FRACTURE ACIDIZING DESIGN: WHAT DOES THE INFORMATION FROM THE LABORATORY REALLY MEAN?

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ABSTRACT

Great many carbonates are stimulated successfully with acid fracturing techniques. There are several models in the industry, which will give relative comparisons of fluid performances under varying reservoir conditions. These are only effective as design tools when validated. However, a great deal of laboratory time is spent testing rocks and fluids for reactivity, diffusivity and leak-off to provide the input values for these models. On most occasions, it is difficult to comprehend the significance of these results.

Presented are the variances in laboratory generated values and their effect on the output of one of the fracture acidizing models commonly used. Several reasons are given as to why these variances occur. These include the difficulty in measuring accurately the surface area of samples tested, the limited amount of reservoir rock to test with equivalent properties, and the impractical amount of time required to perform the tests properly.

INTRODUCTION

A great deal of laboratory testing has been performed over the years to evaluate reaction kinetics, heat of reaction, diffusivity, conductivity, fluid loss, diversion and Brinell Hardness with respect to acid reactivity with carbonates. A theoretical model of the reaction kinetics was developed and compared to laboratory observed reaction data and found to agree at low velocities, but showing lower values than observed at higher velocities.[1] In addition to parallel plate testing a rotating disk device was designed and tested.[2] Utilization of this type of device to evaluate hydrochloric acid reaction with dolomite suggested that adsorption of hydrogen ion on the solid dolomite surface and subsequent reaction of the adsorbed hydrogen ion with the solid dolomite matrix is the reaction mechanism.[3] Further testing of dolomite reactivity with hydrochloric acid proved that below 50°C the dissolution is reaction limited while above 100°C it is controlled by mass transport of hydrochloric acid to the solid surface.[4,5] Additional rotating disk and marble experimentation suggested that the diffusion of ions is also affected by the diffusion layer and the electric field at the surface of the rock.[6] It was also determined that gelation and emulsification of the acid cause a significant reduction in the effective diffusion coefficient. Examination of the effect of reaction heat on fluid temperature and acid penetration has shown that these effects are significant.[7]

A mathematical model using a finite-difference method was presented for describing acid spending in a fracture when the over-all rate of spending is affected by the surface reaction rate.[8] Modeling of reactivity and leak-off of acid in carbonates has demonstrated that there is an optimal acid flux in the generation of wormholes and therefore predicted fluid loss.[9,10] Additional evaluation of fluid loss additives, retarded acids and acidized fracture conductivity showed that the addition of an effective fluid loss additive can significantly improve stimulation from an acid fracturing treatment.[11] As above it was found that viscous and emulsified acids provide retardation of the dissolution of carbonates under field acid fracturing conditions. In addition, a method of predicting the resultant acid fracture conductivity using rock embedment strength and closure stress was developed.[11] A continuation of this work resulted in a finite fracture conductivity model predicting stimulation ratios from acid treatments with good agreement to observed field results.[12] Add to this studies of finite conductivity of fractures intercepting multi-layer reservoirs and models begin to develop to a greater extent.[13] Dynamic acid etching tests have also been performed to support the development of a computerized acid design model.[14]

This data has been used to develop several models to define the penetration of live acid during a hydraulic fracture acidizing treatment and resultant conductivity.[15-23] Each of these models employs various methods of dealing with the reaction at the surface and the issues of mass transport. Some of the models couple fracture propagation and reaction mechanisms to show the importance of the different mechanisms.[18] Also, included is the representation of viscous fingering and wormhole development. Some of the models include a method to characterize the leak-off in acid jobs.[20] Still others expand the modeling to include not just two dimensional analysis but also three dimensional.[21]

In addition, several papers have been written on the use of laboratory testing of acids and formation samples to improve acid fracturing stimulation results.[24-26] These studies have used core flow acid etching of surfaces, Brinell Hardness before and after acidizing as well as rotating disk analysis of reaction rate coefficients, orders and diffusivity. The results of which have proven successful in the design changes to facilitate significant improvements in stimulation results.

This paper presents as evaluation of an acid fracture design model utilizing the sensitivity of laboratory generated support data. Specifically, how the reaction rate coefficient and diffusivity may be affected by the test rock surface area the resultant effect on acid penetration. Also, rock embedment and closure stress variances are discussed and the effect on conductivity that may be observed.

LABORATORY SUPPORT DATA

Surface Area Effect on “Flux” Reaction kinetic parameters are generated using a rotating disk device and evaluation of the calcium and magnesium ions in solution with time. The equations used to develop these values into the parameter values for an acid fracture design model are given below:

$$2HCl + CaCO_3 \rightarrow H_2O + CO_{2(g)} + CaCl_2 \tag{1}$$

$$\frac{[HCl]}{SurfaceArea \bullet Time} = u,\ \text{gmoles/cm}^2\ \text{sec} = Flux \tag{2}$$

$$N_{Sh} = \frac{\nu}{D} \tag{3}$$

$$K = \frac{0.62048 N_{Sh}^{-1/3}}{1 + 0.298 N_{Sh}^{-1/3} + 0.1451 N_{Sh}^{-1/3}} * (\varpi\nu)^{1/2} \tag{4}$$

$$u = K_{mt}(C_b - C_s) = K(C_s)^n \tag{5}$$

$$u = 0.62048 C_b D_{eff}^{2/3} \nu^{-1/6} \varpi^{1/2} \tag{6}$$

$$u = \phi(n') D_{eff} \left(k'/\rho\right)^{\frac{-1}{3(1+n')}} a^{\frac{1-n'}{3(1+n')}} C_b \varpi^{\frac{1}{1+n'}} \tag{7}$$

Equation 2 is the calculation of the change in composition of the system and utilizes the surface area of the rock in the denominator to determine the **Flux**. Traditionally this value is the area of the exposed disk surface assuming a flat continuous plane. However, if there is any irregularity of the surface, even microscopic deviations, there will be a change in the surface area value and the resulting calculated values. **Table 1,** illustrates the pore distribution of a

1-mD limestone.[10] **Figure 1,** graphically illustrates the variance in surface area of the normal 1.25-inch diameter disk used in reaction studies as a function of the pore distribution from **Table 1** at various depths. Using these values to recalculate **Flux** is demonstrated in **Figure 2.** **Figures 3,** shows first the graphical calculation of the reaction rate coefficient from the intercept of the **Flux** plotted as a function of the surface acid concentration on a log-log plot. While **Figure 4** shows the variance when the surface area effects on **Flux** are applied. The order of the reaction (slope of the line) has not changed while the intercept is reduced. This implies a slower reaction at the surface of the rock than would normally be expected. In fact if the value determined from a disk with surface area including pores 0.1 cm deep is correct the value derived from just the disk area means that the reaction was assumed to be going about 400 times faster than it really was proceeding.

As with the reaction rate coefficient, the diffusivity is calculated using the same evaluation of calcium and magnesium ions and the following equation:

$$F = u \bigg/ \phi(n')\left(k'/\rho\right)^{\frac{-1}{3(1+n')}} a^{\frac{1-n'}{3(1+n')}} C_b \tag{8}$$

This function is plotted versus the angular velocity raised to the one over n-prime plus 1. Where n’ is one of the parameters defining fluid rheology. For a Newtonian fluid n’ is one. Since **Flux** (u) is a primary variable in this calculation changes in surface area through a series of tests to determine the diffusivity could have a significant error range. In **Figure 5,** calculated diffusivity is shown as it can be interpreted based on how ionic concentrations are affected by surface area. This illustrates that using the disk area alone, in the calculation process, gives overall low diffusivity values. As was discussed above, researchers have determined that above 25°C (77°F) and 100°C (212°F) the dissolution of limestone and dolomite respectively are limited by the mass transfer process and diffusivity should be lower than the value of the surface reaction rate coefficient.

Rock Embedment Strength Core samples tested for Brinell Hardness before and after exposure to acid define the nature of the softening of the rock by acid. As discussed earlier, a relationship applied in most models for acid fracture design use the rock embedment strength and closure stress to calculate the loss in conductivity due to rock collapse and therefore loss of channel width generated by the acid reaction on the fracture surface. **Table 2** lists some typical reductions in rock embedment strength for several carbonates. As can be seen, this can vary from around a 5% loss to as much as 80% loss in strength. These losses make it extremely difficult for a fracture created with an etched surface to remain open under closure conditions or through continuous production and increased drawdown.

Fluid Loss Data Fluid loss during an acid fracturing treatment is based on either formation rock properties and fluid viscosity or reservoir fluid compressibility. A wall building or filter cake forming fluid composition is ineffective as acid destroys these types of materials. In addition, acid generates its own fluid loss through wormholes. As discussed above viscosity in an acid system or emulsification of an acid system greatly reduces the dissolution of carbonates and has also been found to reduce wormhole growth and therefore fluid loss during fracture acidizing treatments. **Figure 6** is a representation of laboratory core testing to evaluate fluid loss. The core second from the left is typical of a neat acid creating wormholes through a carbonate rapidly. The other core plugs represent the fluid loss characteristics controlled in some way, whether through viscosity or chemical retardation.

MODEL SENSITIVITIES

Conductivity Effected by Reaction Rate Coefficient and Diffusivity Varying the reaction rate coefficient based on the variance in values of surface area is shown in **Figures 7 through 9.** In **Figure 7** the diffusivity is held to 7.075E-05 and the variance in reaction rate coefficients has only a minor effect on the modeled outcome of conductivity and penetration. This is because the diffusivity is controlling the dissolution in almost all four cases. Since two of the reaction rate coefficients are smaller (one being much smaller) than the diffusivity, the reaction at the surface is the controlling mechanism for the dissolution. **Figure 8,** however, shows that with a diffusivity of

7.075E-04 that there is a much larger variance in conductivity. This is due to the values of reaction rate coefficients all being smaller than the diffusivity and therefore the reaction at the surface is the controlling mechanism for dissolution. Lastly, when all of the reaction rate coefficients are larger than the diffusivity there is no negligible difference in outcome **(Figure 9).**

Conductivity Effected by Closure Stress and Rock Embedment Strength **Figure 10** illustrates the effect on the model prediction of conductivity and penetration. Varying the rock embedment strength (25,000 to 100,000 psi) while maintaining a closure stress of 5,000 psi has little effect on acid penetration. However, conductivity is reduced by an order of magnitude when the rock embedment strength is reduced. Maintaining rock embedment strength of 100,000 psi and varying the closure stress (2,500 to 10,000 psi) results in approximately 26% less acid penetration **(Figure 11).** Conductivity is reduced by almost two orders of magnitude with the same change in closure. It is quite evident that knowledge of the rock strength and closure are major factors in how successful an acid fracture treatment is going to be.

Conductivity Effected by Fluid Loss Variance in fluid loss coefficients for an acid system from 10 times larger to 10 times smaller illustrated how significant an effect on acid penetration this parameter can have **(Figure 12).** The distance has a variance of 300 feet. Conductivity is higher for the case of acid with the least fluid loss control (two orders of magnitude higher) but over a very shorter penetration distance. The better fluid loss system demonstrates the ideal acid fracture design with a nearly uniform conductivity over a long penetration distance. Fluid loss control is one of the most important parameters to have control over in order to obtain successful acid fracture stimulation.

CONCLUSIONS

1. Rock embedment and closure stress are two the most important parameters to have knowledge of in order to design and successfully stimulate a carbonate formation with acid fracturing – to get the most out of the conductivity created.
2. Fluid loss control is extremely important to both conductivity and penetration distance of an acid fracture treatment.
3. In most cases, knowing and controlling the diffusivity of the acid system to be used on a particular formation plays a bigger role in the design than the understanding of the reaction rate at the surface.

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Table 1
Carbonate Pore-Size Distribution per Square Centimeter of 1-mD Limestone Surface[10]

Group	Pore Radius, μm	No. of Pores
1	1029	1
2	578	2
3	450	5
4	332	9
5	267	43
6	215	43
7	186	58
8	149	67
9	104	91
10	72	180
11	50	500
12	38	700
13	28	540
14	20	700
15	15	1600

Table 2
Acid Effect on Rock Embedment Strength

Lithology	Rock Embedment Strength, psi	Percentage Softening
Dolomite A	379327	64
Dolomite B	343559	81
Limestone A	60120	4.5
Limestone B	99533	43
Limestone C1	70425	28
Limestone C2	51072	38
Limey Dolomite	59041	34
Dolomite C1	62027	20
Dolomite C2	129988	63

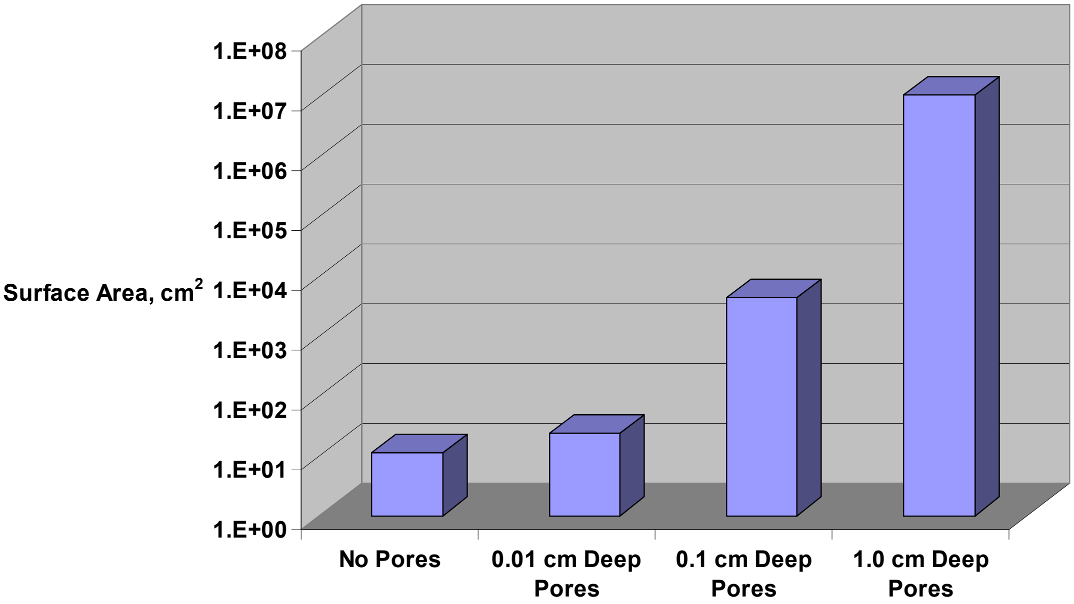

Figure 1 – Effect of Pores of Varying Depth on Potential Surface Area

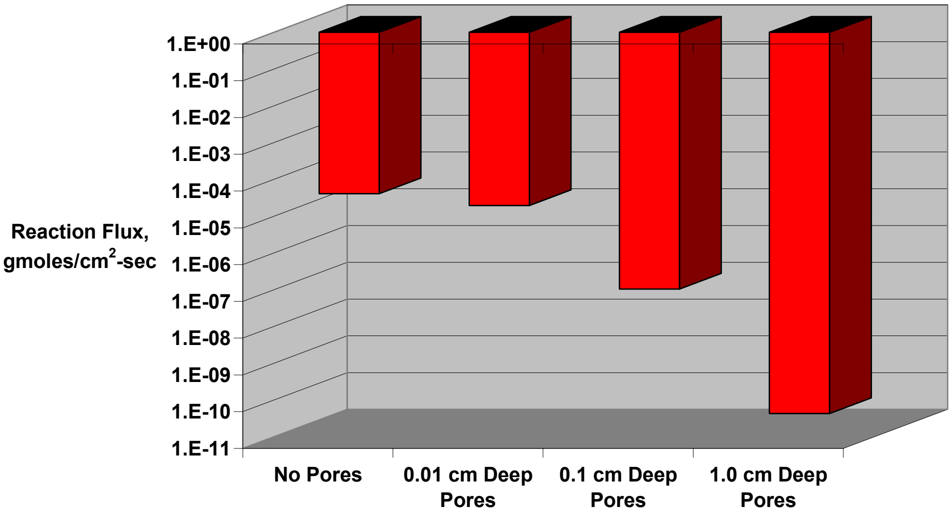

Figure 2 – Effect of the Surface Area Variance from Pores of Various Depths on Reaction Flux of Hydrochloric Acid on Limestone

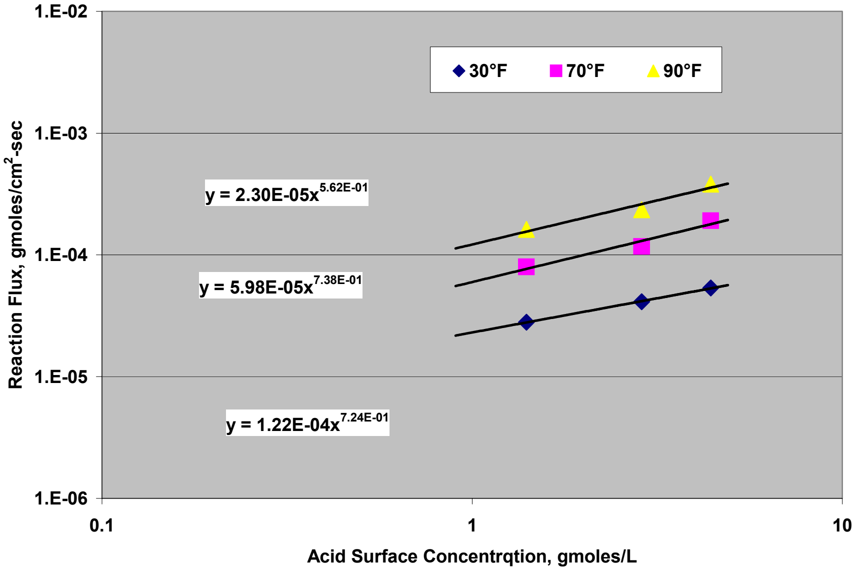

Figure 3 – Normal Graphical Evaluation of “Flux” Data Versus Surface Concentration to Determine Reaction Rate Coefficient (Intercept) and Reaction Order (Slope)

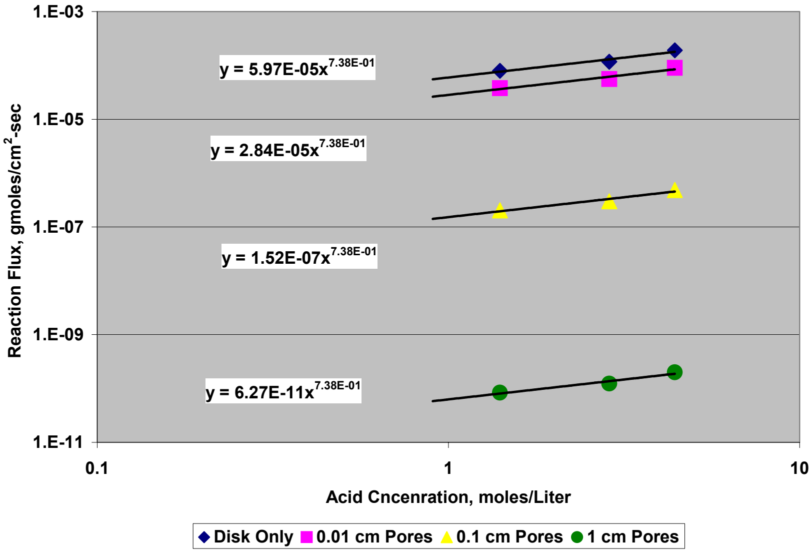

Figure 4 – Graphical Evaluation of “Flux” Versus Surface Concentration at 70°F with the “Flux” Calculated Based on the Variance in Surface Area From Pores

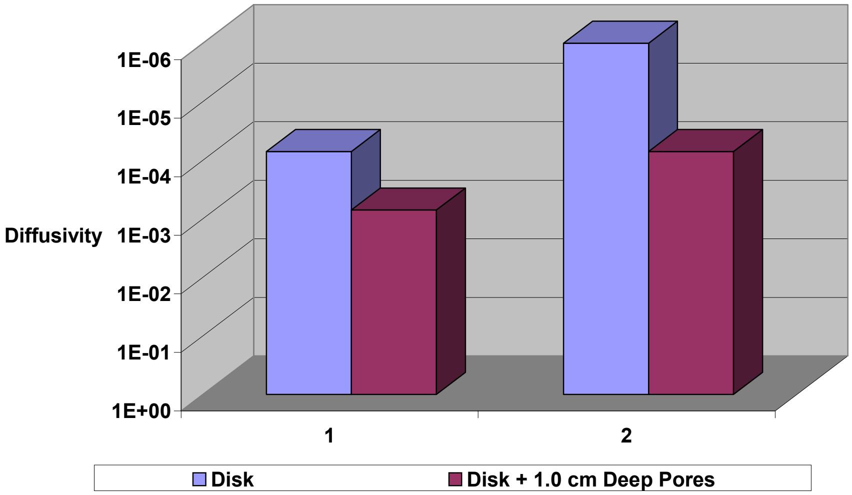

Figure 5 – Potential Error Effects on Diffusivity Calculated From Laboratory Data

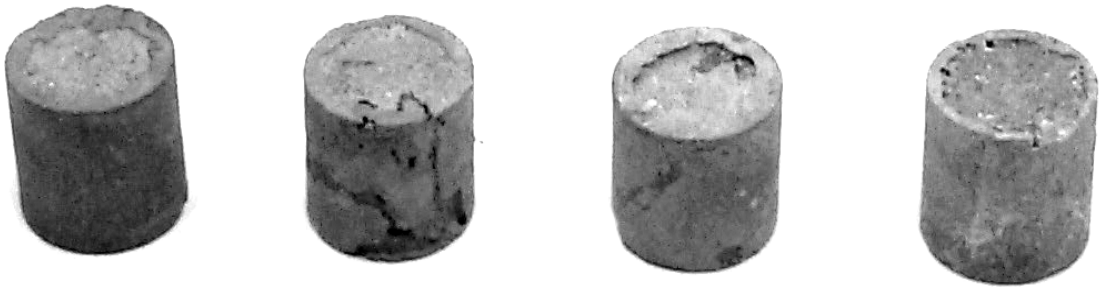

Figure 6 – Pictures of Various Core Plugs Exposed to Acid Fluid Loss Testing

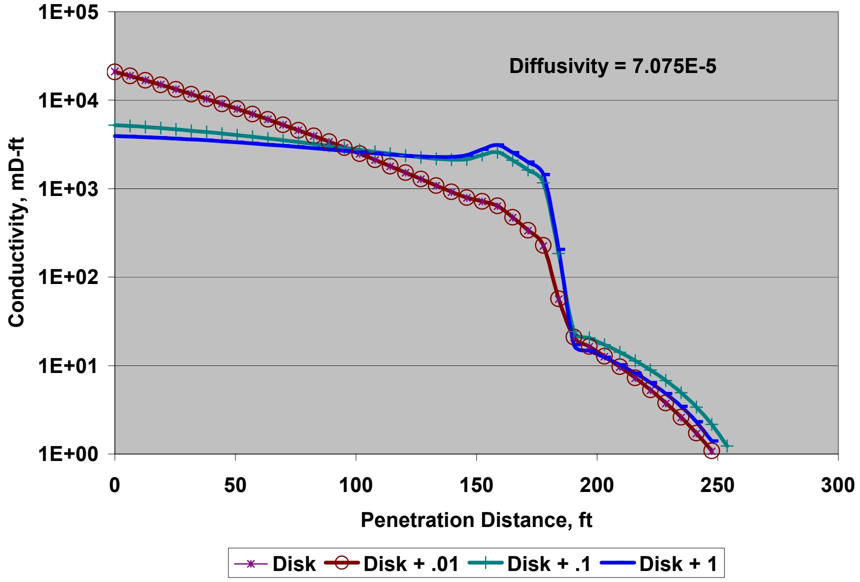

Figure 7 – Effect of Reaction Rate Variance Due to Surface Area Value Used in Calculations of "Flux" on the Predicted Conductivity from an Acid Fracture Design Model (Diffusivity = 7.075E-5)

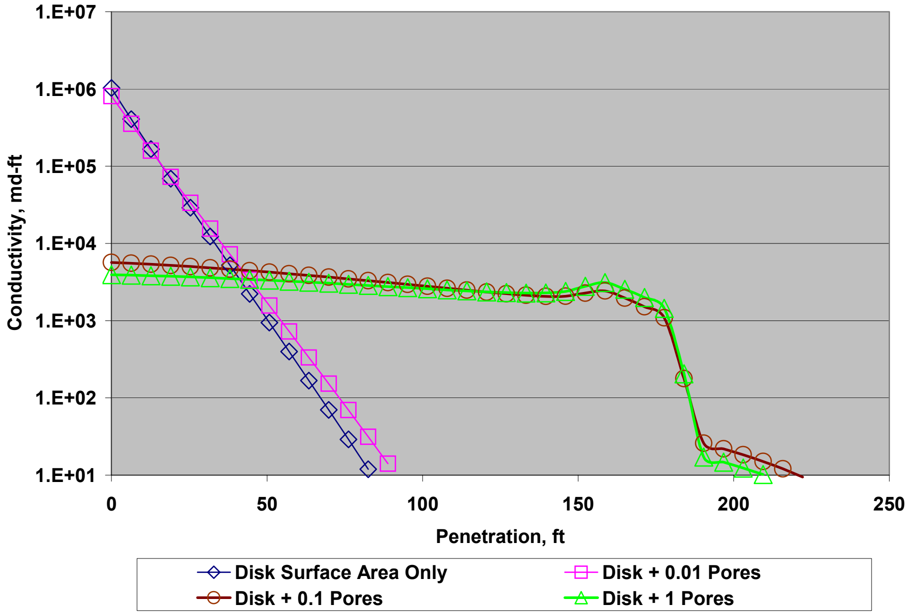

Figure 8 – Effect of Reaction Rate Variance Due to Surface Area Value Used in Calculations of "Flux" on the Predicted Conductivity from an Acid Fracture Design Model (Diffusivity = 7.075E-)

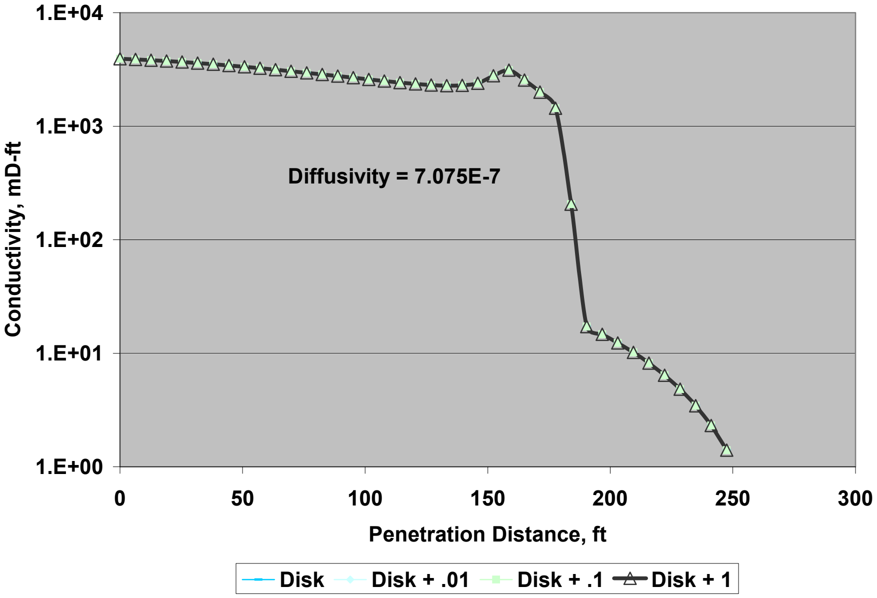

Figure 9 – Effect of Reaction Rate Variance Due to Surface Area Value Used in Calculations of “Flux” on the Predicted Conductivity from an Acid Fracture Design Model (Diffusivity = 7.075E-7)

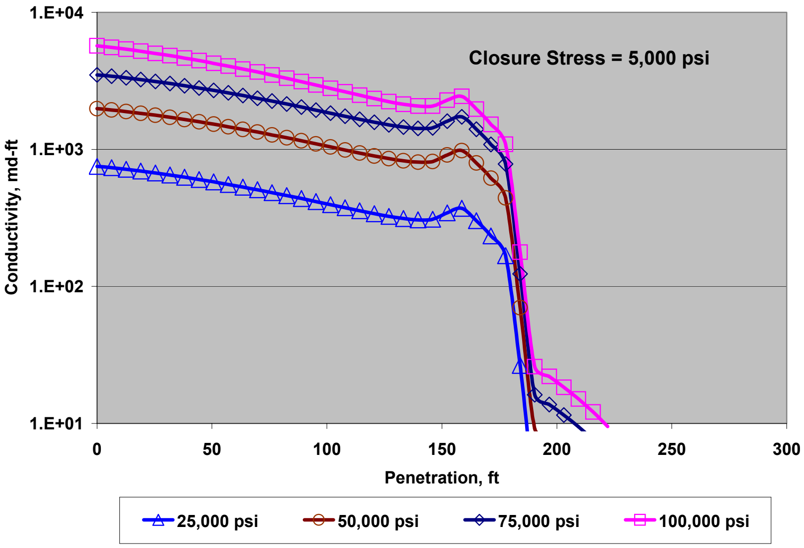

Figure 10 – Effect on Conductivity of Surface Area Calculation Using Disk + 0.1 cm Deep Pores With the Rock Embedment Strength Being Varied

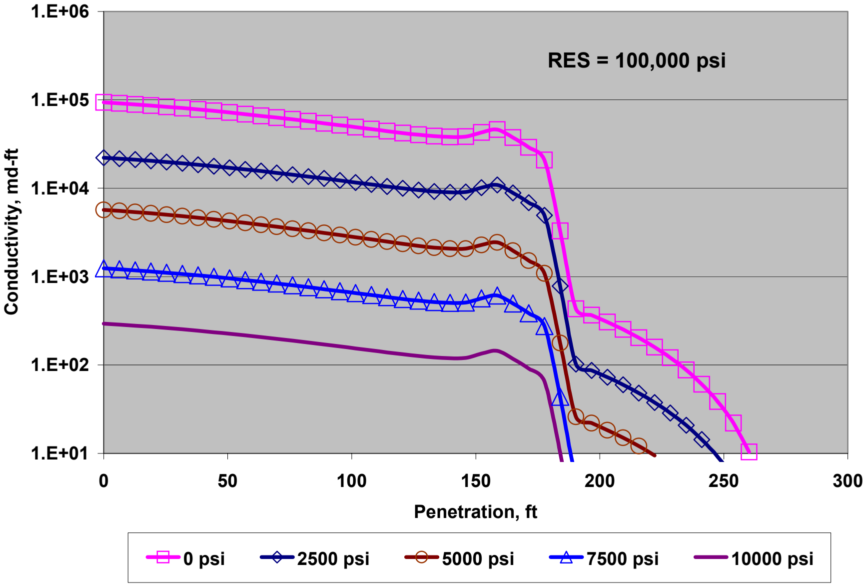

Figure 11 – Effect On Conductivity of Surface Area Calculation Using Disk + 0.1 cm Deep Pores with the Closure Stress Being Varied

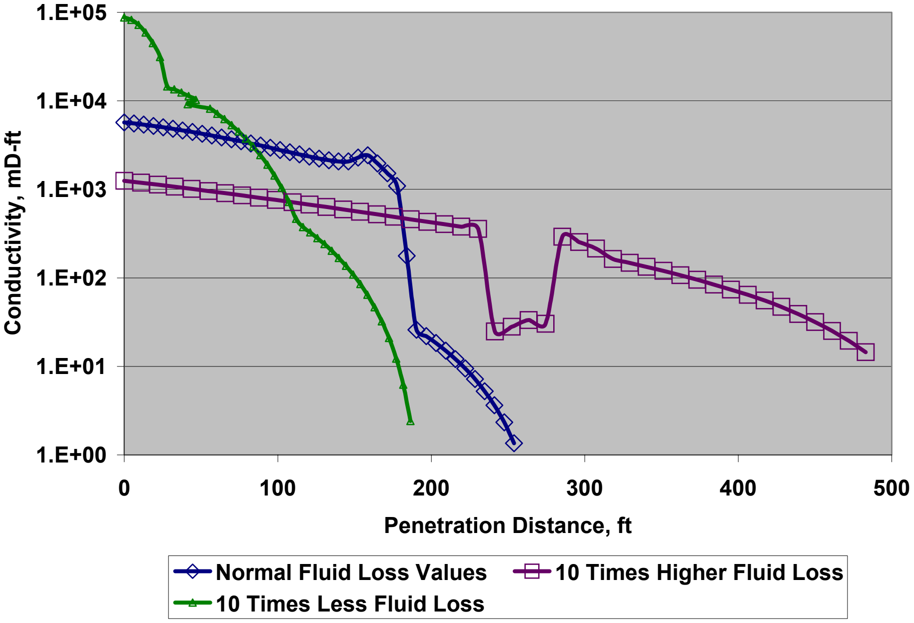

Figure 12 – Effect on Conductivity of Fluid Loss Control Using Disk + 0.1 cm Deep Pores