Proppant Selection
In Unconventional Reservoirs

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Outline

• Introduction
  – Proppants

• Proppant Selection Drivers
  – Importance of Conductivity

• Field Examples
  – Unconventional Reservoirs

• Summary

Two primary papers are the basis for this talk….

=> SPE 106301 & 160206
The Challenge of Tight / Unconventional Reservoirs

- Extremely low permeability formations

Key technologies driving UCR development

- Drilling and Completion advancements in HZ wells
  - HZ Operations - Perfs, plugs, completion designs
  - Multistage hydraulic fracturing

Do we understand our fractures as well as we understand our completions?
Why is this Important?

• Wellbore Specifications
  – Wellhead, casing, tubing, packers, etc
  – Specify grade, pressure service/rating, fluid service, etc

• Fracture Stimulation
  – What are you specifying for your proppant?
    • i.e. proppant type and size, testing requirements, etc.
The Proppant Conductivity Pyramid

Highest Production, EUR, IRR

High strength (minimizes crush)
Uniform size and shape
( maximizes frac porosity and permeability)
Thermal resistant (durable, minimizes degradation)
Engineered, Manufactured Product

Tier 1 - High Conductivity
Ceramic

Tier 2 - Medium Conductivity
Resin Coated Sand

Tier 3 - Low Conductivity
Sand

Low strength
Irregular size and shape
Naturally Occurring Product

99% of all proppants used today fit somewhere in this pyramid
Proppant Selection...can seem difficult

List not complete. Some names are registered trademarks, some historical

<table>
<thead>
<tr>
<th>Other</th>
<th>Sand</th>
<th>Lightweight Ceramic</th>
<th>Int. Density Ceramic</th>
<th>High Density Ceramic</th>
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<tr>
<td>LiteProp 105, 125, 175</td>
<td>Ottawa, Jordan Badger</td>
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With Resins:

- AcFrac CR, PR, Black, Tempered/Super TF
- OptiProp, PowerProp
- Super HS, Prime Plus
- XRTGold

PR = pre-cured
CR = curable
LC = low cost
DC = dual coat

CARBOBond Ceramax E
CARBOBond Ceramax V
CARBOBond Ceramax P
HyperProp

Many resins on any substrate (CARBOBond, Tempered LC, DC, HS, XRT)
Proppant Selection Drivers in Shale Plays

• Availability
• “Bring us what you have”
  – Since 2004, global proppant utilization has increased 15-fold, and is currently estimated at 60-70 billion lbs per year
  – Demand has outstripped the pace of expansion in all Tiers
    • Ceramic Plants, Resin Coating Plants, Sand Mines
  – Driven proppant costs up

• Proppant Quality Can Suffer When Demand is High
  – SPE 84304, 101821, 119242
Quality Control & Assurance

Uncoated Sand
- Strength, Shape
- Sieve Distribution
- Influx of “River” Sand

Resin Coated Sand
- Substrate Quality
- Resin/Coating Technology

Ceramics
- Tight/Broad Sieve
- Raw Material Quality
- Process Controls
- Shape/Strength
- Supply Chain QA

High Quality LWC
Low Quality River Sand
Low Quality IDC
Availability Challenges

• Challenges to Logistics / Distribution
  – Larger volumes per well / pad drilling
  – Tremendous rig counts in a basin (200+)
    • It is estimated that the Eagle Ford alone is using 10-15 billion lbs proppant annually
• Availability

• Fluid system
Fluid System Impacts

- **Fluid Selection**
  - Slickwater systems => 40/70 (& 100 Mesh)
  - Crosslinked (Hybrid) Fluids => 30/50, 20/40 and larger
  - Conductivity needs, rock fabric, cost, etc.
  - Various proppant types and sizes necessary to tailor to each individual application (SPE 115766)
Proppant Selection Drivers in Shale Plays

- Availability
- Fluid system
- Conductivity requirements
Fracture Conductivity

\[ c_f = k_f \times w_f \]

How wide is the road and how good is the pavement?
How much Conductivity do I need?

$$c_f = k_f \times w_f$$

Dimensionless Fracture Conductivity ($F_{CD}$) is a measure of the contrast between the flow capacity of the fracture and the formation.
Common Misperceptions

Misunderstanding the need for conductivity

- “My reservoir has very low permeability….so I don’t need much conductivity”
- “Proppant A is ‘good enough’ at ___ conditions…….”

However, the big issue is whether the Fracture Conductivity is correctly estimated at realistic (downhole) conditions.
How is Conductivity Measured?

ISO 13503-5 Conductivity Test

- Ohio Sandstone
- 2 lb/ft\(^2\) Proppant Loading
- Stress maintained for 50 hours
- 150 or 250° F
- Extremely low water (2% KCl) velocity (2 ml/min)

Reference: API RP 19C
Pro’s & Con’s of Conductivity Testing

Accounts for:
- Proppant Size
- Proppant Strength & Crush “Profile”
- “Wet” system
- Some temperature effects
- Some embedment

Does NOT Account for:
- Non-Darcy Flow
- Multiphase Flow
- Reduced Proppant Concentration
- Gel Damage
- Fines Migration/Cyclic Stress
- Others

Reference: ISO 13503-5
Problem

To obtain a realistic proppant conductivity for design, the API/ISO test results must be reduced to account for:

1. Non-Darcy Flow
2. Multiphase Flow
3. Reduced Proppant Concentration
4. Gel Damage
5. Fines Migration / Cyclic Stress
6. Other
ND Flow Through a Proppant Pack

The following animation depicts the flow through an actual 16/20 Lightweight Ceramic proppant pack, 2 lb/ft² and 4000 psi stress.

ISOTest - 2 ml/min

100 bopd with 50% Sg
Or 120 MSCFD at 1500 psi BHFP

\[ \Delta P/L = \frac{\mu v}{k} \]

*Darcy Dominated*

\[ \Delta P/L = \frac{\mu v}{k} + \beta \rho v^2 \]

*Inertia Dominated*
Multiphase Flow

- **Relative permeability:** Proppant saturated with liquid is less conducive to flowing gas.

- **Saturation changes:** Liquid will tend to accumulate in the frac, occupying porosity that is now unavailable for gas flow.

- **Phase interaction:** The fast-moving gas “wastes” energy accelerating the droplets of liquid. But the liquid often stops at each pore throat, only to be re-accelerated. Very inefficient flow regime!
Other Conductivity Reductions

• Lower Proppant Concentrations
  – Typically <1 lb/ft²
  – Exacerbates ND/MP flow effects

• Gel Damage
  – Residual, Filter Cake, Tip Plugging

• Fines Migration
  – Fines of different proppant types
  – Each proppant type handles fines differently

• Cyclic Stress
  – Each time the bottom hole flowing pressure changes, the proppant pack rearranges and loses conductivity

• Durability
  – Fracture conductivity degrades over time
Conductivity at Realistic Conditions

At baseline conditions, the Tier 1 proppant is 4x the Tier 3, but jumps to over 15x at realistic conditions.
Impact of Realistic Conditions

At baseline conditions the Tier 1 proppant performs 4x the Tier 3.

At realistic conditions, the Tier 1 proppant performs 15x the Tier 3.

References: PredictK & SPE 106301

Conditions: YM=5e6 psi, 250°F, 1 lb/ft², 6000 psi, 500 mcf/d, 1000 psi bhfp, 50 ft H, 2 blpd
• Elevated Temperatures
  – Sand-based proppants lose conductivity at >200 F
  – Ceramic proppants unaffected by temperature
  – Eagle Ford, Haynesville, etc
Additional Conductivity Considerations in UCRs

• Elevated Temperatures
  – Impact on natural proppants at >200 F
  – Eagle Ford, Haynesville, etc

• Soft Formations
  – Increased proppant embedment
  – Many shale plays

• Flow Convergence
  – Transverse fracs in horizontal wells

Tremendous pressure drop!
=> Higher conductivity imperative
The Reality

So in reality…

- The conductivity of our fractures is *much lower* than we think
- Most hydraulic fractures are “*conductivity limited*”
- Modeling and field testing confirms that increasing the fracture conductivity will *increase production/EUR*.
  - SPE 77675 & 134330

But….

- Increasing conductivity typically increases the investment
  - It is a Cost – Benefit decision
Proppant Selection Drivers in Shale Plays

- Availability
- Fluid system
- Conductivity requirements in these formations
- Cost vs Benefit
  - Economic Conductivity™
The Proppant Conductivity Pyramid

Tier 1 - High Conductivity
High strength (minimizes crush)
Uniform size and shape (maximizes frac porosity and permeability)
Thermal resistant (durable, minimizes degradation)
Engineered, Manufactured Product

Tier 2 - Medium Conductivity
Medium strength
Irregular size and shape
Resin Coated Sand

Tier 3 - Low Conductivity
Low strength
Irregular size and shape
Naturally Occurring Product

Higher Conductivity = higher production = higher investment
Proppant Selection is a Cost-Benefit decision
ECONOMIC CONDUCTIVITY PROCESS

Predict the fracture Conductivity at Realistic Conditions

- Some sophisticated Frac Models will do this

Run sensitivities to determine optimal Conductivity

- Provides the highest return on investment

Validate with field results

- Ensure field results support the modeling
Eagle Ford Shale

- Webb County operator
- Evaluated Tier 1 vs Tier 3 proppants
- Compared to internal wells, as well as offset operators

Proppant Selection Field Example #1
Conductivity at Eagle Ford Conditions

Baseline Conductivity, mD-ft

Realistic Conductivity, mD-ft

Baseline Conductivity
Realistic Conductivity

40/80 Tier 1
40/70 Tier 2
40/70 Tier 3
Eagle Ford Production Match/Modeling

Cumulative Production vs Time

<table>
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<tr>
<th>Transverse Fractures</th>
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<th>kfwf (mD-ft)</th>
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<tr>
<td>20</td>
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<tr>
<td>20</td>
<td>250.00</td>
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</table>

Tier 1: +50%
Tier 2: +100%
Tier 3: 

SPE 138425
ECONOMIC CONDUCTIVITY™ - Eagle Ford Shale

Cumulative Frequency for Multiple Operator Comparison Inside Condensate Window in Webb and Dimmit County, TX
6 Month Cumulative Gas Production Equivalents, BCFE

Primarily Tier 3
Primarily Tier 1

SPE 155799
Production Impact of Conductivity

Rosetta Resources Gates Ranch
12 Month Cumulative Gas Production, MMCFE
Well Completions Between Sand and Ceramic Proppant Normalized to Number of Stages

Incremental Value - $1.5 MM (payout in 9 months)

Tier 1 Proppant
Tier 3 Proppant

12 Month Cumulative Gas Production per Stage, mmcfe/stage

Cumulative Frequency, %

SPE 155799

$75/bbl, $3.50/mcf
Haynesville Shale
- Desoto/Caddo Parish by one operator
- 55 Wells – 20 utilized Tier 1 proppant, 35 utilized Tier 2
- All drilled/completed similarly in similar time frame
Actual Production after 2.5 years

Cumulative Gas Production at Month 32

Incremental 30% production (0.5 BCF per well avg) in ~2.5 Years

$1.8 million incremental PV per well after 2.5 years, for a $250k investment

$3.50/mcf
Decline Curve Analysis Projection

Avg. Cumulative Gas Production

Cum Gas (MCF)

Months

0 24 48 72 96 120 144 168 192 216 240

Cum Gas - Premium
Cum Gas - Other
Avg. Hyper Decline - Premium
Avg. Hyper Decline - Other

(~0.5 BCF)

+35% (~1 BCF) in 20 Years

SPE 160206
Proppant Selection Field Example #3

Bakken Shale

- Mountrail County operator
- Evaluated Tier 1 vs Tier 3 proppants
- 10 well internal field trial early in development program

![Map of Trial Wells and Groupings](image)

- Tier 3 Wells
- Tier 1 Wells
Bakken Trial – Conductivity Impact

22 Month Cumulative Production per Well Average

Tier 1 Wells
Tier 3 Wells

Cumulative Production at 22 months, BOE (bbl)
Bakken Trial – Conductivity Impact

A $300k investment in conductivity, has yielded a $1.5 million increase in value per well! *Payout in ~3 months*

$75/bbl, $3.50/mcf
CONDUCTIVITY Considerations in Various Plays

• Marcellus
  – Transverse Fractures, Depth, Realistic Conductivity

• Utica
  – Transverse Fractures, Depth, Oil / Multiple Fluids (similar to EF)

• Granite Wash
  – Transverse Fractures, Depth, High Gas Rate & Realistic Conductivity

• Niobrara
  – Transverse Fractures, Oil / Multiple Fluids

• Most wells should see benefits to conductivity
  – The only question is how much, and is it economic…
Key Take Away Messaging

• The HF process provides two things – reservoir contact and conductive pathway.
  – It is the critical (only) link between the reservoir and the wellbore

• Proppant is the conductivity pathway.

• Proppant Selection cannot be made based on depth, stress, mean particle diameter or what the last engineer did.
  – It must be designed specifically to the deliverability of a given well

• Hydraulic fractures are Conductivity Limited…period.
  – The more you have, the more you make.
  – One must estimate the conductivity of the fracture at realistic conditions

• Proppant Selection is a Cost vs Benefit decision
  – You must determine the economic benefit of increasing the conductivity via frac modeling and field validation
Summary

✓ Availability (& cost) impacting proppant selection
✓ Demand outstripping supply of *quality* proppant
✓ Fluid selection and Conductivity *should* drive proppant selection
✓ Best completion practices require a realistic estimate of conductivity
✓ There is tremendous value at stake