THE USE OF WELL FLOW ANALYSIS IN WELL COMPLETION DECISIONS

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ABSTRACT

Well flow analysis is the examination of well performance based on fundamental mathematical models of flow in well tubulars and flow through porous media. It is used to assign the pressure drop to each part of the flow path existing between the well drainage boundary and the wellhead pressure. Many types of computer software are available to perform the calculations and plot the results in an easy to read chart of well head pressure versus flow rate. Multiple curves can be generated so that actual performance can be compared to predicted performance for different wellbore conditions. Such curves will be used in this presentation to evaluate performance of different wells. One case study will demonstrate the use of well flow analysis to define the wellbore condition after perforating a gas well in South Texas. Well bore condition is defined by the perforation geometry and near perforation permeability. A pressure build-up test will be analyzed to provide a skin factor. This skin factor will be further evaluated using a simple, steady state, radial flow model for perforations to determine the near wellbore permeability.

INTRODUCTION

Well flow analysis has been around for many years under other names like inflow performance, well deliverability, etc. The usefulness of it to evaluate well completions was developed by Joe Mach, Eduardo Proano, and Kermit Brown in 1981 (1). They presented the first approach to tie together reservoir flow, completion pressure drop and flow through tubing into an easy to understand graphical format. This work was for gravel packed wells and calculated the pressure drop for flow though a gravel packed perforation as the completion pressure drop. These equations could not be used for natural perforated completions in competent formations. McLeod presented a paper in 1982 that provided a model of perforations that could be used for this purpose (2). This was a radial model for turbulent flow and is illustrated in Figure 1. It can be thought of as a tiny horizontal wellbore with flow from a formation being equally divided among all the perforations in a zone connected to one vertical wellbore.

The distinctive feature of this perforation model is the compacted zone around the open perforation. This phenomena of shaped charge perforating was first described by Bell, Brieger and Harrigan in 1972 (3). Later Klotz, Krueger, and Pye related API RP 43 Section II flow test data (using a Berea sandstone target) to a wellbore computer model in which they described this compacted, or damaged, zone around the perforation (4). In shaped charge perforating the power of the high velocity metal jet stresses the rock to about one million psi and shatters a hole in the rock which is filled with crushed rock and charge debris. This material is swept out during flow leaving an open perforation. The compacted zone remains which has a permeability less than the original sandstone permeability before perforating.

The most dominant effect on well productivity in a new well is the method of perforating: size gun (perforation length), shot density, type fluid and pressure overbalance or underbalance. Klotz, et. al., provided estimates of the permeability of the compacted zone based upon type of fluid (cleanliness) and well pressure. Table 1 shows the effect of perforating fluid and pressure conditions on the permeability of the rock around the perforated hole. These guidelines were later confirmed by McLeod who evaluated flow tests of several perforated wells. (See Table 2).

That process of well evaluation will be illustrated in this paper through interpretation of well performance using the systems analysis model (SAM) provided by Soft Search, Inc. This easy to use model for a personal computer uses data screens with blanks to fill in for specific well data. It executes the calculations and plots the results on the computer monitor screen. It can also print out the results in tabular data hard copy or can provide graphical hard copy with a plotter. Such a plot is shown in Figure 2 for a Lobo gas well in South Texas, the example well to be described next. Figure 2 shows the inflow performance curve of flow through the reservoir and through the completion along with the tubing intake pressures (flowing bottom hole pressure) for different wellhead pressures. Where these two curves intersect is the solution point for that particular wellhead pressure. There will be different solution points, or flow rates, for each wellhead pressure; i.e., the lower the wellhead pressure the higher the flow rate out of the well. These results can also be plotted on a sensitivity curve of flow rate versus wellhead pressure. (See Figure 3). This particular plot can be used to evaluate a well's performance onsite by the well operator. The plot is based upon probable well condition (type of perforating and expected wellbore damage using the guidelines suggested by Klotz et. al. in Table 1).

The pressure drop through the completion (perforated wellbore) can also be modelled using the differential pressure plot from SAM as in Figure 4. This shows the pressure drop as a result of turbulent flow through the rock into these small perforations. In this well, pressure drop through the reservoir was 786 psi, whereas the pressure drop due to flow into the perforations is an additional 1243 psi. If the perforations are later damaged by killing the well, the permeability around the perforations will be lowered and the pressure drop will be higher, or the rate will be decreased. Such a case will be discussed later in this paper.

In the case of the Lobo well in Figure 2, the measured bottom hole pressure was matched by assuming a perforation length of 4.5 inches. One could also analyze the well based on measured wellhead pressures as long as the reservoir permeability is known or can be estimated from other data. The wellhead pressure was used to calculate a flowing bottom hole pressure which was 200 psi less than measured. Even with this much difference, the performance was matched by assuming a perforation length of 4.2 inches, a difference of only .3 inches in length. This shows how sensitive the pressure drop is to perforation length in a gas well. Either of these lengths is consistent with known perforating data and supports the finding of undamaged rock around the perforated wellbore.
An example of comparing different perforating techniques follows.

COMPLETION DECISIONS BASED ON PERFORATION DAMAGE

The greatest source of damage to an oil well or gas well occurs around the wellbore during perforating. The perforating process creates about a 1/2- inch thick damaged zone around each perforation in the formation. This damaged, or compacted, zone around the perforation can greatly reduce the productivity of an oil or gas well. The degree of damage, or the reduction in permeability in this compacted zone, depends on the amount of suspended solids in the perforating fluid and the degree of underbalance or overbalance of pressure within the wellbore. Perforating overbalanced with a dirty fluid allows solids to penetrate the compacted zone around the perforation and further reduces the permeability of that compacted zone.

Table 3 summarizes reservoir data from the above Lobo gas well in Webb County, Texas. This well was perforated with a 1 9/16-in. hollow carrier, thru-tubing gun with a pressure underbalance of 2000 psi at 8240-50 ft. The completion fluid opposite the zone was 11.5 ppg calcium chloride brine. Fresh water was placed in the tubing to provide a wellbore hydrostatic pressure 2000 psi less than reservoir pressure. Well tests made after completion and clean-up showed ideally clean perforations (no damaged compacted zone) and the well had an AOF of about 3000 MSCFD.

Table 4 compares different perforating alternatives. The actual completion was better than what could have been attained with casing guns under overbalanced conditions where fluid is lost to the formation through the perforations. The larger tubing conveyed gun could also have provided ideal perforations (no damage) since it allows perforating with a large underbalance.

If one calculates bottom hole pressure during flow from the reservoir without any formation damage or perforation restriction, he would have what we call flowing sand face pressure. If one then calculates the bottom hole pressure entering the tubing with a given wellhead pressure, he would have the flowing bottom hole pressure. The difference between this sand face pressure and the bottom hole pressure is called available pressure drop. This is the pressure difference available to push flow through the completion. There will be one unique rate where the completion pressure drop will equal the available pressure drop. Plots of available pressure drop and completion pressure drop for different perforated completions are shown in Figures 5 through 8.

Figures 5 thru 8 show various comparisons of flow performance using well flow analysis charts. The pressure drop available curve decreases with flow rate and is controlled by reservoir flow properties and flow through 2-3/8 in. O.D. tubing with a flowing wellhead pressure of 1500 psi. The completion pressure drop curve increases with flow rate and is controlled by the quality, size and number of perforations. The intersection of the two curves gives the well production rate for the given conditions.

Figure 5 shows that through-tubing perforating with the 2000 psi underbalance was much more productive than could be obtained with perforating overbalanced with a larger cased hole gun even with ideal, "super clean" perforating fluids. If deep penetrations of 15 inches could be obtained with a casing gun at this depth in this formation, an equal well productivity could be obtained with a casing gun as shown in Figure 6. However, "super clean" perforating conditions would be necessary. Deep penetrations of 15 inches in poorly filtered fluids would still not provide a productivity equal to that provided by underbalanced, through tubing perforating.

Figure 7 compares alternatives of underbalanced perforating. The use of a larger tubing-conveyed gun with 120° phasing and 2000 psi underbalance could provide almost twice the productivity of the smaller gun.

Figure 8 compares the four-inch guns with different shot densities. Overbalanced perforating requires 16 SPF with clean brine and 32 SPF with dirty brine to equal 4 SPF perforated underbalanced.

Perforating underbalanced with a large gun (tubing conveyed perforating gun) provides cleaner perforations, but it is often more expensive. An operator can estimate the economic benefits and select the optimum perforating system and procedures with the aid of predictions from the SAM Well Flow Analysis Program and completion cost estimates. The use of more expensive perforating equipment and quality control with perforating fluids can result in ideal holes. If less expensive guns and low quality fluids are used, the damage can be offset to some degree by the use of additional perforations.

The following procedures are necessary to obtain cleaner perforating whether overbalanced or underbalanced. The main source of contaminating solids is the mud and cement residue left on the wall of the casing after the cementing operation. Even though five casing volumes of water are circulated through the tubing-casing annulus, significant quantities of cement and mud still adhere to the pipe wall and remain in the cracks between threads at the casing collar connection. In a 10,000 foot string of 7 5/8 inch casing, this mud volume is equivalent to 1 barrel of mud solids. Several bit and scraper runs are required to dislodge pipe wall residue while circulating with a brine or fresh water. However, this is not enough. A cleaning and scouring fluid is necessary before a clean completion fluid can be placed in the wellbore. This cleaning slurry usually consists of three stages: (1) a mud solvent (fresh water, caustic and detergent for water base muds or a diesel/surfactant mixture for oil base muds), (2) gelled water with scouring material (100 mesh sand or blast sand) and (3) gelled water to provide an interface between the scouring stage and the following completion fluid. Some operators have even circulated weak acid (3% to 5% HCl) as a final clean-up.

The completion fluid to be used (filtered to less than 100 parts per million) is pumped down the annulus after the other stages and reverse circulated back-up the work string. When the final gel pill exits the tubing into the tanks, the completion brine following is switched to the completion brine tank and circulated and filtered until the overall solids content in the return fluid falls below 500 parts per million. These steps insure a clean wellbore with a clean fluid for whatever type of perforating method is chosen.

When competent sands are perforated with a large enough underbalance, the compacted zone created around the hole is collapsed and blown out of the hole into the wellbore (5). This is the best type of cleaning that can occur during perforating. Also following this procedure, the well can flow to the surface and completely recover all completion fluids leaving formation fluid in the wellbore. The underbalance required to get clean perforations is discussed by Crawford (6).

OTHER WELL EXAMPLES

The evaluation shown in Figure 2 was based on bottom hole pressure bomb measurements from a pressure buildup (PBU) test. This test is plotted in Figure 9 and was used to calculate a skin factor of 11. This skin results in completion efficiency of less than 50 %. Evaluating the skin from the PBU test alone would lead one to believe the well was damaged. In fact, the well is not damaged; the permeability around each perforation is the same as out in the reservoir. These calculations are shown in Appendix A along with a nomenclature in Appendix B. The skin is caused by turbulent flow into the tiny perforations created by the 1 9/16-in, through tubing gun.

A similar well producing both gas and condensate and drawn down by a compressor produced a skin factor of 28. This was interpreted as severe damage. The well was acidized and production was cut in half. Later well flow analysis was used and showed that permeability around the perforations was undamaged prior to acidizing. The high skin was caused by a combination of turbulent gas flow and two-phase liquid/gas flow and was amplified by flow into tiny perforations.

Similar analyses were done for other perforated wells by McLeod. The results are listed in Table 2. Crawford and others have provided similar data from similar analyses (6). One well described by Crawford is of particular interest because it shows the changing permeability around the perforations in a well damaged by killing it with brine and subsequently cleaning up. The flow test data are shown in Table 5. Gas flow partly removed plugging materials from the perforations during clean-up. The well did not completely clean-up. The data demonstrates that underbalanced perforating provided clean perforations and that the perforation damage was caused by killing the well with brine to repair a tubing leak.

Another interesting example in selecting the best completion technique for a well was also described by Crawford. The typical field procedure of perforating overbalanced with a wireline gun was compared to underbalanced perforating with a tubing conveyed gun. Table 6 shows the predicted rates for tubing conveyed gun perforating and the actual rates and pressures measured after completion. Also shown are the rates and pressures for an offset well using the old way of perforating. The economic benefit of perforating with the new underbalance technique was additional income of 20 million dollars from this well for one year.

CONCLUSIONS

1. Modern well flow analysis with user friendly computer software

provides an excellent tool for aiding completion decisions.

2. Gas well performance in sandstone reservoirs can be predicted using this software and guidelines on perforation conditions provided by Klotz, Krueger and Pye.

3. Skin factors obtained by pressure build-up analyses can be misleading unless well flow analyses are also done to identify the cause of the skin factor.

4. Changing wellbore conditions in a well can be monitored with stabilized well flow tests and interpreted with the aid of well flow analysis software.

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APPENDIX A

COMPLETION PRESSURE DROP ANALYSIS CALCULATIONS

Lobo Gas Well

Production Data (Well Test):

$q = 2111$ MSCFD

$\overline{P}_r = 5508$ psia

$P_{wf} = 3481$ psia ($P_{wh} = 2686$ psia)

$k = 5$ md (from pressure build-up test)

$h = 10$ ft

$z = 1.05$

$T = 699^{o}R$

$\mu = .0255$ cp , $G = .71$

$r_e = 933$ ft (80 acre spacing)

$r_w = .35$ ft

Perforation Data:

4 shots per foot

1 9/16-in. gun

zero degree phasing

perforated 2000 psi underbalanced

Approximate perforation dimensions:

$r_p = .15$ ins.

$L_p = 5$ ins.

Find:

Factors S and D at this flow rate and predict completion pressure drop at 2900 MSCFD.

$$\overline{P}_r^{\,2} - P_{wf}^2 = \frac{1424\,\mu zTq}{kh}\left[\ln r_e/r_w - .75 + S + Dq\right] \qquad (1)$$

$$\ln r_e/r_w - .75 = \ln(933/.35) - .75 = 7.14 \qquad (2)$$

$$S = S_d + S_p + S_{dp} \qquad (3)$$

Assume $S_d = 0$; i.e., no drilling damage ($k_d = k$) (4)

$S_p = 1.8$ (geometry skin factor for 0^o phasing) (5)

$$S_{dp} = \frac{h}{NL_p}\ln(r_{dp}/r_p)(k/k_{dp} - k/k_d) \qquad (6)$$

$$= \frac{1}{(4)(5/12)}\ln(.65/.15)(5/k_{dp} - 1)$$

$$= \frac{4.4}{k_{dp}} - .88 \qquad (7)$$

$$S = 0 + 1.8 + 4.4/k_{dp} - .88$$

$$= .92 + 4.4/k_{dp} \qquad (8)$$

$$D = 2.22\,(10)^{-15}\left(\frac{\beta_{dp}}{N^2 L_p^{\,2}\, r_p}\right)\left(\frac{kh\,\gamma}{\mu}\right) \qquad (9)$$

$$= 2.22\,(10)^{-15}\left(\frac{\beta_{dp}}{(40)^2(5/12)^2(.15/12)}\right)\left(\frac{(5)(10)(.71)}{(.0255)}\right)$$

$$= 8.9\,(10)^{-13}\,\beta_{dp} \qquad (10)$$

$$\beta_{dp} = 2.6\,(10)^{10}\,k_{dp}^{-1.2} \qquad (11)$$

$$D = \frac{.02314}{k_{dp}^{1.2}} \qquad (12)$$

$$Dq = \frac{48.84}{k_{dp}^{1.2}} \qquad (13)$$

From (1) above:

$$S + Dq = \frac{(\bar{p}_r^{\,2} - p_{wf}^{\,2})\ kh}{1424\mu zTq} - (\ln r_e/r_w - .75) \qquad (14)$$

$$= \frac{(5508^2 - 3481^2)\ (5)(10)}{(1424)(.0255)(1.05)(699)(2111)(7.14)} - 7.14 = 16.19 - 7.14$$

$$= 9.05$$

From (8), (13) and (14) :

$$S + Dq = .92 + 4.4/k_{dp} + 48.84/k_{dp}^{\,1.2} = 9.05$$

Rearranging:

$$k_{dp} = .54 + 6.01/k_{dp}^{\,.2} \qquad (15)$$

By trial and error:

k_{dp} = 4.9 md, or 98% of reservoir permeability, k.

Perforations are quite clean, but Dq is still significant at this permeability.

$$S = .92 + 4.4/k_{dp} = 1.82$$

$$S_p = 1.8$$

$$S_{dp} = .02 \quad (\text{negligible})$$

$$D = .02314/k_{dp}^{\,1.2} = .00343$$

Completion Pressure Drop:

$\Delta P_c = P_s - P_{wf}$; P_s = sandface pressure .

$$\bar{p}_r^{\,2} - p_s^2 = \frac{1424\mu zTq}{kh}\left[\ln(r_e/r_w) - .75\right]$$

$$p_s^2 = \bar{p}_r^{\,2} - \frac{1424\mu zTq}{kh}(\ln r_e/r_w - .75)$$

$$= \bar{p}_r^{\,2} - \frac{(1424)(.0255)(1.05)(699)}{(5)(10)}(7.14)$$

$$= \bar{p}_r^{\,2} - 3805.6\ q$$

$$p_s^2 - p_{wf}^{\,2} = \frac{1424\mu zTq}{kh}(S + Dq)$$

$$p_{wf}^{\,2} = p_s^2 - \frac{1424\mu zTq}{kh}(S + Dq)$$

$$= p_s^2 - \frac{(1424)(.0255)(1.05)(699)}{(5)(10)}\ q(S + Dq)$$

$$= p_s^2 - 533\ q\ (S + Dq)$$

$$= p_s^2 - 533\ q\ (1.82 + .00343\ q)$$

q MSCFD	$\bar{P}_r$ psi	P_s psi	P_{wf} psi	ΔP_c psi
2111	5508	4723	3480	1243
2900	5508	4393	1054	3339

APPENDIX B
NOMENCLATURE

D - rate parameter for non-darcy flow, $\frac{1}{MSCFD}$

G - gas gravity, dimensionless.

h - net pay, ft.

k_d - permeability of damaged zone around wellbore as a result of invasion by drilling mud and cement filtrates, md.

k_{dp} - permeability of damaged, compacted zone around perforation in rock, md.

k_o - reservoir permeability, md.

L_p - length of perforation in rock, ft.

N - total number of perforations.

$\overline{P}_r$ - average reservoir pressure (bottom hole static pressure), psia.

P_{wf} - flowing bottom hole pressure, psia.

Q - gas flow rate, MSCFD.

r_d - radius of damaged zone around wellbore, ft.

r_{dp} - radius of compacted zone around perforation, ft.

r_e - well drainage radius in reservoir, ft.

r_p - radius of perforation in rock, ft.

r_w - wellbore radius (1/2 of bit diameter), ft.

S - overall skin factor for viscous or laminar darcy flow through restrictions around wellbore, dimensionless.

S_d - skin factor for flow through damaged zone around wellbore caused by drilling mud and cement filtrates.

S_{dp} - skin factor for flow through damaged and compacted zone around perforation.

S_p - skin factor for effect of flow converging into perforations around wellbore.

T - formation temperature, °Rankine (°F + 460).

z - gas deviation factor, dimensionless.

β - velocity coefficient, ft^{-1} (for effects of turbulent or non-darcy flow through porous media).

μ - viscosity, cp.

Table 1
Guidelines for the Effect of Perforating Conditions on Perforation Quality

Perforating Conditions		Perforation Parameters	
Fluid	Pressure	CFE	k_c/k
High solids, mud in hole	+ Δp	.3	.01 - .03
Low solids, mud in hole	+ Δp	.4	.02 - .04
Unfiltered salt water	+ Δp	.5	.04 - .06
Filtered salt water	+ Δp	.7	.08 - .16
Filtered salt water	- Δp	.8	.15 - .25
Clean, nondamaging fluid, best techniques available	- Δp	.9	.30 - .50
Clean, nondamaging, ideal perforator	- Δp	1.0	1.00

(After McLeod, SPE, 1983)

Table 2
Well Test Evaluation of Compacted Zone Permeability

Well	K (md)	Kc/K	Kc (md)	Perforating Fluid	Pressure Overbalance(+) Pressure Underbalance(-) (psi)
1	200.	.025	5.	Mud	+500
2	8.6	1.0	8.6	Brine	-500
3	318.	.13	41.	Brine	+200
4	35.(*)	.4	14.	Brine	-800
5	35.(*)	1.0	35.	Brine	-2085

(*) Permeability of mud filtrate damaged zone (estimated to be 50% of formation permeability (70 md).

(After McLeod, SPE, 1983)

Table 3
Lobo Gas Well Reservoir Data

NET PAY	- 10 FT.
GAS VISCOSITY	- .0255 CP
GAS GRAVITY	- .71
FORMATION TEMPERATURE	- 239°F
Z FACTOR	- 1.05
FORMATION PERMEABILITY	- 5 MD
DRAINAGE RADIUS	- 933 FT.
WELLBORE RADIUS	- .35 FT.
RESERVOIR PRESSURE	- 5508 PSIA

Table 4
Perforating Alternatives

SIZE GUN (INCHES)	PRESSURE (PSI) UNDERBALANCE (-) OVERBALANCE (+)	K_c/K	L_p (IN.)	D_p (IN.)	AOF (MSCFD)
UNDERBALANCED PERFORATING					
1 9/16	-500	.4	5	.3	1922
1 9/16	-2000	1	5	.3	2997
2 1/8	-500	.4	6	.4	2484
2 1/8	-2000	1	6	.4	3697
4	-2000	1	9	.5	5419
OVERBALANCED PERFORATING					
UNFILTERED BRINE					
4	+500	.05	9	.5	1305
FILTERED BRINE					
4	+500	.12	9	.5	2132

Table 5
Effect of Kiling a Well and Clean-up on Permeability of Compacted Zone

TEST	FLOW RATE, MMCFD	COMPLETION PRESSURE DROP, PSI	KC/K, %
	------------Before Killing Well------------------		
1	2.7	3	64.
	------------After Killing Well with Brine---------		
2	2.1	75	3.3
3	4.1	120	5.7
4	6.5	180	9.5
5	9.8	200	13.0

(After Crawford, SPE, 1989)

Table 6
Performance of Offset California Gas Wells

WELLHEAD PRESSURE PSI	WELL GAS FLOW RATES MMCFD		
	Perforated Underbalanced		Perforated Overbalanced
	Predicted	Measured	Measured
2600 (SI)	0	0	0
2400	5.6	2.8 to 5.6	.5
2200	10	10	1.2
2000	13	13	2.1
1600	17.2	18	3.6
1500	18.0	20	4.0
1400	---	--	4.5

(After Crawford, SPE, 1989)

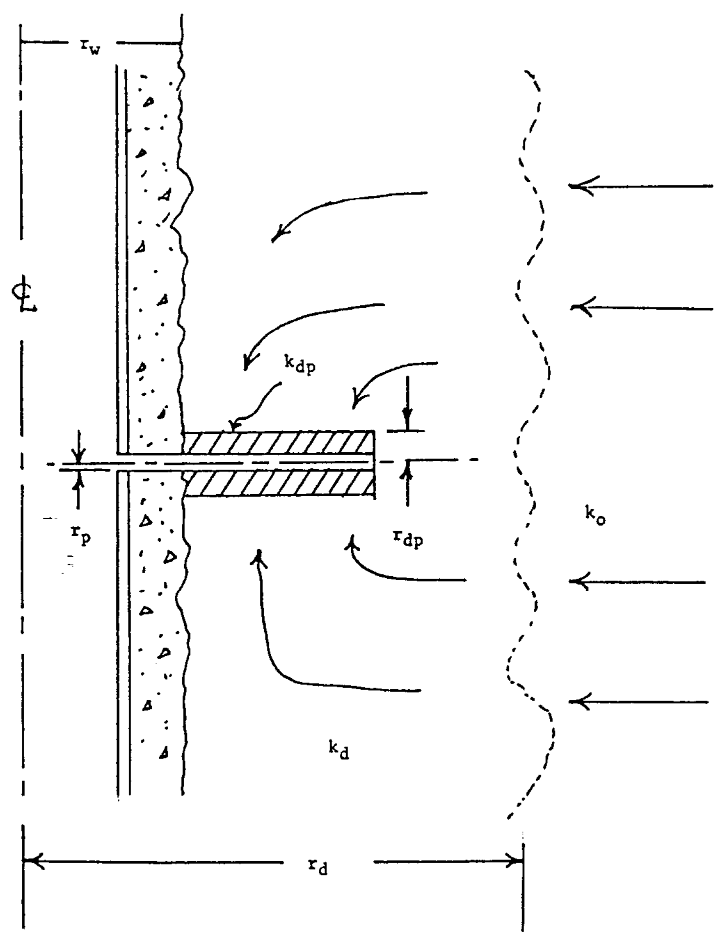

Figure 1 - Flow into a perforation

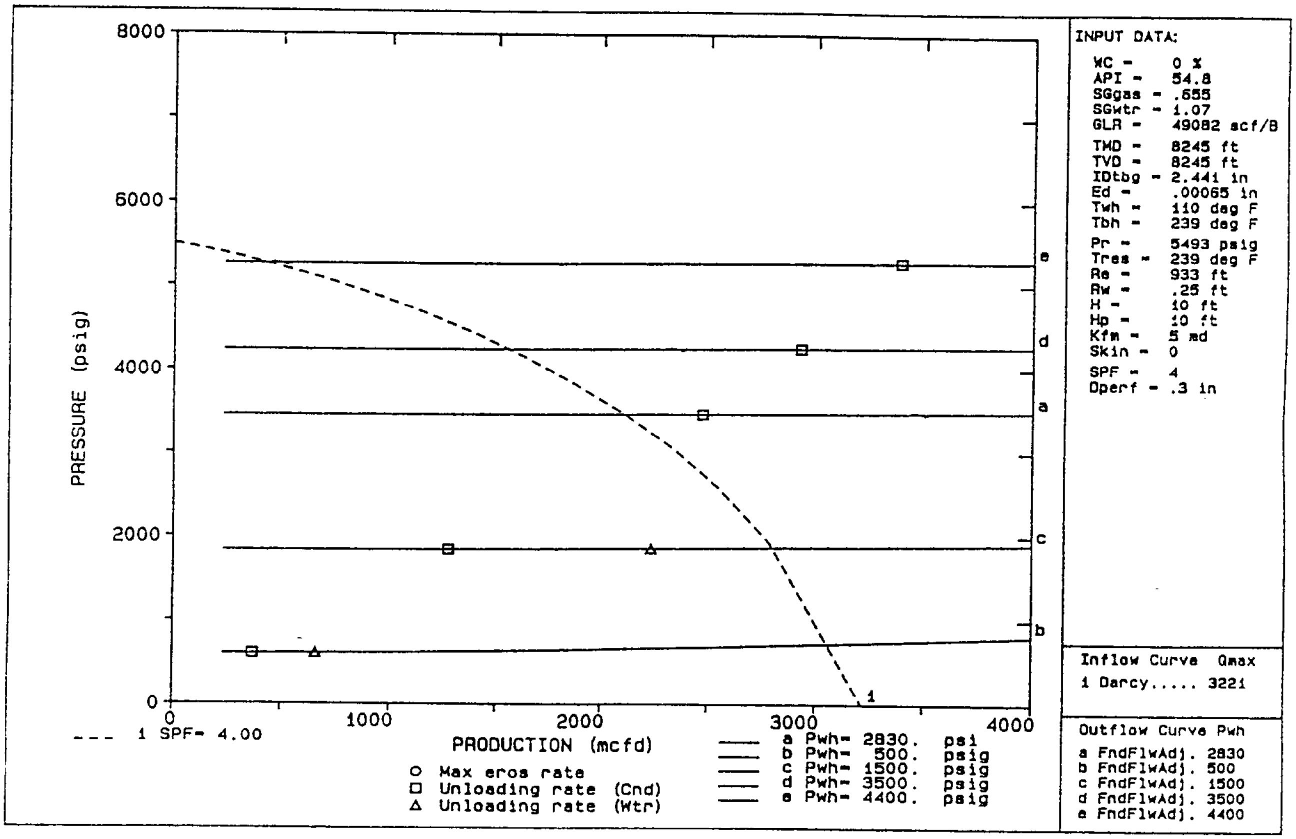

Figure 2 - Lobo gas well–systems analysis plot

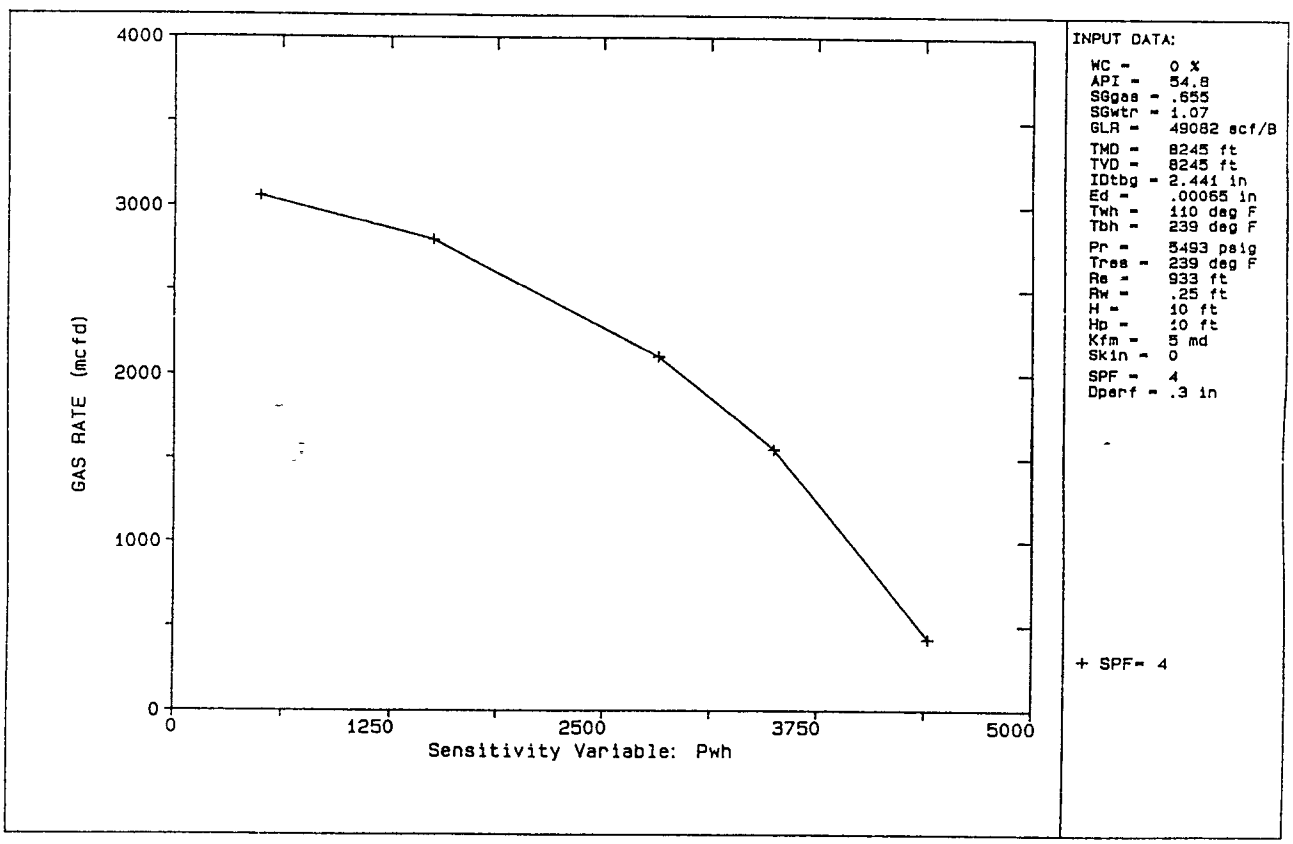

Figure 3 - Lobo gas well–outflow sensitivity
(gas rate vs. wellhead pressure)

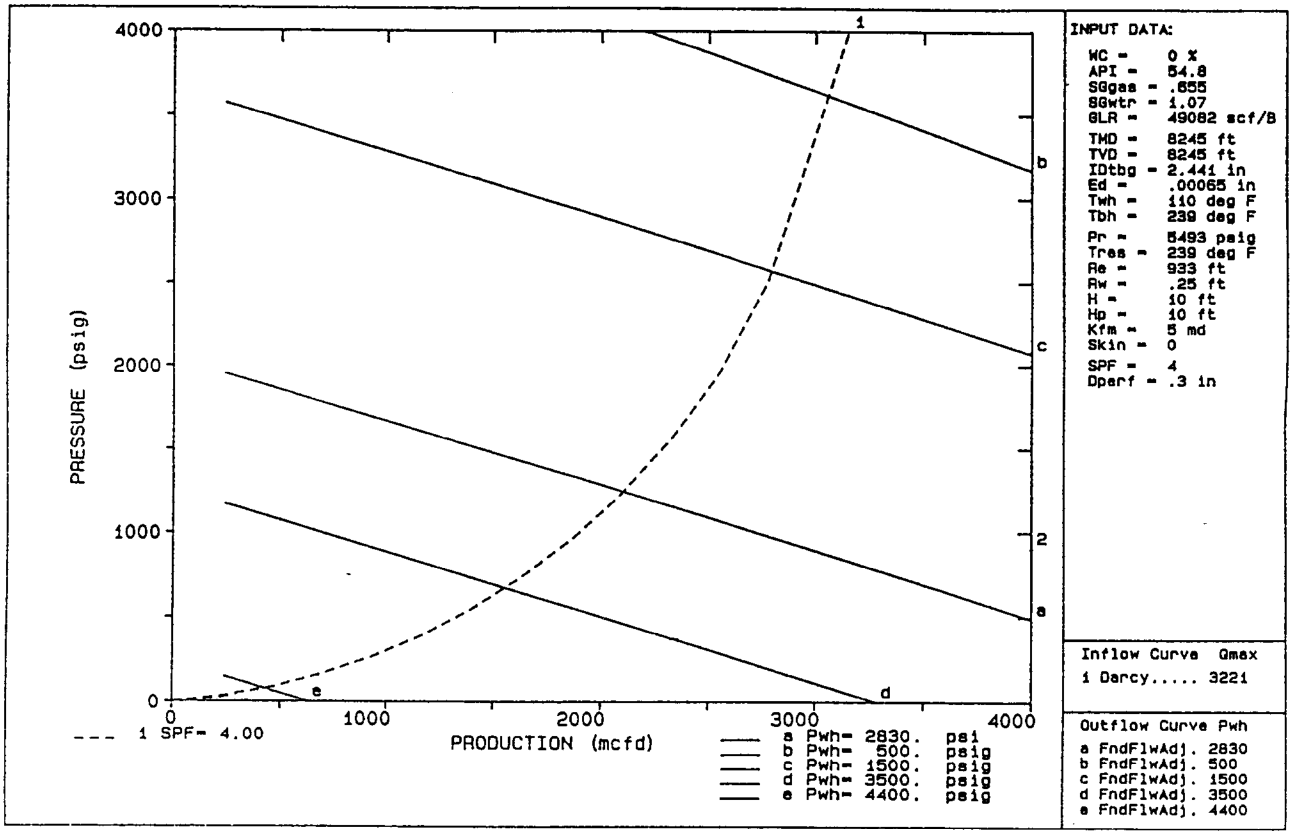

Figure 4 - Lobo gas well–differential curve
(completion pressure drop)

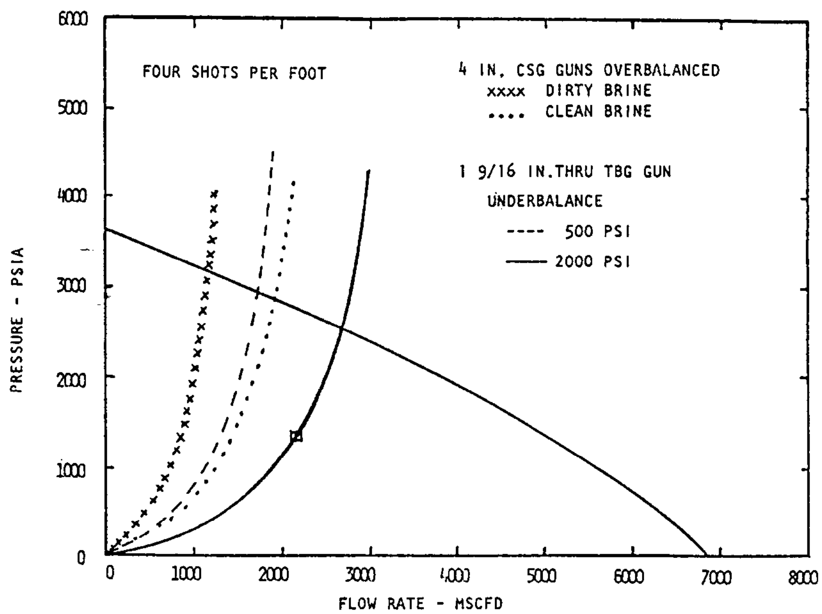

Figure 5 - Completion pressure drops for through-tubing
and casing guns

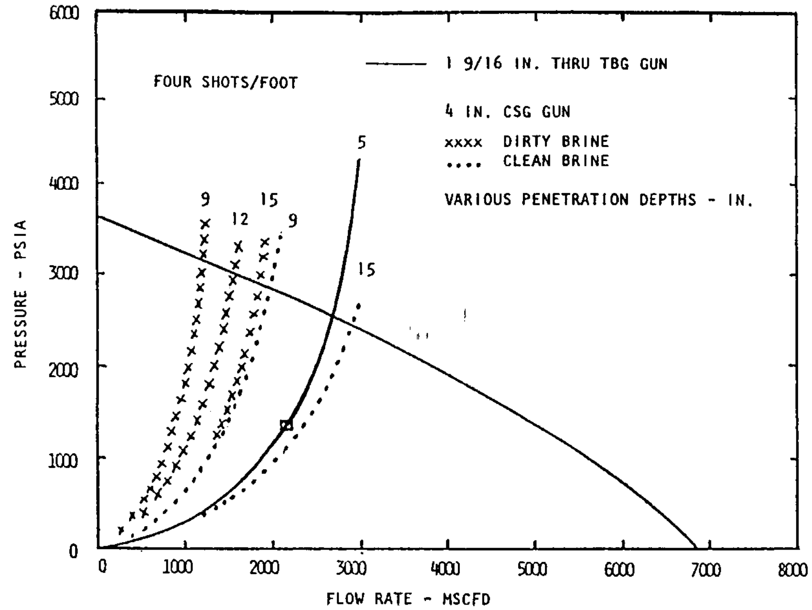

Figure 6 - Effect of casing gun perforation penetration on well performance

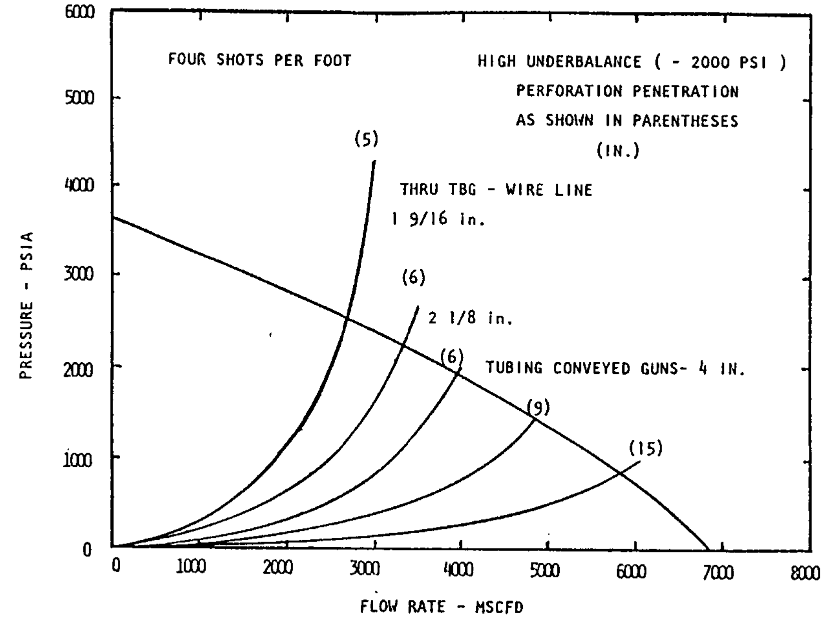

Figure 7 - Effect of gun size on well performance when perforated underbalanced

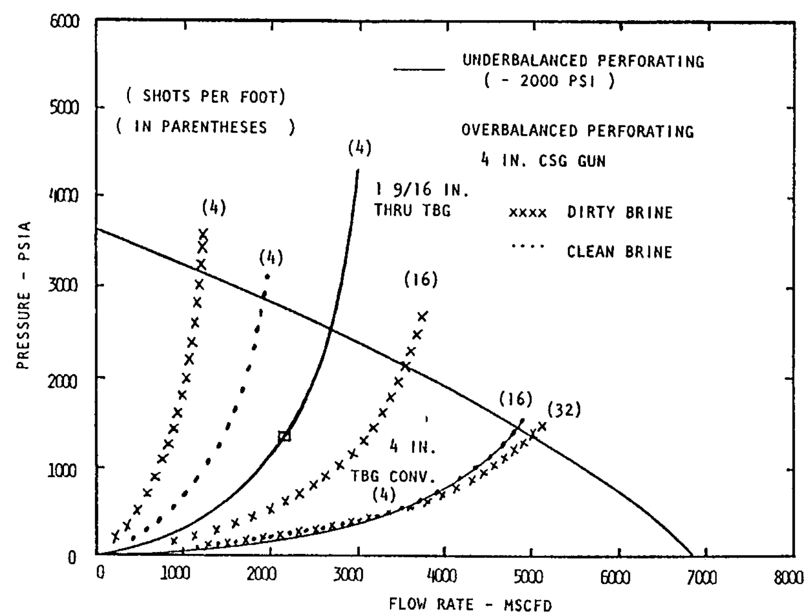

Figure 8 - Effect of shot density on well perforated with four-inch guns

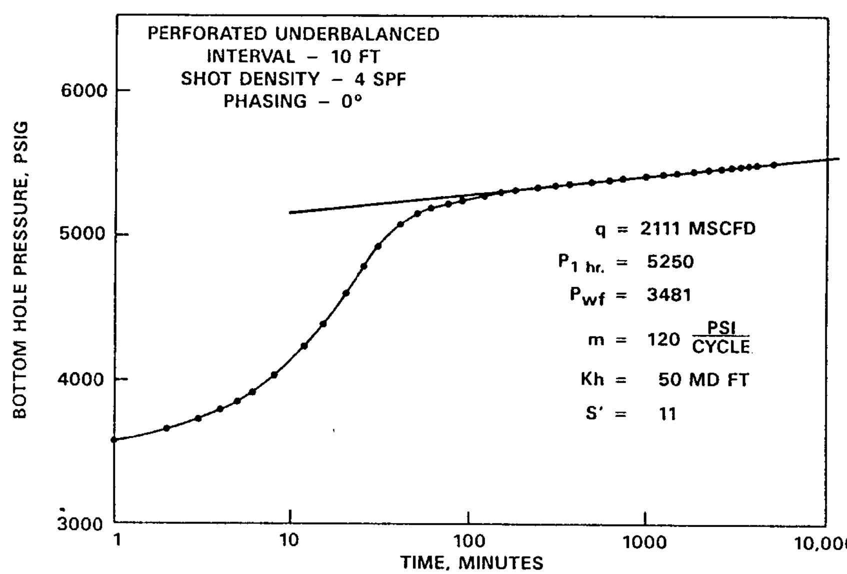

Figure 9 - Pressure build-up on South Texas gas well