Hydraulic Fracture Design Considerations – Realistic Conducivity

Dallas YP Extended Session

Terry Palisch

July 9, 2009

Dallas, TX

SPE International

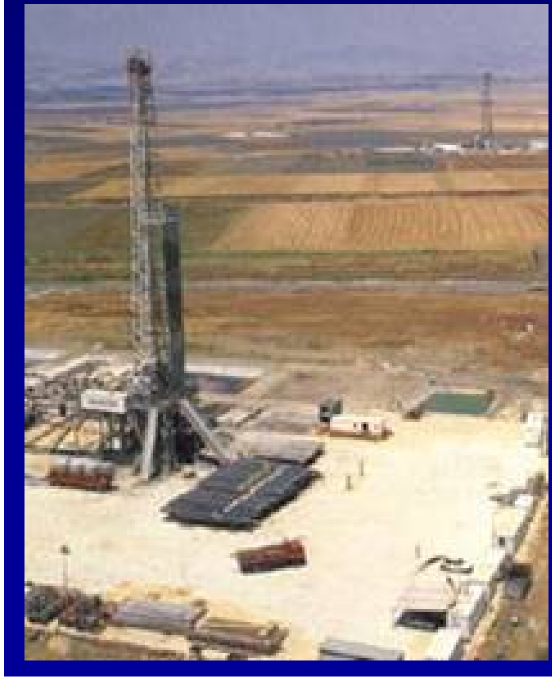
Society of Petroleum Engineers

CARBO CERAMICS

Getting a well to production…

***We drill it…
with efficient
bits, fluids,
rigs, etc.***

***We frac it…
using high-tech
equipment and
fluids, elaborate
designs, state-of-the art
monitoring, etc.***

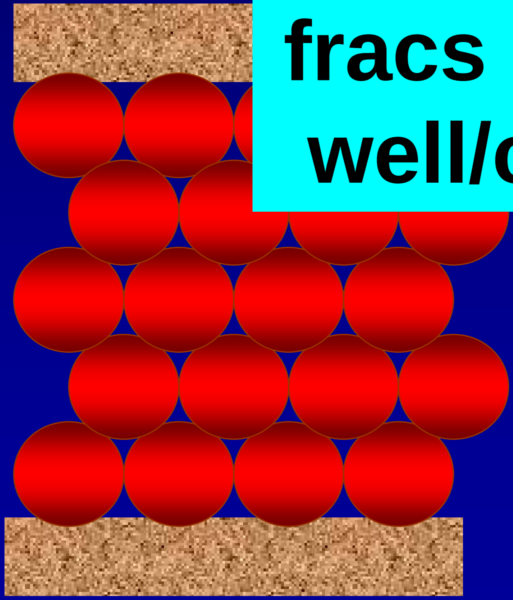


***We complete it…
with long lasting
tubulars &
jewelry, high tech
perf techniques,
etc.***

And when we are done…

All of this equipment is gone and all that is left is th

But how many of us understand our fracs as well as our well/completions?



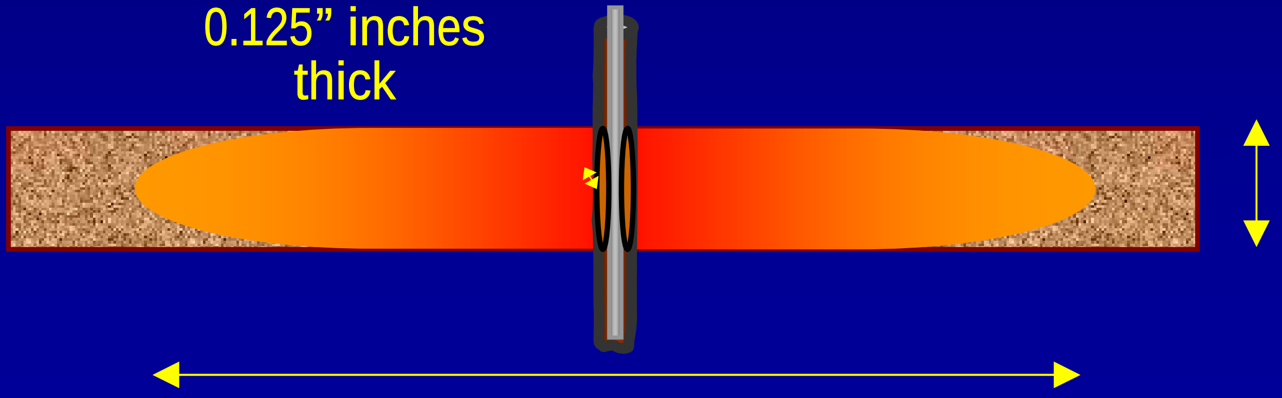
….and the frac

Dollar Bill vs Frac

0.0043 inches thick

2.61 inches tall

6.14 inches long



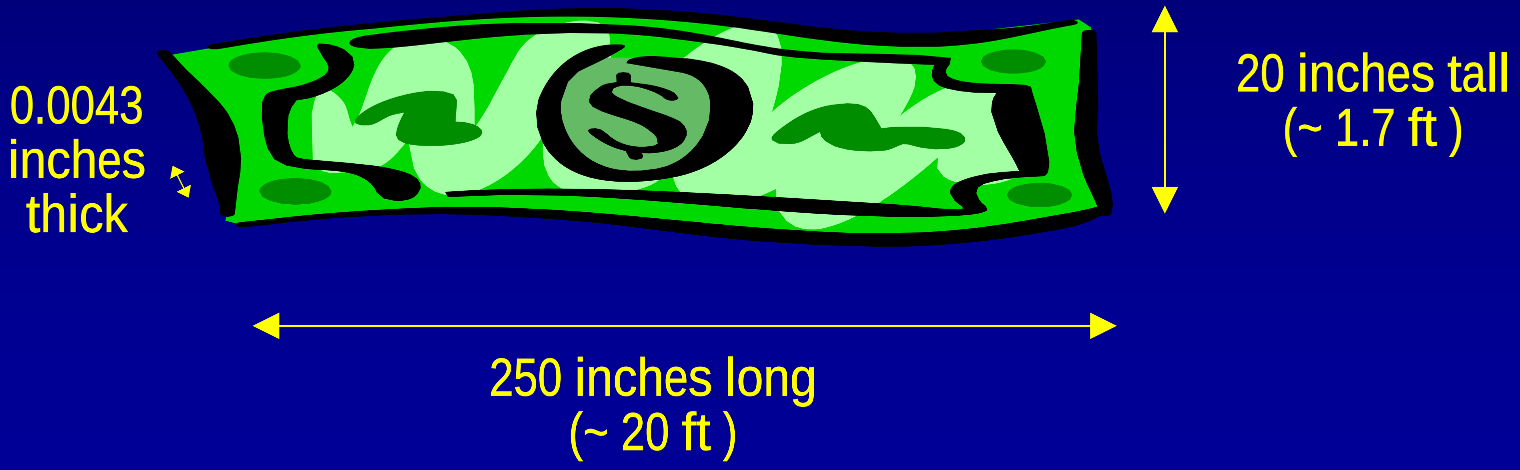
0.125” inches thick

50 feet tall

600 feet long

Proportions of a frac

- So if we wanted to print a bill on the same paper, but in the correct proportions to our 50’ x 600’ x 0.125” frac, we’d want a bill that is…



Realistic Conductivity Outline

1. What is conductivity and how is it measured?
2. Estimate impact of factors not addressed by the ISO Conductivity Test
   - ***Non-Darcy Flow***
   - Reduced Proppant Concentration
   - ***Multiphase Flow***
   - Cyclic Stress
   - Gel Damage
   - Fines Migration
3. Field Results
4. Conductivity Needs in Horizontal Wells

Additional Details can be Found in

SPE 106301

Determining Realistic Fracture Conductivity and Understanding its Impact on Well Performance – Theory and Field Examples

Terry Palisch, CARBO Ceramics, Inc.
Lucas Bazan, BP America, Inc
Harmon J. Heidt, BP America, Inc
George Turk, BP America, Inc
Robert Duenckel, CARBO Ceramics, Inc.

SPE International
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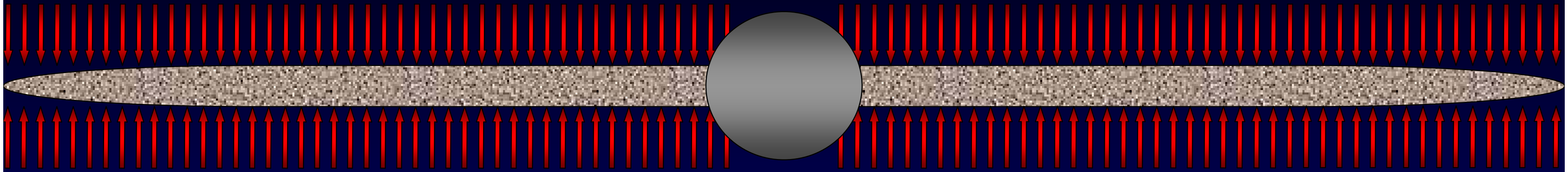
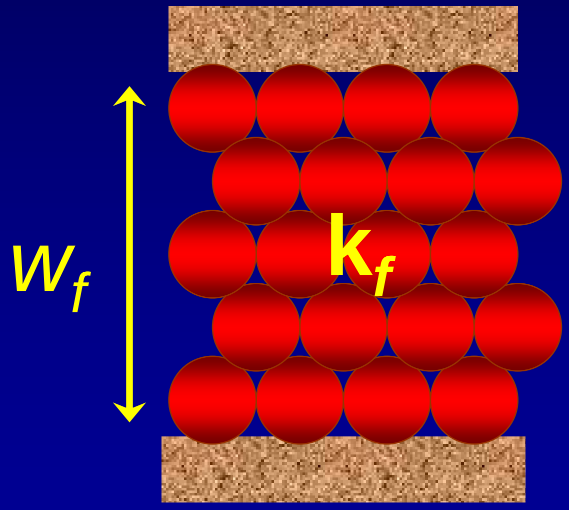
Proppant Conductivity

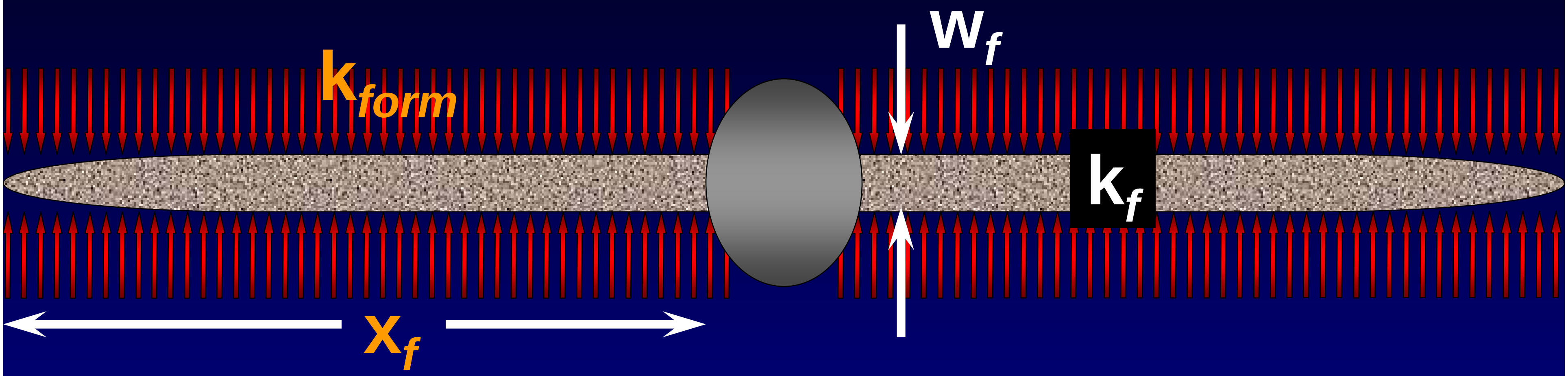


$$\boxed{c_f = k_f * w_f}$$



Conductivity (C_f) is a measure of the fracture's ability to transmit fluids

Why is Conductivity Important?



$$\boxed{F_{CD} = \frac{k_f * w_f}{k_{form} * x_f}}$$

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

Common Fracture Design and Optimization "Tools"

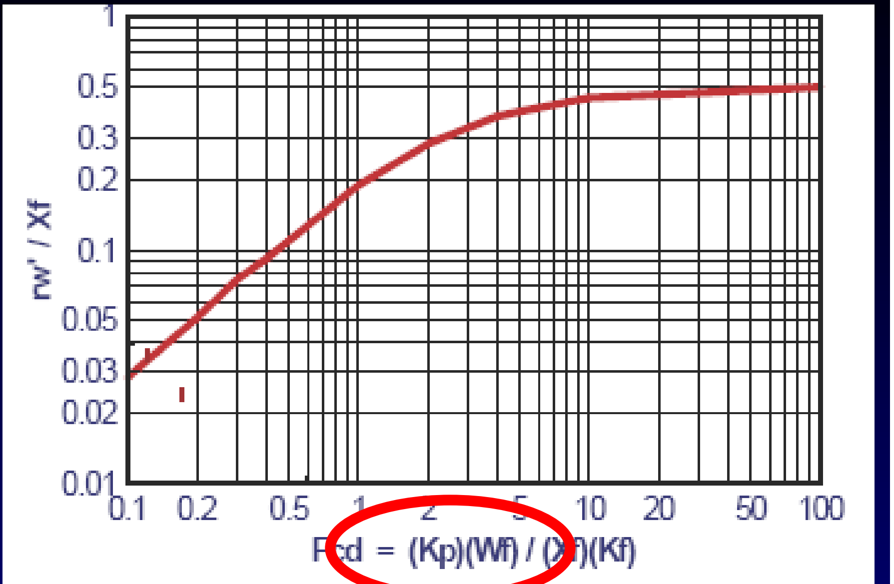


Fig. 1 – Effective Wellbore Radius for Finite-Capacity Fractures

Prats

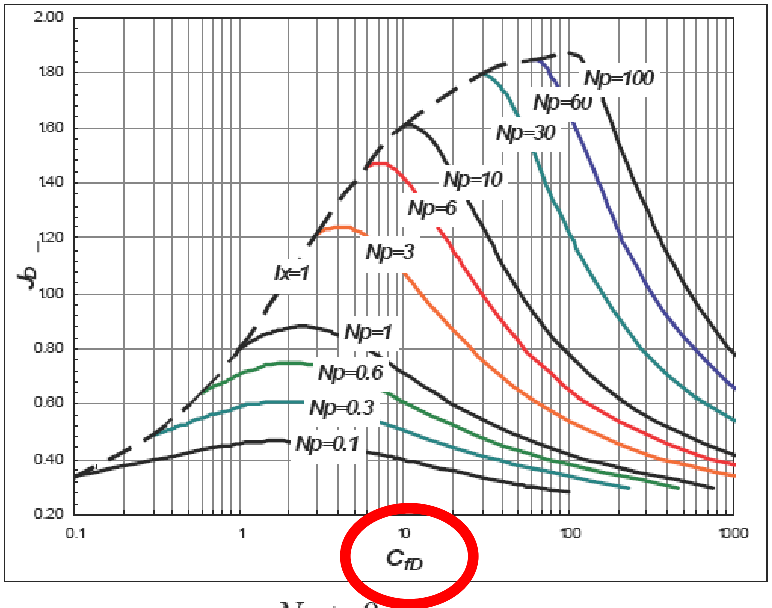


Figure 2. J_D vs. C_{fD} for $N_p \geq 0.1$ from Economides et al. (2002)

Economides

McGuire & Sikora

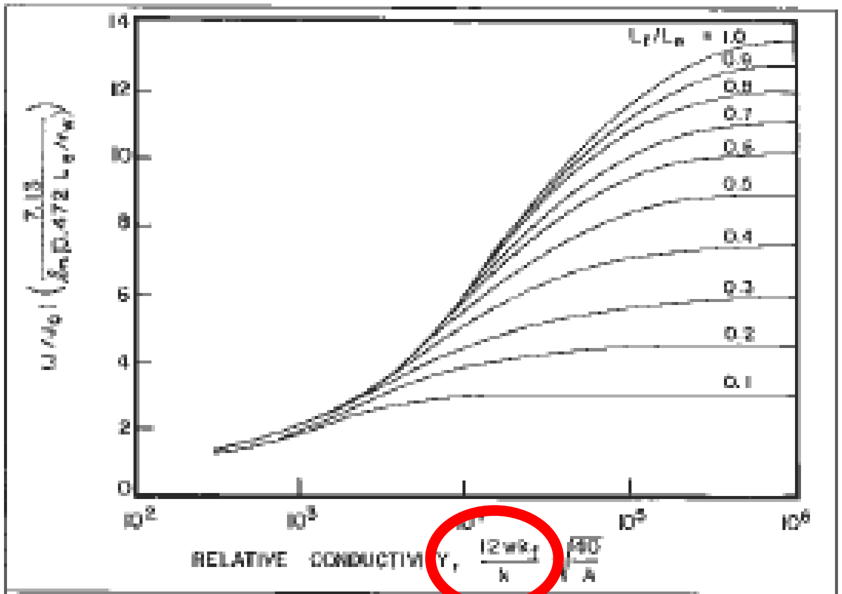
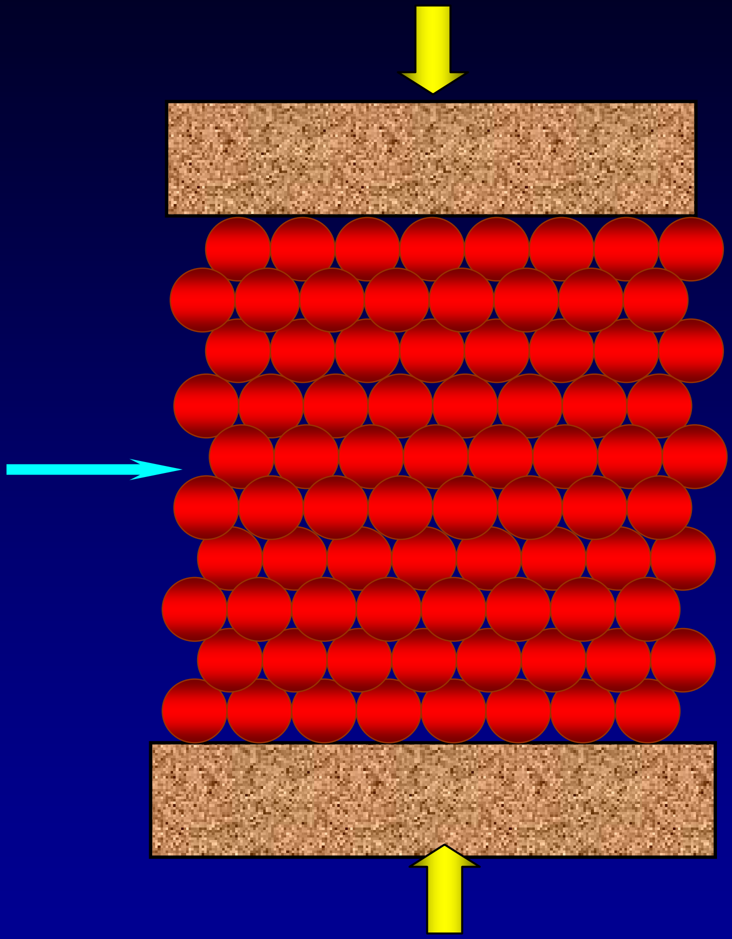


Fig. 15.3—McGuire and Sikora's[3] correlation of increase in productivity from fracturing.

How does the ISO Conductivity Test Work?

ISO 13503-5 Conductivity Test

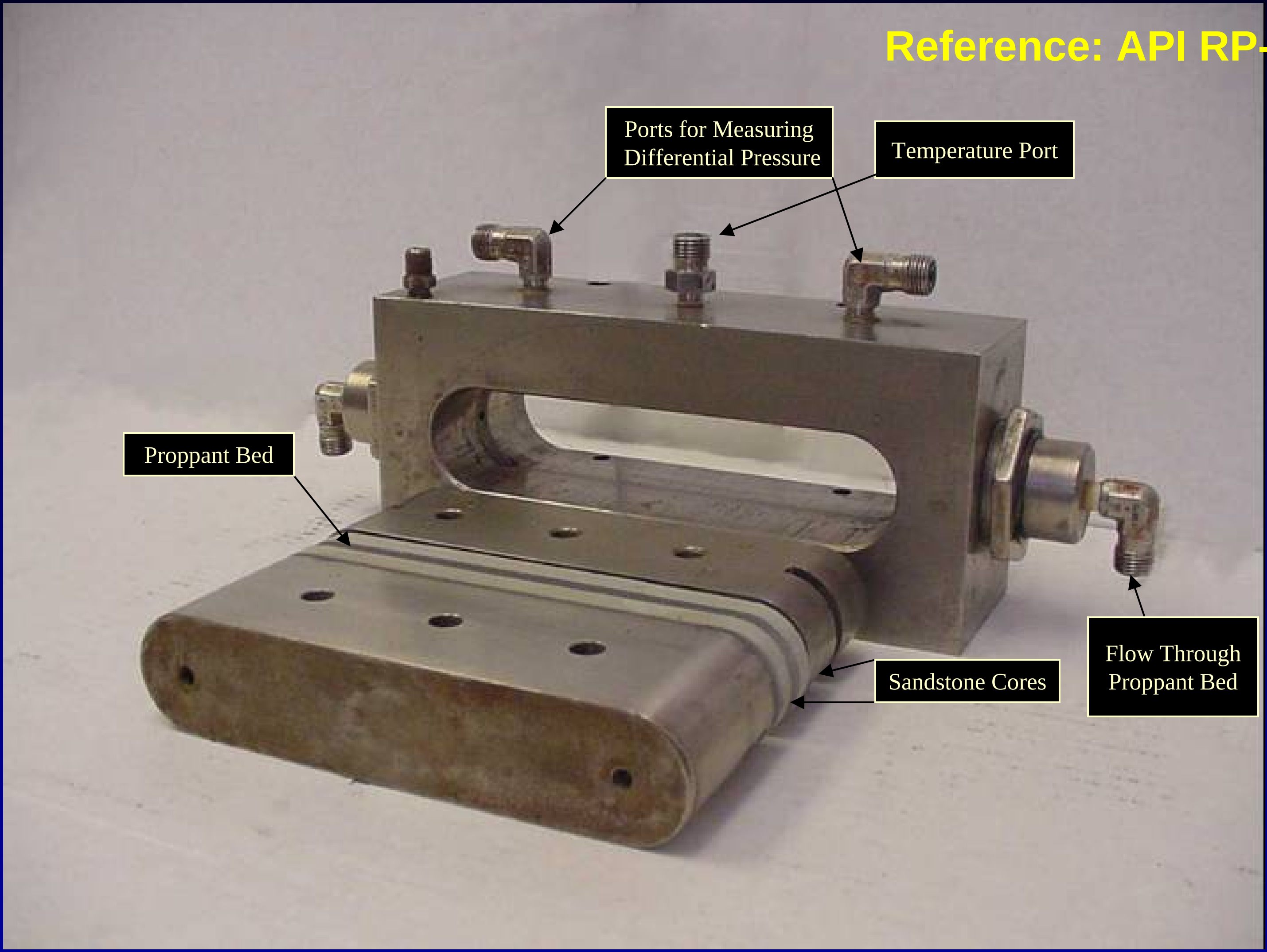
- <u>Ohio Sandstone</u>
- 2 lb/ft^2 Proppant Loading
- Stress maintained for <u>50 hours</u>
- <u>150 or 250° F</u>
- Extremely low water (2% KCl) velocity (2 ml/min)



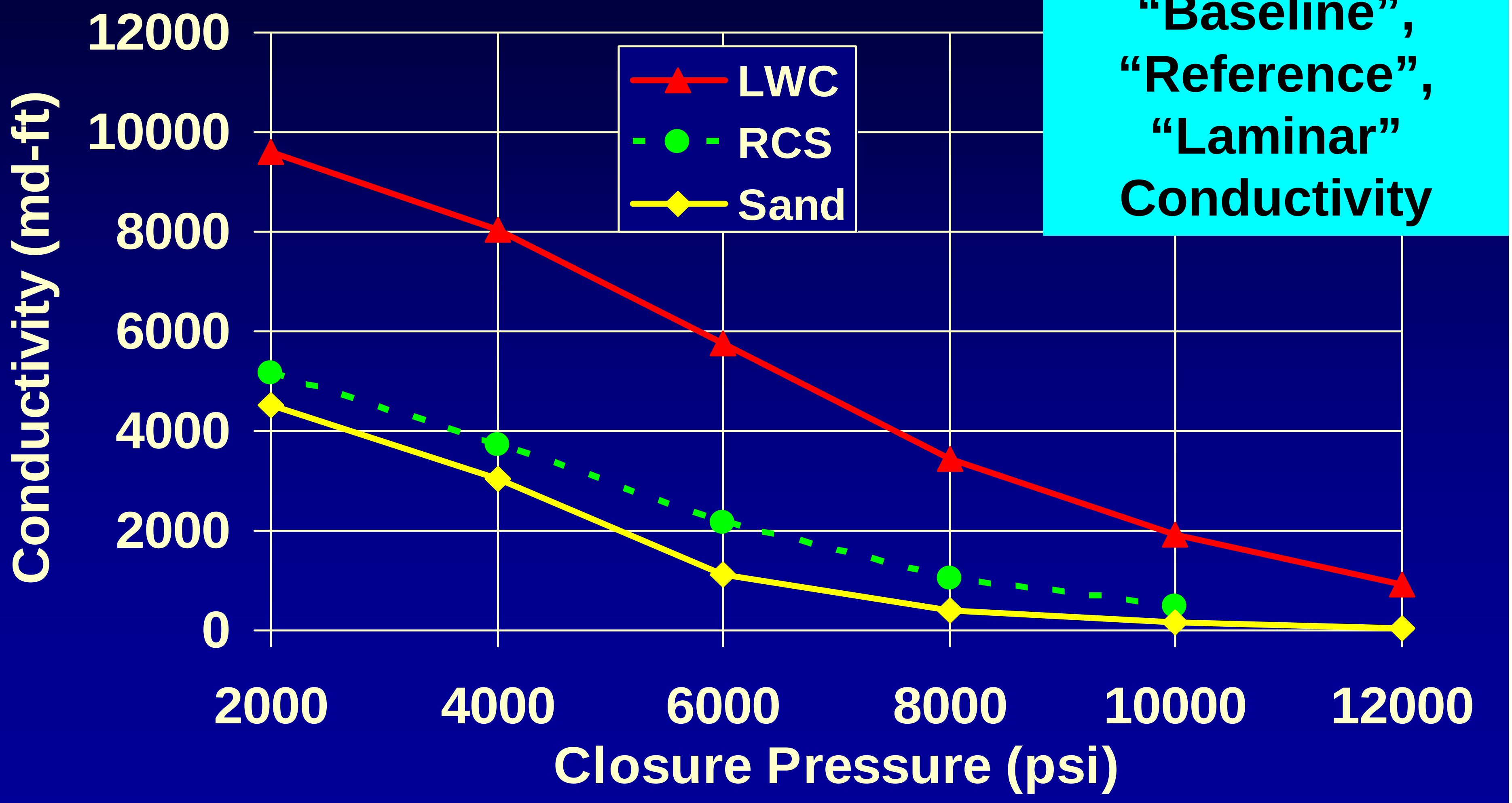
Typically referred to as a "<u>Long</u> Term" Conductivity Test

Reference: ISO 13503-5

Disassembled API Proppant Cell


Reference: API RP-61

Typical Proppant Conductivity Curve
ISO 13503-5 Procedure



“Baseline”,
“Reference”,
“Laminar”
Conductivity

Test Conditions: 2 lb/sq ft, 250°F, zero gel damage, YM = 5e6 psi, SLFrac 2001

Problem

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

1. Non-Darcy Flow
2. Multiphase Flow
3. Reduced Proppant Concentration
4. Gel Damage
5. Other Effects, including
    - Cyclic Stress
    - Fines Migration

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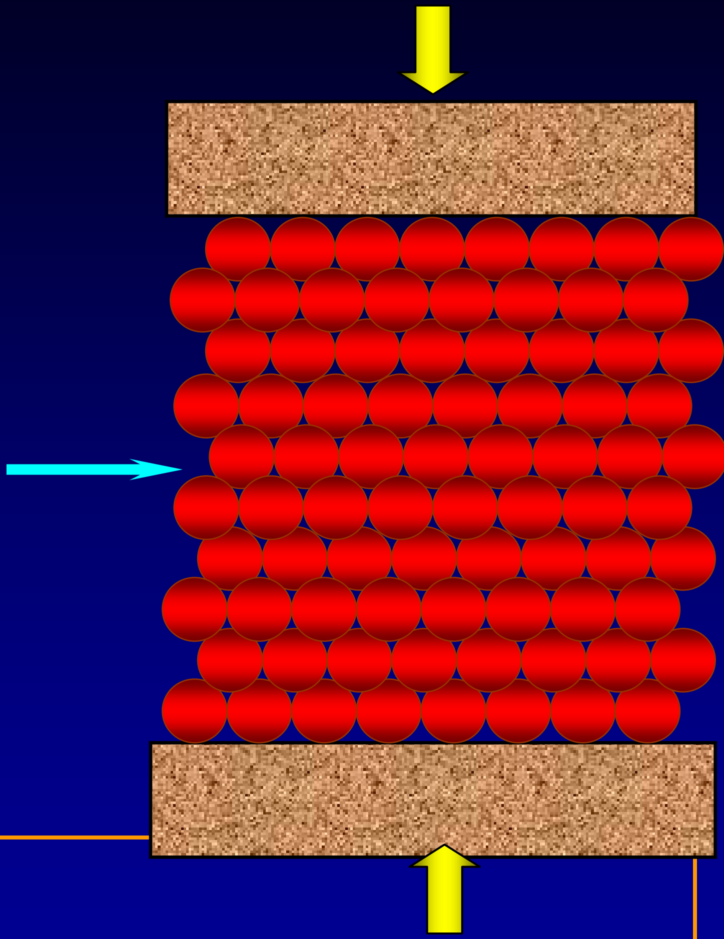
Modified API RP-61 Conductivity Test



- Ohio Sandstone
- 2 lb/ft^2 Loading
- Stress maintained for 50 hours
- 150 or 250 degrees
- Extremely low water velocity (2 ml/min)

- Velocity of distilled water:
  - – 2 ml/min equates to ~0.2 inches per minute or 8 bwpd from bi-wing frac, 30 ft frac height, 2lb/sq ft

Reference: API RP-61

Darcy's Equation

$$Q = K * \frac{(h_2 - h_1)}{L}$$

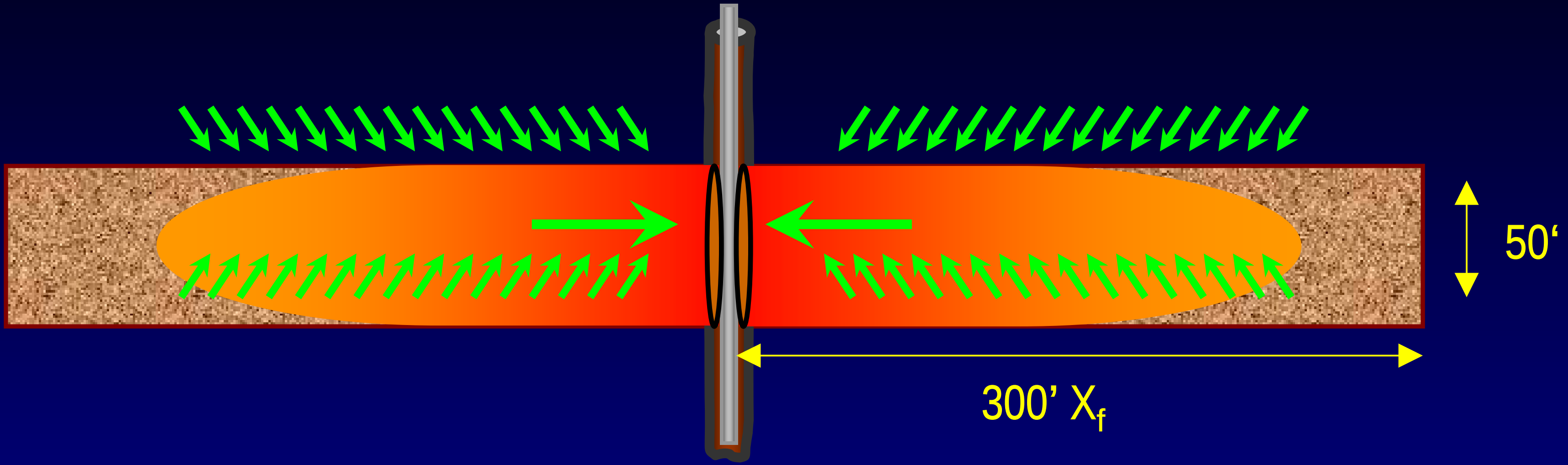
↓ **re-arrange**

$$\Delta P/L = \mu v / k$$

Applicable only with low fluid velocity

Typically valid for **matrix flow**
distant from the wellbore

Flow Convergence



With 300 ft half-length and 50 ft frac height,

60,000 ft^2 of reservoir rock which is in contact with the fracture

If we generate ¼ inch frac width (~2 lb/ft^2 or 10 kg/m^2)

Our fracture cross section is merely = 2 ft^2

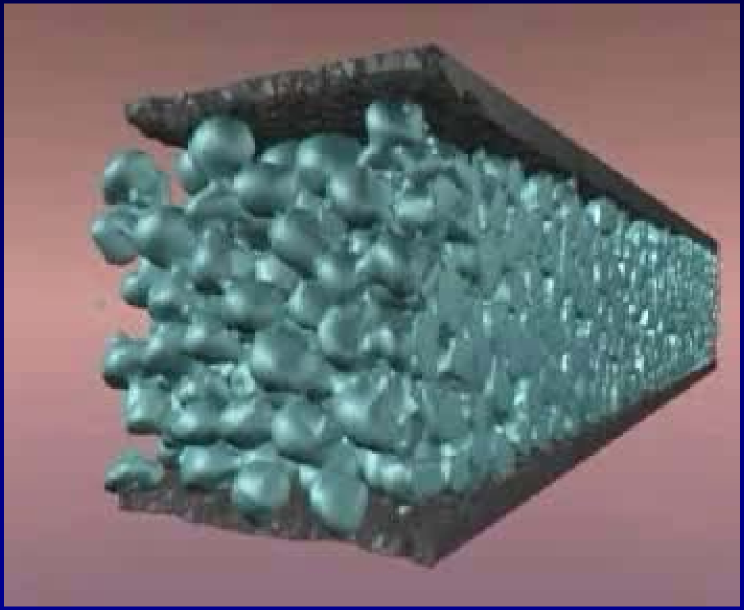
60,000 ft^2 of reservoir rock is “feeding” 2 ft^2 of fracture cross section

Superficial velocity within the fracture is 30,000 times greater than in the formation!
Fracture conductivity frequently constrains production!

Non-Darcy Flow

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

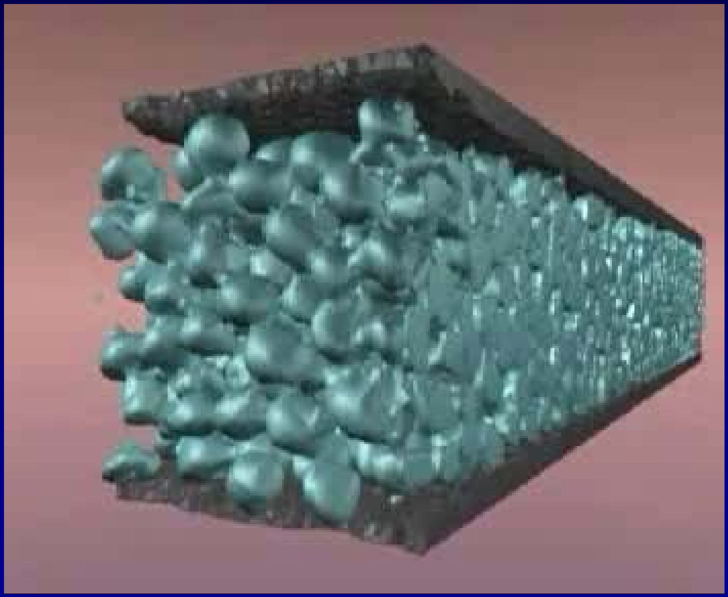
API/ISOTest - 2 ml/min



$$\Delta P/L = \mu v / k$$

Darcy Dominated

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

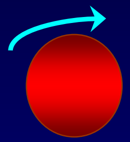


$$\Delta P/L = \mu v / k + \beta \rho v^2$$

Inertia Dominated

Darcy Flow (Friction Effects)

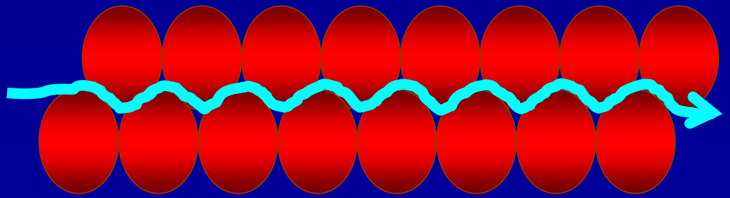
In the API test, the fluid velocity is extremely low. Pressure losses are dominated by friction, and can be described by Darcy’s Law.



$$\Delta P/L = \mu v / k$$

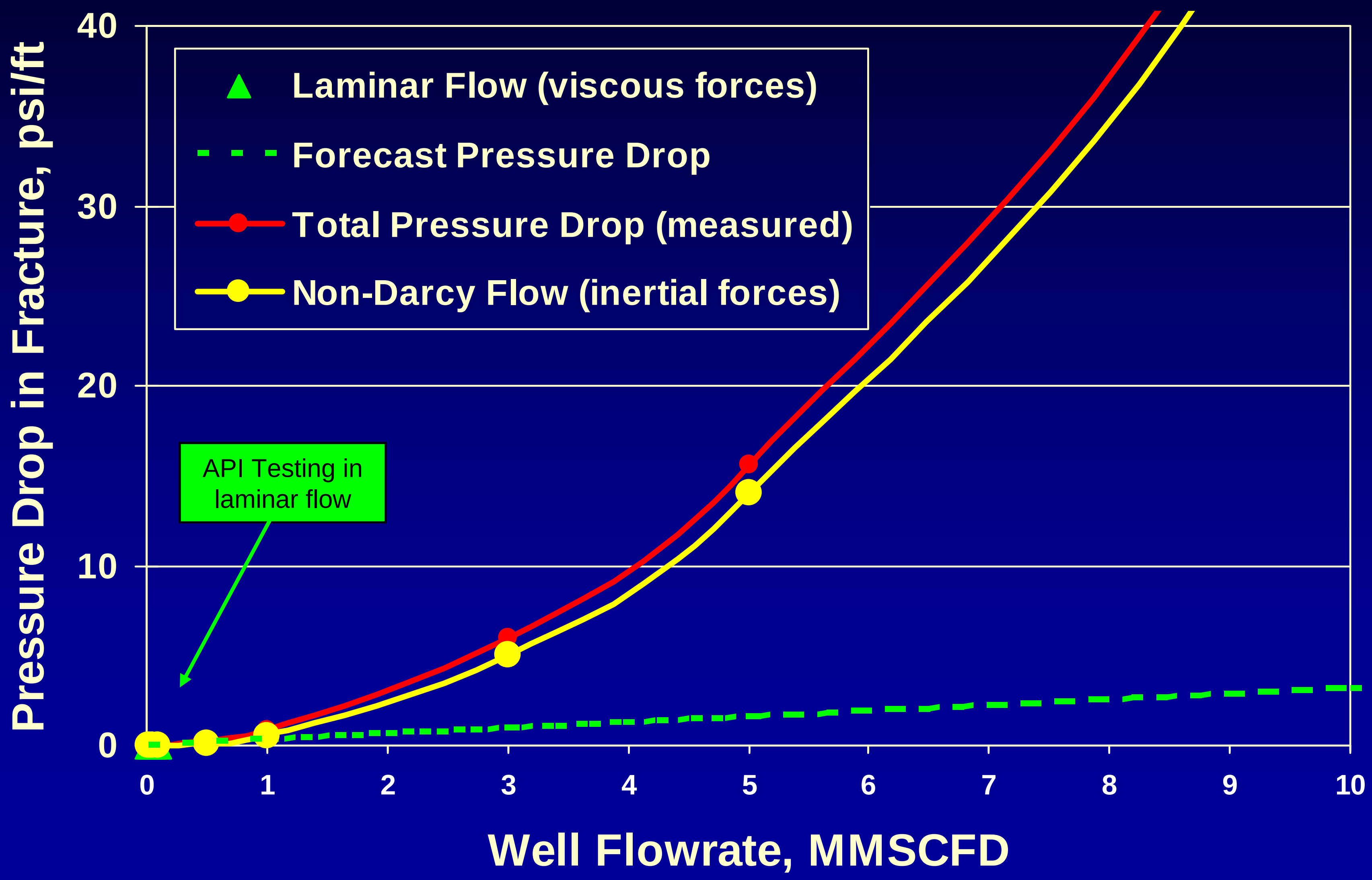
Non-Darcy Flow (Inertial Effects)

In realistic tests, the fluid velocity is high. Pressure losses are dominated by acceleration (inertial effects), and are described by Forchheimer’s Equation. This departure from Darcy’s Law can be considered a loss of effective conductivity.



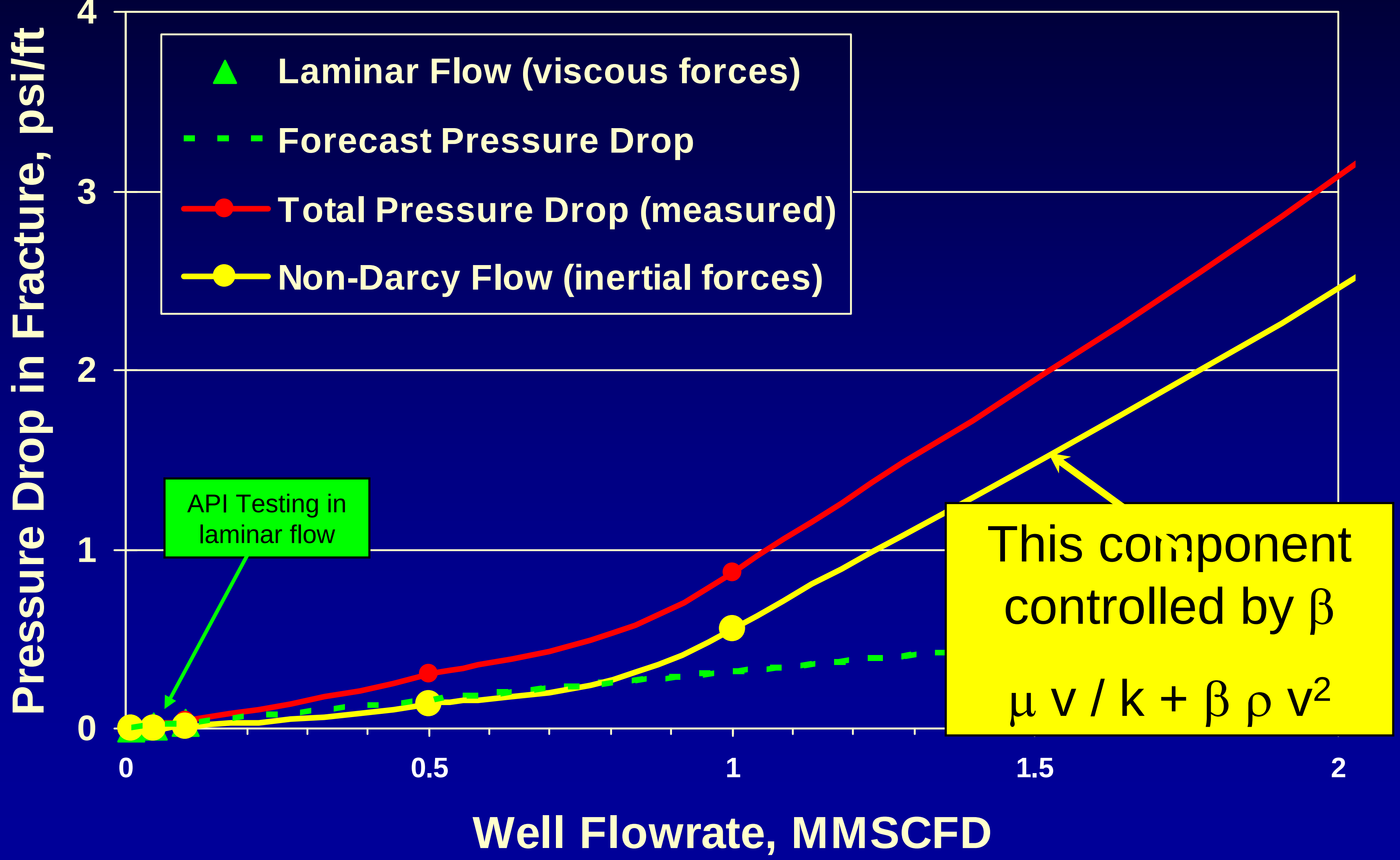
$$\Delta P/L = \mu v / k + \beta \rho v^2$$

Comparison of Viscous and Inertial Flow Effects - Dry Gas Well



Conditions: 20/40 Jordan Sand, 4000 psi stress, 50% gel damage, 50 ft frac height, 0.20 inch width, 1000 psi BHFP, SLFrac 2001

Comparison of Viscous and Inertial Flow Effects - Dry Gas Well



API Testing in laminar flow

This component controlled by β

$\mu\ v\ /\ k + \beta\ \rho\ v^2$

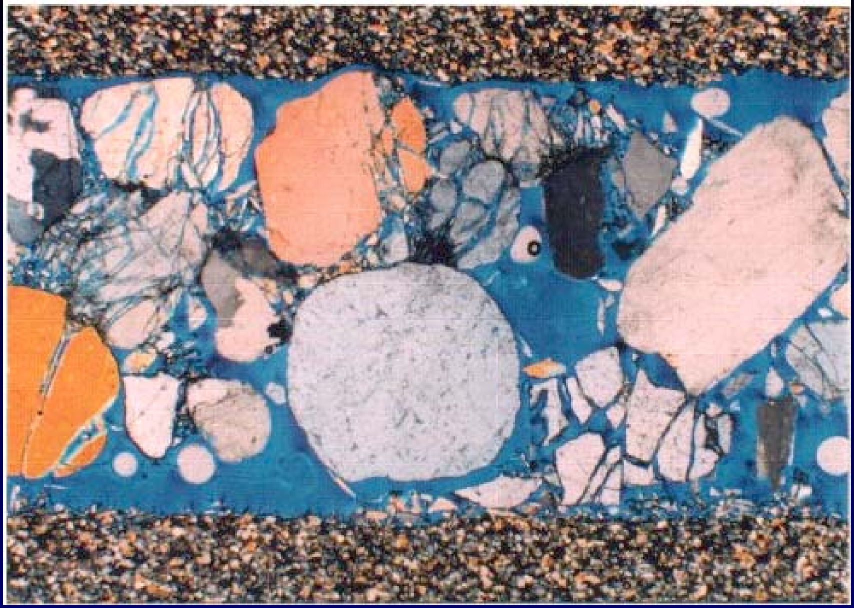
Conditions: 20/40 Jordan Sand, 4000 psi stress, 50% gel damage, 50 ft frac height, 0.20 inch width, 1000 psi BHFP, SLFrac 2001

Beta Factor

- A material property that can be experimentally measured for each proppant size and type.

- Essentially a measure of the tortuosity of the flowpath within the proppant pack.

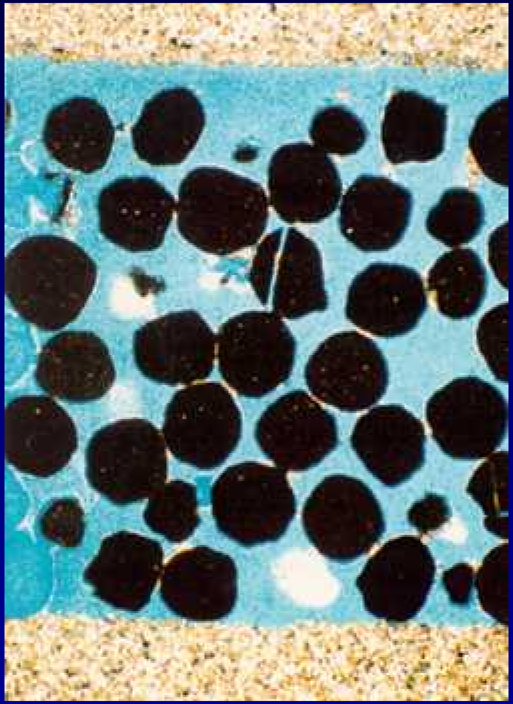
- Beta can be reduced by:
  - High Initial Permeability/Porosity (high perm equates to less tortuous flow path).
  - Tight Size Distribution (uniform pore size, and high porosity minimizes expansion/contraction losses).
  - High proppant sphericity (angularity is bad).
  - Smooth Proppant Surface



12/20 Hickory/Brady Sand at 6000 psi.

Courtesy Stim-Lab, Inc. Proppant Consortium

Which has the lowest Beta?



Resin Coated Sand at 8000 psi.

Courtesy Stim-Lab, Inc. Proppant Consortium

Intermediate Strength Ceramic at 8000 psi.

Courtesy Stim-Lab, Inc. Proppant Consortium

Problem

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

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2. Multiphase Flow
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Multiphase Flow Effects

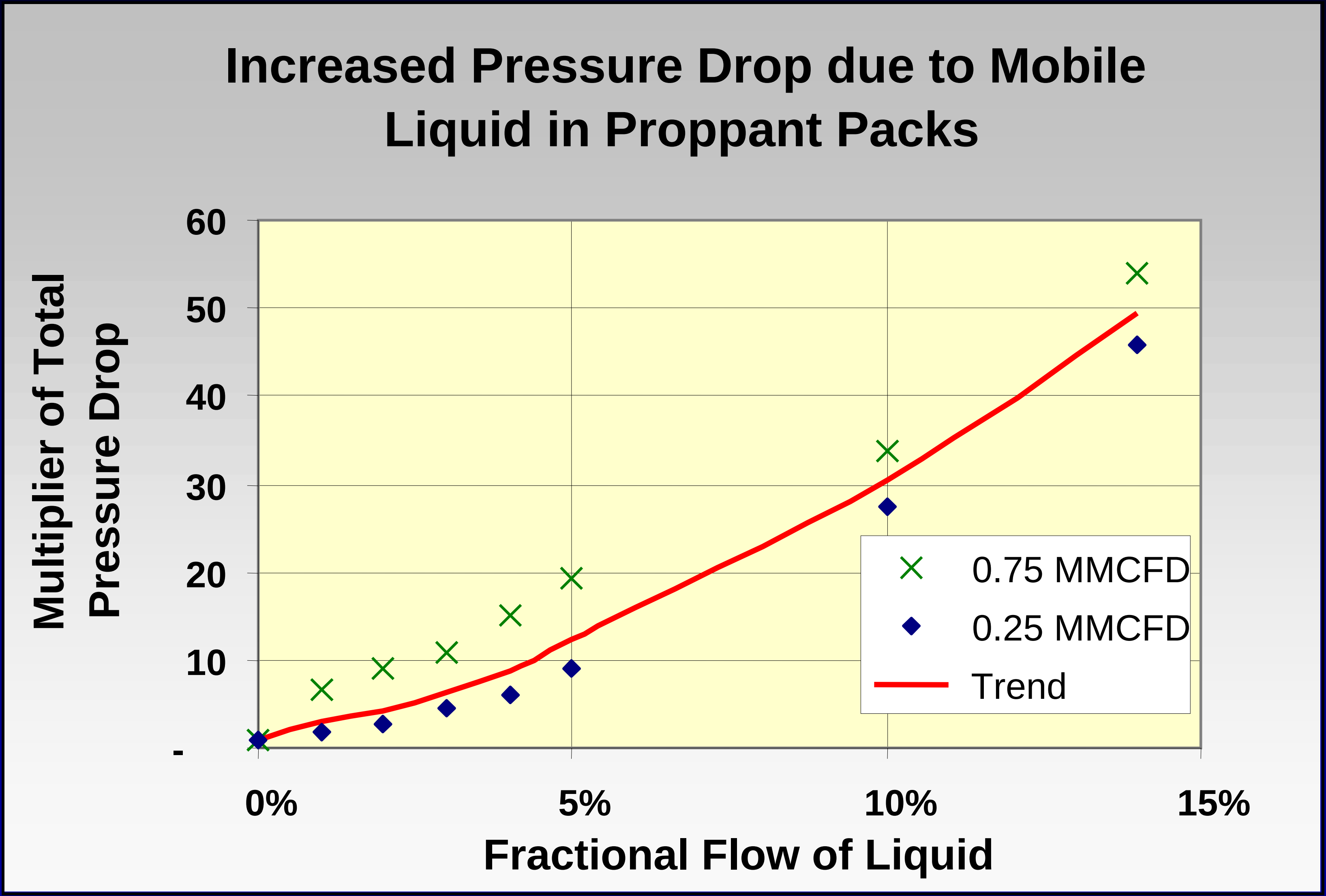
What causes pressure losses in gas wells?

- 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

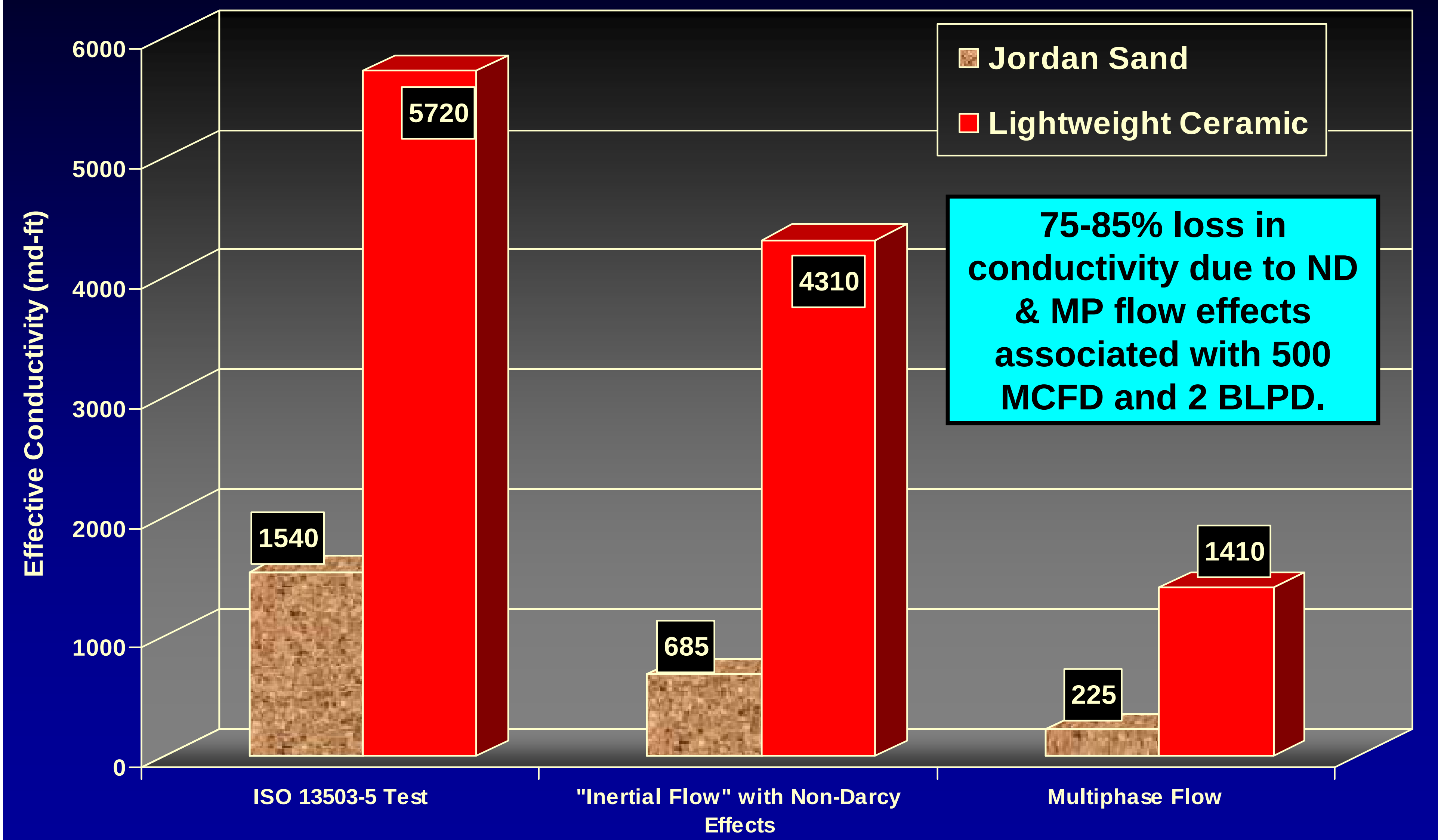
- Phase interaction:
  The fast-moving gas “wastes” energy accelerating the droplets of liquid. But the liquid often stops at each pore throat, only to be re-accelerated. Very inefficient flow regime!

Effect of liquid on dry gas flow



Source: Stim-Lab Proppant Consortium, Feb. 2001. 2.8 lb/sq ft CarboLite at 4000 psi stress, 550 Darcy reference perm. Multiplier is incremental to total pressure drop under non-Darcy conditions with dry gas. Equivalent rates from 50’ frac height at 2000 psi BHFP.

Non-Darcy and Multiphase Flow Effects



75-85% loss in conductivity due to ND & MP flow effects associated with 500 MCFD and 2 BLPD.

Conditions: YM=5e^6 psi,, 250°F, 1 lb/ft^2, 6000 psi, 500 mcfd, 1000 psi bhfp, 50 ft H, 2 blpd

References: PredictK & SPE 106301

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Lower Proppant Concentration

- In the API/ISO test, proppant is uniformly distributed at 2 lb/ft^2
- In actual fractures, the actual concentration is typically much lower
  - Typical Tight Gas fracturing it is < 1 lb/ft^2
- Realistically, the proppant is not uniformly placed, inside of uniform fracture faces

If the **concentration were halved** in typical well, there would be a corresponding **65% decrease in conductivity** due to non-Darcy effects.

Problem

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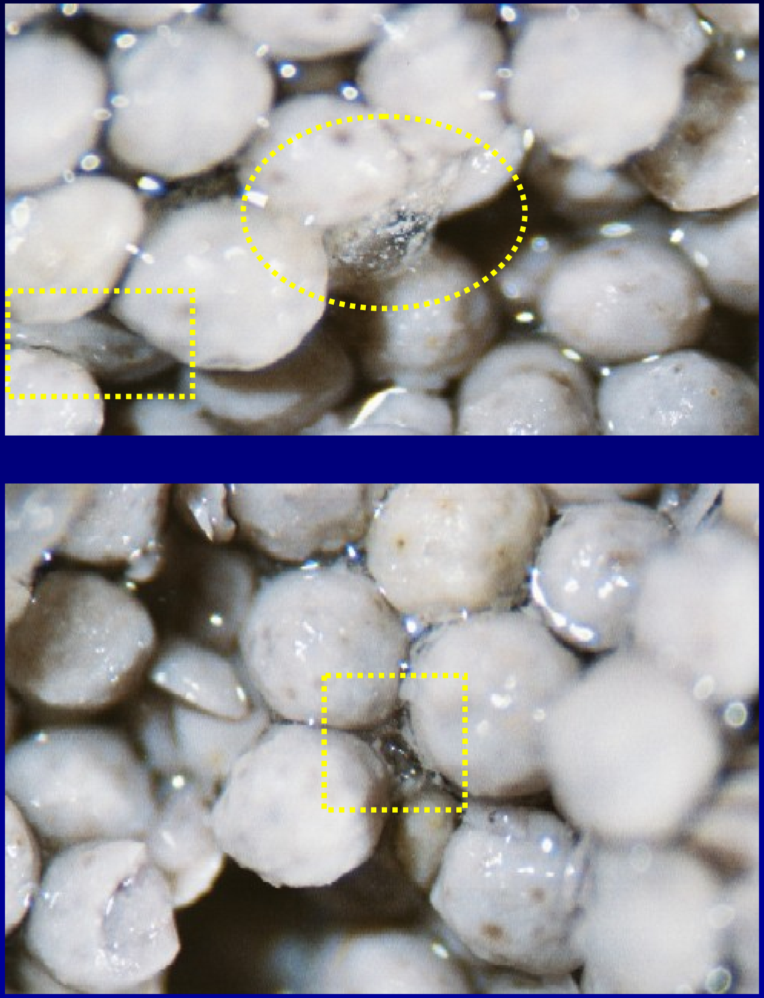
Gel Damage

May be considered as three phenomena:

- Distributed gel damage, “residual” “regained”
- Loss of effective width due to filtercake build-up
- Loss of effective length due to static gel plug in tip

Distributed Gel Residue

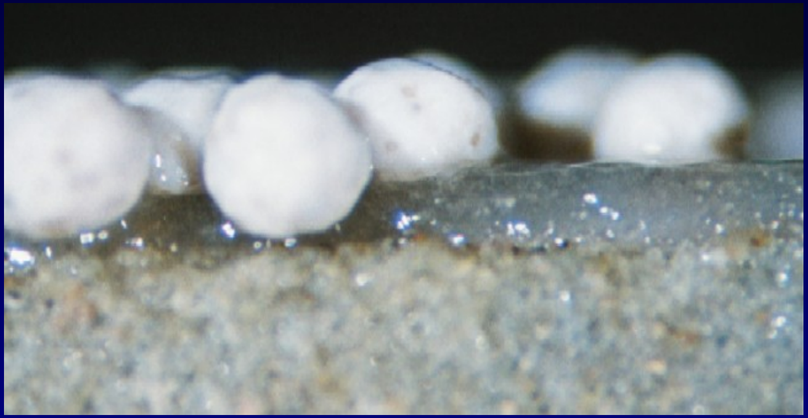
Photos from recent Stim-Lab study showing gel residue from 35ppt CMHPG + Zr in 20/40 LWC



Filter Cake -Loss of Effective Width

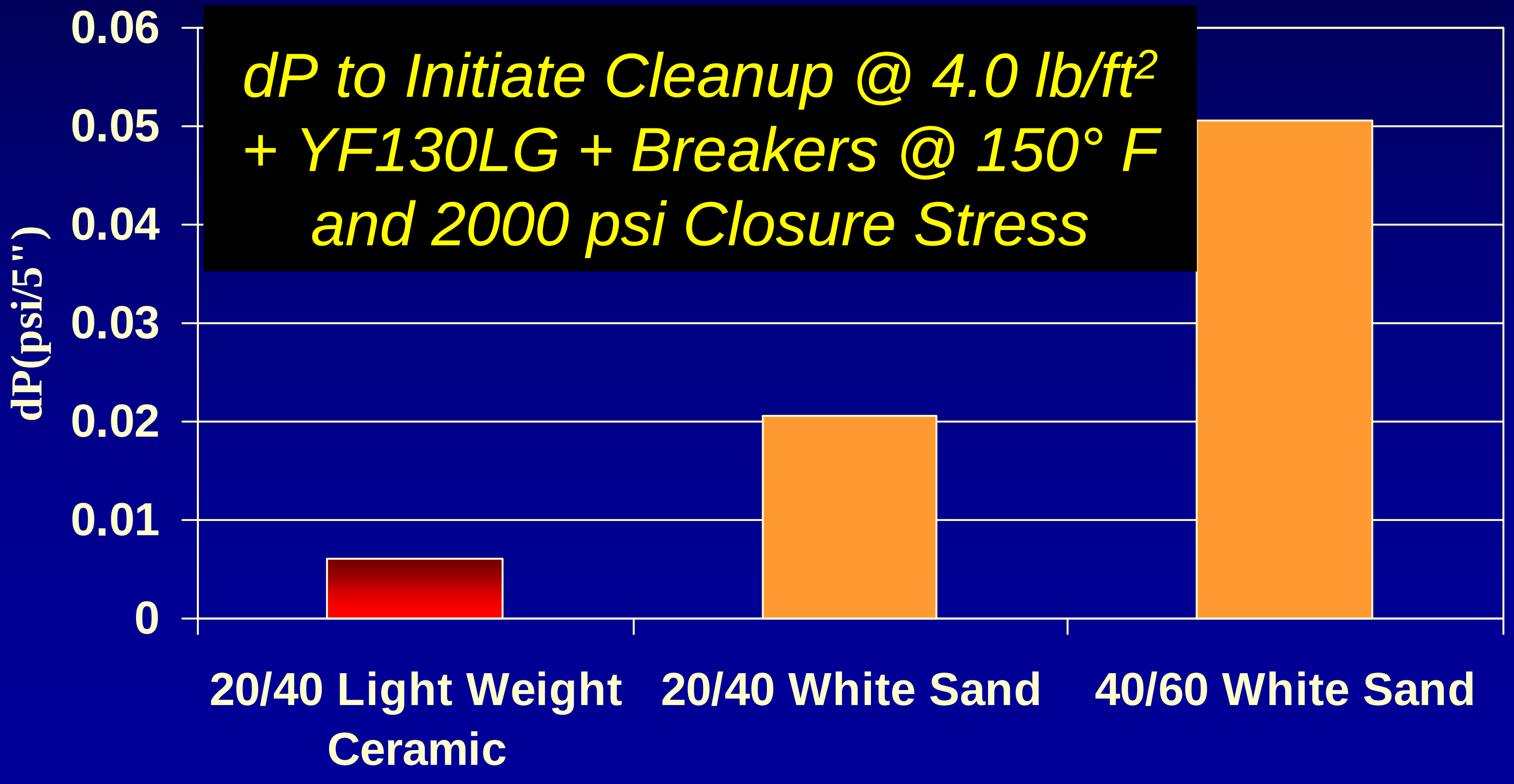
Photos from recent Stim-Lab study of filtercake formed from 35ppt CMHPG + Zr

Here the filtercake reached .75 grain diameter of 20/40 LWC



Gel Plugging – Length of Fracture that Will Clean Up

- Gel is not a Newtonian Fluid
  - Must achieve some “yield” or threshold pressure differential before it will begin to move



dP to Initiate Cleanup @ 4.0 lb/ft^2 + YF130LG + Breakers @ 150° F and 2000 psi Closure Stress

Source: Stim-Lab 12/97

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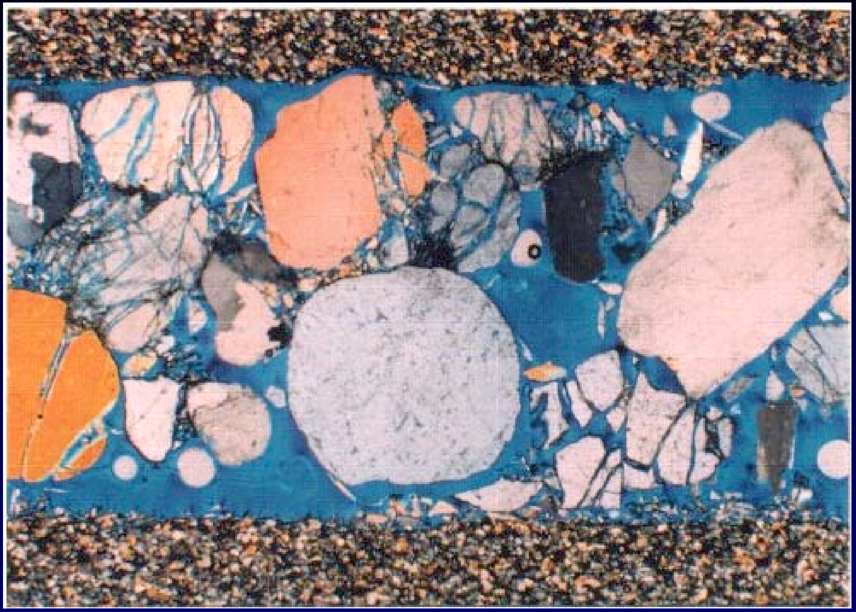
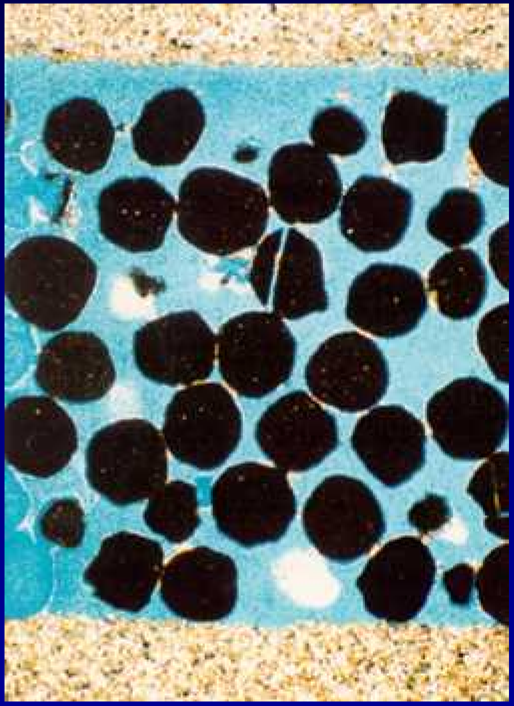
Fines Migration & Plugging



12/20 Hickory/Brady Sand at 6000 psi.

Courtesy Stim-Lab, Inc. Proppant Consortium



Resin Coated Sand at 8000 psi.

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Intermediate Strength Ceramic at 8000 psi.

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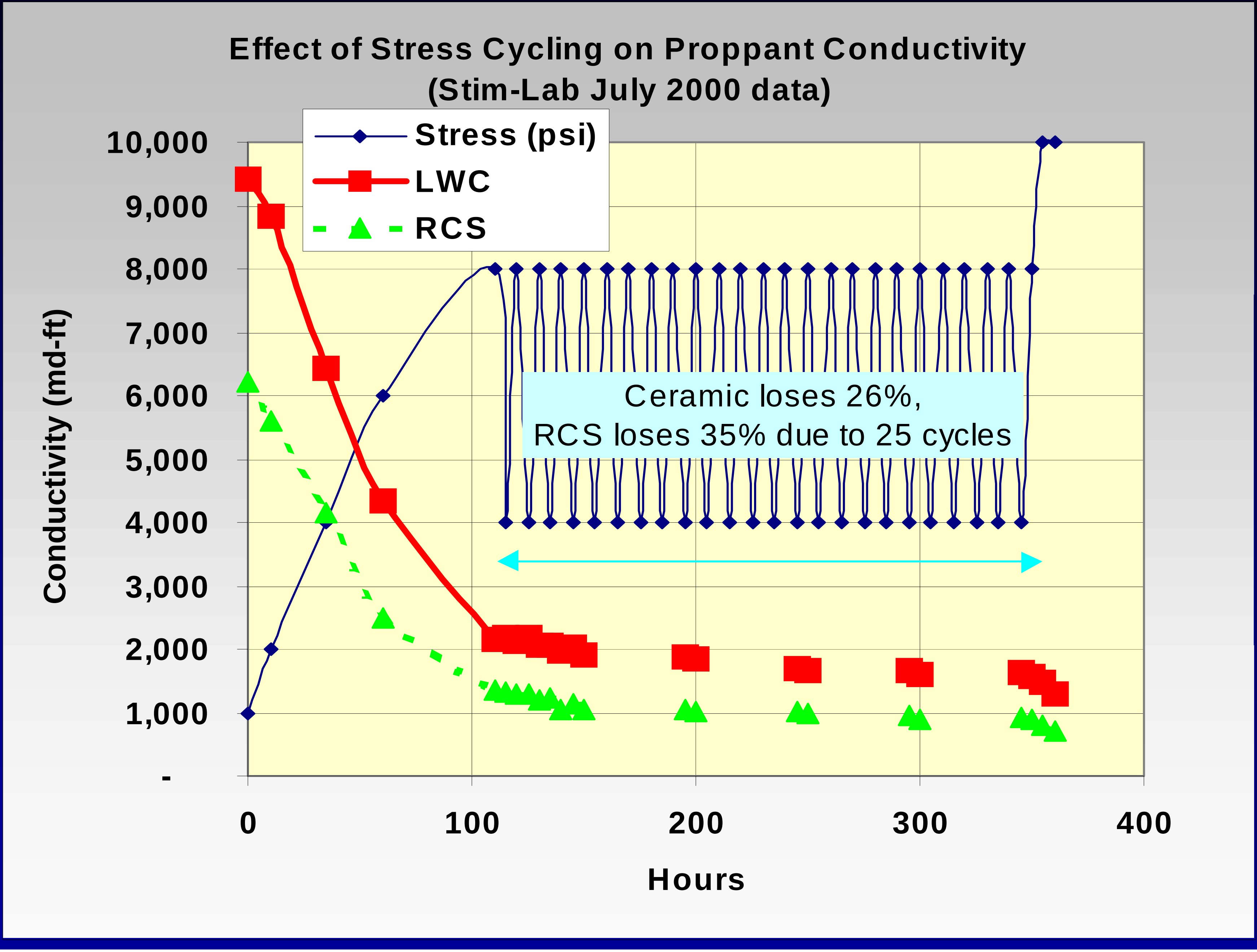
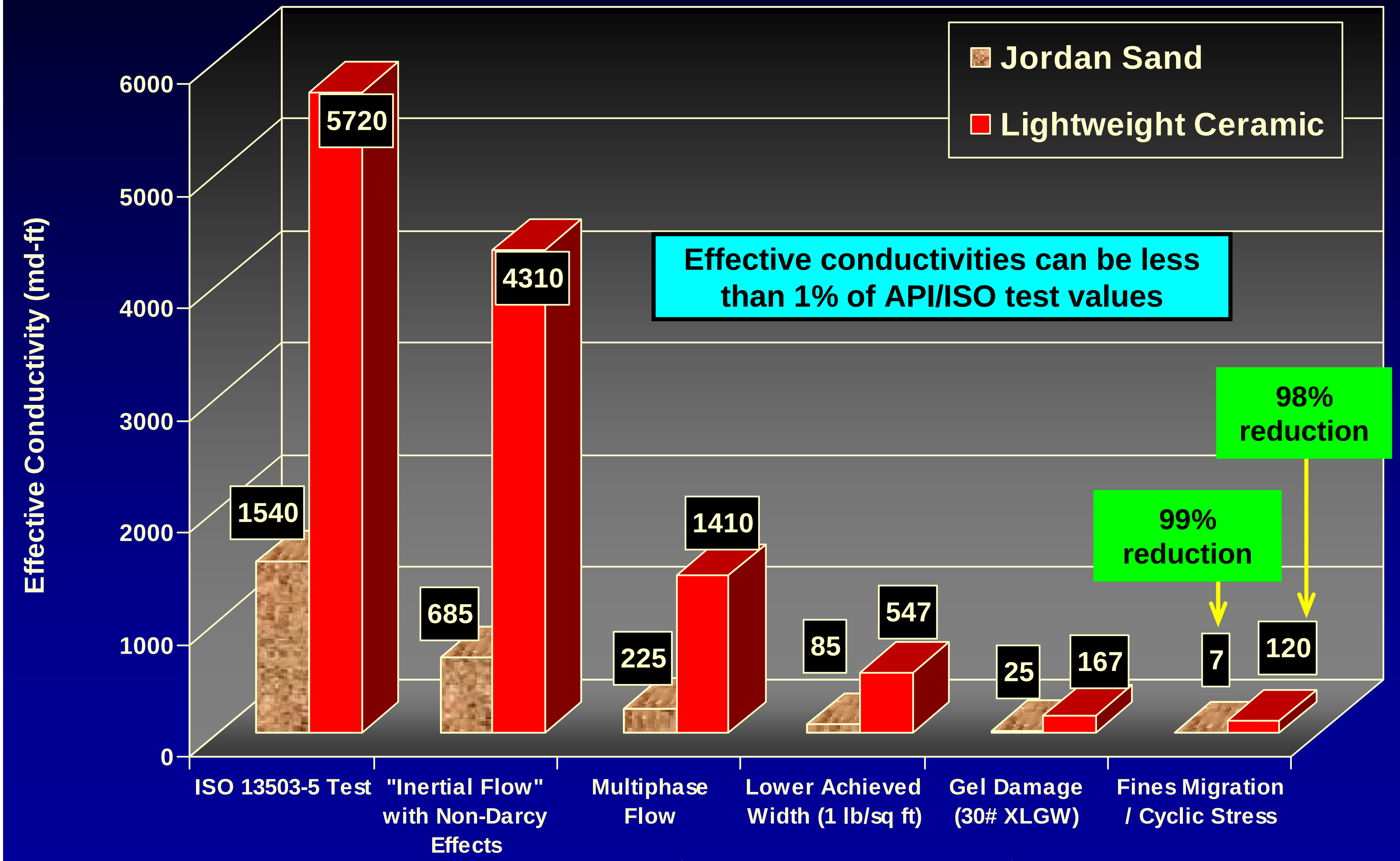
Cyclic Stress



Effect of Stress Cycling on Proppant Conductivity
(Stim-Lab July 2000 data)

Ceramic loses 26%,
RCS loses 35% due to 25 cycles

Cumulative Conductivity Reductions



Effective conductivities can be less than 1% of API/ISO test values

99% reduction

98% reduction

Conditions: YM=5e^6 psi, 50% gel damage, 250°F, 1 lb/ft^2, 6000 psi, 500 mcfd, 1000 psi bhfp, 50 ft H, 2 blpd

References: PredictK & SPE 106301

Realistic Conductivity Estimates

- Even *these* values may be optimistic!
  - Fail to account for:
    - Extended duration testing

      (see SPE 14133, 12616, SPE Drilling April 1986 p5)
    - Higher temperatures
    - Non-uniform proppant distribution
      - Increased crush
      - Chokes or “pinch points” where inadequately propped
    - Flow convergence with limited-entry perforating
    - Emulsions, foaming, frothing
    - Asphaltenes, wax, scale fouling
    - Severe conditions (the example used minimal damage factors!)

Realistic?

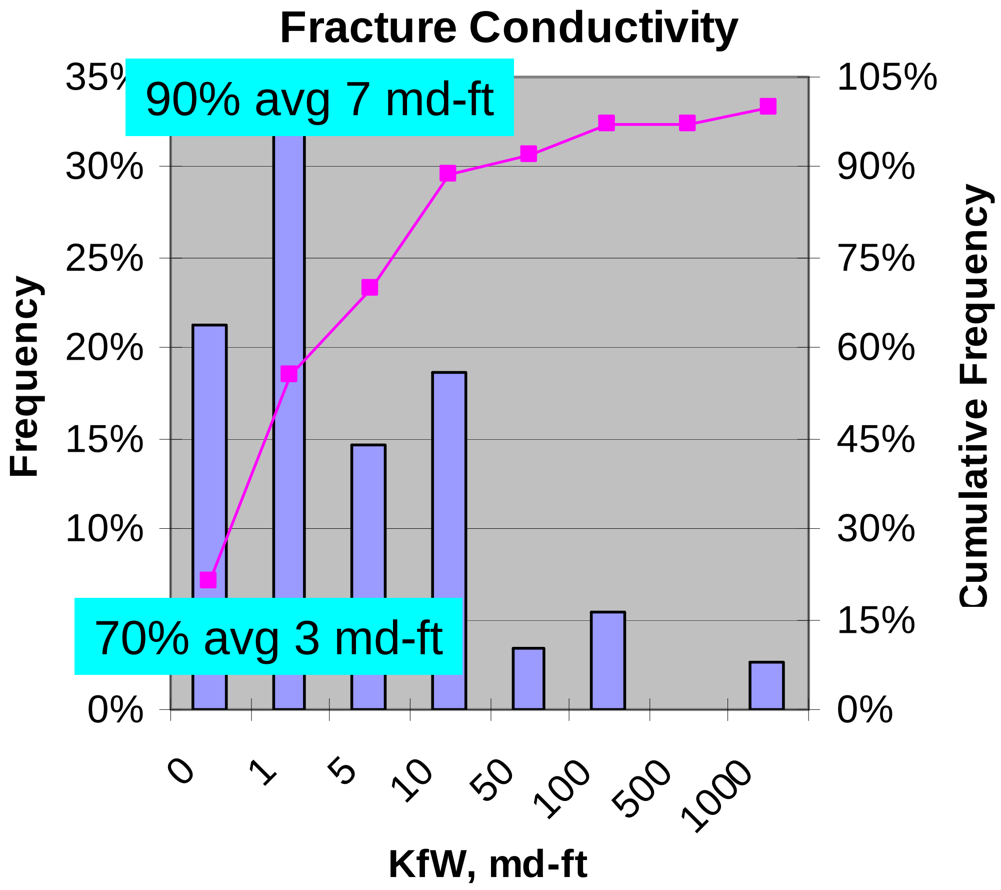
Is it realistic to believe that our fractures have lost over 95% of their reference conductivity?

Wamsutter Development

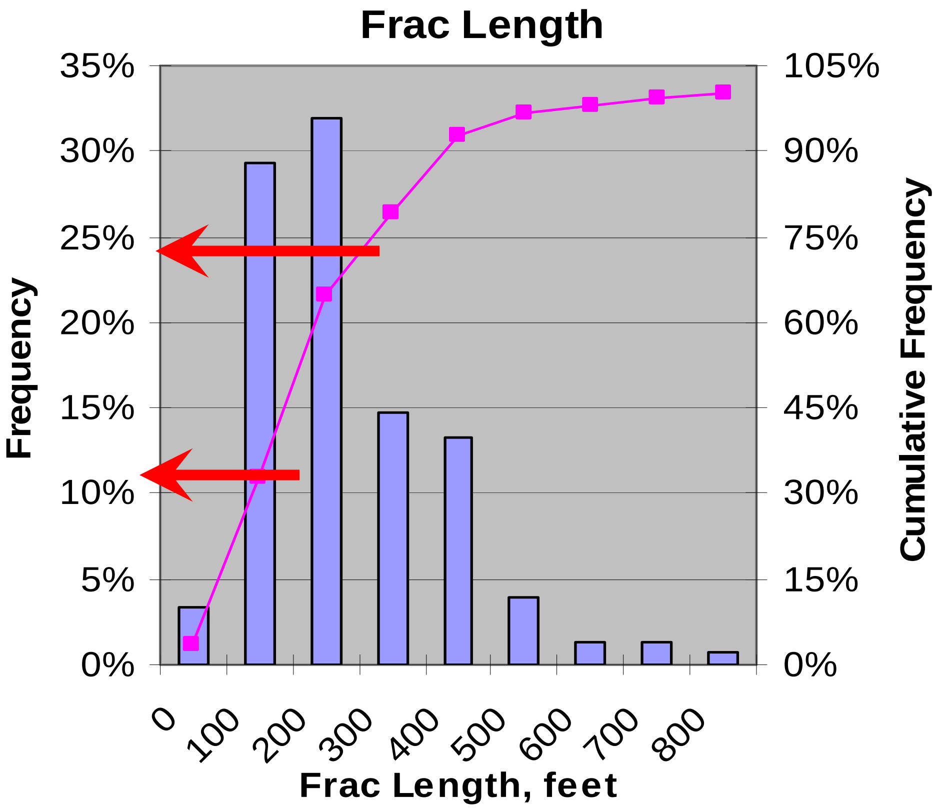
Mesaverde & Almond
9000 – 13000’
6500 psi Closure
0.002-0.150 md

600 wells drilled by
operator since 2001

Results of AGTC Analyses on 150 wells frac'd from 2002-2004

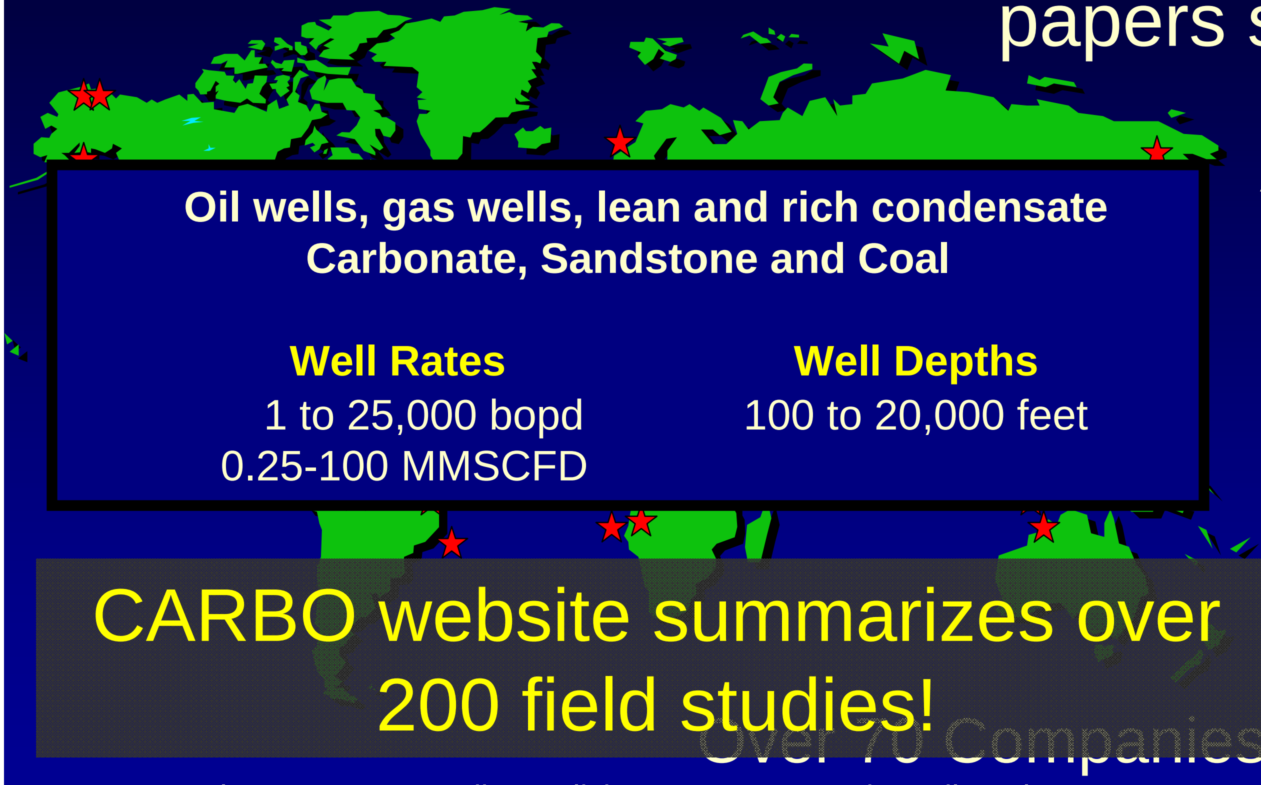


- Avg Concentration: 0.5 lb/ft2
- Designed Half Length: 600'
- Avg Reference Conductivity: 200-1000 md-ft
- Realistic Conductivity: 3-15 md-ft



SPE Papers Documenting Benefit of Increased Conductivity

- SPE 77675 summarized 80 SPE papers since 1973



Oil wells, gas wells, lean and rich condensate
Carbonate, Sandstone and Coal

Well Rates	**Well Depths**
1 to 25,000 bopd 0.25-100 MMSCFD	100 to 20,000 feet

CARBO website summarizes over 200 field studies!

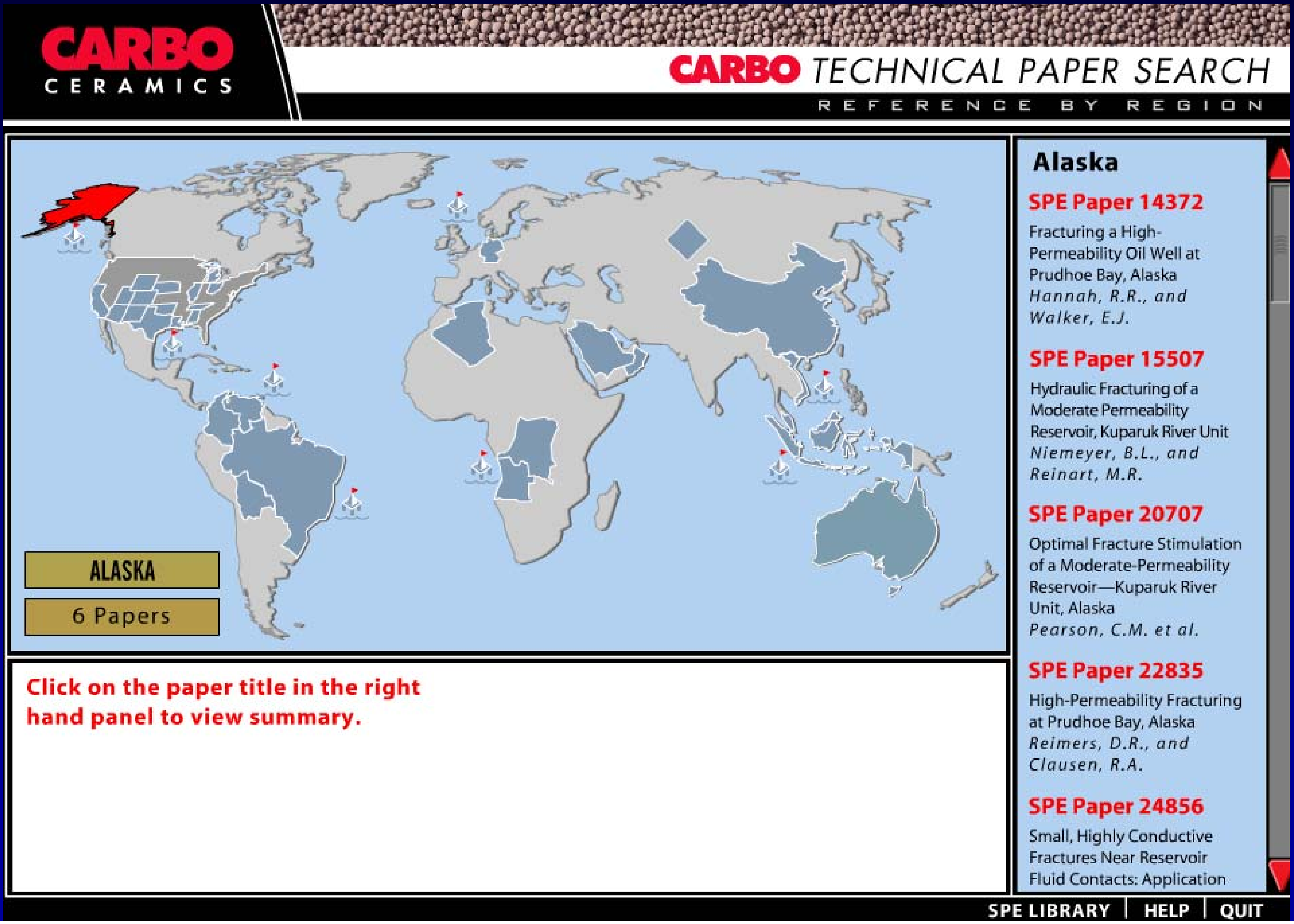
35 Regions

Alaska, Algeria, Angola, Appalachians, Australia, Bolivia, Borneo, Brazil, California, China, Colorado, Colombia, Europe, Germany, Gulf of Mexico, Illinois, Iowa, Indonesia, Java Sea, Louisiana, Malaysia, Nebraska, New Mexico, North Sea, Norway, Ohio, Oklahoma, Oman, Siberia, Sumatra (Indonesia), Texas, Venezuela, Vietnam, Wyoming, Zaire (W Africa),

Over 70 Companies

AGL Petroleum, Amoco, Andina-Bolivia, ARCO, ARI, Baker Oil Tools, Bannon Energy, Barrett Resources, BEB, Bergeson and Assoc., BJ Services, Black Sea Energy, British Gas, BP, CARBO Ceramics, Chevron, CJSC Tura Petroleum, Completion Eng., Corpoven, Crown Central Petro, Ely & Assoc., East Ohio Gas, Esso/Exxon, Falcon, Forest Oil Corp., Gidley, GRI/GTI, Gulf, Halliburton, Holditch-Reservoir Technologies, Imperial, Insight Consulting, JOB P-Gulf, Kinder Morgan, Koninklijke, Langfang Branch of RIPED, Mitchell Energy, Mobil, Norsk Hydro, Norton, NSI, *Oil and Gas Journal* editors, Pennzoil, PERTAMINA, Petrobras, Petrofina, Petroleum Development-Oman, Petronas, RPI-Scandpower, Repsol-YPF, Santos, Saudi Aramco, (Dowell) Schlumberger, Shell, Sohio, Sonatrach, Standard Oil, Statoil, Stim-Lab, Sun E&P, Tejas Gas, Texaco, Texas A&M, Total-Fina-Elf, The Western Company, U.S. DOE, U.S. National Energy Technology Lab, Unocal, Vastar Resources, Vietsovpetro, and various consultants

Searchable map available on CD or www.carboceramics.com



Click on the paper title in the right hand panel to view summary.

Alaska

SPE Paper 14372

Fracturing a High-Permeability Oil Well at Prudhoe Bay, Alaska
Hannah, R.R., and Walker, E.J.

SPE Paper 15507

Hydraulic Fracturing of a Moderate Permeability Reservoir, Kuparuk River Unit
Niemeyer, B.L., and Reinart, M.R.

SPE Paper 20707

Optimal Fracture Stimulation of a Moderate-Permeability Reservoir—Kuparuk River Unit, Alaska
Pearson, C.M. et al.

SPE Paper 22835

High-Permeability Fracturing at Prudhoe Bay, Alaska
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SPE Paper 24856

Small, Highly Conductive Fractures Near Reservoir Fluid Contacts: Application

Other Field Evidence

- Frontier, Green River Basin WY (SPE 67299)
  - Benefits of ceramics vs sand in low perm rock
- Haynesville Lime, East TX (SPE 84307)
  - Demonstrates the benefits of ceramics vs RCS
- Fruitland Coal, San Juan Basin (SPE 77675)
  - Benefits of ceramics vs sand in CBM
- Mesa Verde, Pinedale Anticline (SPE 90620)
  - Benefits of ceramics vs sand in low permeability rock
- Mesa Verde, Pinedale Anticline (SPE 96559)
  - Benefits of tighter sieve proppant in low permeability rock
- Cotton Valley-Taylor, E TX (SPE 110451)
  - Benefits of ceramics vs sand/RCS in slickwater
- Canyon Sand, Sonora TX (SPE 117538)
  - Benefits of ceramics vs sand in low rate gas wells
- Bakken Formation, ND & Montana (SPE 110679)
  - Benefits of ceramics vs sand in horizontal wells

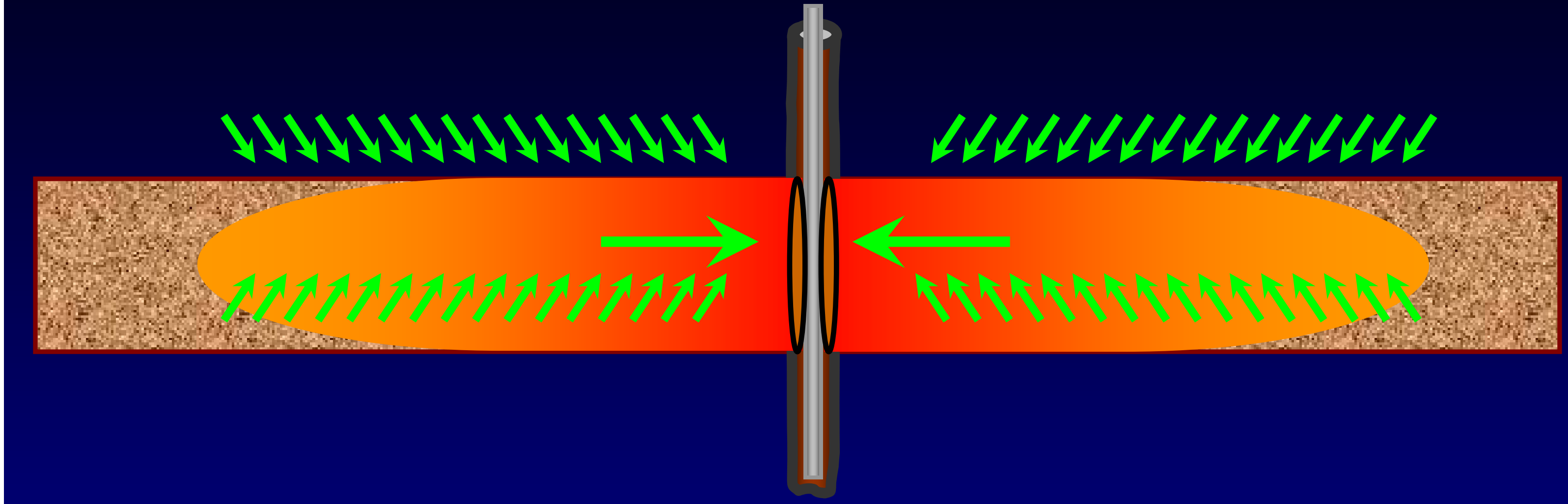
Conductivity Requirements in Horizontal Well Fracs

Frac Orientation –
Longitudinal versus Transverse

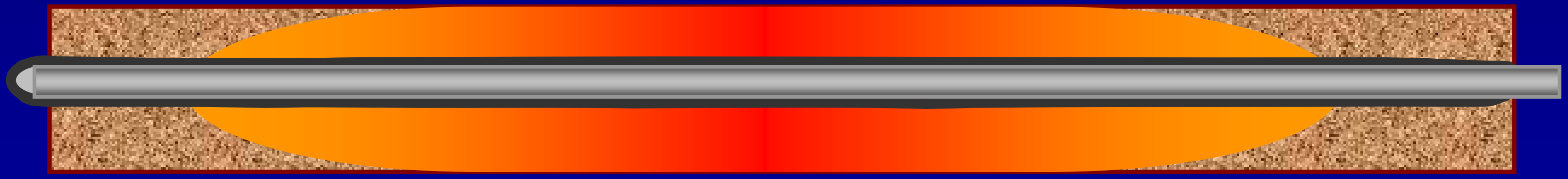
Introduction

- When horizontal wells are fracture stimulated,
  - one of the most important questions is the orientation of the fracture

Intersection of Wellbore and Fracture



Vertical Well: Typically conductivity-limited



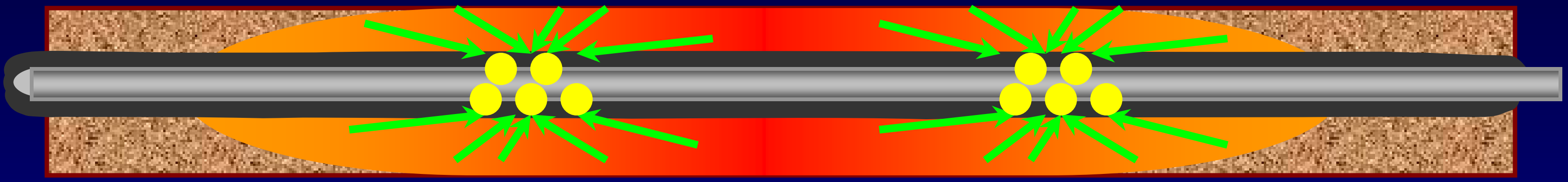
Horizontal Well with Longitudinal Frac:

<u>Uncemented or fully perforated liner</u>

Good connection, fluid only needs to travel ½ the pay height within the frac.

Proppant conductivity requirements are trivial – anything goes!

Intersection of Wellbore and Fracture Cemented Liner



Horizontal Well

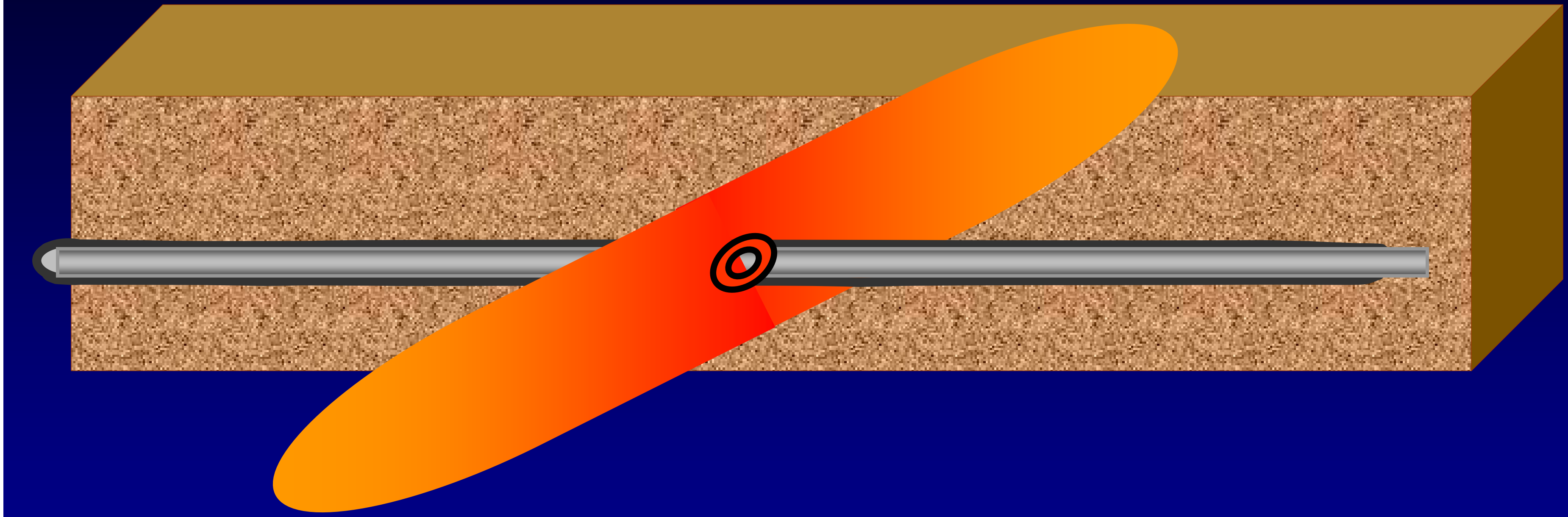
Cemented liner with limited perforations

Fluid travels shorter distances within the frac, but there is significant flow convergence around perfs.

Proppant conductivity requirements must be considered

Intersection of Wellbore and Fracture

What if the fracs are NOT longitudinal?



Horizontal Well with Transversely Intersecting Frac:

(Orthogonal, perpendicular, transverse, imperfectly aligned)

Oil/gas must travel hundreds/thousands of feet within fracture, and converge around a very small wellbore – high velocity within frac!

Horrible Connection and Enormous fluid velocity

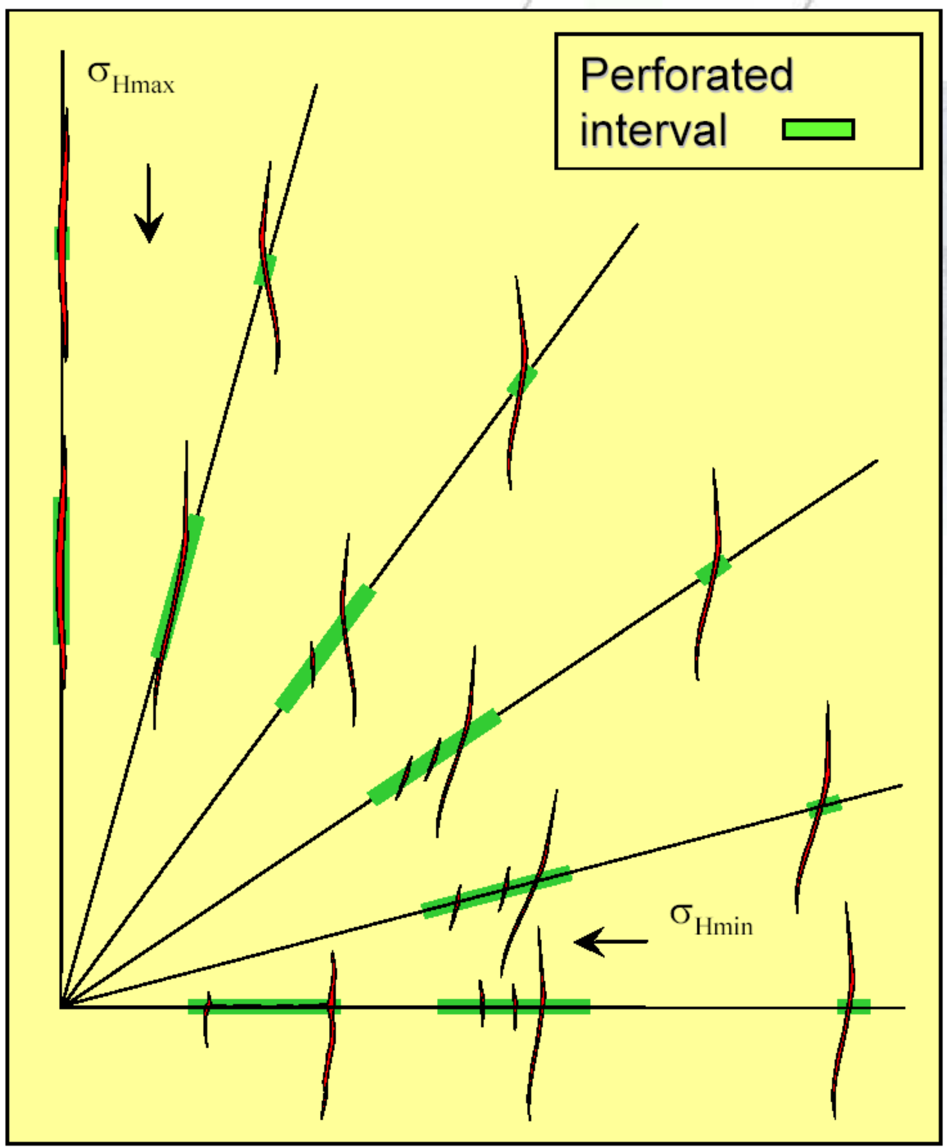
Proppant Characteristics are key!

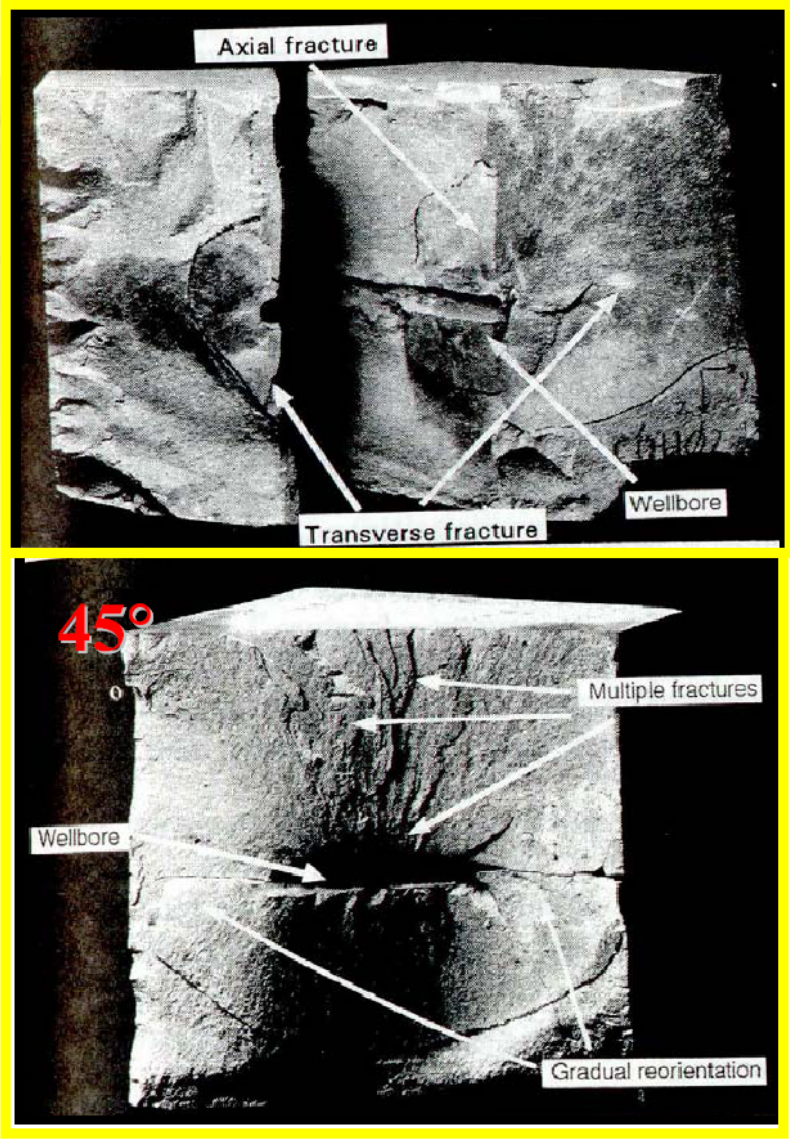
So the Dilemma:

- Scenario 1 -
  - Longitudinal frac – openhole or fully perforated
    - you don't care about the proppant type, concentration, over-displacing treatment, gel residue, treatment QA/QC, etc.
- Scenario 2 -
  - Longitudinal frac – cemented liner w/ limited entry perforations
    - You probably care.
- Scenario 3 -
  - Transverse frac
    - Proppant type and concentration are critical.
    - Anything you can do to improve near-wellbore conductivity should pay tremendous benefits

- Which scenarios are likely?

Fracture Initiation and Intersection with Wellbore Depend on Azimuth





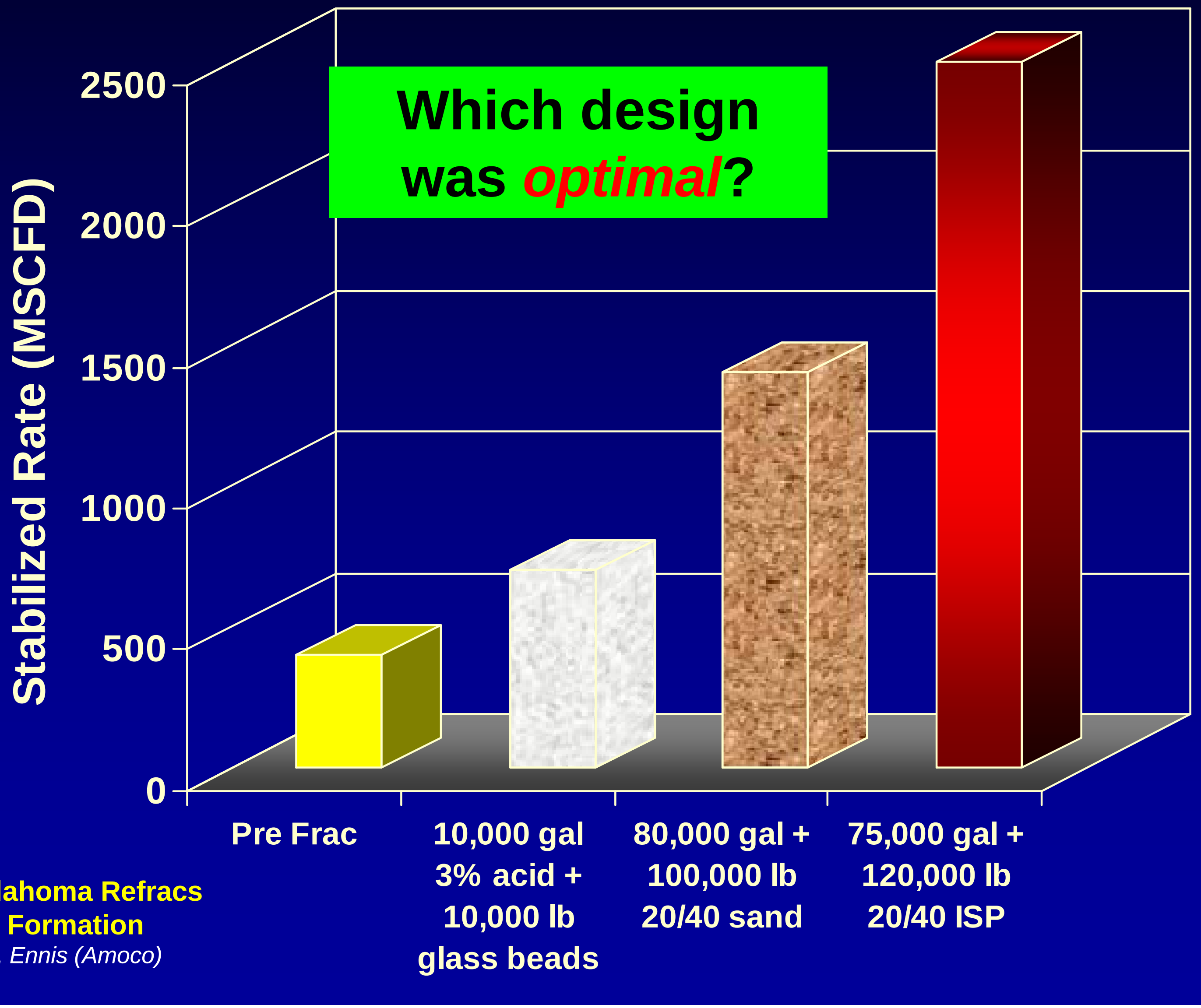
A.V. Brovchuk, A.V. Liplyanin and I.R. Diyashev, Sibneft
D. Grant Jr., D. Oussoltsev and K.Butula, Schlumberger

Source: Production Enhancement in Russian Oil and Gas Fields utilizing Horizontal, Sidetrack, Extended Reach and Multilateral wells, ATW 3-6 Feb-2006, Moscow

Overall Summary

- Fractures *RARELY* provide infinite conductivity.
- The Conductivity requirements in horizontal wells is *entirely* dependent on fracture orientation.
- Fractures must be designed to accommodate realistic conductivity reductions not considered by the ISO test.
- Models using Non-Darcy, Multiphase Flow, Gel Clean up Effects and other realistic reductions tend to be a much better predictor of post frac rates.
- Failure to consider these effects will result in <u>less than optimal well performance</u>, and a loss of revenue compared to what could be achieved.

If we are really off by over 95% on our conductivity predictions, then why do our fracs work most of the time? (or….why isn't everyone doing this already?)



Which design was *optimal*?

Western Oklahoma Refracs
Morrow Formation
SPE 18861, Ennis (Amoco)

Questions?

Shameless advertisement….if you want to learn more about proppants, come to the SPE Production Study Group Luncheon on July 29th!!

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