A Key to Understanding Hydraulically Fractured Well Performance- Proppant Conductivity Assessment

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Bob Duenckel is Vice President, Stim-Lab Division of Core Laboratories where he leads the Stim-Lab Proppant Consortium and supports the various unique testing capabilities Stim-Lab provides to the industry. Prior to joining Stim-Lab he was Director of Technical Development with CARBO Ceramics, Inc. In this role he directed the Proppant Research and Development activities for CARBO. Before joining CARBO he had held various engineering, supervisory and management positions with Marathon Oil Company. His primary areas of interest are in oil and gas exploitation and development with emphasis in hydraulic fracture optimization and diagnostics. He holds 11 US patents and has co-authored numerous technical papers. He holds a B.S. in Petroleum Engineering from the Missouri University of Science and Technology.

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Poll Question

Current duties involved with hydraulically fractured well design and/or evaluation

Poll Question

Total Experience, years

Outline

Proppant Conductivity and Importance to Hydraulically Fractured Well Performance

Measuring Proppant Conductivity

Deficiencies/Considerations in Measurement

Factors Affecting Conductivity

Extension to Reservoir Conditions

Summary

What is Fracture (Proppant) Conductivity?

Simply stated:

Proppant pack permeability * Fracture width=
Fracture Conductivity

Units are generally stated in millidarcy- feet (md-ft)

Generally shown as k_f*w or k*w_f

Why is Fracture Conductivity Important?

Potential production benefit of the hydraulic fracture is controlled by both:

1. The capacity of the formation to deliver fluids
   - Defined as *kX_f where k = reservoir permeability and X_f* = fracture half length

   AND

2. The capacity of the fracture to produce fluids to the wellbore
   - Defined as *k_fw where k_f = proppant pack permeability and w = width of the fracture*

These two capacities are most commonly related as dimensionless fracture conductivity:

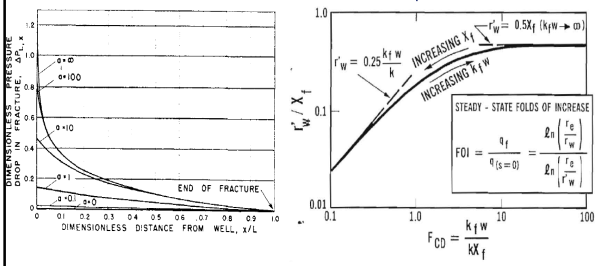
$$C_{fD} = F_{CD} = \frac{k_f w}{k X_f}$$

Various analytical approaches for calculating improved production from fracturing have been developed for steady state, semi-steady state and transient behavior including:

Prats 1961, McGuire and Sikora 1960, Cinco-Ley et al.1978, Agarwal et al. 1979, 1998

Why is Fracture Conductivity Important?

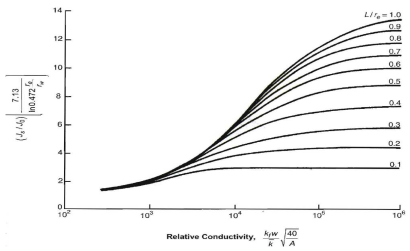
"Effect of Vertical Fractures on Reservoir Behavior- Incompressible Fluid Case"



SPE 1575-G- Prats, 1961

Why is Fracture Conductivity Important?

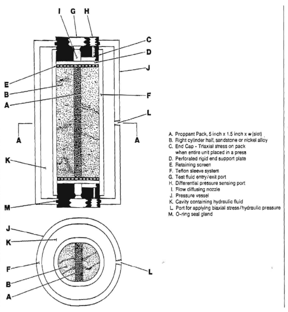
"The Effects of Vertical Fractures on Well Productivity"



SPE 1618- McGuire and Sikora, 1960

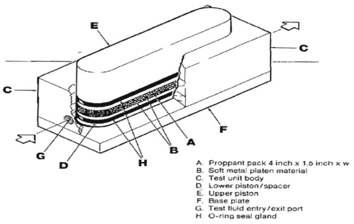
History of Conductivity Testing

- Interest in the evaluation of proppants began shortly after the introduction and acceptance of hydraulic fracturing
- A number of companies proposed various methods of evaluation- notably Amoco, Gulf and Mobil
- Tested configurations included Hassler sleeve type systems (show here), radial flow cells and linear flow cells



History of Conductivity Testing

- The Mobil apparatus is shown below- advantage of linear configuration and fracture widths could be easily measured
- This type of system gained further acceptance following work described by Cooke using similar type cell. (SPE 4117)



API Standard

- The first API Standard for measuring proppant pack conductivity was issued in October, 1989 following some 8 years of development
- API Recommended Practice 61 (RP61): "Recommended Practices for Evaluating Short Term Proppant Pack Conductivity"
- Commonly referred to as "Short Term Conductivity"
- Document carried this caution:
  - "***CAUTION:*** The testing procedures in this publication are not designed to provide absolute values of proppant conductivity under downhole reservoir conditions."

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API RP-61 (1989) Short-Term Conductivity Apparatus

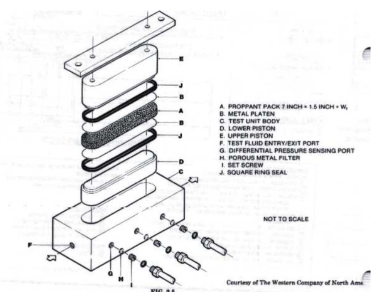

FIG. 2.5
EXPLODED SCHEMATIC DIAGRAM OF
API PROPPANT PACK CONDUCTIVITY TEST UNIT

To calculate conductivity:

$$kw_f = \frac{\mu Q}{\Delta P}$$

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API RP-61 (1989) Short-Term Conductivity Test

General Procedures

- 10 inch square flow path (1.5w x 7.0L inch cell)
- Deionized or distilled water
- Flow rate in the range of 2-6 ml/min
- Conducted at ambient temperature- 75 +/- 5F
- Proppant loaded at volume equivalent to 0.25 inch width or 2 lb_m/ft^2
- Proppant confined between steel platens
- Proppant stressed for 15 minute periods at each stress
- Recommended stresses varied by size and type of proppant
- Stresses ranged from 1 to 14K psi

API RP 61 recognized test deficiencies:

"Long-term test data …have shown that time (within a few days), elevated temperature, fracturing fluid residues, embedment, and formation fines may reduce fracture proppant pack conductivity by up to 90% or more. A recommended design procedure to address longer term conductivity reduction may be considered in future API work"

"Long Term Conductivity"

- During the same period the API RP61 was being developed, a Consortium of some 20 operators, service companies and proppant suppliers began further research into the measurement of conductivity
- SPE 16900 (Penny) was published in 1987 describing the work of the Consortium and addressed a number of the deficiencies present in API RP61
  - Replaced the stainless steel platen with a sandstone core from the Scioto member of the Cuyahoga Formation found in Ohio (thus the common terminology of "Ohio Sandstone core")
    - Typical properties of Ohio SS- 19% porosity, 0.2md perm, YM 5MM psi
  - Replaced deionized water with 2% KCl.
    - Silica saturation was required to prevent dissolution of the Ohio core
  - Observed that conductivities decreased rapidly initially and tended to begin to stabilize between 50 and 100 hours – 50 hours at stress was suggested
  - Test to be run at temperatures of 150- 250F

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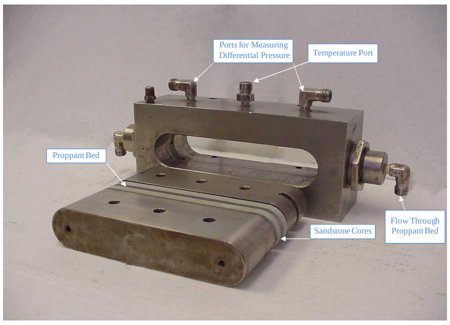
Long Term Conductivity Cell



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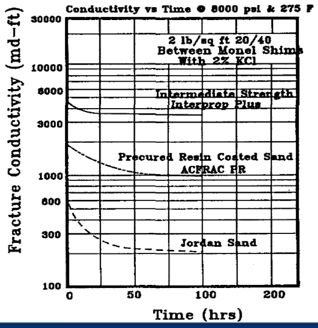
Effect of Time at Stress on Conductivity



SPE 16900- Penny, 1987

Effect of Temperature on Conductivity

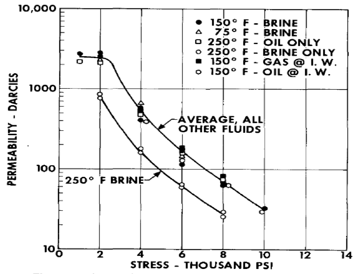
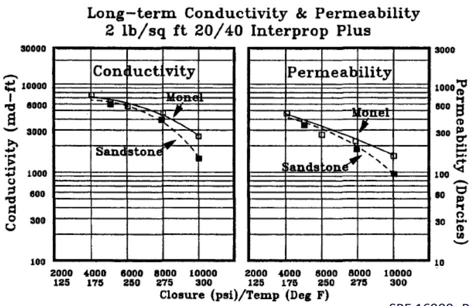


Fig. 2—Effect of stress, fluid, and temperature on the permeability of 8-12 mesh sand.

SPE 4117- Cooke, 1973

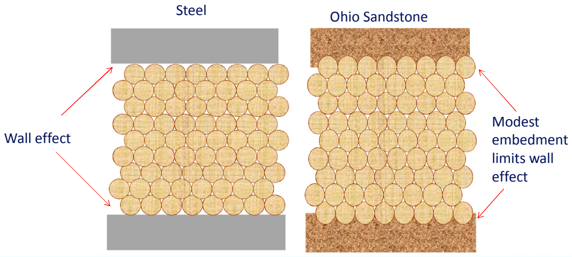
Effect of Sandstone Core vs Steel



SPE 16900- Penny, 1987

Effect of Sandstone Core vs Steel

"Wall effect" refers to high permeability region at interface of proppant and core. Present with steel platens. Modest embedment and spalling with sandstone core eliminated most of this wall effect except at low stresses



Long Term Conductivity- Industry Standard

The procedures outlined in SPE 16900 became recognized in the industry commonly as "long-term" conductivity or "reference" conductivity

API RP61 procedures were commonly referred to as "short term" conductivity- short term conductivities are of little value- might be used in a manufacturing setting

Key components of "long-term" test:

- 2#/ft2 loading
- Ohio (Scioto)Sandstone cores
- Silica saturated 2% KCl
- Temperature- generally 150F for natural sands, 250F for RCS and ceramics
- Held at stress for 50 hours

Long Term Conductivity- Industry Standard

The "long term" conductivity test became the basis for comparing proppant performance

Most proppant suppliers and manufacturers utilize the "long-term" test to demonstrate performance of their products and as a basis for monitoring and adjusting manufacturing processes

Operators can use reference conductivities in fracture design decisions

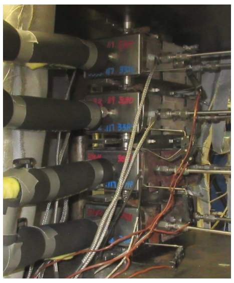
In 2003 an ISO committee formed to write conductivity testing standard

The "long-term" test was officially established as a "standard" through ISO policy procedures and ISO 13503-5 was issued in 2006 (SPE 110697- Kaufman, et.al., 2007)

API subsequently adopted ISO 13503-5 as API RP19D - is available from API

API RP19D has been reaffirmed- in the process of update/revision

Photos of 4-Cell Conductivity Evaluation Stack



Operational Considerations in Conductivity Testing

- Piston seal design-
  - Possible non-uniform stress distribution
- Core seal failure
  - Provides unwanted flow path, lowers dp
- Cell loading
  - Inconsistent loading can significantly affect conductivity
- Integrity of sandstone core
  - Core breakage can create unwanted flow path and lower dp
- Temperature control
  - Affects viscosity determination
- Test fluid
  - Silica saturation (prevent core/proppant dissolution) and deoxygenation (prevents corrosion in lines and pack)

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Statistical Accuracy of the Long Term Conductivity Test

- Some variability is a common outcome in repeated tests of the same proppant
  - Generally thought in part to be related to the somewhat random nature of the loose packing of a particulate material
  - Variability of results may be +/- 15%
- Due to this variability, a single result should be used with caution, multiple tests of the same material necessary to improve statistical accuracy
- Despite variability, the long term conductivity test is the best approach for uniform comparison of proppant performance
  - Useful for manufacturers and suppliers in resource evaluation and process optimization
  - Useful for operators in determining best proppant option

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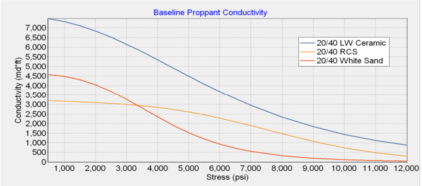
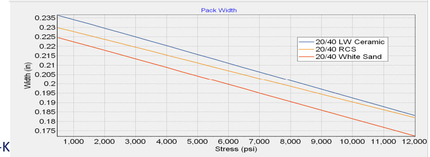
Reference Conductivities

Comparison of Proppant Types





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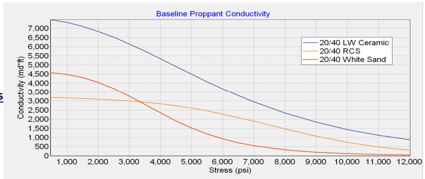
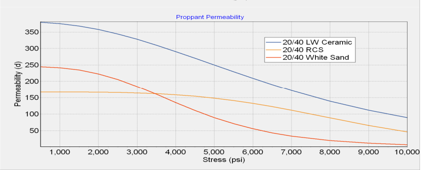
Reference Conductivities

Comparison of Proppant Types





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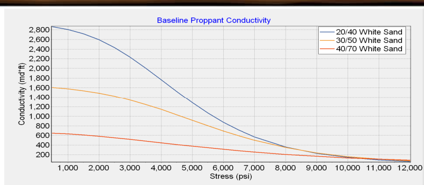
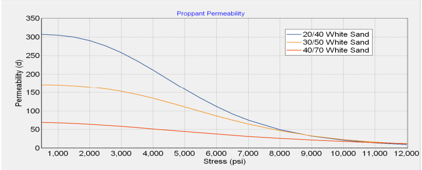
Reference Conductivities

Comparison of Proppant Sizes





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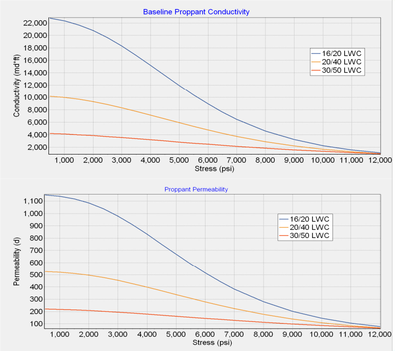
Reference Conductivities

Comparison of Proppant Sizes



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Applying Reference Conductivities to Reservoir Conditions

API RP19D is a significant improvement over the API RP61- includes effects of:

- Temperature (tests performed at 150F or 250F)
- Some embedment effects (Ohio Sandstone YM= 5mm psi)
- Longer time at stress (stress held for 50 hours)

Other important conductivity impairment processes to be considered:

- Loadings other than 2#/ft^2
- Higher reservoir temperatures
- Rate dependent permeability- non-Darcy effects
- Effects of core degradation with varying rock properties
- Stress cycling
- Multiphase flow
- Gel damage
- Conductivity degradation due to longer times at temperature and stress
- Fines migration
- Salt, scale deposition

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Measurements with API Conductivity Apparatus

The API conductivity apparatus can be utilized in non-standard testing to measure:

- Effect of proppant loading (i.e. #/ft^2) on conductivity
- Effect of reservoir core vs Ohio sandstone
- Frac fluid damage
- Longer times at stress and temperature
- Non-Darcy flow effects
- Cyclic Stress

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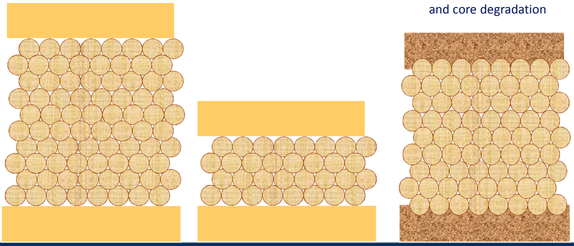
Proppant loading Effects

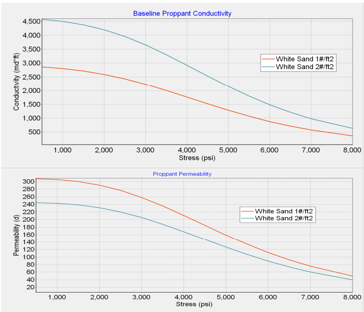
Wall effect can be significant at low stress and more significant with lower proppant loadings, less effect at higher stress due to embedment and core degradation

At low stresses wall effects can be significant and are relatively more significant at low proppant loadings

At high stress wall effects are diminished due to embedment and core degradation



Wall Effect and Proppant Loading



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Effect of Reservoir Core- Core Degradation

1#/ft² 40/70 sand- shale formation
250F, 10,000 psi closure
Limited embedment

1#/ft², 20/40 ISP, shale formation
250F, 10,000 psi closure
Limited embedment- Core degradation evident

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Gel Damage

Post-test photo of remaining filtercake
40 ppt Guar, 250°F and 4000 psi
Proppant pack/core interface

Post-test photomicrograph of remaining gel
40 ppt Guar, 250°F and 4000 psi
Interior proppant pack

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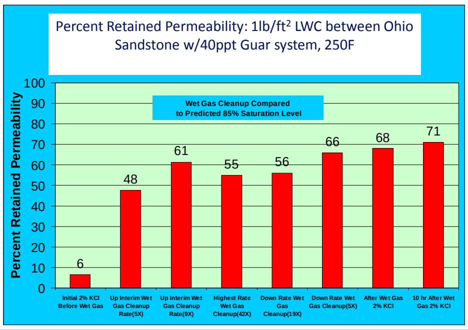
Gel Clean-up Measurements



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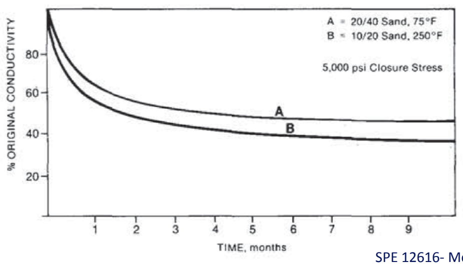
Time at Stress



SPE 12616- Montgomery and Steanson, 1985

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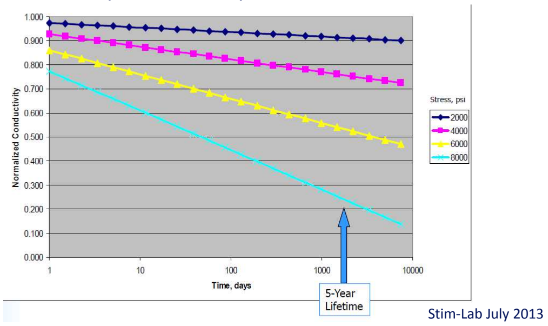
Predict-K Time Dependent Conductivity correlation- Generic Sand



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Non-Darcy Flow Effects

Long –term conductivity testing at low rates- equivalent to superficial velocities of less than 0.2 ft/min – viscous forces dominate

Actual velocity in a propped fracture can be several ft/sec – inertial forces will dominate- increasing pressure drop

Forchheimer equation has been used to account for these velocity effects:

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

Beta factor, β, is a function of proppant type and stress

Forchheimer equation can be linearized and rewritten as:

$Y = 1/k + \beta X$, where $Y = \Delta P/L\mu v$ and $X = \rho v/\mu$

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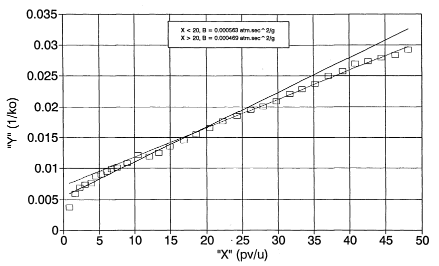
Forchheimer Plot



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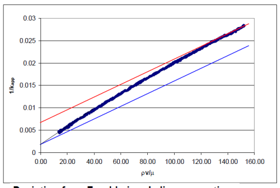
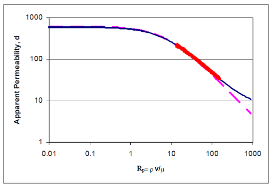
Correction for Non-linearity of Forchheimer Equation



Deviation from Forchheimer's linear equation



Log-Dose curve fit to lab data

Logistic-Dose Equation: $$k_{app} = k_{\min} + \frac{(k_d - k_{\min})}{\left(1 + R_e^F\right)^E}.$$

SPE 89325, Barree and Conway, 2004

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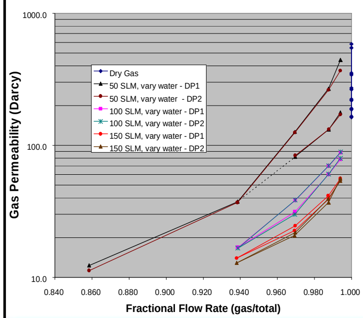
Multiphase Flow Effects



Test conditions:

2.8 lb/ft^2 of 20/40 LWC
65 ^{o}F and 4000 psi closure stress

Rates selected represented:
- 250 – 1,500 mscf/day
- 10 – 100 barrels water per mmcf
- 50 ft. frac height
- Flowing pressure of 2000 psi.

Stim-Lab Feb. 2001

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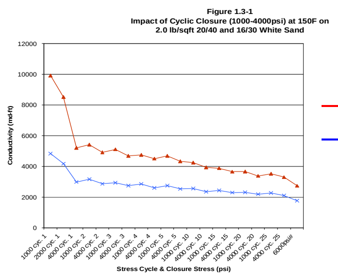
Effects of Stress Cycling on Conductivity



2.0 lb/sq. ft. 16/30 White Sand
2.0 lb/sq. ft. 20/40 White Sand

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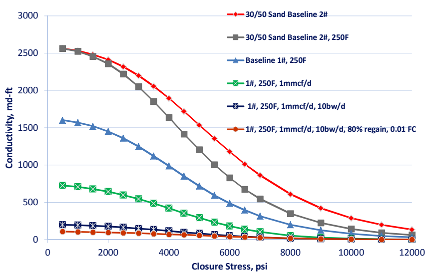
30/50 White Sand - From Reference Conductivity to Reservoir Conditions



30ft Frac Height
1000 psi FBHP

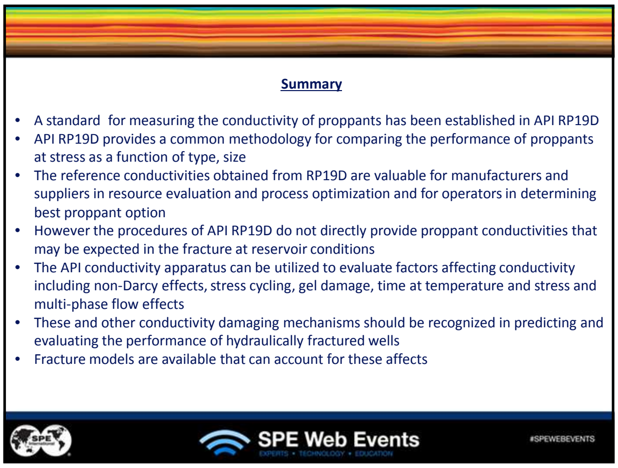
Predict-K

From Reference Conductivity to Reservoir Conditions

- While a number of these conductivity damaging mechanisms can be tested- generally not practical to do so
- Solution is comprehensive software package that can address and estimate these effects
- There are available software packages that can do this- user needs to be aware of how these are handled.
- The same consortium that was responsible for the work published in SPE 16900 is still active and involved in ongoing research
- The Stim-Lab Proppant Consortium has developed a software package: Predict-K (PDK)
- PDK is built upon correlations for the prediction of proppant performance based on hundreds of conductivity tests run over the 29 year life of the Proppant Consortium

Predict-K Capabilities/Applications

- Predict-K :
  - Compares reference conductivities of proppants
  - Predicts dynamic conductivities including the effects of non-Darcy flow, multi-phase flow and gel damage
- In the production analysis mode, Predict-K:
  - Compares various completion strategies or predicts well production for a specific fracture geometry
  - Assists in optimizing completion techniques related to proppant/fluid selection, stage/well spacing or treatment size/rate
  - Matches historical production to calibrate the model for future optimizations
  - Provides effective fracture length and fracture conductivity for inputs into reservoir model


Summary
• A standard for measuring the conductivity of proppants has been established in API RP19D
• API RP19D provides a common methodology for comparing the performance of proppants at stress as a function of type, size
• The reference conductivities obtained from RP19D are valuable for manufacturers and suppliers in resource evaluation and process optimization and for operators in determining best proppant option
• However the procedures of API RP19D do not directly provide proppant conductivities that may be expected in the fracture at reservoir conditions
• The API conductivity apparatus can be utilized to evaluate factors affecting conductivity including non-Darcy effects, stress cycling, gel damage, time at temperature and stress and multi-phase flow effects
• These and other conductivity damaging mechanisms should be recognized in predicting and evaluating the performance of hydraulically fractured wells
• Fracture models are available that can account for these affects
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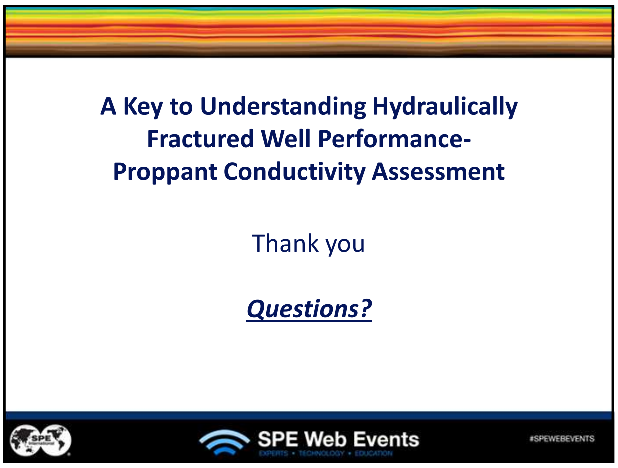
A Key to Understanding Hydraulically
Fractured Well Performance-
Proppant Conductivity Assessment
Thank you
Questions?
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