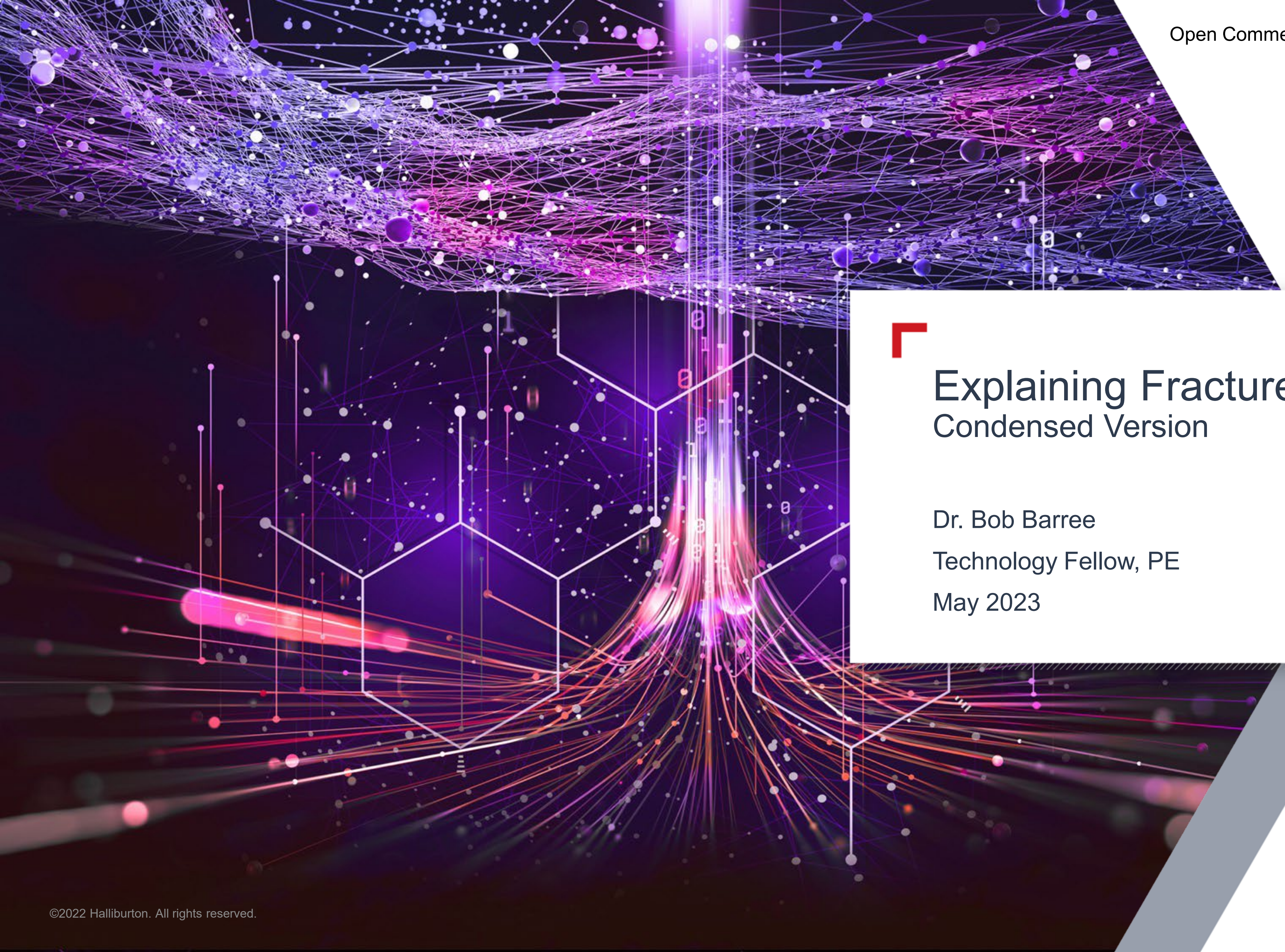
Open Comments along right edge or in upper left for detailed discussion



Explaining Fracture Conductivity
Condensed Version

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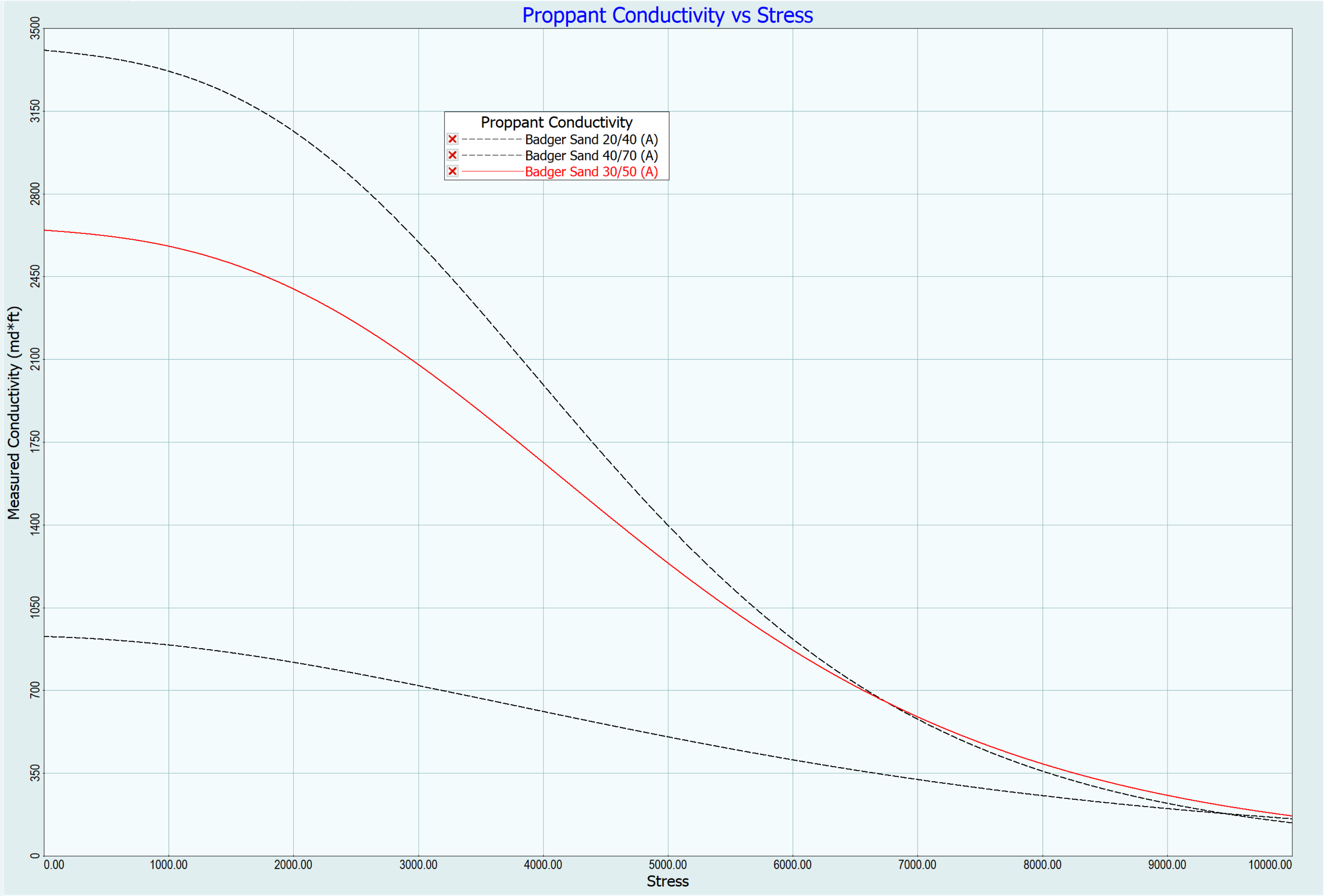
Brief overview of fracture conductivity

Evolution of fracture conductivity over multiple steps

- Baseline conductivity: usually given as md-ft (absolute permeability times proppant pack width)
  - Pack width depends on mass of proppant per area, packing or porosity, particle density, and closure stress.
  - Proppant pack width is often 0.1-0.2" (0.008-0.017 ft)
  - Absolute permeability is generally independent of mass/area concentration (above 2 lb/ft^2) and depends on median particle size and packing.
  - Baseline conductivity declines over time at continuous stress and temperature.
- Proppant pack conductivity is reduced by two- or three-phase flow conditions
  - Equilibrium multi-phase flow drops effective conductivity to less than 10% of baseline conductivity.
  - Three-phase flow reduces overall conductivity much more than two-phase flow.
- Actual effective conductivity in a producing well is further reduced by inertial or non-Darcy flow
  - Inertial losses are caused by millions of accelerations and decelerations in the pore throats and bodies of the proppant pack.
  - In multi-phase flow conditions, each phase has its own density, velocity, and flow path and therefore Reynolds Number, with a different inertial loss.
  - The combination of multi-phase flow and inertial losses reduces realistic effective conductivity to about 1% of the baseline conductivity.
- The dependence of conductivity on flow velocity means that most of the applied wellbore drawdown is lost very near the well, where velocity in the fracture is highest
  - Flowing pressure in the fracture increases from the well bottomhole pressure, with distance from the wellbore because of cumulative flow resistance in the proppant pack.
  - The differential pressure between the formation around the fracture, and the pressure in the proppant pack, determines the inflow from the formation at each point along the length of the pack.
  - At some distance from the wellbore, the differential pressure between formation and fracture is too low to overcome capillary blockage on the fracture face or in the water-saturated pack, and conductivity in the fracture effectively drops to nothing.
- Proppant pack conductivity degrades over time from progressive damage by salt, fines, wax, and asphaltene deposition
  - Consider that the proppant pack acts as a fixed sand-pack filter between the reservoir and the production tubing, accumulating all plugging material in a very small flow area.

Example baseline conductivity for "premium white" frac sand



The chart describes clean conductivity under Darcy flow conditions for 2 lb/ft^2 concentration at 250F on 5e6 psi Young's Modulus sandstone.

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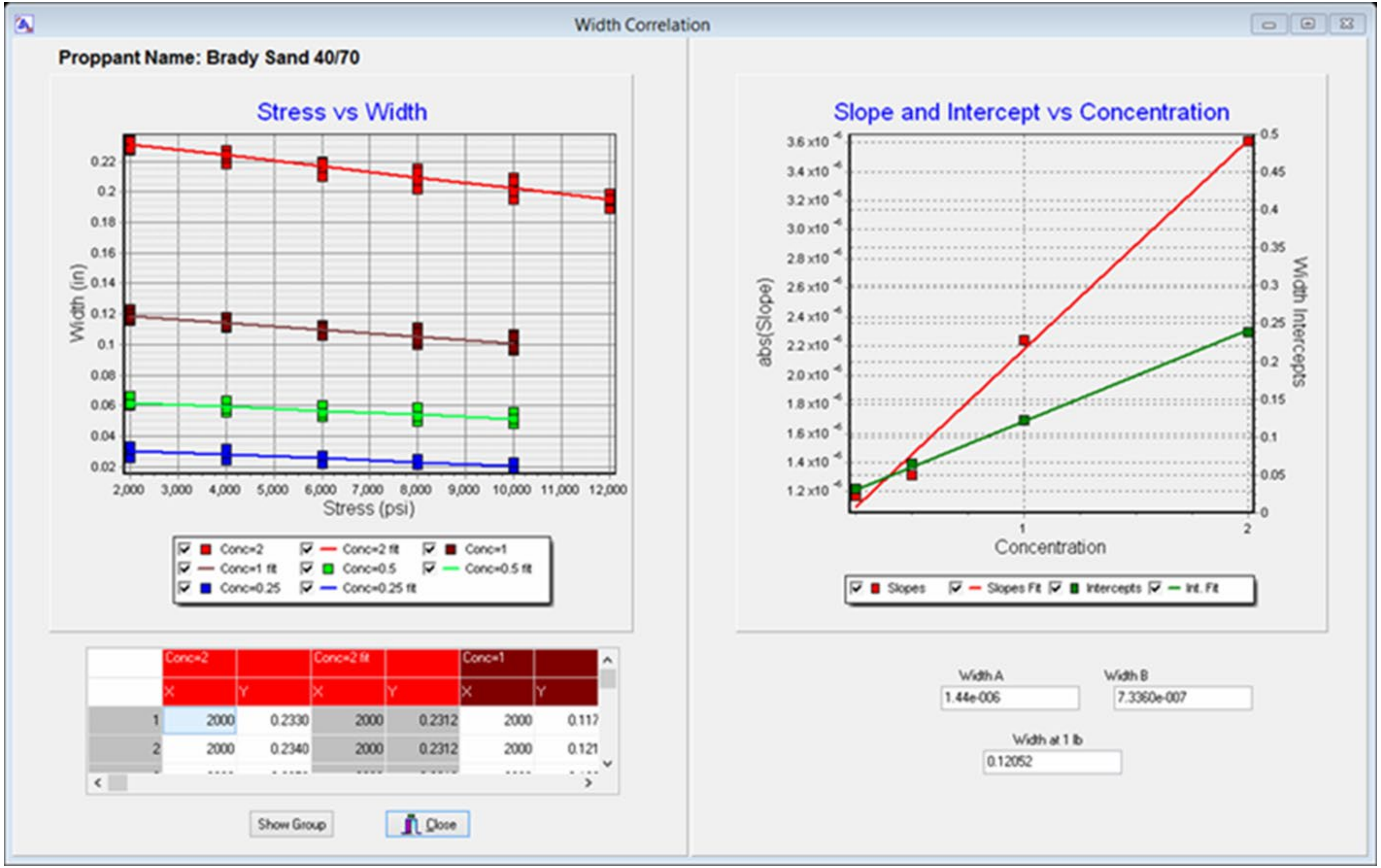
Pack width changes with stress and mass/area concentration



Correlations to the three width-factors determined from multiple lab tests allow calculation of pack width for any stress and concentration condition.

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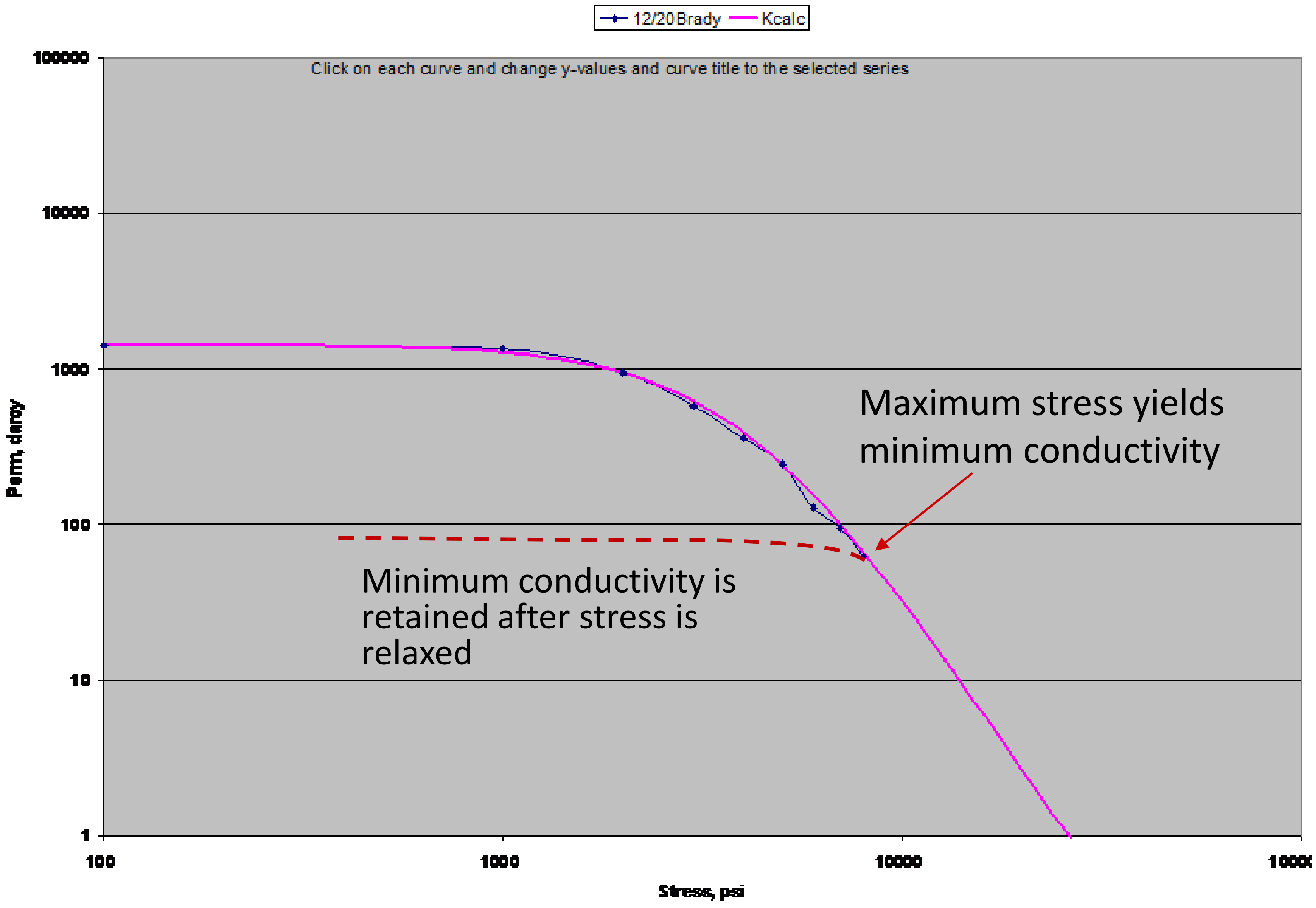
Permeability changes with applied closure stress



$$k_s = k_m + \frac{(k_o - k_m)}{\left[1+\left(\sigma / S_c\right)^F\right]^E}$$

Permeability at given net stress (ks)
Zero-stress perm (ko)
Critical Transition Stress (Sc)
Sharpness of failure (F)
Perm-stress exponent (E)
Minimum perm (km)

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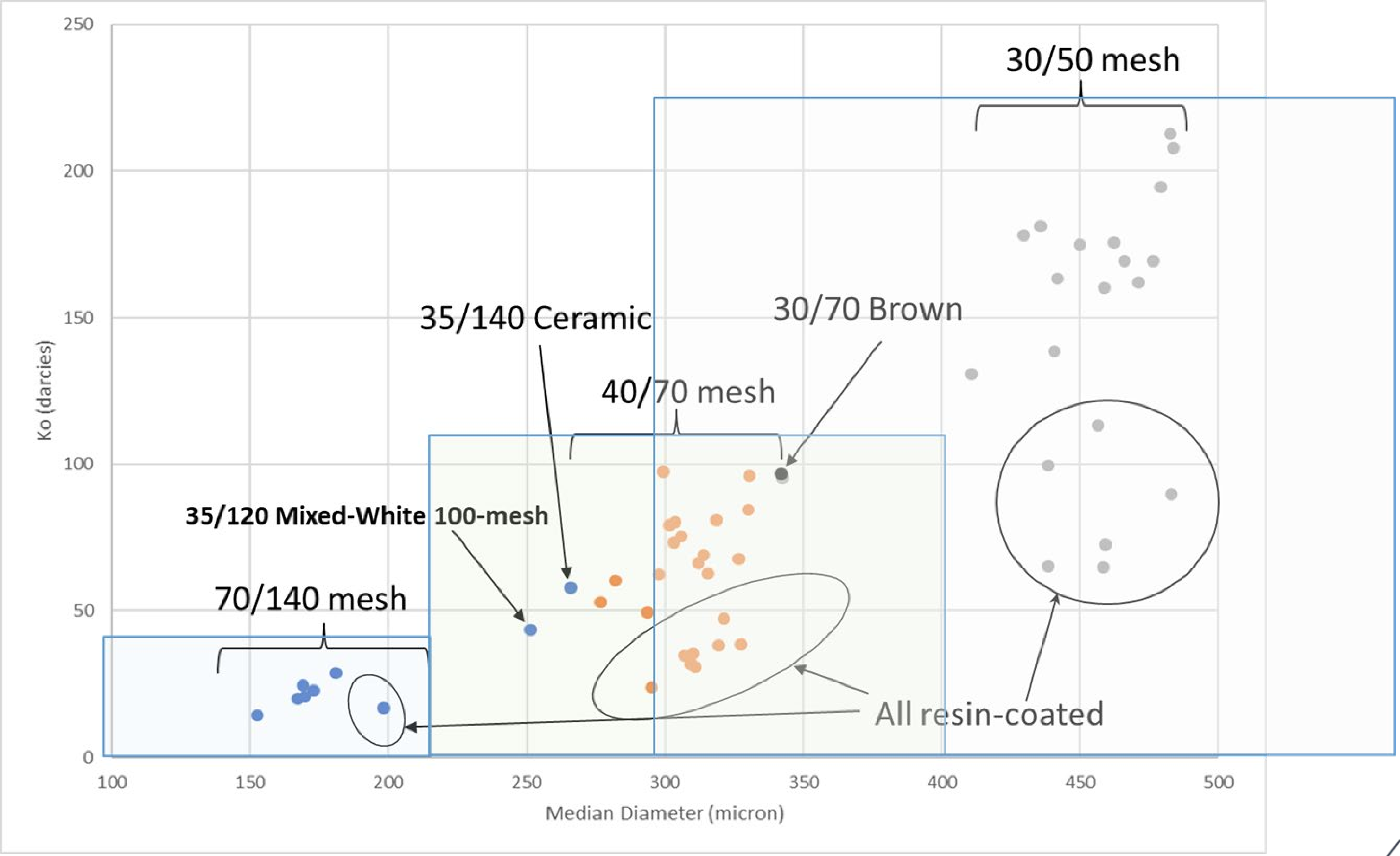
Laboratory Data Regression K_0 vs. Median Diameter

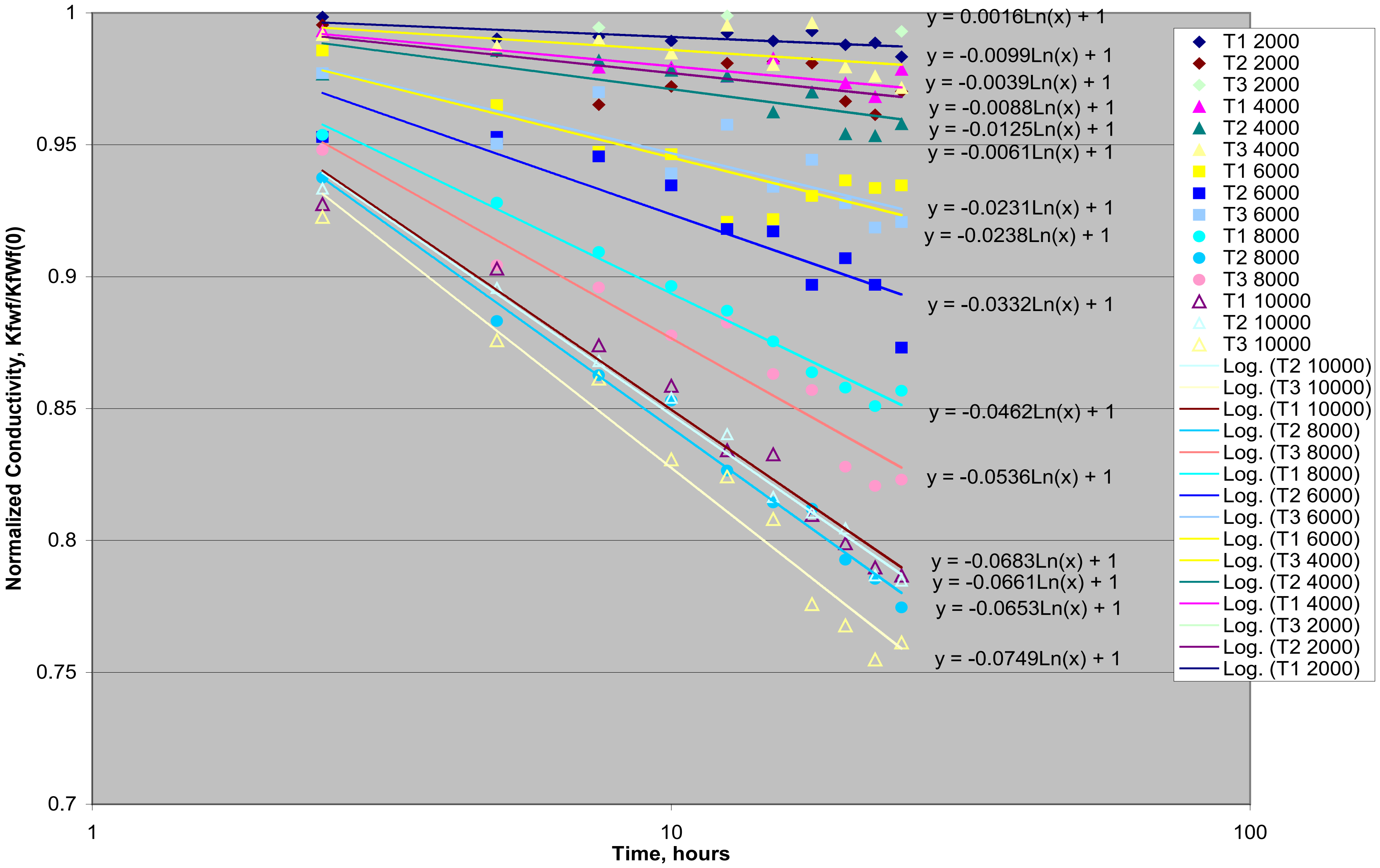


The unstressed k_0 in the previous equation can be estimated from the median particle diameter in the sieve distribution.

The transition stress correlates well to particle density.

SPE 194382-MS

Normalized conductivity with time at stress for 40/70 PRC (Corrected Starting KfWf)



Baseline conductivity data are reported at a normalized time of 50-hours.

Conductivity continues to decline over the life of the well and proppant pack.

The decline rates shown here are for flow with clean, filtered brine and no progressive damage from reservoir influx.

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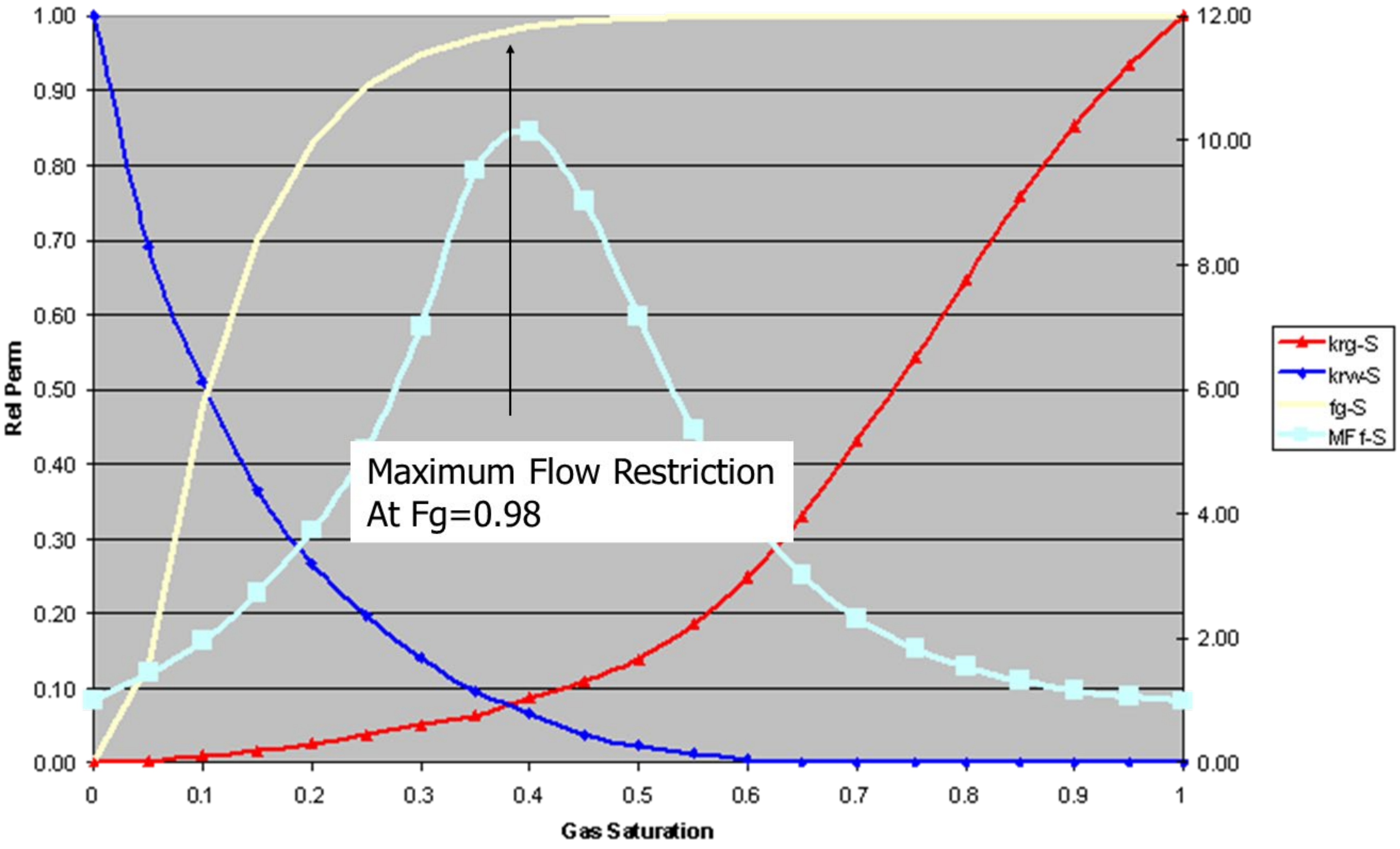
Muti-phase relative permeability curves for all well-sorted proppants are similar



Data shown are for gas-water flow. Oil-water curves are similar.

Three-phase flow is usually described with gas permeability a function of gas saturation, and the same for water (assuming water-wet system). Oil is trapped between the strongly wetting and non-wetting phases and suffers the highest loss of apparent permeability.

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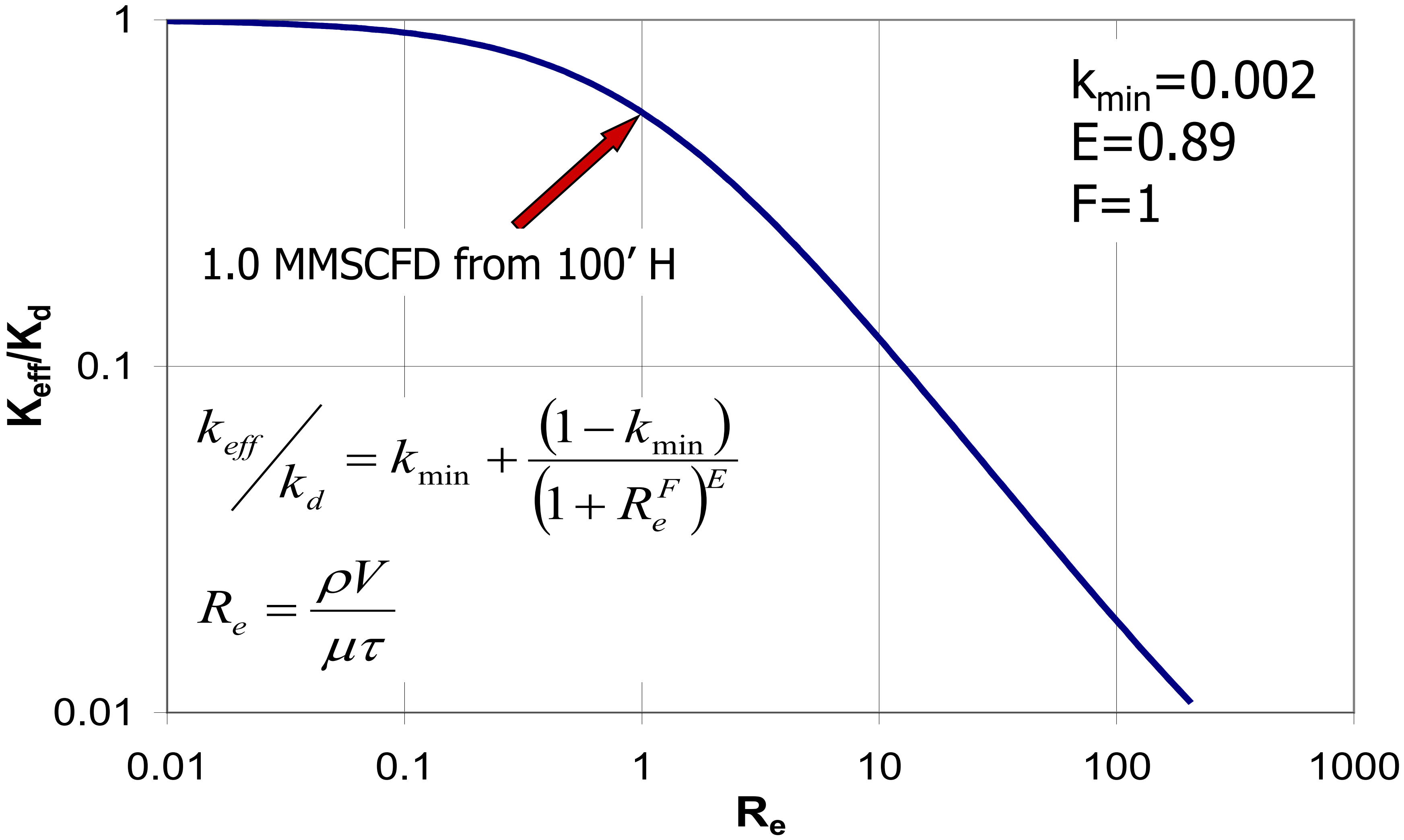
Non-Darcy Flow in a Propped Fracture



$$k_{eff} / k_d = k_{min} + \frac{(1 - k_{min})}{(1 + R_e^F)^E}$$

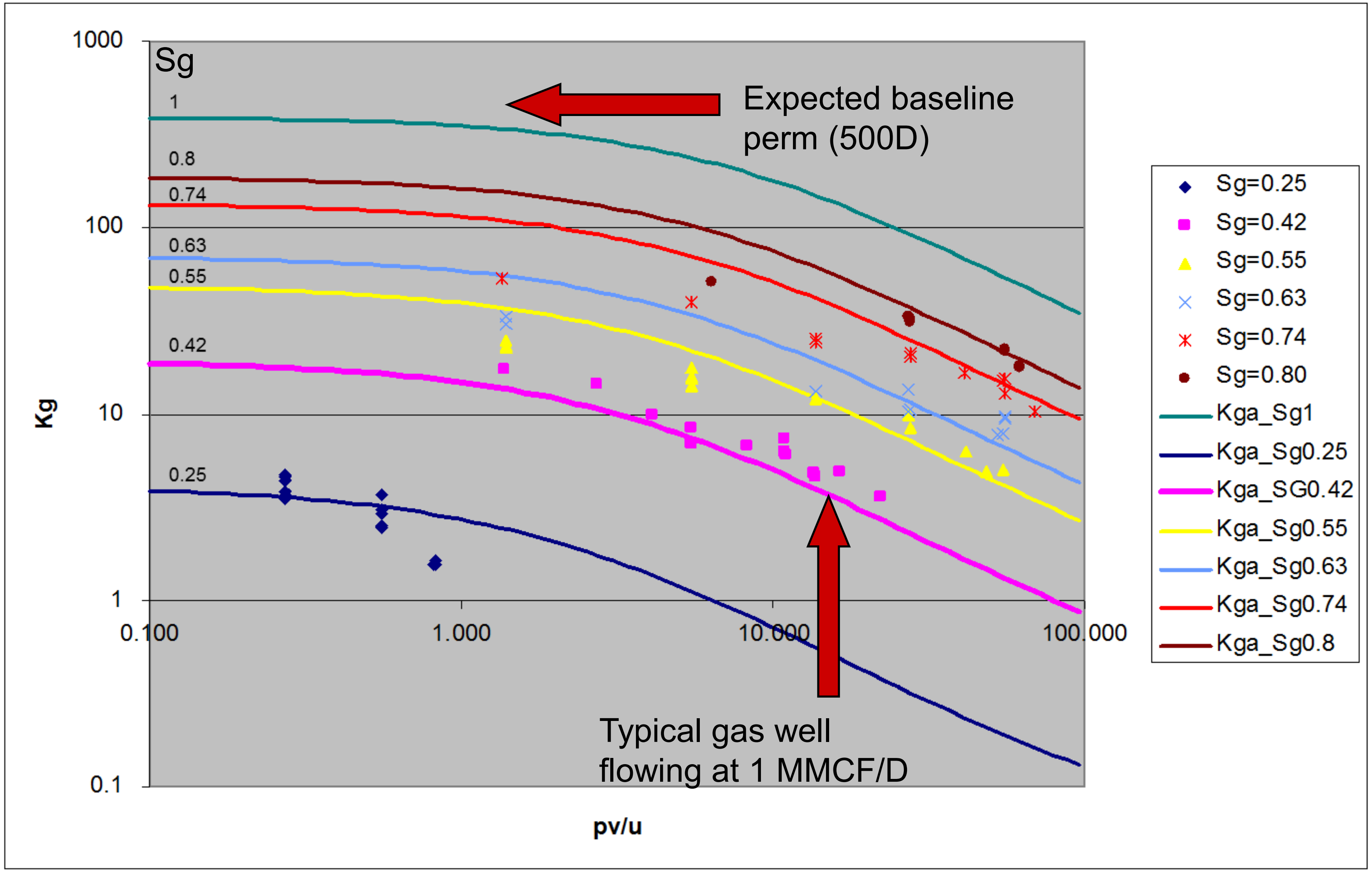
$$R_e = \frac{\rho V}{\mu \tau}$$

All single-phase flow in a proppant pack can be described with a single dimensionless curve, shown here.

The parameter τ correlates to median particle size in the sieve.

At R_e=1, half the baseline permeability is lost.

Loss of effective gas permeability in two-phase (gas/water) non-Darcy flow



Vertical axis is effective gas permeability in darcies.

Sg column shows equilibrium gas saturation in each test.

The horizontal axis is "pseudo-Reynolds Number", ρv/μ, for each experimental flow test (points).

Lines are predicted permeability from the published theory (SPE 109561).

At common flow conditions the effective gas permeability is 1% of baseline, with no mechanical damage to the pack.

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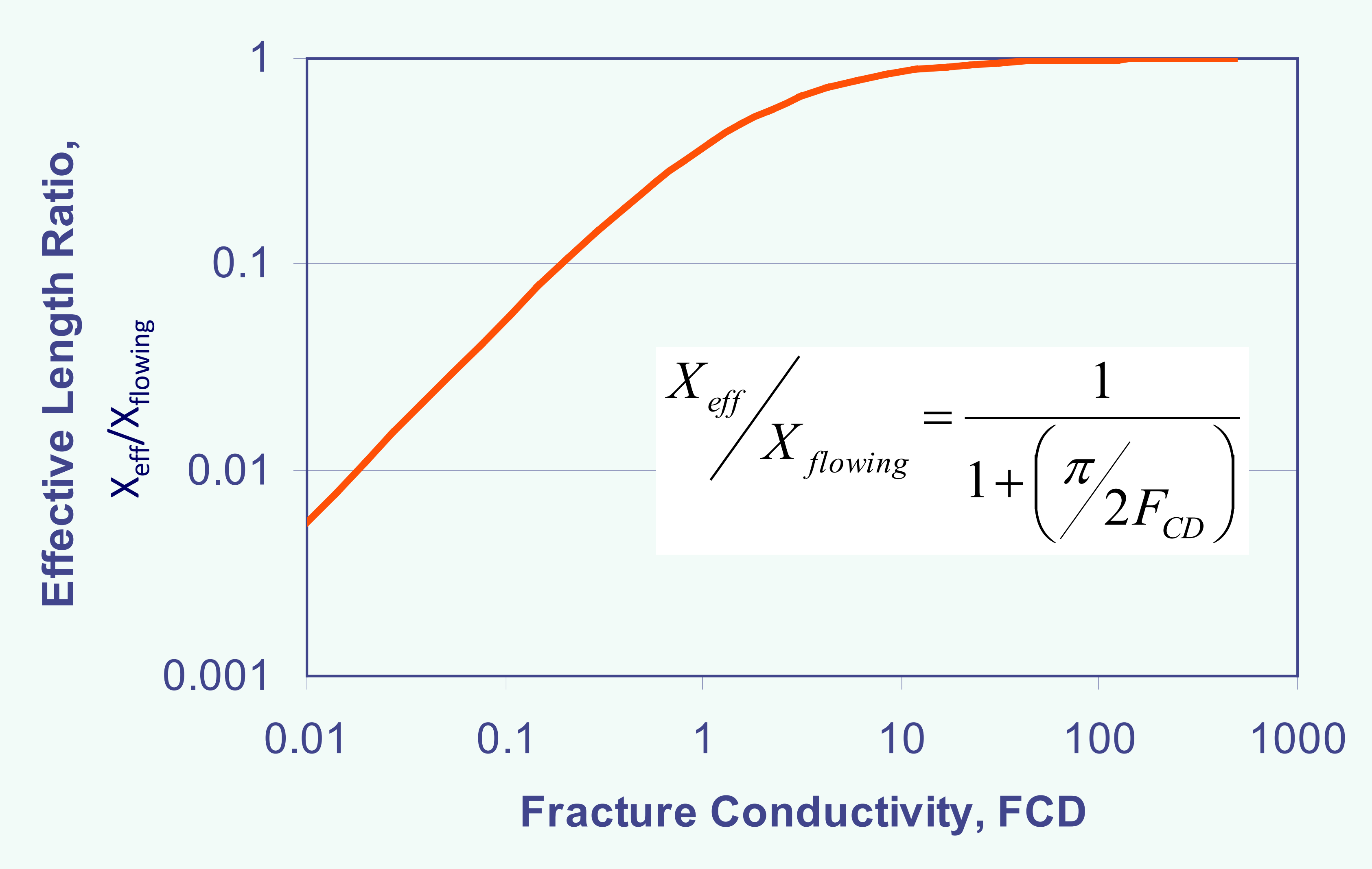
Effective dynamic fracture length depends on dimensionless conductivity and cleanup



$$X_{eff}/X_{flowing} = \frac{1}{1+\left(\pi/2F_{CD}\right)}$$

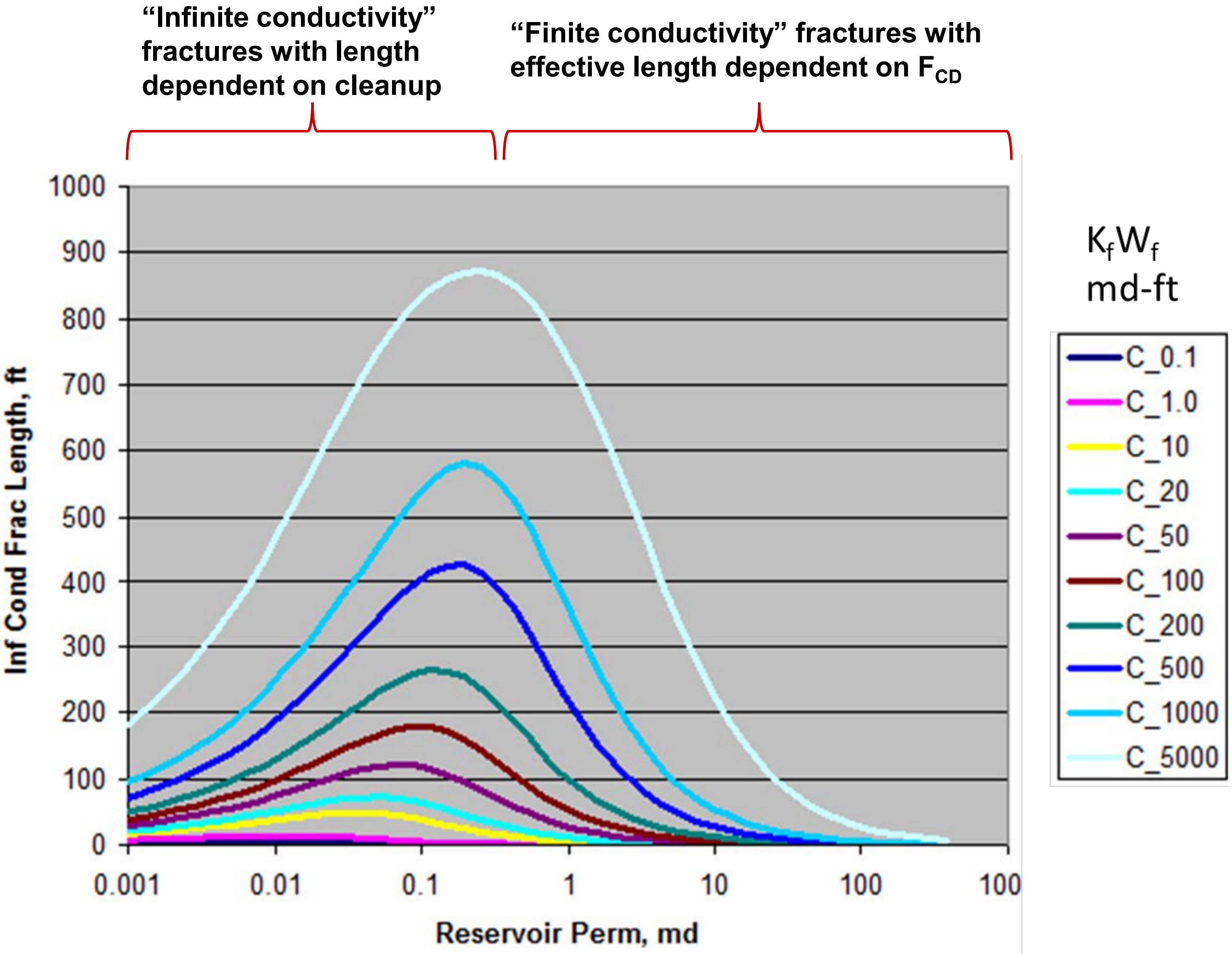
Equivalent R_{wa} for pseudo-radial flow:

$R_{wa}=X_{eff}/2$

Skin: s = -ln(Rwa/Rw)

These approximations may apply for reservoir linear flow, after transverse fractures coalesce drainage areas.

Infinite-conductivity length for a propped length of 1000 ft



Each curve shows proppant pack conductivity adjusted for damage and dynamic flow conditions.

Large created gross fracture lengths often result in short effective producing lengths.

In unconventional reservoirs the deformation of the entire affected reservoir volume causes enhanced permeability that accounts for long-term stimulated well performance.

Thank You!

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Production Enhancement

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