
  – Be prepared to develop parallel or complementary streams over time and with more experience

• Understand Roles and Importance of Peers/Mentors