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Well Stimulation and Sand Production Management
(PGE 489)

Hydraulic Fracturing (2/3)

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Stimulation of Shale Gas Reservoirs

What is shale?

- Clay minerals:
  - Kaolinite, Illite, Chlorite, Smectite/Montmorillonite
- But ALSO:
  - Quartz
  - Feldspars
  - Carbonates (calcite, dolomite, siderite)
  - Pyrite
  - Organic Matter (=carbonaceous material)
  - Cherts

What is shale?

- Always LAMINATED
- Composition of the laminated = very heterogeneous
  - Silts / sand
  - Carbonates
  - Pyrite
  - Organic Matter

What is shale?

	Shaw and Weaver (1965)	Hillier (2006)
Quartz	30.8	23.9
Feldspar	4.5	3.7 (K-spar) 2.4 (Plag.)
Carbonate	3.6	7.5 (Calcite) 1.3 (Dolomite) 0.5 (Siderite
Fe-oxides	0.5	0.8
Clay minerals	60.9	47.7 (Di-clay) 7.5 (Tri-clay)
Other minerals	2	0.5 (Pyrite)
Organic matter	1	Not determined

Petrophysics of Shale

- POROSITY:
  - Generally: 1% < ϕ < 8%
- MACROPOROSITY:
  - In laminations of carbonates, silts/sand and cherts.
  - Non-mineralized natural fractures
- MICROPOROSITY:
  - In the bulk volume of shale

Petrophysics of Shale

- PERMEABILITY:
  - Extremely variable: 0.0001mD to 0.1mD

- Depends on:
  - Presence of natural fractures (non mineralized)
  - Presence of laminae of silts/sand, carbonates or cherts, and their extension, and their degree of diagenesis

Shale Rock

Shale Gas Reservoir

- Reservoir = shale formation, organic-rich

- Gas Composition:
  - Either thermogenic gas:
    reservoir = source rock (heavier HC)
  - Either biogenic gas:
    microbes introduced by fresh water aquifers (essentially methane)

- Characterized by a very low permeability (K_{matrix}<0.1 mD)
- Natural fractures or consequent silt/carbonate beds are therefore required to achieve economical production

Mechanisms of Gas Storage

- Microporosity in the shale matrix (<5%)
- Macroporosity in the natural fractures and the silts/carbonates/cherts laminae
- By ADSORPTION of the gas on the surface of the organic matter (Van der Waals forces)

Production of Shale Gas Reservoirs

- Desorption of gas from organic matter into matrix porosity

- Diffusion of gas from matrix porosity into natural fractures

- These processes are governed by the exchange surfaces (organic matter/matrix and matrix/frac)

Stimulation of Shale Gas Wells

- Need to connect the network of natural fractures to the wellbore => HYDRAULIC FRACTURING STIMULATION

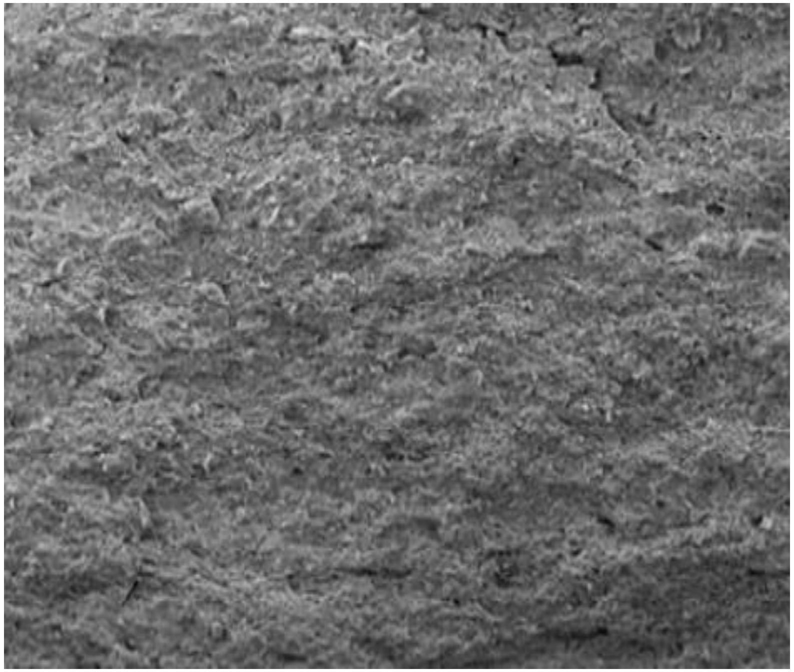
- Usually, fracturing fluids are water-based, with pH $\approx$7.

Effect of Surface Reactive Fluids

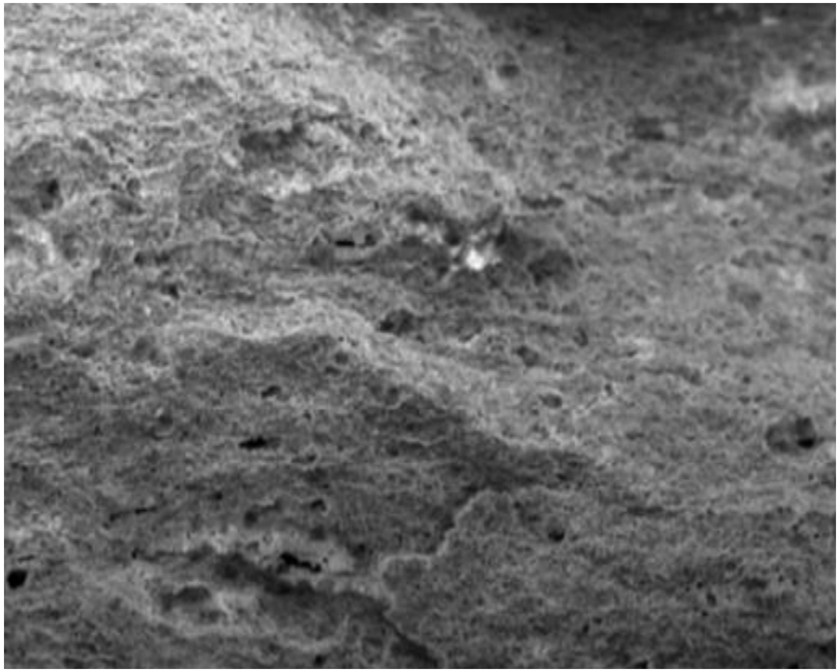
- Shale is considered as little or non reactive with acid (clay, fine quartz, organic matter)
- However, highly heterogeneous at microscopic scale: calcite, dolomite, siderite…
- These minerals can be dissolved with HCl

Shale Reactivity

Before Acid Treatment

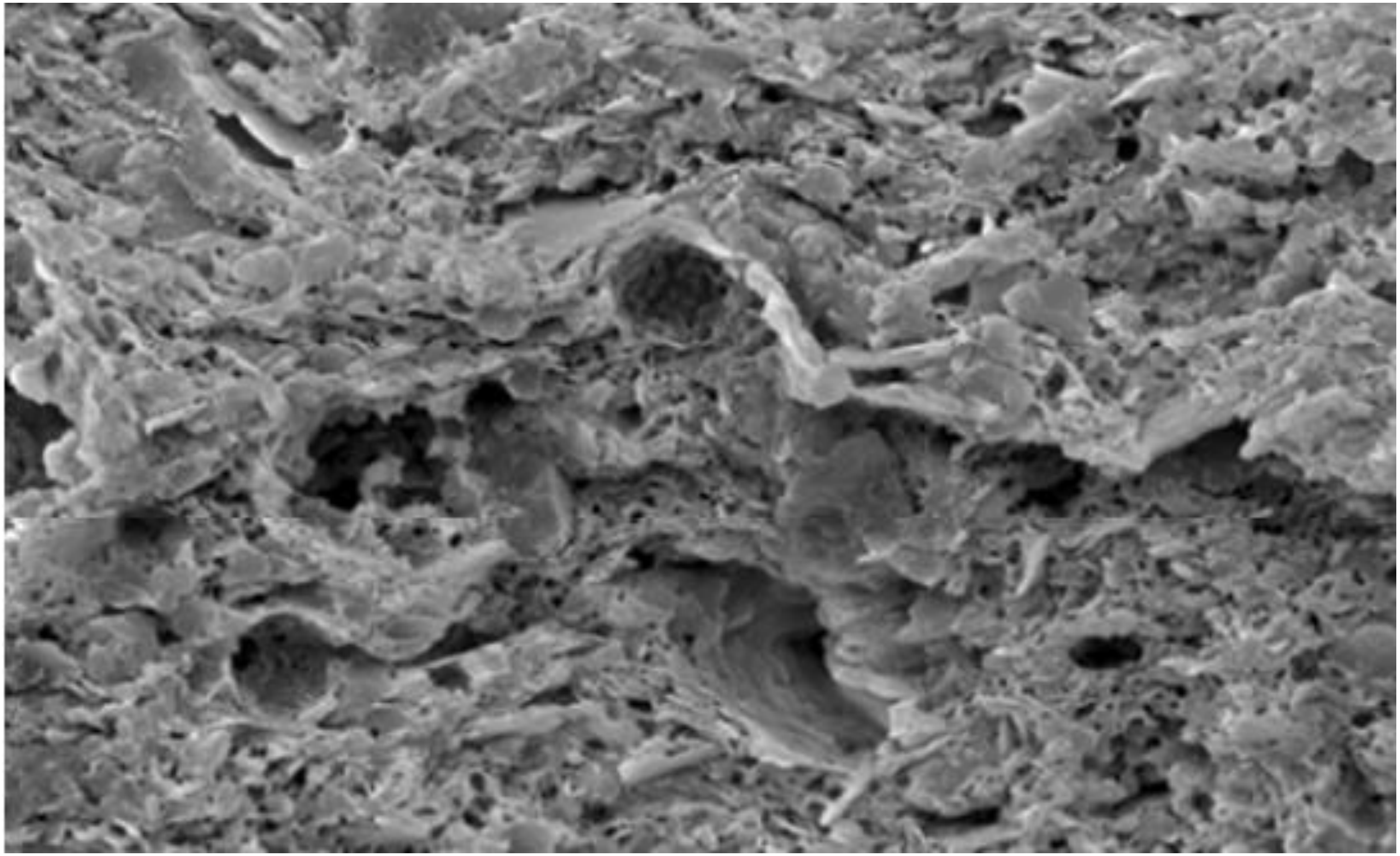


After Acid Treatment (3 wt% HCl at 125ºF)

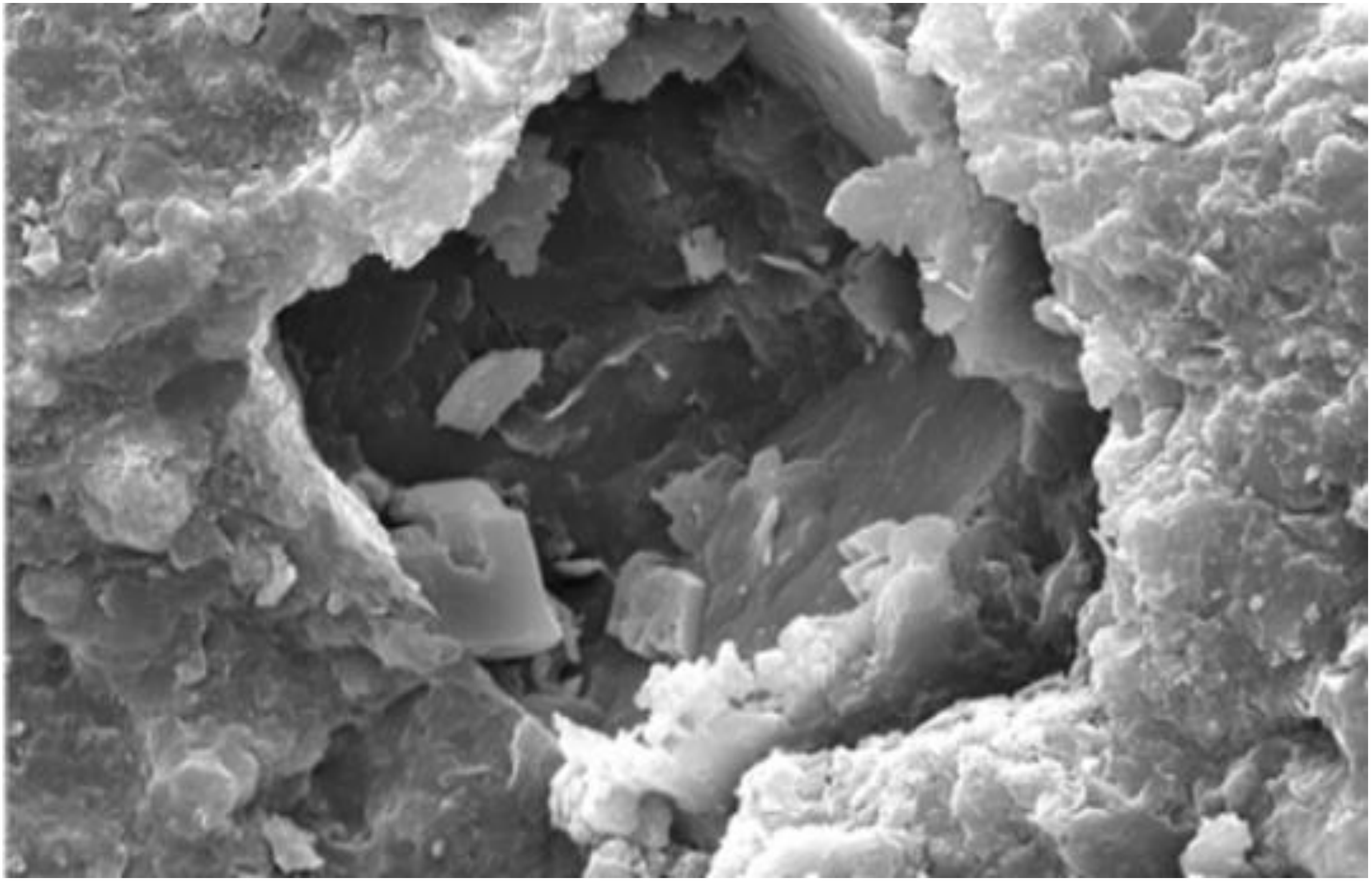


Surface Increase up to 100 times

Acid-Etched Shale



Dolomite Removal from the Shale



Consequences of Using Acid-Base Fracturing Fluid

- It might enhance permeability by dissolving some minerals in the natural fractures
- MAIN CONTRIBUTION of micro-etching: increase of exposed shale surface area
  - Increased diffusivity (more contact matrix/fracture)
  - Increased desorption (more contact organic matter/micropores and organic matter/macropores)
- Productivity of the well is enhanced

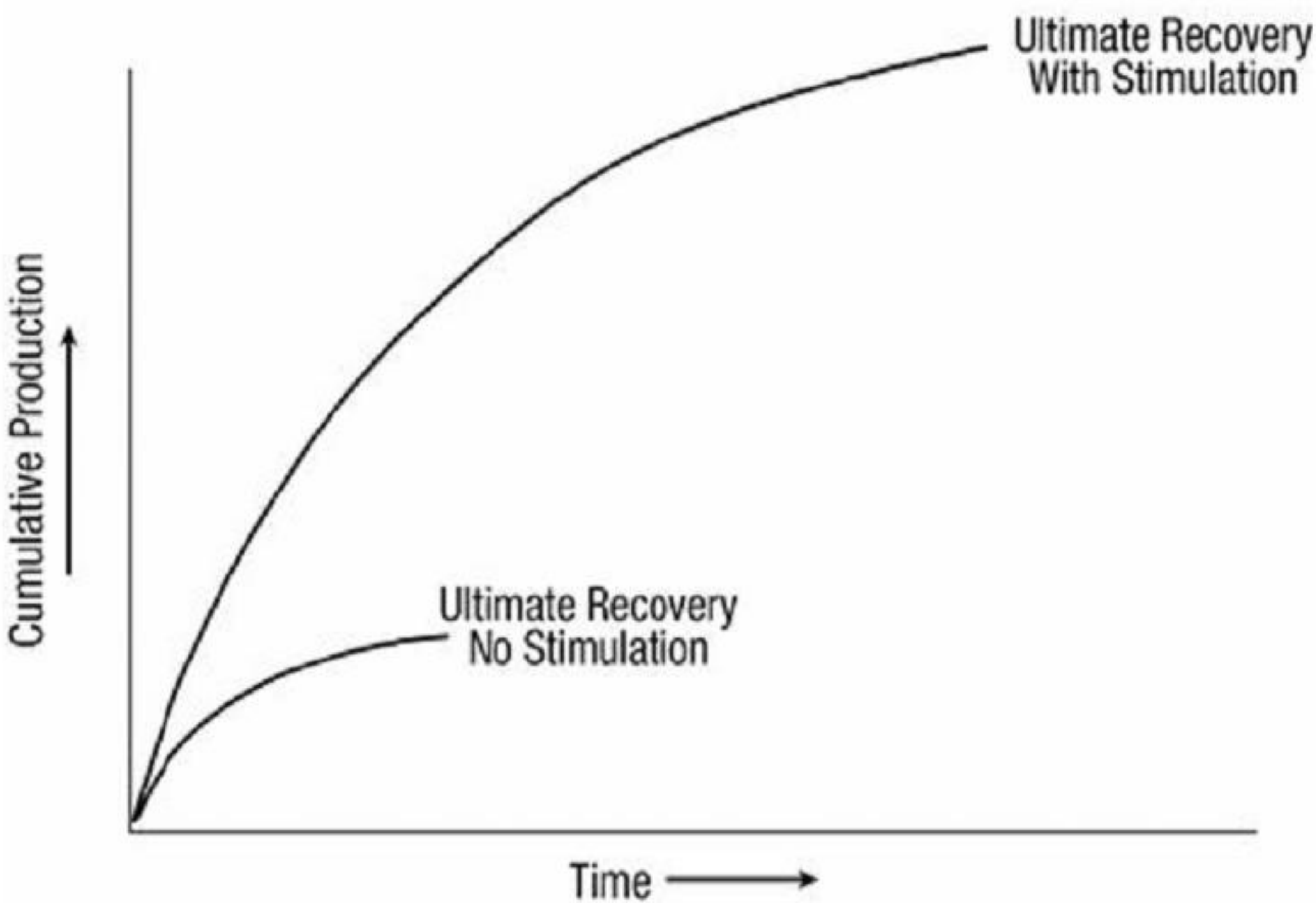
Consequences of Using Acid-Base Fracturing Fluid

- Acid–based fracturing fluids can be used in shale gas reservoirs

- Need to know perfectly the mineralogical composition and structure of the shale

- Need to do some lab experiments before going to the field

Why Hydraulic Fracturing



Pseudo-Steady State Productivity Index

$$q = J\Delta p$$

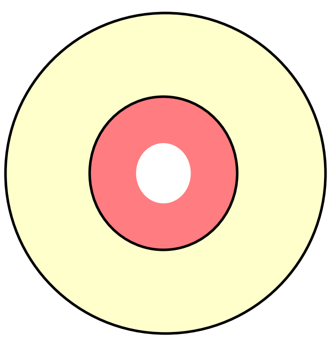
Production rate is proportional to drawdown, defined as average pressure in the reservoir minus wellbore flowing pressure

$$q = \left(\frac{2\pi kh}{B\mu} \right) J_D \Delta p$$

Drawdown

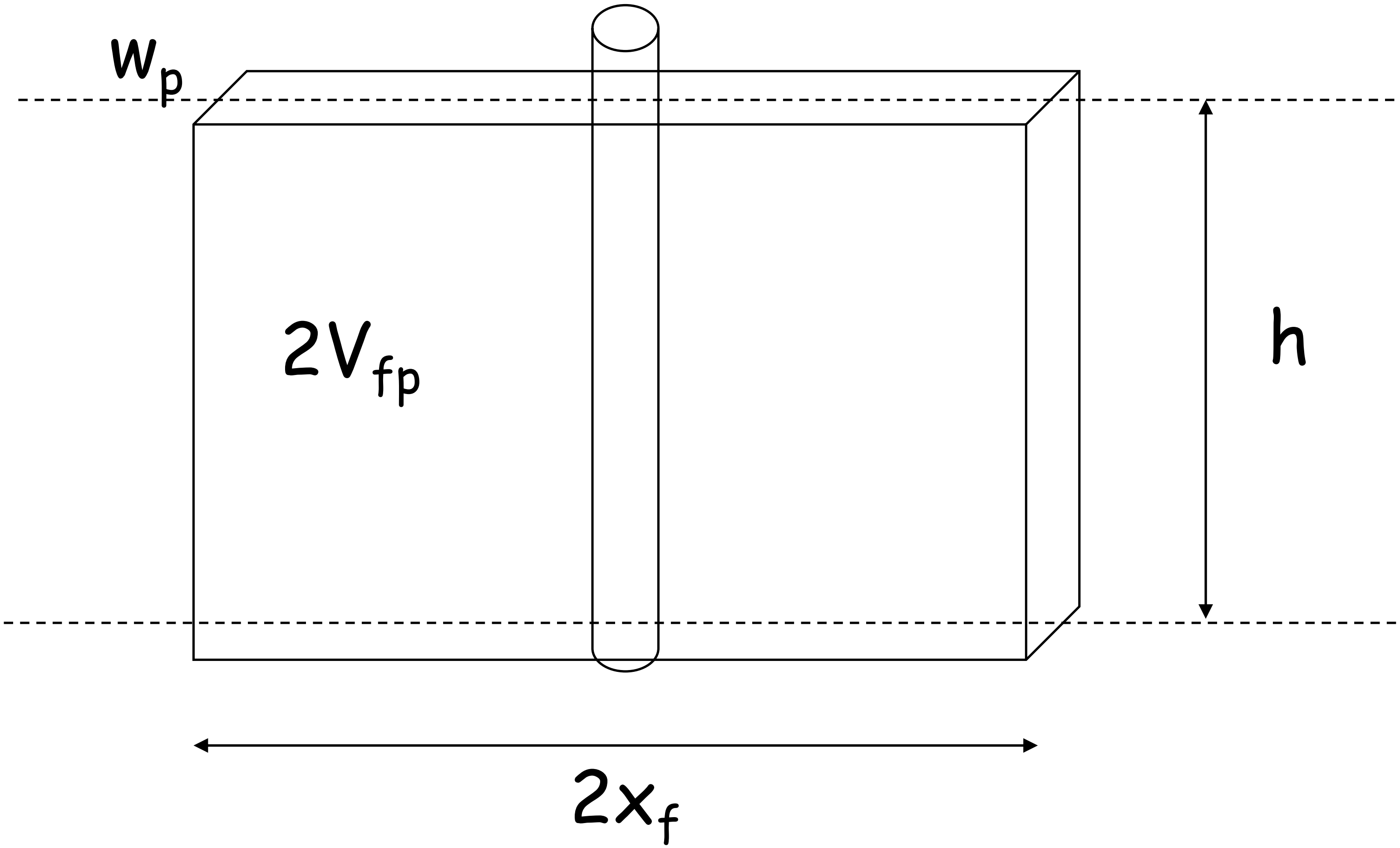
Dimensionless Productivity Index

Circular:

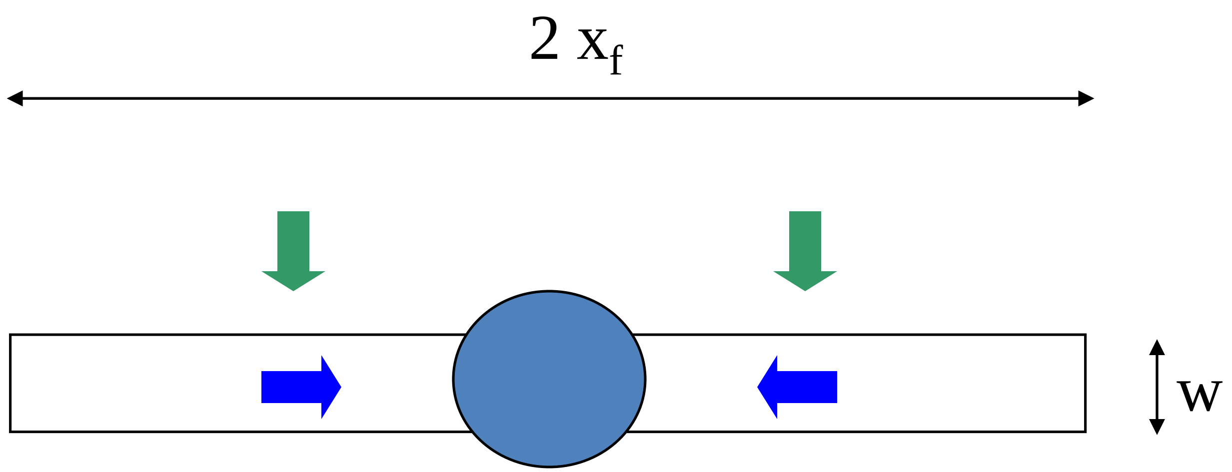


$$J_D = \frac{1}{\ln\left(\frac{r_e}{r_w} \right) - \frac{3}{4} + s}$$

Fully penetrating vertical fracture: Relating Performance to Dimensions



Dimensionless Fracture Conductivity



Dimensionless fracture conductivity

$$C_{fD} = \frac{k_f w}{k x_f}$$

$$\frac{\textit{fracture conductivity}}{\textit{no name}}$$

Prat's Number

- In 1961, Prats provided pressure profiles in a fractured reservoir as functions of the fracture half length and the relative capacity, ***a***, which he defined as

$$a = \frac{\pi k x_f}{2 k_f w}$$

$$r_w' = r_w e^{-S_f}$$

- Prats (1961) also introduced the concept of dimensionless effective wellbore radius in a hydraulically fractured well,

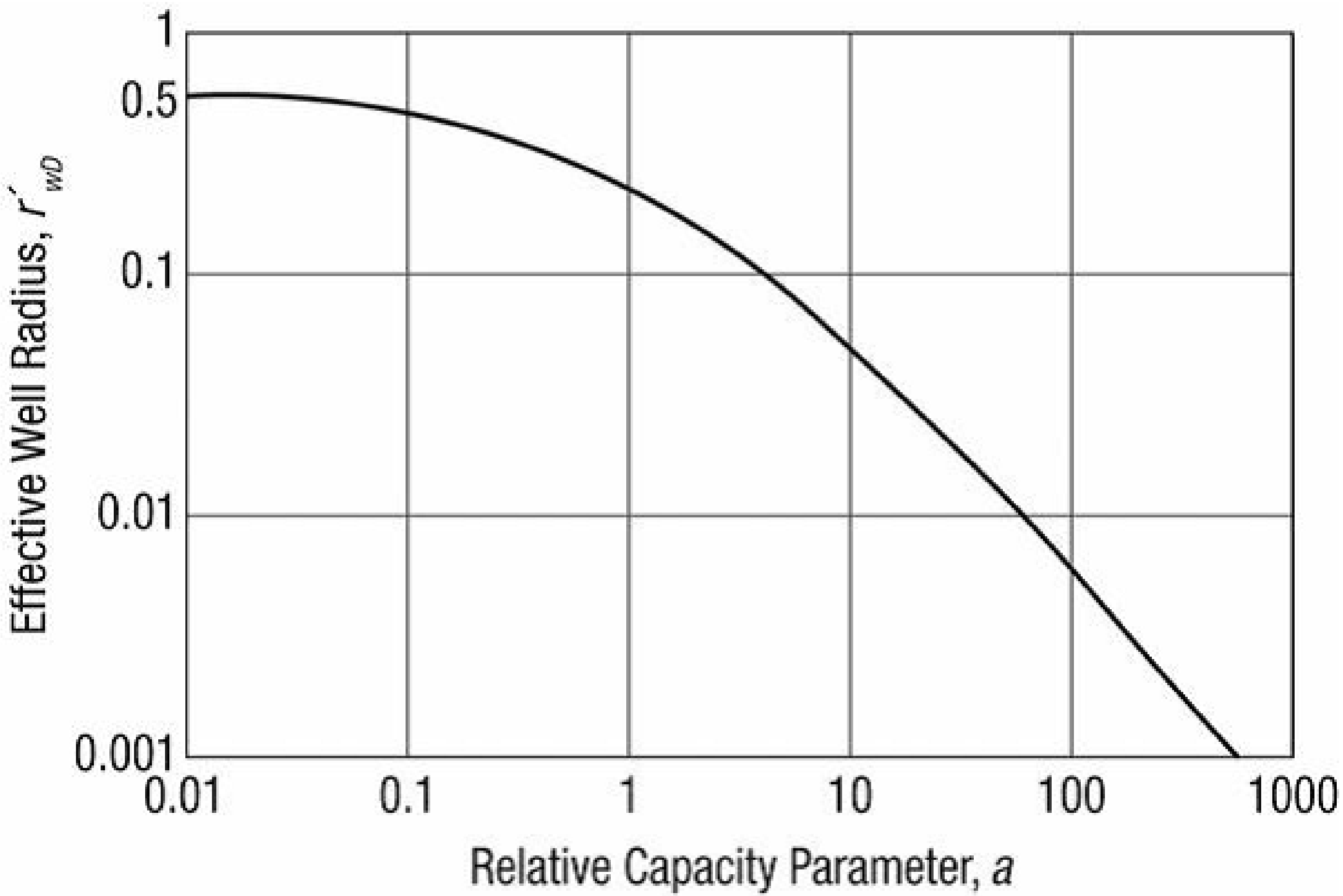
$$r_w' = \frac{x_f}{\dfrac{\pi}{C_{fD} + 2}}$$

$$r_w' = \frac{x_f}{2}$$

$$q = \frac{kh\left(\bar{p} - p_{wf}\right)}{141.2 B\mu\left[\ln\left(0.472 r_e / r_w\right) + S_f\right]}$$

$$r_{wD}' = \frac{r_w'}{x_f}$$

Prat’s Number



Accounting for PI: s_f , f and r'_w

$$q = J\Delta p$$

s_f is pseudo skin factor used *after* the treatment to describe the productivity

$$J = \left(\frac{2\pi kh}{B\mu}\right)\frac{1}{\ln[\frac{r_e}{r_w}] - 0.75 + s_f} = \left(\frac{2\pi kh}{B\mu}\right)J_D$$

J_D is a function of:
•half-length,
•dimensionless fracture conductivity
•Drainage radius, r_e

s_f is a function of:
•half-length,
•dimensionless fracture conductivity
•wellbore radius, r_w

Pseudo-skin, equivalent radius, f-factor

$$J = \frac{2\pi kh}{B\mu\left[\ln 0.472\,\frac{r_e}{r_w} + s_f\right]}$$

or

$$J = \frac{2\pi kh}{B\mu\left[\ln 0.472\,\frac{r_e}{r'_w}\right]}$$

Prats

$$f\,(C_{fD})$$

$$J = \frac{2\pi kh}{B\mu\left[\ln\frac{0.472 r_e}{x_f} + \left(s_f + \ln\frac{x_f}{r_w}\right)\right]} = \frac{2\pi kh}{B\mu\left[\ln\frac{0.472 r_e}{x_f} + f\right]}$$

Cinco-Ley

Dimensionless Productivity Index, s_f and f and r'$_w$

$$J_D = \frac{1}{\ln 0.472\dfrac{r_e}{r_w} + s_f}$$

or

$$J_D = \frac{1}{\ln 0.472\dfrac{r_e}{r'_w}}$$

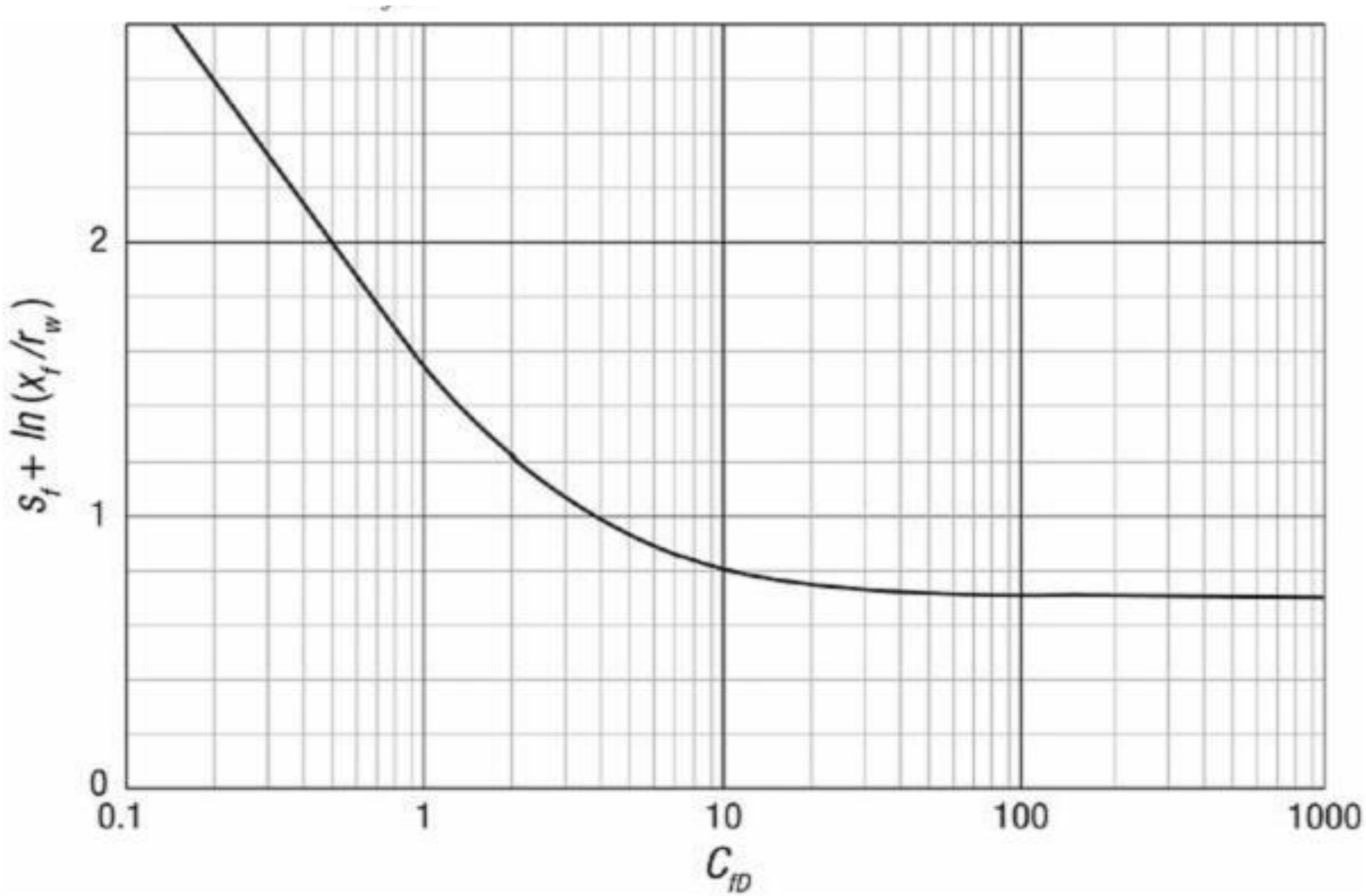
Prats

$f(C_{fD})$

$$J_D = \frac{1}{\ln \dfrac{0.472 r_e}{x_f} + \left(s_f + \ln \dfrac{x_f}{r_w}\right)} = \frac{1}{\ln \dfrac{0.472 r_e}{x_f} + f}$$

Cinco-Ley

Dimensionless Productivity Index, s_f , f and r'_w



Calculation of the Equivalent Skin Effect from Hydraulic Fractures

Assuming that $k_f w$ = 2000 mD-ft, k = 1 md, x_f = 1000 ft, and r_w = 0.328 ft. Calculate the equivalent skin effect and the folds of well productivity increase (at steady-state flow) for a reservoir with drainage radius, r_e = 1490 ft (160 acres) and no pretreatment damage. What would be the folds of increase for the same fracture lengths and $k_f w$ if k = 0.1 mD and k = 10 mD?

$$C_{fD} = \frac{k_f w}{k x_f} = \frac{2000}{(1)(1000)} = 2$$

$$S_f = -\ln \frac{r_w^{'}}{r_w} = -\ln \frac{280}{0.328} = -6.75$$

$$r_w^{'} = \frac{x_f}{\frac{\pi}{C_{fD}} + 2} = \frac{1000}{\frac{\pi}{2} + 2} = 280 \ ft$$

$$\frac{J}{J_o} = \frac{\ln \frac{r_e}{r_w}}{\ln \frac{r_e}{r_w} + S_f} = 5$$

Calculation of the Equivalent Skin Effect from Hydraulic Fractures

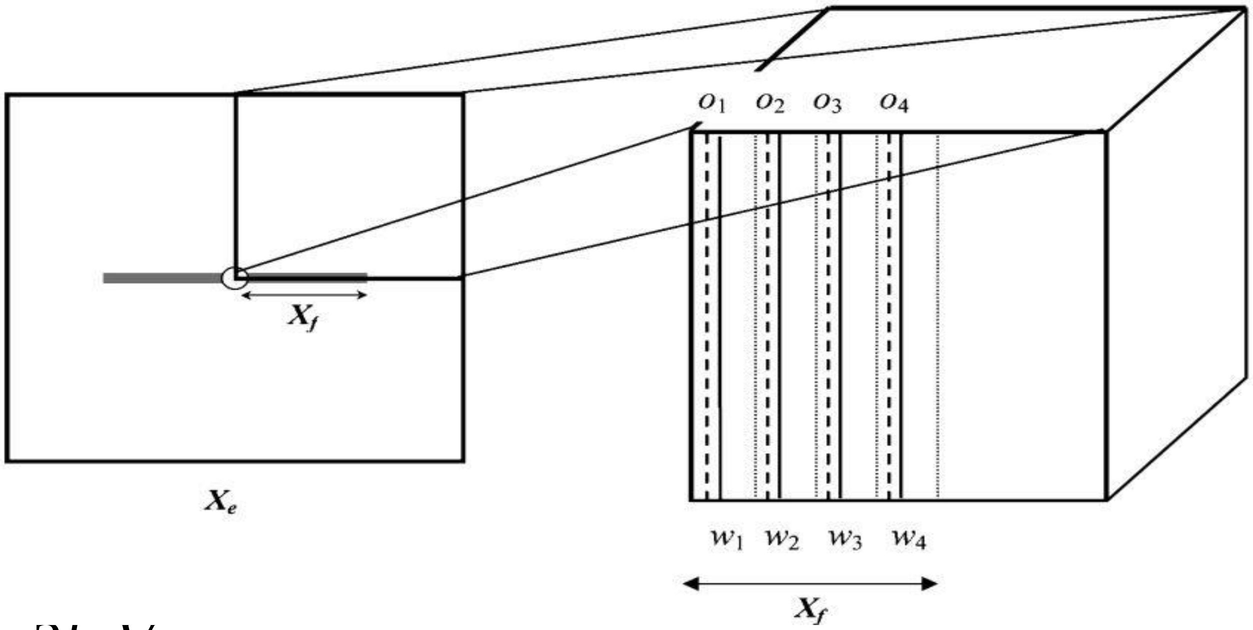
Similarly,

- For k = 0.1 md, C_{fD} = 20, r_w' = 464 ft, S_f = -7.3 and J/J_o = 7.5
- For k =10 md, C_{fD} = 0.2, r_w' = 56.5 ft, S_f = -5.1 and J/J_o = 2.5

Penetration Ratio
Proppant Number

$$I_x = \frac{2x_f}{x_e}$$

$$C_{fD} = \frac{k_f w}{k x_f}$$



$$N_{prop} = \frac{4k_f V_{f,prop,1-wing}}{kV_{res}} = \frac{2k_f V_{f,prop,2-wing}}{kV_{res}} = (I_x)^2 C_{fD}$$

$$N_{prop} = I_x^2 C_{fD} = \frac{4k_f x_f w}{k x_e^2} = const$$

Penetration Ratio
Proppant Number

The Dimensionless Proppant Number, N_{prop}, is nothing else but the ratio of two volumes:

1- The propped volume in the pay divided by

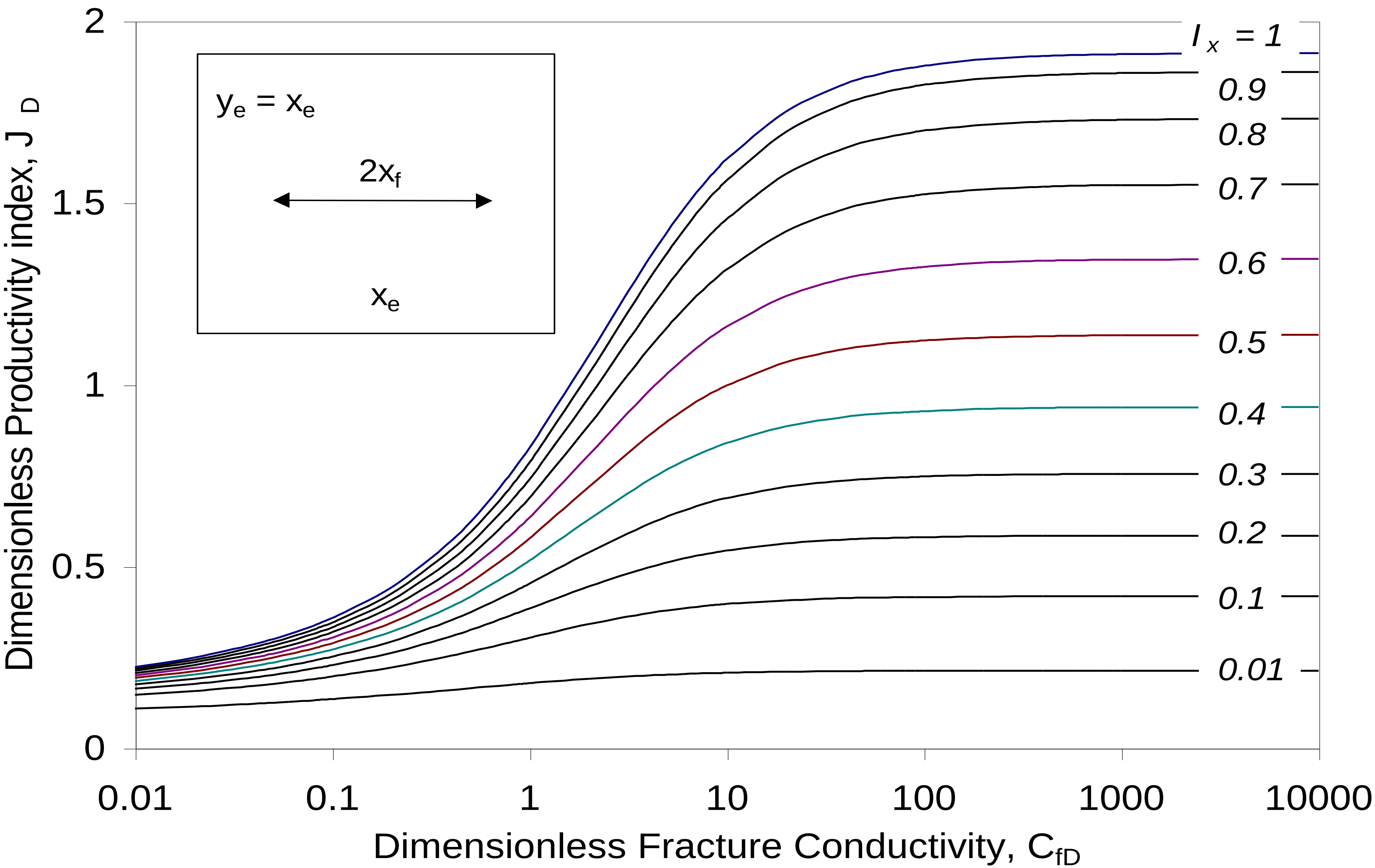
2- The reservoir volume in the pay. $N_{prop} = \frac{4k_f V_{f,prop,1-wing}}{kV_{res}} = \frac{2k_f V_{f,prop,2-wing}}{kV_{res}} = (I_x)^2 C_{fD}$

Both volumes weighted by their permeability, respectively.

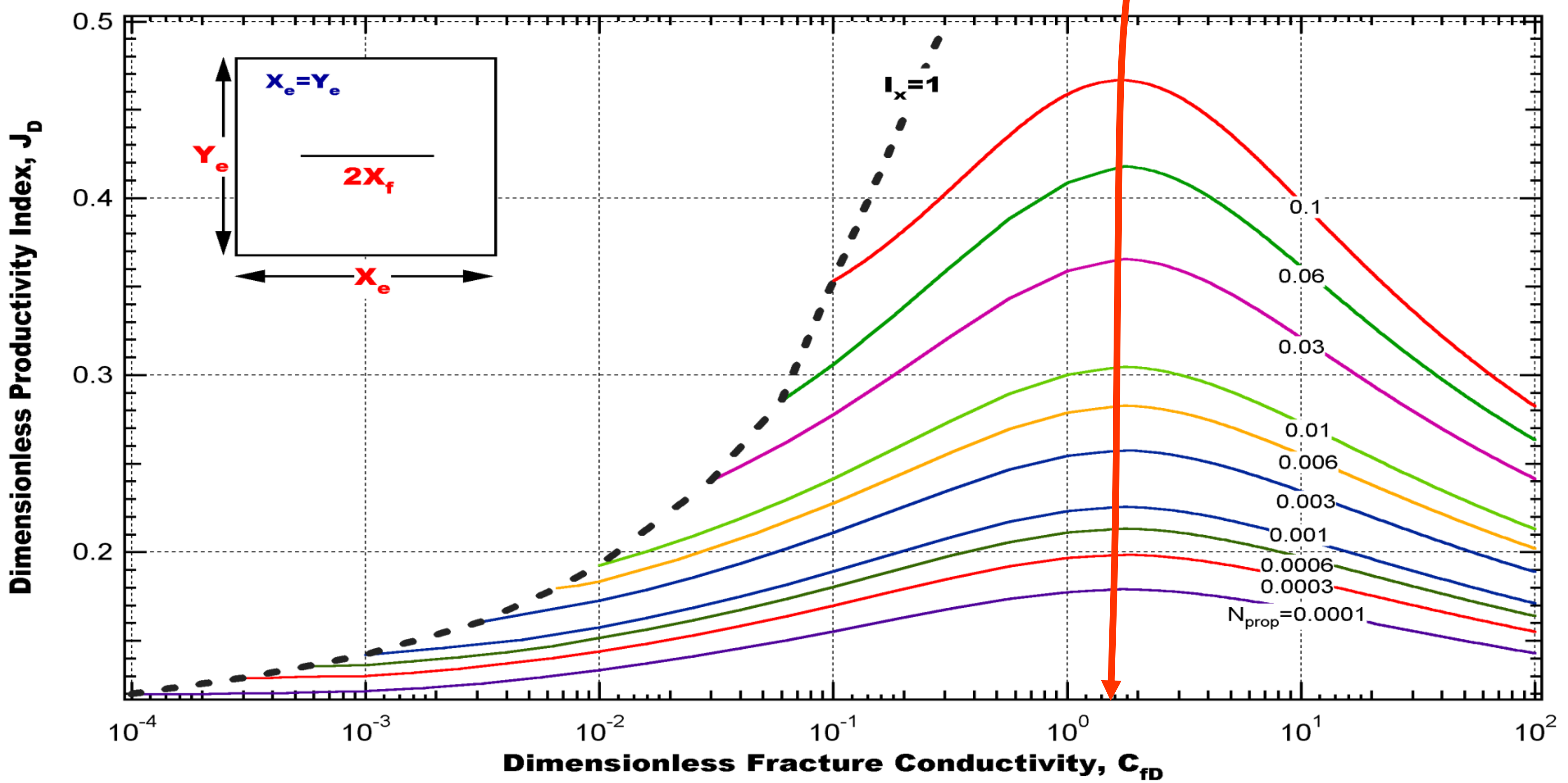
In addition, a factor of two is used in front of the propped volume.

Note: The proppant number is the **most important** parameter in fracture design.

Penetration Ratio
Proppant Number

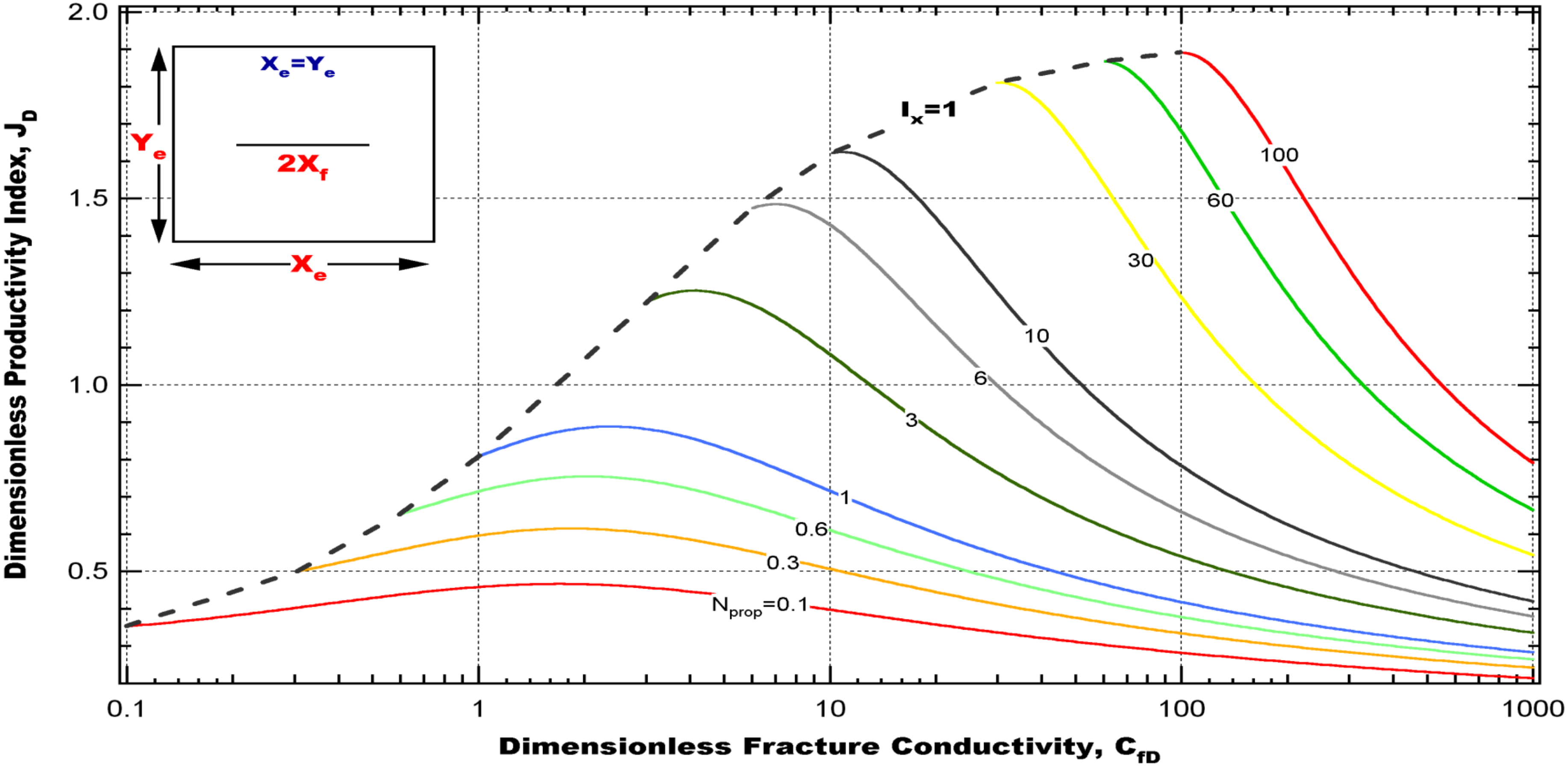


Penetration Ratio
Proppant Number



Dimensionless productivity index as a function of dimensionless fracture conductivity and proppant number (for $N_{prop} < 0.1$)

Penetration Ratio
Proppant Number



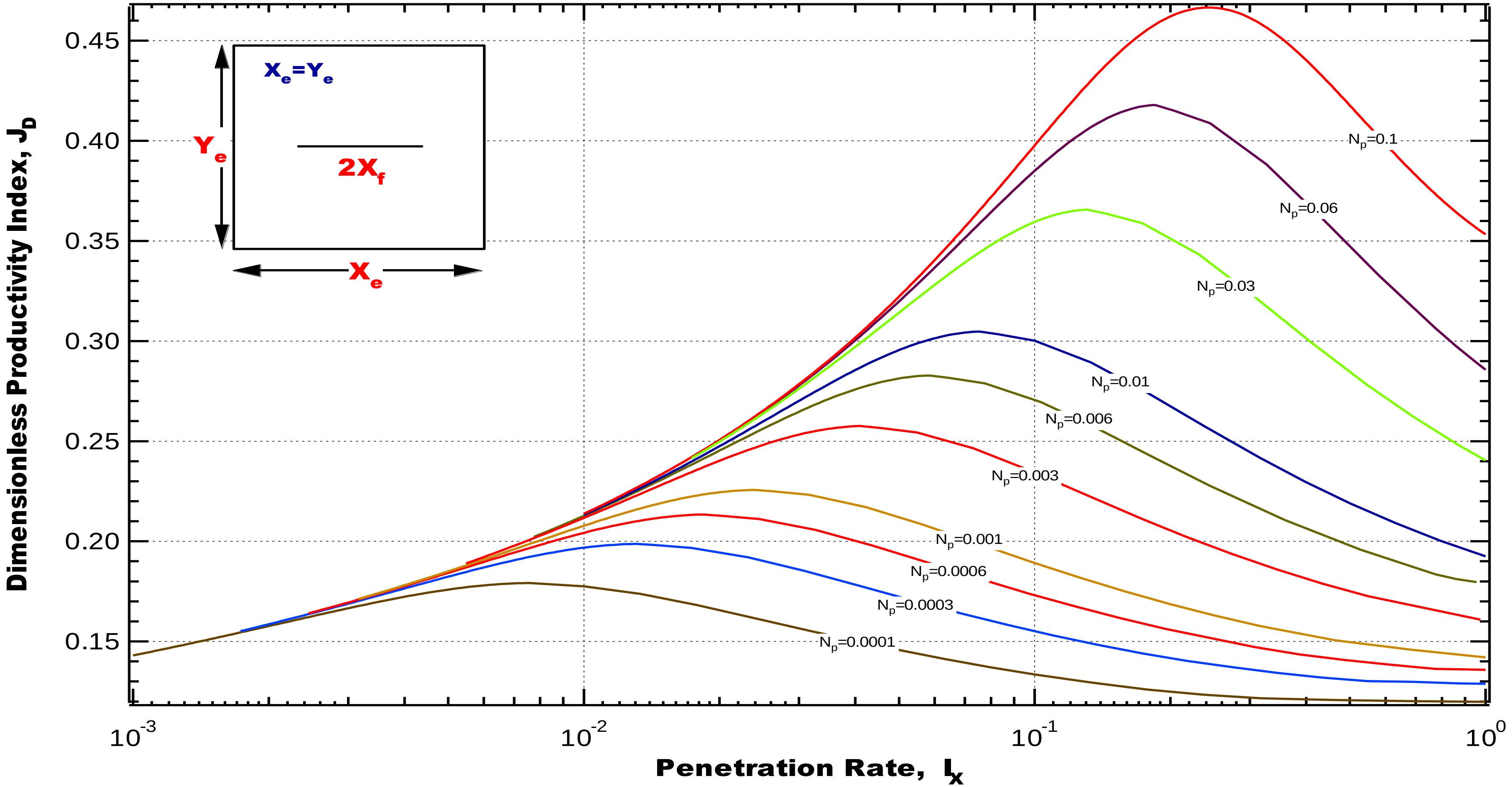
Dimensionless productivity index as a function of dimensionless fracture conductivity and proppant number (for $N_{prop} > 0.1$)

Penetration Ratio
Proppant Number

- It is noted that for a given value of N_{prop} , that is for a fixed amount of available proppant, there exists an optimal dimensionless fracture conductivity, representing the optimal compromise between the ability of the fracture to conduct the flow into the wellbore and its ability to get inflow from the formation.

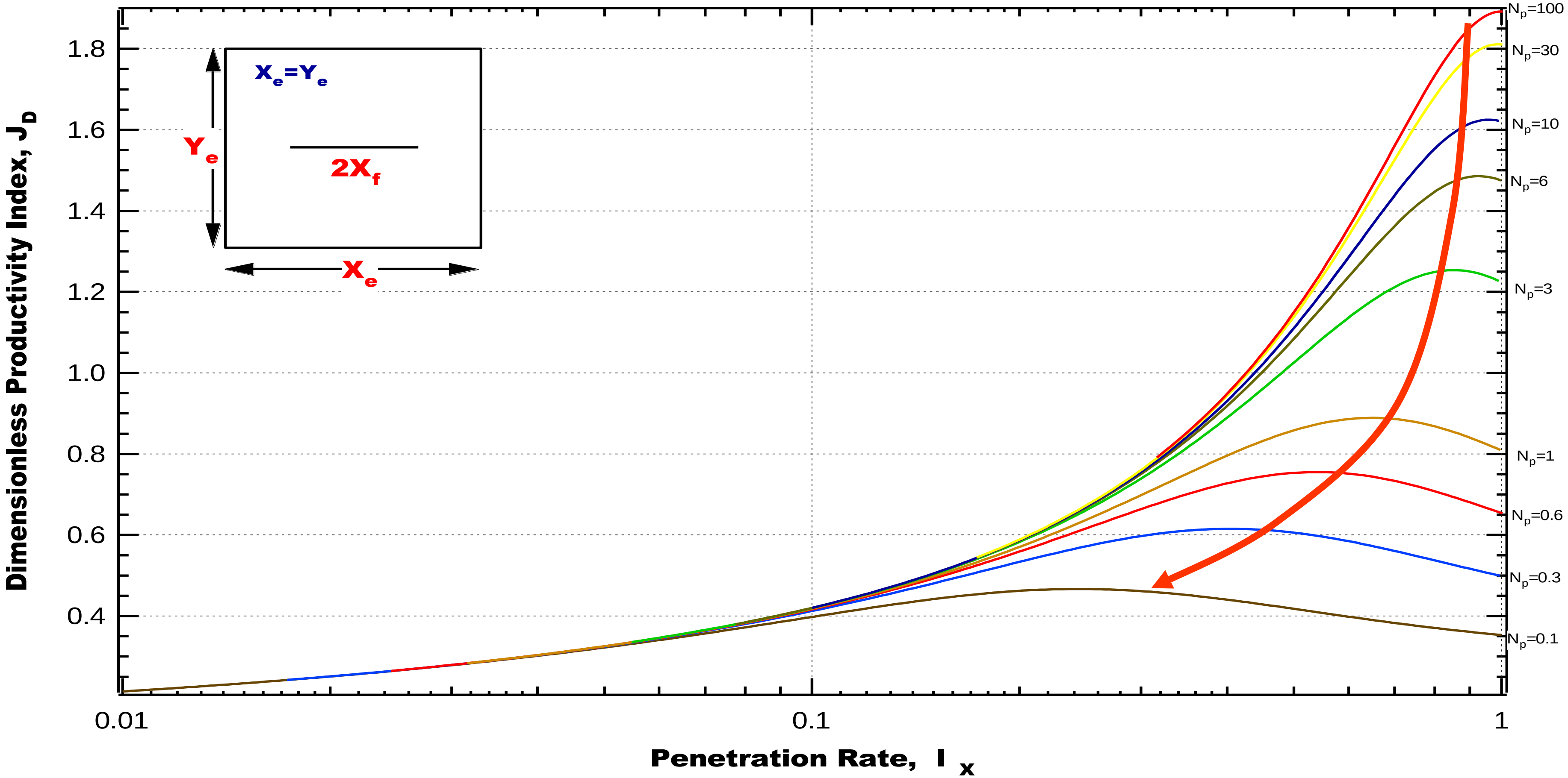
- At low proppant numbers the optimal compromise occurs at C_{fD} = 1.6. The behavior at large N_{prop} is as expected because the absolute maximum for J_D is $6/\pi = 1.909$ (this value is the productivity index for a perfect linear flow in a square reservoir.

Penetration Ratio
Proppant Number



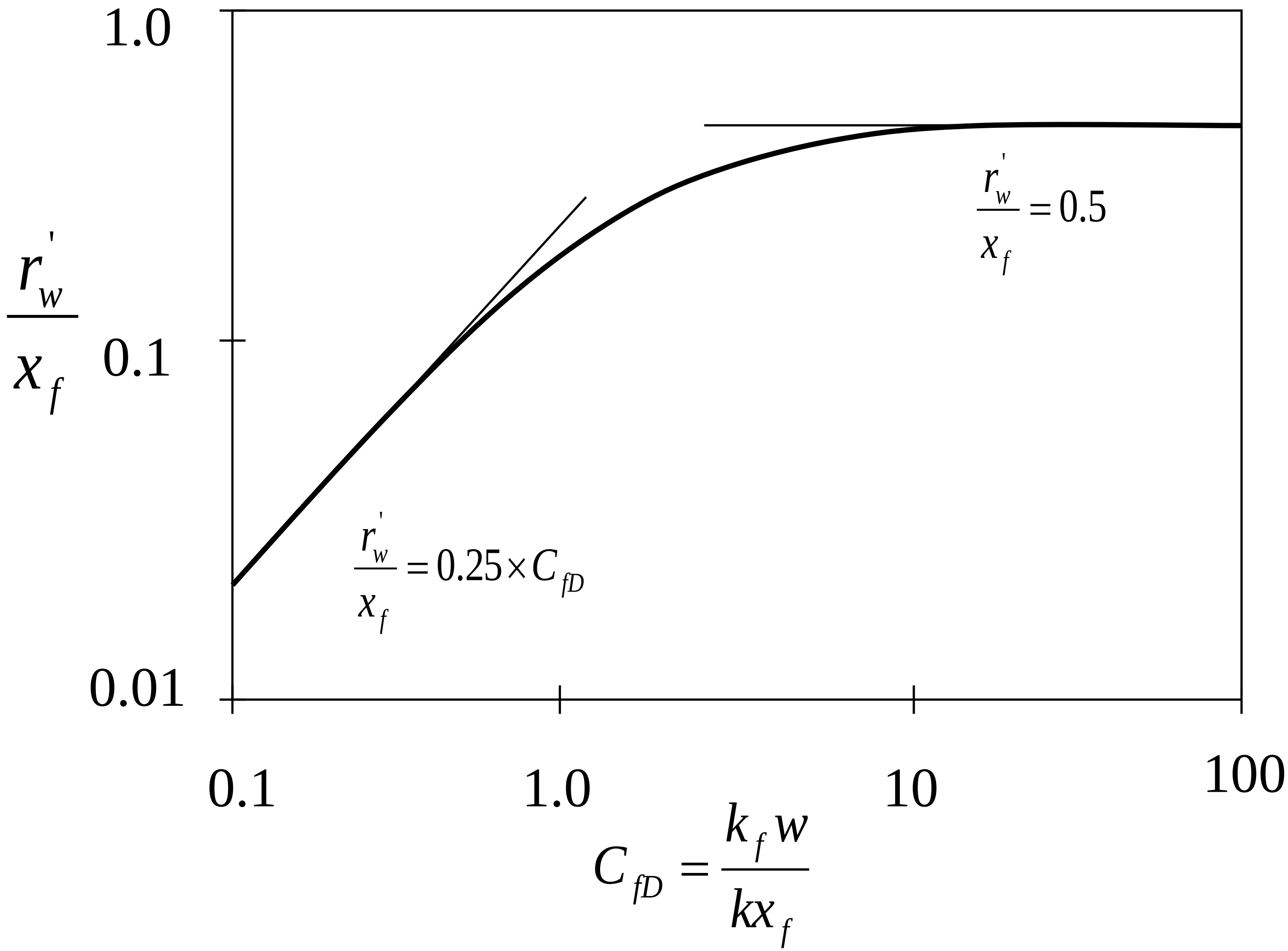
Dimensionless productivity index as a function of penetration ratio and proppant number (for $N_{prop} < 0.1$)

Penetration Ratio
Proppant Number



Dimensionless productivity index as a function of penetration ratio and proppant number (for $N_{prop} > 0.1$)

Prats' Dimensionless Wellbore Radius (N_{prop}<0.1)



More concepts

- Infinite conductivity fracture
- Uniform flux fracture
- Finite conductivity fracture with flux distribution

General Theory

- Square drainage area
- Pseudo-steady state
- Two symmetrical wings
- Vertically fully penetrating fracture
- Average width
- Constant proppant permeability
- Single phase (moderate velocity) flow

Example

Determine the "folds of increase" if 40,000 lb_m proppant (pack porosity 0.35, specific gravity 2.6, permeability 60,000 md) is to be placed into a 65 ft thick formation of 0.5 md permeability. Assume all proppant goes to pay.

The drainage radius is r_e = 2100 ft, the well radius is r_w = 0.328 ft, the skin factor before fracturing is s_{pre} = 5.

Determine the optimal fracture length and propped width.

Solution

40,000 lbm proppant, specific gravity 2.6, pack porosity 0.35
packed volume is 40,000/62.4/2.6/(1-0.35) = 380 ft^3

$$N_{prop} = \frac{2 \times \left(60 \times 10^3\, md\right) \times \left(380\, ft^3\right)}{\left(0.5\, md\right) \times \left(2100^2\, ft^2\right) \times \pi \times \left(65\, ft\right)} = 0.1$$

Folds of Increase

FracPi
0.467

or $\frac{1}{0.99 - 0.5 \ln 0.1} = 0.467$

$$\frac{J_{post}}{J_{pre}} = \frac{J_{D,\max}}{\dfrac{1}{\ln[\dfrac{2100}{0.328}] - 0.75 + 5}}$$

0.0768

FOI: 6.1 with respect to skin 5
FOI: 3.8 with respect to skin=0

Optimum frac dimensions

The volume of two propped wing is

$2V_{1wp} = 380\ \text{ft}^3$

The proppant number is still OK so $C_{fD,opt} = 1.6$

$$x_f = \left(\frac{\overbrace{\frac{380\ \text{ft}^3}{2}}^{V_{1wp}}(60{,}000\ \text{md})}{1.6 \times (65\ \text{ft})(0.5\ \text{md})} \right)^{1/2} = 468\ \text{ft}$$

The propped width is

$$w_p = \frac{V_{1wp}}{h\ x_f} = 0.0062\ \text{ft} = 0.075\ \text{in.} = 1.8\ \text{mm}$$

Fracture Modeling

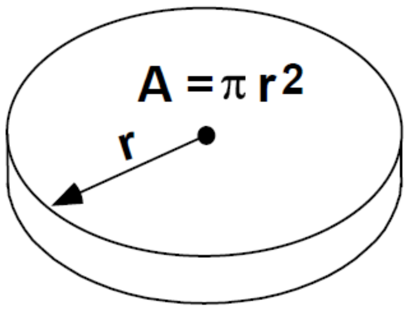
The various fracture geometry models are:

- **2D**
  - PKN
  - KGD
  - Radial
- **3D**
  - Lumped P3D
  - Discrete cells P3D
  - Planar 3D
- **Multilayered**
  - PKN fractures
  - P3D fractures.

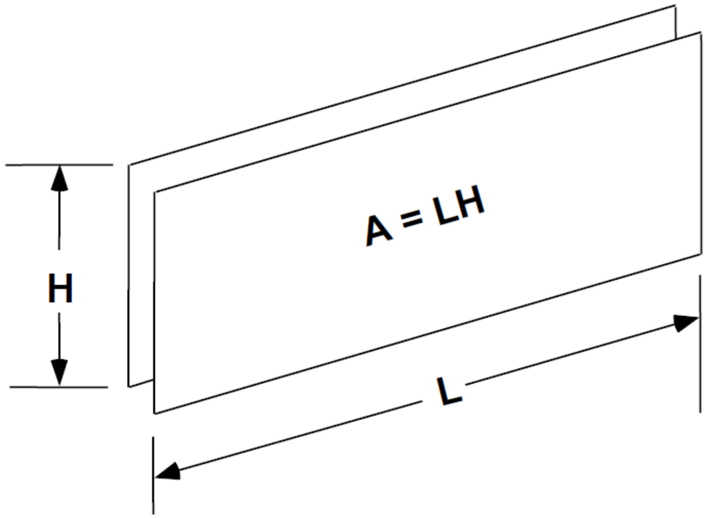
Hydraulic Fracturing

Radial Fracture Model

A simple radial (penny-shaped) crack/fracture was first presented by Sneddon and Elliot (1946). This occurs when there are no barriers constraining height growth or when a horizontal fracture is created. Geertsma and deKlerk (1969) presented a radial fracture model showing that th fracture width at wellbore is given by:



$$w_w = 2.56\left[\frac{\mu q_i(1-\nu)R}{E}\right]^{\frac{1}{4}}$$



w_w = fracture width at wellbore, in.
μ = fluid viscosity, cP
qi = injection rate, bpm
R = radius of fracture, ft
E = Young's modulus, psi
ν = Poission ratio

Assuming the fracture width drops linearly in the radial direction, the average fracture width may be expressed as:

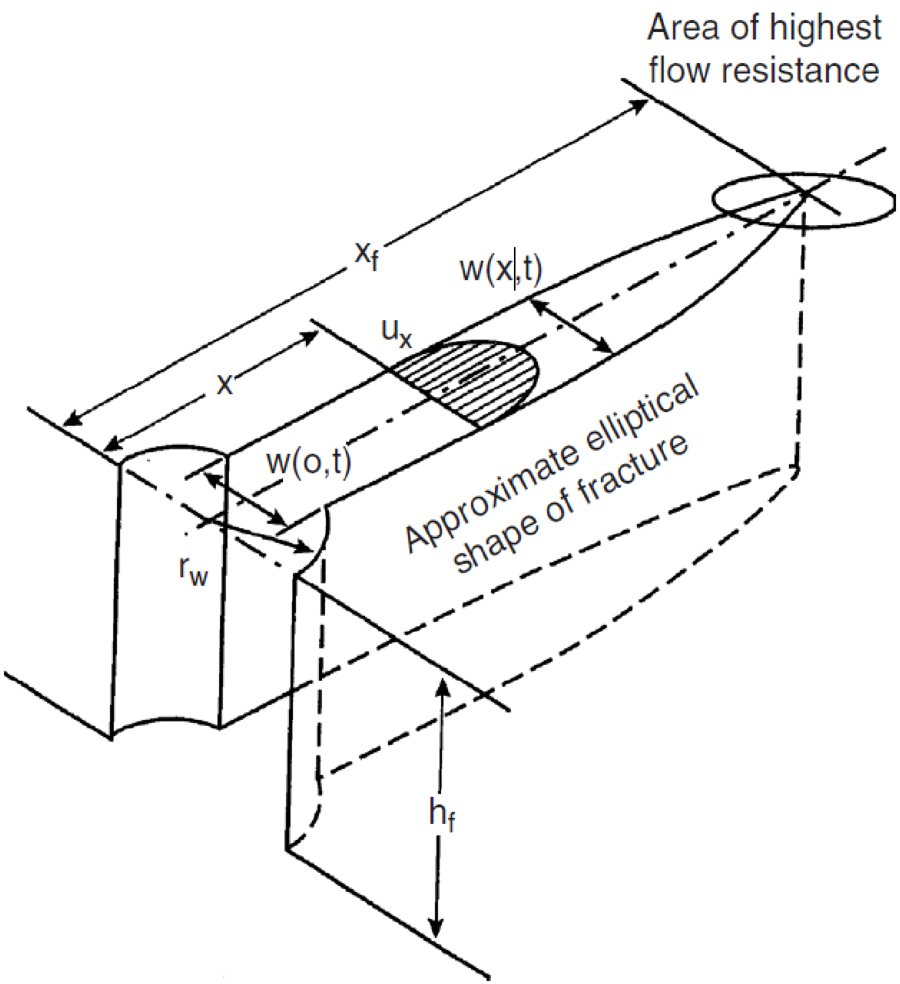
$$\bar{w} = 0.85\left[\frac{\mu q_i(1-\nu)R}{E}\right]^{\frac{1}{4}}$$

Hydraulic Fracturing

The KGD Model

Assuming that a fixed-height vertical fracture is propagated in a well-confined pay zone (i.e., the stresses in the layers above and below the pay zone are large enough to prevent fracture growth out of the pay zone). The model assumes that the width of the crack at any distance from the well is independent of vertical position, which is a reasonable approximation for a fracture with height much greater than its length. The average width of the KGD fracture is expressed as:

$$\bar{w} = 0.29\left[\frac{\mu q_i (1-\nu) x_f^2}{G h_f}\right]^{\frac{1}{4}}\left(\frac{\pi}{4}\right)$$



Where;

$\bar{w}$ = average width, in

q_i = injection rate, pbm

μ = fluid viscosity, cP

G = shear modulus = E/2(1+ν), psi

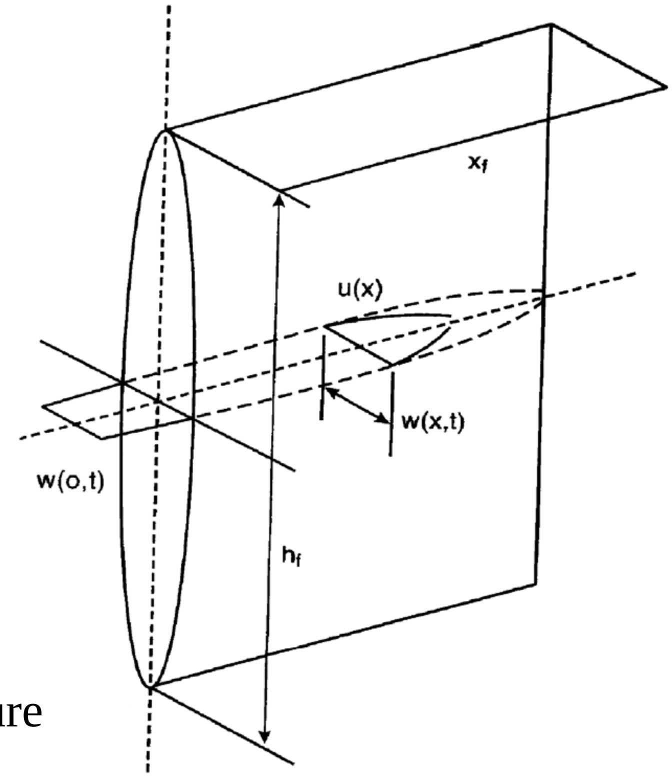
h_f = fracture height, ft

Hydraulic Fracturing

The PKN model

Perkins and Kern (1961) derived a solution for a fixed height vertical fracture. Nordgren (1972) added leakoff and storage within the fracture (due to increasing width) to the Perkins and Kern model, deriving what is now known as the PKN model. The average width of the PKN fracture is expressed as:

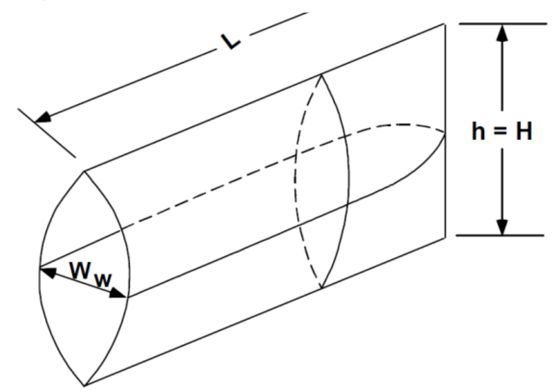
$$\bar{w} = 0.3\left[\frac{\mu q_i (1-\nu) x_f}{G}\right]^{\frac{1}{4}}\left(\frac{\pi}{4}\gamma\right)$$



Where γ = 0.75. PKN model can be applied only if fracture length is at least three times the height

$$w_{\max} = 2.31\left[\frac{q_i \mu (1-\nu) x_f}{G}\right]^{1/4}$$

$$G = \frac{E}{2(1+\nu)}$$



Example: PKN model

What will be the maximum and average fracture width when the fracture half-length is 1000 ft, the apparent viscosity of the fluid is 100 cP, and the injection rate is 40 bpm? Assume that $\upsilon=0.25$ and $E = 4\times10^6$ psi.

- What would be the average width when $x_f = 2000$ft?
- Calculate he volume of the created fracture if $h_f = 100$ ft when $x_f = 100$ ft for the formation described above.
- What fracture length would result in a chalk formation with $E = 4\times10^5$ psi for the same volume? Assume h_f and ν are the same.

MatLab codes (next class tutorial)