FORMATION SENSITIVITY TO FRAC FLUID- HOW IT EFFECTS PRODUCTION

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ABSTRACT

Dehydration and of the proppant crushing inside the fracture, are the two damage mechanisms mostly recognized as the main contributors to the overall reduction in fractured well productivity. Fracture face damage caused by the fracturing fluid loss through the four fracture faces also creates additional pressure drop that may further reduce the effective wellbore radius. The magnitude of the effect depends on reservoir characteristics, fracture geometry, extent of fluid leakoff into the reservoir, and the viscosity of the fracturing fluid filtrate. **A** step-by-step approach to predict the fluid loss through the fracture faces during the fracture treatment is explained in this paper. The depth of penetration through the fracture face and the resulting skin values for both the wall building and viscosity controlled leak-off model are determined. This study employs a simple approach that is based on the work of Cinco-Ley & Samaniego that assumes that damage through the fracture face is only caused by fluid saturation changes. The production-forecast simulator used to analyze the effect of various fracture face skin values on oil and gas well productivity agrees with Cinco-Ley and Samaniego study that shows the effect on the effective wellbore radius is negligible when skin value is less or equal to 0.1. In general, the study shows that fracture face damage has a negative effect on productivity only during the wellbore storage and fracture linear flow period. The magnitude of pressure drop increases with increase in reservoir permeability, damage ratio and fracturing fluid leakoff-viscosity.

INTRODUCTION

Hydraulic fracturing technology has been traditionally used by the oil and gas industry to solve a variety of problems related to low oil and gas productivity. These problems ranges from drilling induced near-wellbore damage to extremely low reservoir permeability. Fracture stimulation, if properly designed and executed may eliminate these problems and ultimately increase the effective wellbore radius and effective fracture conductivity to the wellbore.

In most cases, fracture stimulation results in a negative skin value but there are other post-fracture treatment effects that introduce additional pressure drop that may prevent the fractured well from producing up to its true capacity. Some of these effects include gel dehydration, crushing or embedment of proppant inside the fracture, choking the fracture through over flush, and fluid leak-off through the fracture faces.

This paper presents a procedure to compute the fluid leak-off through the four fracture faces, depth of penetration into the formation, and the resulting fracture face skin values for both oil and gas well reservoirs. The effect of fracture face skin on well productivity will also be studied using the production-forecast simulator.

LITERATURE REVIEW

The effects of flow impairments along the face and near wellbore area of the fracture on the transient behavior of finite-conductive vertical fractures were investigated by Cinco-Ley and Samaniego'. Fluid-loss flow impairment along the fracture surface in the reservoir is commonly referred to as fracture face skin effect. Flow impairment caused by reduced conductivity in the fracture near the wellbore is commonly described as a choked fracture. Both of these types of flow impairments in fractured wells result in a lowered productivity than would be obtained if flow impairments were not present.

Fluid-loss damage in the reservoir adjacent to the fracture is illustrated in **Fig. 1. A** choked fracture with a significant fracture conductivity reduction in the vicinity of the wellbore is shown in **Fig. 2.** The effect on the transient behavior of finite-conductivity fractures resulting from fracture damage skin effects is illustrated in **Fig. 3.** The effects on the effective wellbore radius of choked and damaged infinite-conductivity fractures in the pseudoradial regime are compared in **Fig. 4.**

Cinco-Ley and Samaniego-V introduced a relationship for quantifying fracture damage skin effects in terms of the fracture half-length X_f, width of penetration into the reservoir normal to the fracture plane b_s and undamaged-to-damaged permeability ratio K/K_s as:

$$S_{fs} = \frac{\pi b_s}{2X_f}\left(\frac{K}{K_S} - 1\right) \quad (1)$$

FLUID-LOSS IN THE FRACTURE

Harrington et al presented the following simple, elegant and accurate equation to calculate the total fluid loss into the fracture:

$$V_{st} = AC_t\left(8T\right)^{0.5} \quad (2)$$

Where:

A is the fracture face area created during injection, (ft^2)

T is the total time of injection, (min) and

C_t is the total leakoff or fluid loss coefficient, usually the combined effect of C_v, C_c and C_w, (ft/min0.5)

C_v, C_c and C_w denote leakoff coefficient due to viscosity, compressibility, and wall-building effect respectively.

Carter defined total leakoff C_t for a wall building leakoff model as:

$$C_t = \frac{1}{\left(1/C_v + 1/C_c + 1/C_w \right)} \quad (3)$$

For viscosity controlled leakoff, C_t is represented by C_{cv} as follows:

$$C_{cv} = \frac{2C_cC_v}{C_v + \sqrt{C_v^2 + 4C_c^2}} \quad (4)$$

Where:

$$C_v = 0.0148\sqrt{\frac{K\phi\Delta P}{U_f}} \quad (5)$$

$$C_c = 0.00118\Delta P\sqrt{\frac{K\phi C_f}{U_r}} \quad (6)$$

C_w is experimentally determined in the lab for a wall building fluid.

Crawford proposed the following modification that yielded better results for total fluid loss into all four-fracture faces,

$$V_{st} = A\left(3C_tT^{0.5}\right) \quad (7)$$

Fluid loss into each face is thus represented as:

$$V_s = A\left(0.75C_tT^{0.5}\right) \quad (8)$$

Correcting for spurt loss in a wall building controlled leakoff gives:

$$V_s = A\left(0.75C_t T^{0.5} + Spurt\right) \quad (9)$$

The distance into the reservoir to which the fracturing fluid has penetrated through each face of the fracture (b_s) is estimated volumetrically for an oil well as:

$$b_s = \frac{V_s}{\phi h X_f \left(S_{oi} - S_{or}\right)} \quad (10)$$

Where ***h*** is the fracture leakoff height in feet, S_{oi} is the initial oil saturation and S_{or} is the residual oil saturation.

For gas wells,

$$b_s = \frac{V_s}{\phi h X_f \left(S_{gi} - S_{gc}\right)} \quad (11)$$

Where S_{gi} is the initial gas saturation and S_{gc} is the critical gas saturation.

S_{FS} COMPUTATION & PRODUCTION-FORECAST FOR VARIOUS DAMAGE RATIOS

Algorithms that incorporate Eq. (1) through (11) for fluid loss and fracture face skin computations were used along with the example data detailed below for oil and gas wells respectively. Effect using different leakoff model (wall building and viscosity controlled), half-lengths and reservoir permeabilities were studied. For this study, total injection time of two hours into the reservoir was picked as the reference point for the analysis. This represent average time for most of the hydraulic fracturing jobs. This can be changed depending on job time and time to fracture closure. Production-forecast simulator was used to predict production rates at different time interval for various damage ratios. The simulation was done for different half-lengths, high and low fluid leakoff viscosities and different permeability cases.

RESULTS AND DISCUSSION

Various fracture face skin values computed from the analysis are shown in **Table 1-4**. These values are used as inputs in production-forecast simulator and the results for various damage ratios are graphically shown in **Fig. 5 and *6*.**

The results in general show reduction in flow rate at very early time when skin value is greater than 0.1. Rate reduction is generally seen at high reservoir permeability, short half-length and high fracturing fluid leak-off viscosity. Production rate plots for all the cases show the damage ratios converging after the initial early-time pressure drop. This effect is also noticed at high permeability and high leakoff viscosity well.

CONCLUSIONS

1. Fracture face skin is negligible in low permeability oil and gas wells treated with either Viscoelastic Surfactant fluid or Polymer based gel fluid. Hence the effect of fracture face damage on productivity is negligible at low reservoir permeability.
2. Fluid loss in extremely high permeability oil and gas wells can induce high fracture face skin, S_{fs} Effect on productivity can be noticed at early time period when $S_{fs} > 0.1$. This is more pronounced when fluid leakoff viscosity is high i.e 100cp or greater.
3. Fracture face skin has no effect on productivity at late time.
4. Findings/Theory of Cinco-Ley and Samaniego study was validated at $S_{fs} > 0.1$.
5. The results presented in this paper are based on the assumption that damage through the fracture face is only caused by fluid saturation changes only. The additional effect of capillary pressure and surface tension changes need to be looked at separately in an independent study.

NOMENCLATURE

A	= Area of one face of the fracture which is created during injection, ft^2 [m^2]
A_d	= Reservoir drainage area, acres [m^2]
b_s	= Wdth of fluid loss through the fracture face, in
C_c	= Leak-off coefficient far compressibility and viscosity of formation fluid, $ft/min^{0.5}$ [$m/s^{0.5}$]
C_{cv}	= C_c for viscosity controlled leak-off, $ft/min^{0.5}$ [$m/s^{0.5}$]
C_f	= Compressibilty of reservoir fluid, psi^{-1} [kPa]
C_t	= Total leak-off coefficient, usually the combined effect of C_v, C_c and C_w, $ft/min^{0.5}$ [$m/s^{0.5}$]
C_v	= Leak-off coefficient for fracturing fluid viscosity, $ft/min^{0.5}$ [$m/s^{0.5}$]
C_w	= Leak-off coefficient far wall building effect of fluid loss additives, $ft/min^{0.5}$ [$m/s^{0.5}$]
h	= Reservoir net height, ft [m]
h_f	= Fracture height, ft [m]
K	= Reservoir permeability, md
K_f	= Fracture permeabilty, md
K_s	= Damaged zone permeability, md
P_b	= Reservoir bubble point pressure, psi [kPa]
P_f	= Fracturing Pressure, psi [kPa]
P_r	= Reservoir pressure, psi [kPa]
P_{wf}	= Bottomhole flowing pressure, psi [kPa]
S_{fs}	= Fracture face skin
S_{gc}	= Critical gas saturation
S_{gi}	= Initial gas saturation
S_{oi}	= Initial oil saturation
S_{or}	= Residual oil saturation
S_w	= Water saturation
T	= Total injection time, min
U_f	= Viscosity of fracturing fluid filtrate, cp [mPa.s]
U_r	= Viscosity of reservoir fluid, cp [mPa s]
V_s	= Fluid loss through one fracture face, ft^3 [m^3]
V_{sf}	= Total fluid loss through four fracture facer, ft^3 [m^3]
w	= Fracture width, in [m]
X_f	= Fracture half-length, ft [m]
Δp	= Pressure difference from fracture to reservoir, $(P_f - P_r)$, psi [kPa]
ϕ	= Reservoir Porosity

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Input Data (Oil well):

MD	8,000 ft
Top Zone	7,000 ft
Net Height, *h*	65 ft
Fracture Height, h_f	65 ft
Casing	5 ½”, 17#/ft, N80
BHST	200 degF
Porosity, ϕ	0.2
S_{oi}	0.5
S_{or}	0.15
S_w	0.3
C_t	2.89E-06 1/psi
U_r	0.6
K	0.01 – 1000md
K_s	10 – 90% K
U_f	0.5cp and 100cp
C_w	2E-03 ft/min0.5
Spurt	0.5 gal/100ft^2
X_f	50 - 1000ft
$K_f w$	200 - 5000md
P_r	3000 psi
P_f	5000 psi
P_h	1500 psi
"API	35
A_d	120 acres
P_{wf}	1500 psi
Total Injection Time, *T*	120 mins

Input Data (Gas well):

MD	8,000 ft
Top Zone	7,000 ft
Net Height, *h*	65 ft
Fracture Height, h_f	65 ft
Casing	5 ½”, 17#/ft, N80
BHST	200 degF
Porosity, ϕ	0.2
S_g	0.5
S_{gc}	0.05
S_w	0.3
C_t	2.89E-06 1/psi
U_r	0.019
K	0.01 – 1000md
K_s	10 – 90% K
U_f	0.5cp and 100cp
C_w	2E-03 ft/min0.5

Spurt	0.5 gal/100ft^2
X_f	50 - 1000ft
$K_f w$	200 - 5000md
P_i	3000 psi
P_f	5000 psi
P_b	4000 psi
°API	35
A_d	120 acres
P_{wf}	1500 psi
Total Injection Time, T	120 mins

Table 1
Fracture Face Skin Analysis for Oil Well With Leakoff Viscosity =0.5cp

Damage	10%	30%	50%	70%	90%
K	0.01	0.01	0.01	0.01	0.01
K	0.009	0.007	0.005	0.003	0.001
C^s	1.98E-04	1.98E-04	1.98E-04	1.98E-04	1.98E-04
X^t	1000	1000	1000	1000	1000
b^f	0.393	0.393	0.393	0.393	0.393
$K^f w$	200	200	200	200	200
C'alculated					
S	**0.00001**	**0.00002**	**0.00005**	**0.00012**	**0.00046**
F^{fs}_{cd}	**20.00**	**20.00**	**20.00**	**20.00**	**20.00**

Damaae	10%	30%	50%	70%	90%
K	10	10	10	10	10
K	9	7	5	3	1
C	1.55E-03	1.55E-03	1.55E-03	1.55E-03	1.55E-03
X^t	200	200	200	200	200
b^f	2.302	2.302	2.302	2.302	2.302
$K^f w$	1000	1000	1000	1000	1000
C'alculated					
S	**0.00017**	**0.00065**	**0.00151**	**0.00351**	**0.01356**
F^{fs}_{cd}	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**

Damage	10%	30%	50%	70%	90%
K	100	100	100	100	100
K	90	70	50	30	10
C	1.83E-03	1.83E-03	1.83E-03	1.83E-03	1.83E-03
X^t	50	50	50	50	50
b^f	2.696	2.696	2.696	2.696	2.696
$K^f w$	2000	2000	2000	2000	2000
C'alculated					
S	**0.00078**	**0.00303**	**0.00706**	**0.01647**	**0.06353**
F^{fs}_{cd}	**0.40**	0.40	**0.40**	**0.40**	**0.40**

Damage	10%	30%	50%	70%	90%
K	1000	1000	1000	1000	1000
K	900	700	500	300	100
C	1.94E-03	1.94E-03	1.94E-03	1.94E-03	1.94E-03
X^t	20	20	20	20	20
b'	2.853	2.853	2.853	2.853	2.853
$K^f w$	5000	5000	5000	5000	5000
C'alculated					
S	**0.00207**	**0.008**	**0.01867**	**0.04357**	**0.16804**
F^{fs}_{cd}	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**

Table 2
Fracture Face Skin Analysis for Oil Well with Leakoff Viscosity = 100cp

Damage	10%	30%	50%	70%	90%
K	0.01	0.01	0.01	0.01	0.01
K_s	0.009	0.007	0.005	0.003	0.001
C_t	1.62E-04	1.62E-04	1.62E-04	1.62E-04	1.62E-04
X_f	1000	1000	1000	1000	1000
b_s	0.343	0.343	0.343	0.343	0.343
$K_f w$	200	200	200	200	200
Calculated					
S_{fs}	**0.000005**	**0.000019**	**0.000045**	**0.000105**	**0.000404**
F_{cd}	**20.00**	**20.00**	**20.00**	**20.00**	**20.00**

Damaae	10%	30%	50%	70%	90%
K	10	10	10	10	10
K_s	9	7	5	3	1
C_t	5.13E-03	5.13E-03	5.13E-03	5.13E-03	5.13E-03
X_f	200	200	200	200	200
b_s	7.336	7.336	7.336	7.336	7.336
$K_f w$	1000	1000	1000	1000	1000
Calculated					
S_{fs}	**0.000534**	**0.002058**	**0.004802**	**0.011204**	**0.043214**
F_{cd}	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**

Damage	10%	30%	50%	70%	90%
K	100	100	100	100	100
K_s	90	70	50	30	10
C_t	1.62E-02	1.62E-02	1.62E-02	1.62E-02	1.62E-02
X_f	50	50	50	50	50
b_s	22.952	22.952	22.952	22.952	22.952
$K_f w$	2000	2000	2000	2000	2000
Calculated					
S_{fs}	**0.006676**	**0.025751**	**0.060086**	**0.140201**	**0.540776**
F_{cd}	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**

Damase	10%	30%	50%	70%	90%
K	1000	1000	1000	1000	1000
K_s	900	700	500	300	100
C_t	5.13E-02	5.13E-02	5.13E-02	5.13E-02	5.13E-02
X_f	20	20	20	20	20
b_s	72.333	72.333	72.333	72.333	72.333
$K_f w$	5000	5000	5000	5000	5000
Calculated					
S_{fs}	**0.052600**	**0.202886**	**0.473402**	**1.104604**	**4.260614**
F_{cd}	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**

TABLE 3
Fracture Face Skin Analysis For Gas Well With Leakoff Viscosity = 0.5cp

Darnaue	10%	30%	50%	70%	90%
K	0.01	0.01	0.01	0.01	0.01
K_s	0.009	0.007	0.005	0.003	0.001
C_t	6.64E-04	6.64E-04	6.64E-04	6.64E-04	6.64E-04
X_f	1000	1000	1000	1000	1000
b_s	0.816	0.816	0.816	0.816	0.816
$K_f w$	200	200	200	200	200
Calculated					
S_{fs}	**0.000012**	**0.000046**	**0.000107**	**0.000249**	**0.000961**
F_{cd}	**20.00**	**20.00**	**20.00**	**20.00**	**20.00**
Darnaue	10%	30%	50%	70%	90%
K	10	10	10	10	10
K_s	9	7	5	3	1
C_t	1.88E-03	1.88E-03	1.88E-03	1.88E-03	1.88E-03
X_f	200	200	200	200	200
b_s	2.149	2.149	2.149	2.149	2.149
$K_f w$	1000	1000	1000	1000	1000
Calculated					
S_{fs}	**0.000156**	**0.000603**	**0.001406**	**0.003282**	**0.012658**
F_{cd}	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
Damage	10%	30%	50%	70%	90%
K	100	100	100	100	100
K_s	90	70	50	30	10
C_t	1.96E-03	1.96E-03	1.96E-03	1.96E-03	1.96E-03
X_f	50	50	50	50	50
b_s	2.237	2.237	2.237	2.237	2.237
$K_f w$	2000	2000	2000	2000	2000
Calculated					
S_{fs}	**0.000651**	**0.002510**	**0.005856**	**0.013664**	**0.052705**
F_{cd}	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
Darnaue	10%	30%	50%	70%	90%
K	1000	1000	1000	1000	1000
K_s	900	700	500	300	100
C_t	1.99E-03	1.99E-03	1.99E-03	1.99E-03	1.99E-03
X_f	20	20	20	20	20
b_s	2.266	2.266	2.266	2.266	2.266
$K_f w$	5000	5000	5000	5000	5000
Calculated					
S_{fs}	**0.001648**	**0.006357**	**0.014833**	**0.034609**	**0.133493**
F_{cd}	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**

Table **4**
Fracture Face Skin Analysis For Gas Well With Leakoff Viscosity = 100cp

Damage	10%	30%	50%	70%	90%
K	0.01	0.01	0.01	0.01	0.01
K	0.009	0.007	0.005	0.003	0.001
C^s	2.64E-04	2.64E-04	2.64E-04	2.64E-04	2.64E-04
X^f	1000	1000	1000	1000	1000
b^f	0.379	0.379	0.379	0.379	0.379
$K^f w$	200	200	200	200	200
C'alculated					
S	**0.000006**	**0.000021**	**0.000050**	**0.000116**	**0.000446**
F^{fs}_{cd}	**20.00**	**20.00**	**20.00**	**20.00**	**20.00**
Damage	10%	30%	50%	70%	90%
K	10	10	10	10	10
K	9	7	5	3	1
C^s	8.36E-03	8.36E-03	8.36E-03	8.36E-03	8.36E-03
X^f	200	200	200	200	200
b^f	9.244	9.244	9.244	9.244	9.244
$K^f w$	1000	1000	1000	1000	1000
C'alculated					
S	**0.000672**	**0.002593**	**0.006050**	**0.014116**	**0.054449**
F^{fs}_{cd}	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
Damage	10%	30%	50%	70%	90%
K	100	100	100	100	100
K	90	70	50	30	10
C^s	2.64E-02	2.64E-02	2.64E-02	2.64E-02	2.64E-02
X^f	50	50	50	50	50
b^f	29.039	29.039	29.039	29.039	29.039
$K^f w$	2000	2000	2000	2000	2000
C'alculated					
S	**0.008447**	**0.032580**	**0.076021**	**0.177382**	**0.684187**
F^{fs}_{cd}	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
Damage	10%	30%	50%	70%	90%
K	1000	1000	1000	1000	1000
K	900	700	500	300	100
C	8.36E-02	8.36E-02	8.36E-02	8.36E-02	8.36E-02
X^f	20	20	20	20	20
b^f	91.636	91.636	91.636	91.636	91.636
$K^f w$	5000	5000	5000	5000	5000
C'alculated					
S	**0.066637**	**0.257030**	**0.599736**	**1.399384**	**5.397623**
F^{fs}_{cd}	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**

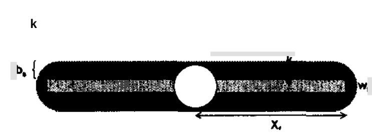

Figure 1 – Fracture Face Skin Effect Damage Flow Impairment

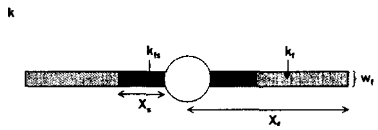

Figure 2 – Choked-fracture Flow Impairment

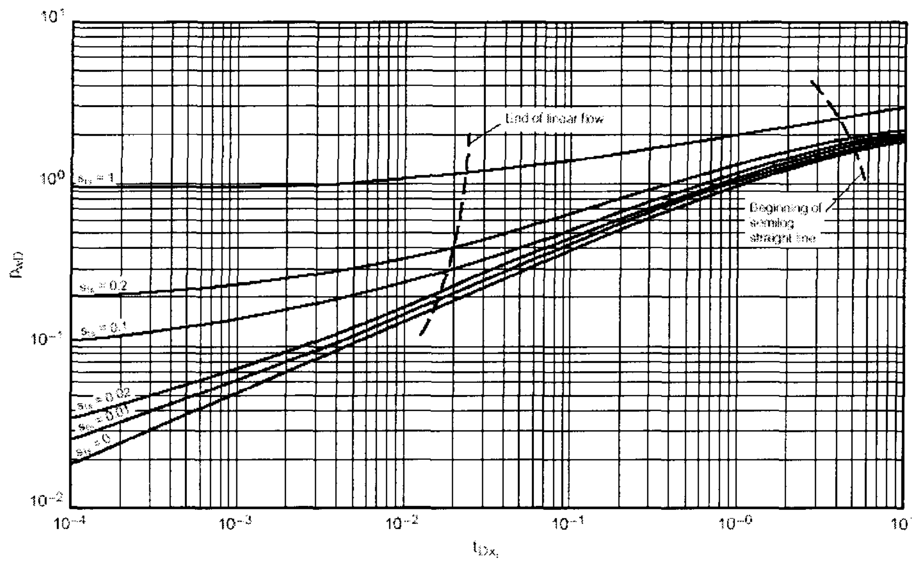

Figure 3 – Damaged Fracture Pressure Response

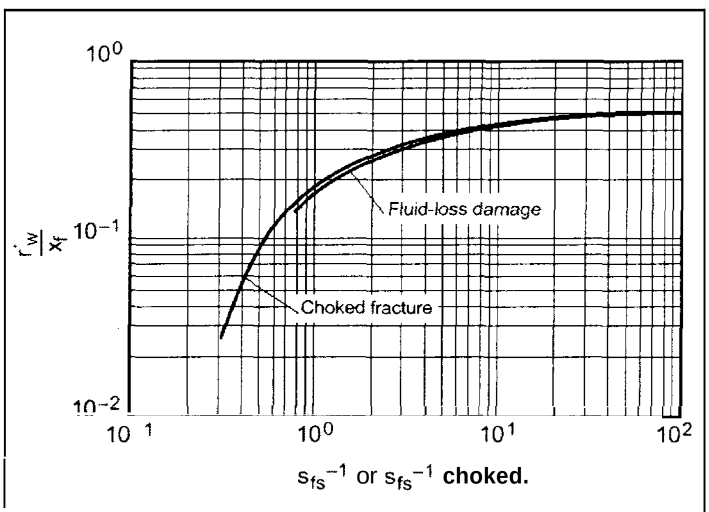

Figure 4 – Effect of Damaged Fractures on Effective Wellbore Radius

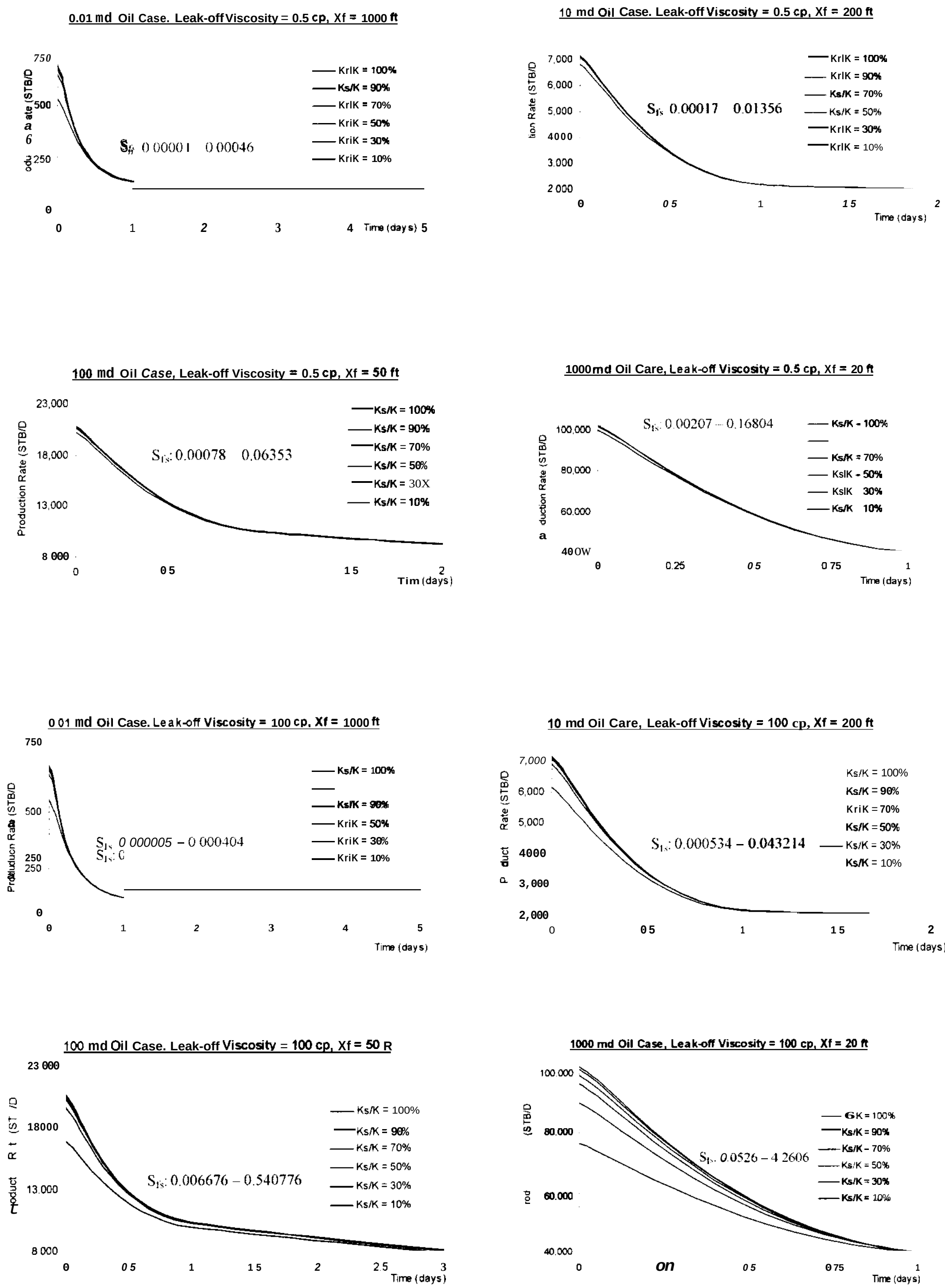

Figure 5 – Early Time Production Forecast for Various Damage Ratios in Oil Well

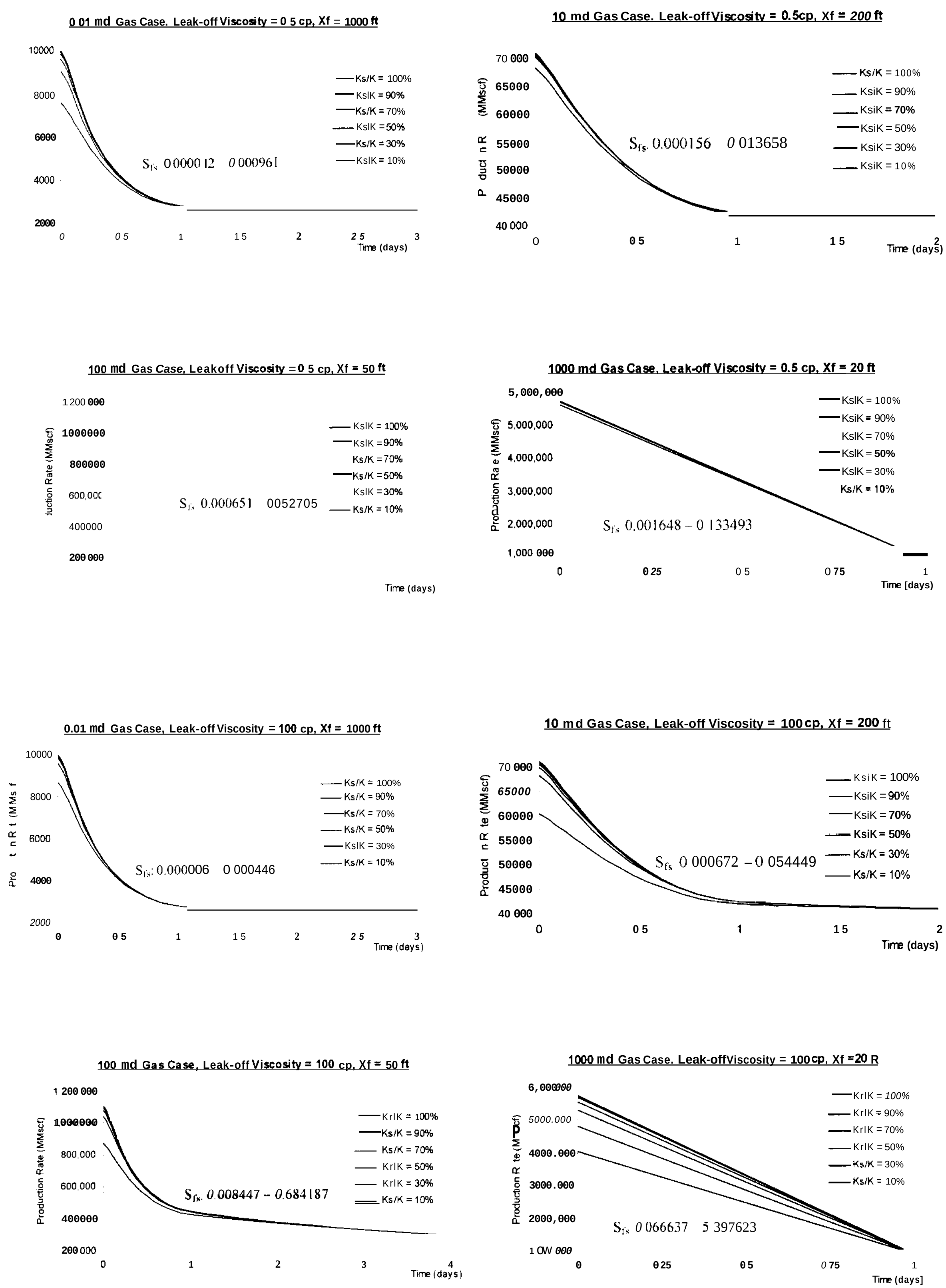

Figure 6 – Early Time Production Forecast for Various Damage Ratios in Gas Well