THE EFFECTS OF SOLID CONTAMINANTS ON FIELD OPERATIONS

FTC

FOREFRONT OF FILTRATION TECHNOLOGY

WWW.FTC-HOUSTON.COM FILTRATION TECHNOLOGY CORPORATION • 11883 CUTTEN ROAD • HOUSTON, TX 77066 • (713) 849-0849 • FAX: (713) 849-0202

FTC Pub. 100 (rev.6/02)

IX. CONCLUSION

In conclusion, the major points of discussion have been summarized below:

Solid contaminants in workover and completion fluids can cause loss in well productivity by plugging action in the following areas:

a. Formation Matrix
b. Perforation Crushed Zone
c. Perforation Tunnels
d. Gravel Packed Perforations

Solid contaminants can cause failures in cement squeeze operations, downhole tool malfunctions, fishing jobs, and the neccessity for frequent well stimulation treatments.

The removal of all solid particle contaminants larger than 2 microns in diameter flow completion, workover, and stimulation fluids is essential for maximizing well productivity and minimizing other well problems.

TABLE OF CONTENTS

I. INTRODUCTION

II. FORMATION DAMAGE THEORY

- Bridging Theory
- Critical Partical Size
- Actual Micron Sizes of Critical Particles

III. RELATIONSHIP OF FORMATION PLUGGING TO WELL PRODUCTIVITY

- Particle Mixing Theory
- How Permeability Reductions Affect Productivity

IV. APPLICATIONS OF PRINCIPLES TO AN OPEN HOLE COMPLETION

V. PERFORATION THEORY

- Perforation Shot Density
- Compacted Zone
- Perforation Plugging

VI. APPLICATION OF PRINCIPLES TO A CASED HOLE COMPLETION

VII. GRAVEL PACKING COMPOUNDS THE PROBLEM

VIII. OTHER PROBLEMS CAUSED BY DIRTY FLUIDS

IX. CONCLUSION

I. INTRODUCTION

Since the early 1970's, oil companies have increased their effort to eliminate solid contaminants from completion, workover, and stimulation fluids in an attempt to achieve higher well productivities. By allowing contaminants such as cuttings, drilling muds, rust, scale, pipe dope, paraffin, additives, polymers, and impurities in salts and other additives to remain in well fluids, the chances of creating irreparable problems are significantly increased.

Many of the recommended procedures and field results of these programs are written up in various SPE papers and magazine articles. Some of the more well-known authors and companies represented include:

a. George Maly - Union Oil
b. Derry Sparlin - Conoco
c. George Suman - Shell
d. Jim Rike - Rike Service
e. R.N. Tuttle - Shell
f. T.W. Muecke - Exxon Production Research
g. Arthur Nall - Conoco

The general consensus of this group is as follows:

> **The use of clean, compatible fluids during all post drilling operations plays an important role in maximizing well productivity.**

One of the easiest and most economic methods of obtaining the required level of fluid cleanliness is through the use of a surface filtration system. However, a problem exists in choosing the proper equipment necessary to achieve desired result. This confusion is the result of a lack of an industry consensus as to what size particles actually cause the most formation damage. Without specific guidelines as to the maximum sized particles that can be tolerated in workover, completion, and stimulation fluids, oil companies will continue to spend millions of dollars each year on fluid filtration and still not achieve their well productivity projections.

When all the solids settle to the bottom of the well, how many inches of solids will be on top of the packer?

Calculation of volume of fluid between tubing and casing is as follows:

Volume = Area x Depth
= (3.14) (15.78) (6000) (12)
= 3,567,542 cubic inches

500 ppm = (500) (3,568)
= 1784 cubic inches solids

Inches of fill on top of packer is:

$$\frac{\textbf{Total Volume Solids}}{\textbf{Area Between Tubing \& Casing}} = \frac{\textbf{1784 cubic inches}}{\textbf{49.5 Sq. Inches}}$$

$$= \textbf{36.04 inches}$$

Therefore, using a 500 ppm packer fluid could result in over 3 feet of solids settling on top of the packer. This well would certainly be a likely candidate for a fishing job.

The following table can be used to estimate the number of inches of fill that would result from packer fluids with different ppm solids at varying completion depths. (Fig 21.)

PPM SOLIDS CONTENT

DEPTH IN FEET	25	50	75	100	250	500	1000
3000	0.9	1.8	2.7	3.6	9.1	18.2	36.4
4000	1.2	2.4	3.6	4.8	12.1	24.2	48.5
5000	1.5	3.0	4.5	6.1	15.2	30.3	60.6
6000	1.8	3.6	5.4	7.2	18.0	36.0	71.9
7000	2.1	4.2	6.3	8.4	21.0	42.0	84.0
8000	2.4	4.8	7.2	9.6	24.0	48.1	96.2
9000	2.7	5.4	8.1	10.8	27.1	54.1	108.3
10000	3.0	6.0	9.0	12.0	30.1	60.2	120.4

Inches of Fill Inside 9-5/8" Casing with 3-1/2" Production Tubing

Fig 21.

VII. OTHER PROBLEMS CAUSED BY DIRTY FLUIDS

Solids contamination can create many different well problems in addition to permeability and productivity losses. The SPE paper 9752 by Rike and Pledger (referred to earlier) points out some other problems associated with the use of dirty fluids.

> **Plugged perforations are the probable cause of almost all second, third and fourth squeezes to effectively seal off a perforated interval. Furthermore, solids-laden fluid is a fundamental deterrent to effectively displacing a channel behind pipe with a squeeze cement slurry.**
>
> **Solids-laden fluid may often be responsible for sticking pipe when small clearances are desirable or mandatory, such as in concentric tubing operations offshore.**

Other points that shoud be considered when studying the economics of using clean fluids in all post drilling operations include the following:

> **Clean fluid completions require fewer stimulation treatments and those that are necessary will have a higher degree of success.**
>
> **Many downhole tool failures can be directly attributed to solid particle contaminants in the well fluid.**

Since many fishing jobs are associated with pulling "retrievable" completion packers, the following example highlights the importance of using clean packer fluid.

Example: **A completion packer is set in 9-5/8", 47 lb casing at a depth of 6000 feet. The completion string is 3-1/2" tubing. The packer fluid contains 500 ppm solids.** (Fig 20.)

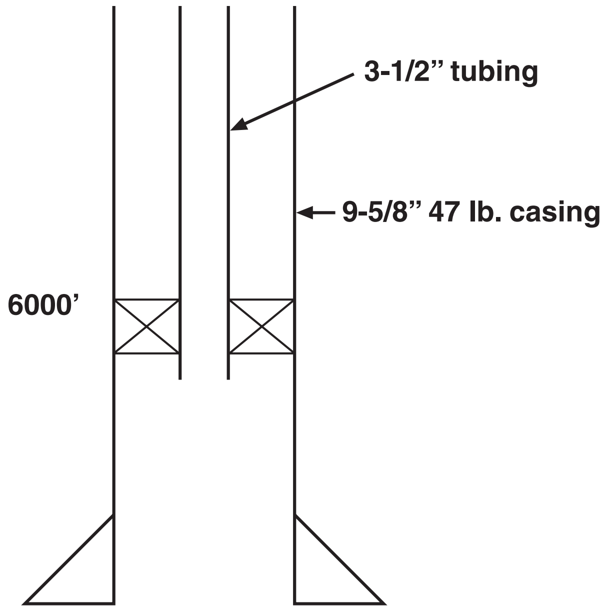


Fig 20.

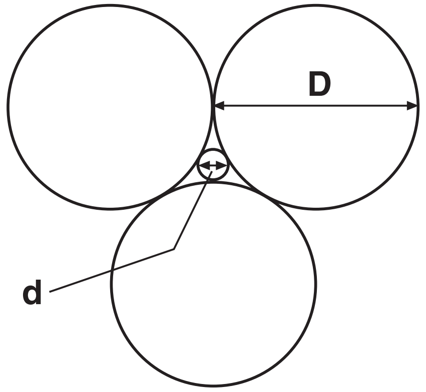
II. FORMATION DAMAGE THEORY

The determination of critical size ranges for fluid contaminants involves a basic understanding of particle bridging theory, the effects of particle plugging on formation permeability, and the correlation between permeability reduction and productivity loss.

Bridging Theory

During the 1930's C.J. Coberly and E.M. Wagner conducted extensive experiments with spherical bodies in order to determine how these objects form stable bridges over openings larger than their own diameters. The following principles were published in their paper entitled "Some Considerations in the Selection and Installation of Gravel Pack for Oil Wells".

> **The predominant form of sand grain packing is hexagonal and this packing arrangement is the controlling factor in determining the size of openings to be bridged in the sand grains.** (Fig 1.)



D = diameter of formation sand grain

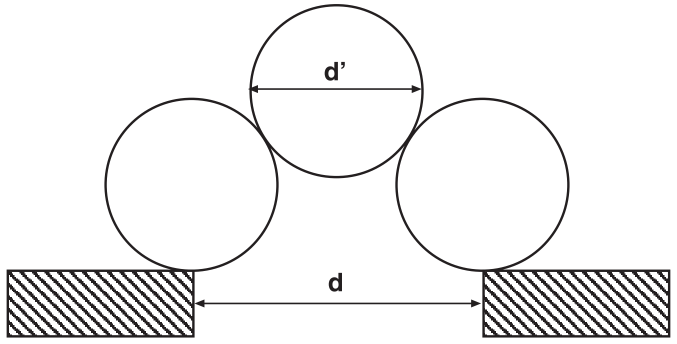
d = diameter of inscribed circle (representing diameter of pore throat)

$d = (0.1547)D$

$D = (6.4641)d$

Fig 1. HEXAGONAL PACKING OF FORMATION SAND GRAINS

Assuming hexagonal packing, stable bridging of small particles over the spaces between large sand grains occurs when the diameter of the circle inscribed in the space between the large grains is approximately two times the diameter of the small particles. (Fig 2.)



d' = diameter of bridging particle
d = diameter of pore throat
If $d \le 2d'$, STABLE BRIDGES WILL FORM

Fig 2.

Relating these basic principles to formation plugging, it is evident that particles with a diameter approximately 13 times smaller than the average formation sand grain size will still bridge on the pore throat opening and not pass into the formation matrix itself. The direct implication of this analysis is as follows:

> **Particles with diameters smaller than 13 times the diameter of the average formation sand grain will invade the pore space and possibly become trapped within the formation matrix itself.**

General Particle Size Ratios

Additional research has been done to more clearly define the range of particle sizes that will invade formation sands and plug up the pore spaces. A. Abrams' SPE paper 5713, "Mud Design to Minimize Rock Impairment Due to Particle Invasion", states that:

> **Core permeability studies confirmed that particles with diameter size ranges between 1/3 and 1/7 the size of the pore throat will plug pore channels.**
>
> **Particles smaller in size than 1/7 the size of the pore throat will migrate freely through the formation matrix.**

To understand how such small particles become trapped, it is necessary to realize that oil and gas producing formations are excellent depth filters. Their many interconnecting pores vary greatly in diameter with pore entries and exits usually smaller than the pore spaces themselves. This structure causes fluids passing through the formation to change direction and velocity frequently while being subjected to many different pressure drops.

The physical characteristics of the matrix and the non-uniform flow of fluid cause the three basic mechanisms of filtration to come into play:

a. Screening (Pore Openings)
b. Adsorption (High Surface Area)
c. Sedimentation (Pore Depth)

Particles being transported with fluid flow through the pore spaces may be "screened out" by path restrictions smaller than the particle diameter. They will form stable bridges if the restricitons are between 2 to 3 times the particle diameter.

Even if particles are small enough to pass through physical pore restrictions, they still have a good chance of becoming trapped by the other filtration mechanisms. Particles that come in contact with the pore walls may remain there due to ionic forces if the fluid velocity is not high enough to overcome these charges. If pore space is deep enough and the fluid velocity slow enough, gravitational forces may be strong enough to cause the particles to "settle" to the bottom of the space.

If the plugging solids plate out on the crushed zone surface and do not significantly invade the entire zone, **25 to 50 cubic inches of contaminants** may be enough to completely plug all the perforations in the gravel pack.

The following table may be used to estimate the volume of contaminants that will be found in fluids containing various ppm solids content. (Fig 19.)

PPM SOLIDS

BARRELS OF FLUID	25	50	75	100	250	500	1000
25	6	12	18	24	60	120	240
50	12	24	36	48	120	240	280
75	18	36	54	72	180	360	720
100	24	48	72	96	240	480	960
250	60	120	180	240	600	1200	2400
500	120	240	360	480	1200	2400	4800

Estimated Cubic Inches of Solids per Barrel & PPM of Fluid

Fig 19.

VII. GRAVEL PACKING COMPUNDS THE PROBLEM

Almost all authorities agree that the use of clean fluids during gravel packing operations are essential for obtaining acceptable well performance. In cased hole gravel packs the most critical area is the perforation tunnels. In order to eliminate severe pressure drops through perforations, these tunnels must be packed with clean, properly sized gravel.

SPE paper 3590, "Productivity of Gravel Pack Completions", written by B.B. Williams, L.S. Elliott, and R.H. Weaver clearly points out perforation tunnels can be a major obstacle to obtaining good productivity out of a gravel packed completion.

> **A study of flow resistances imposed by gravel packing a cased well has shown that the largest resistance is often that produced by fluid flow through the sand filled perforations.**
>
> **Because of the potential limitations imposed by gravel in the perforations, sand used in the pack should be properly sized to stop formation fines and should also contain a minimum quantity of fines.**
>
> **Fluids used to place the gravel pack sand should be clean and free of particulate matter to minimize damage to sand in the perforations.**

Since gravel packs are designed to fill all perforation tunnels with gravel pack sand, the number of solid contaminants required to completely plug these tunnels is significantly less than those required in a non-gravel pack completion.

Let's look at the previous cased hole example and determine the number of solids necesary to completely fill the perforation tunnels and crushed zones.

From previous examples we found:

Crushed Zone Pore Space Volume = 106.76 cubic inches
Perforation Tunnel Volume = 62.8 cubic inches

Filling the perforation tunnel with 20/40 mesh sand, we can estimate pore space volume in sand, we can estimate pore space volume in sand filled tunnels by estimating porosity at 40%.

Total Pore Space Volume in Perforation Tunnels
= Porosity x Total Tunnel Volume
= (0.4) (62.8)
= 25.12 cubic inches

Therefore, the total solids required to completely plug the perforation tunnels and crushed zone is only 131.88 cubic inches.

Actual Micron Sizes of Critical Particles

If the size of an average pore space opening is known for a specific formation, it is easy to calculate the actual micron sizes of particles that would invade the formation matrix and cause plugging. For instance, if a formation had an average pore size of 15 microns, the critical size range for contaminants would be 5 to 2.1 microns.

However, since core samples are not always available to determine pore space sizes, a method of estimating pore space size can be helpful. Harris and Odom's article "Effective Filtration in Completion and Other Wellbore Operations Can be Good Investment" in the September 20, 1982 issue of the Oil & Gas Journal provides the following rule of thumb for estimating pore space size in the Gulf Coast:

> **The pore size in microns equals the square root of the permeability in millidarcies.**
>
> **Example: For a reservoir where the permeability is 900 md, the pore size would be 30 microns and the critical plugging size is 10 to 4.2 microns.**

Using this rule of thumb, the following table shows the different critical plugging sizes associated with various permeabilities. (Fig 3.)

Permeability (Millidarcies)	Pore Size (Microns)	Critical Plugging Range (Microns)
100	10	3.3 to 1.4
250	15.8	5.2 to 2.2
500	22.4	7.4 to 3.2
750	27.4	9.1 to 3.9
1000	31.6	10.5 to 4.5
1500	38.7	12.9 to 5.5
2000	44.7	14.9 to 6.3

Fig 3.

After studying the table, it is apparent that even sands with very high permeabilities are still subject to plugging by low micron sized contaminants. This potential for small micron particles to create irreparable formation damage has forced many companies to establish the following filtration guideline:

> **Completion, workover, and stimulation fluids should be filtered to remove all particles larger than 2 microns in diameter.**

III. RELATIONSHIP OF FORMATION PLUGGING TO WELL PRODUCTIVITY

Since a direct relationship exists between the pore space and permeability, any reduction in the actual pore space will result in a corresponding reduction in permeability. The effect of particle invasion into a formation matrix is to fill the pore spaces with solid material and thereby reduce the total pore volume. To determine the amount of permeability reduction, it is necessary to consider the effects of mixing large amd small particles together.

Particle Mixing Theory

Many people erroneously assume that if quantities of two different sized particles are mixed together the resulting permeability of the mixture would be the weighted average of the two permeabilities. Derry Sparlin's SPE paper 4772, "Sand and Gravel - A Study of Their Permeabilities", presents a much different conclusion:

> **In the actual case of a mixture, the smaller particles tend to fill the void spaces between the larger particles so that the permeability of the mixture is almost always less than the permeability of the smaller particle matter.**

An easy way to illustrate this phenomenon would be to take two identical boxes (A and B) and fill A with golf balls and B with gravel. The golf balls represent formation sand grains and the gravel represent contaminant particles 20 to 40 times smaller than the formation sand. The permeability of the box of balls is much greater than the permeability of the box of gravel. (Fig 4.)

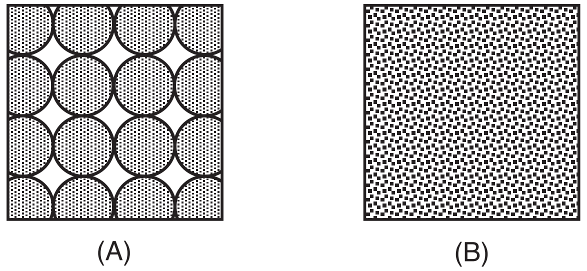
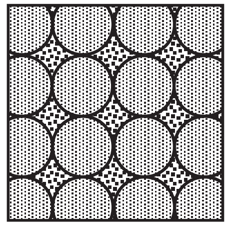


Fig 4.

Pore Space of (A) = Area Box - Area Balls

Pore Space of (B) = Area Box - Area Gravel

When the gravel is mixed with the balls, the pore spaces between the balls becomes filled. Now the total resulting pore space in the box is even less than the total pore space in the box of gravel. Therefore, the permeability of the mixture is even less than the permeability of the box of gravel. (Fig 5.)



(C)

Pore Space of (C) = Pore Space of (B) minus the pore spaces that would normally lie within the areas occupied by the golf balls.

Fig 5.

Total Volume for all Perforations

$$\begin{aligned} V_{CET} &= VCE * \#\text{ of Perforations} \\ &= 1.84\ in^3 * 40 \\ &= 73.6\ in^3 \end{aligned}$$

$$\begin{aligned} V_{PET} &= VPE * \#\text{ of Perforations} \\ &= 2.83\ in^3 * 40 \\ &= 113.2\ in^3 \end{aligned}$$

Total Volume of Solids Required

$$\begin{aligned} V_{TET} &= V_{CET} + V_{PET} \\ &= 73.6\ in^3 + 113.2\ in^3 \\ &= 186.8\ in^3 \end{aligned}$$

Total Fluid Loss to Create the Damage Described in this Case

$$\begin{aligned} F_L &= 186.3\ in^3 * 16.387\ \frac{cm^3}{in^3} = 3061.1\ cm^3 \approx 3061.1\ g \\ &= 3061.1\ g * 1000\ \frac{mg}{g} = 3061100\ mg \\ &= 3061100 \div 500\ ppm \\ &= 6.122.2\ l \\ &= 51.3\ \text{barrels} \end{aligned}$$

Therefore, there are enough solid contaminants in 51.3 barrels of fluid containing 500 ppm solids to fill 60% of the perforation tunnels and all the pore space in all the perforation crushed zones in a 10 foot completion having 4 shots per foot.

The production loss is the multiple of all three effects.

Actual production = (0.8) (0.56) (0.87) original production without well impairment

Actual productivity ratio = 0.39

Undamaged production = $\frac{\textbf{195 bbl/day}}{\textbf{0.39}}$

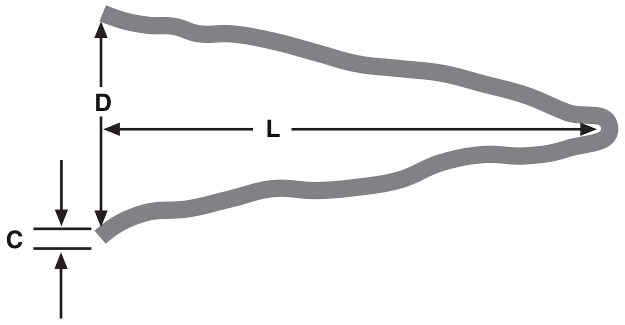
Therefore, production loss is 305 barrels per day.

Using the value of \$20.00 per barrel oil, lost revenue is 305 x \$20 = \$6100 per day.

First year revenue loss = \$2,226,500

How Many Solids Contaminants are Necessary to Create the Damaged Described in this Case?

Volume of Each Perforation Tunnel



$$
\begin{aligned}
V_P &= 1/3\pi r^2L \\
&= 1/3\pi(0.75)^2 8 \\
&= 4.71\ \text{in}^3
\end{aligned}
$$

Volume of Perforation Plus Crush Zone

$$
\begin{aligned}
V_T &= 1/3\pi[(r+C)^2(L+C)] \\
&= 1/3\pi[(0.75+0.5)^2(8=0.5)] \\
&= 1/3\pi[(1.5625)(8.5)] \\
&= 13.91\ \text{in}^3
\end{aligned}
$$

Volume of Crushed Zone

$$
\begin{aligned}
V_C &= V_T - V_P \\
&= 13.91^3 - 4.71^3 \\
&= 9.2\ \text{in}^3
\end{aligned}
$$

Effective Volume of Crushed Zone (w/20% Porosity)

$$
\begin{aligned}
V_{CE} &= V_C * \text{Porosity} \\
&= 9.2\ \text{in}^3 * 0.2 \\
&= 1.84\ \text{in}^3
\end{aligned}
$$

Effective Volume of Perforation (w/60% Plugging)

$$
\begin{aligned}
V_{PE} &= V_P * \%\ \text{Plugging} \\
&= 4.71\ \text{in}^3 * 0.6 \\
&= 2.83\ \text{in}^3
\end{aligned}
$$

How Permeability Reductions Affect Productivity

Several studies have been conducted on the relationship between wellbore damage and loss in well productivity. The results of Tuttle and Barkham (1974) are well accepted and are presented below. (Fig 6.)

EFFECT OF DEGREE OF PERMEABILITY IMPAIRMENT AND DEPTH OF DAMAGE ON RELATIVE PRODUCTION

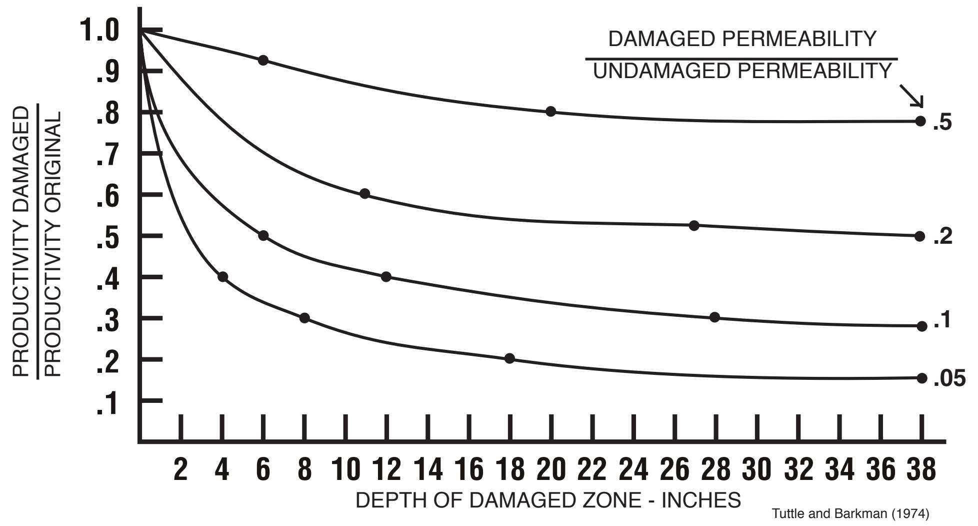


Fig 6.

Tuttle and Barkman (1974)

In studying the graph, the following points become evident:

The ratio of damaged productivity to original productivity is related to the degree of permeability impairment and to the distance that this impairment extends radially from the wellbore.

Productivity loss is not a linear function and it is possible for a few inches of severe damage to have more effect than several inches of moderate damage.

These points are easily illustrated by comparing the productivity loss resulting from a 2 inch damage zone having 5% original permeability to the loss associated with a 12 inch damage zone having 20% original permeability. In these cases, the resulting productivity ratios are 0.5 and 0.6 respectively. (Fig 7.)

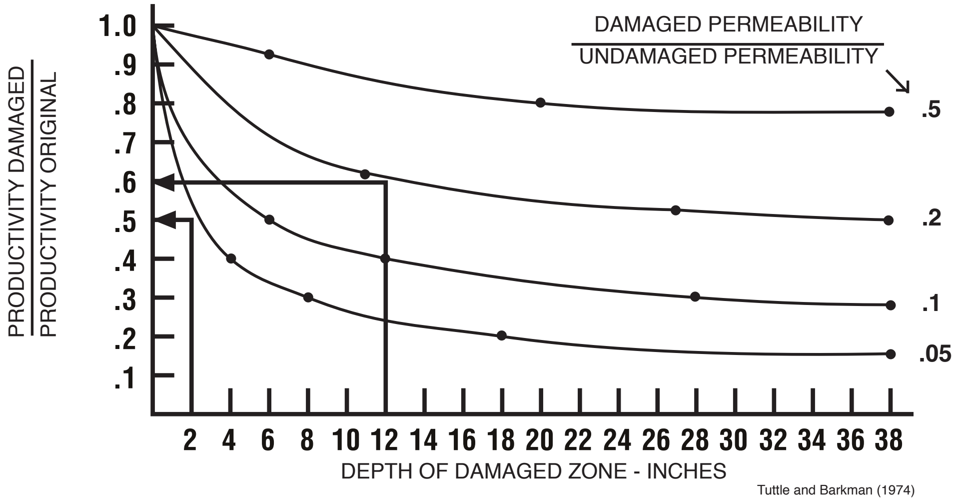


Fig 7.

Tuttle and Barkman (1974)

IV. APPLICATIONS OF PRINCIPLES TO AN OPEN HOLE COMPLETION

The real significance of using clean fluids becomes apparent when the principles of formation plugging are applied to actual well parameters.

Example: **Open hole completion with 7" wellbore and 10 foot producing interval.**

During completion, dirty fluids created a zone of reduced permeability that extends 2 inches radially from the wellbore. Permeability of zone is equal to 20% of original permeability. (Fig 8.)

The resulting production is 425 barrels of oil per day.

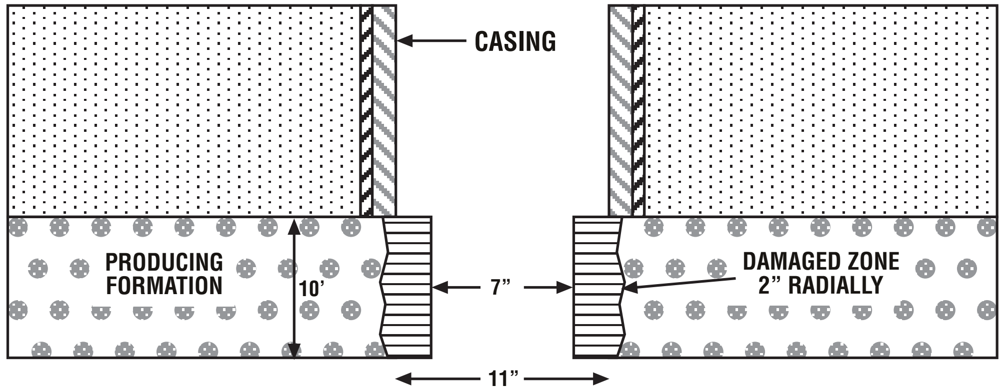


Fig 8.

What is the loss in production?

Productivity coefficient is determined from Fig 6.

$$\frac{\textbf{Productivity Damaged}}{\textbf{Productivity Original}} = \mathbf{0.85}$$

$$\textbf{Undamaged Production} = \frac{\textbf{Damaged Production}}{\textbf{Productivity Coefficient}}$$

$$= \frac{\mathbf{425\ bbl/day}}{\mathbf{0.85}}$$

$$= \mathbf{500\ bbl/day}$$

Therefore, loss production is 75 barrels per day.

Using a value of \$20.00 per barrel of oil, the lost revenue is 75 x \$20 = \$1500 per day or \$547,500 in the first year.

From McLeod's paper:

Productivity of uncontaminated crushed zone = 80% of original productivity

Productivity of contaminated crushed zone = 56% of non-contaminated crushed zone

From Fig 17., the effect of 60% plugging is estimated as follows:

If all tunnels are filled 60%, then the relative depth is reduced to 3.2 inches.

Productivity ratio = 0.9

THE EFFECT OF SHOT DENSITY AND DEPTH ON RELATIVE PRODUCTIVITY

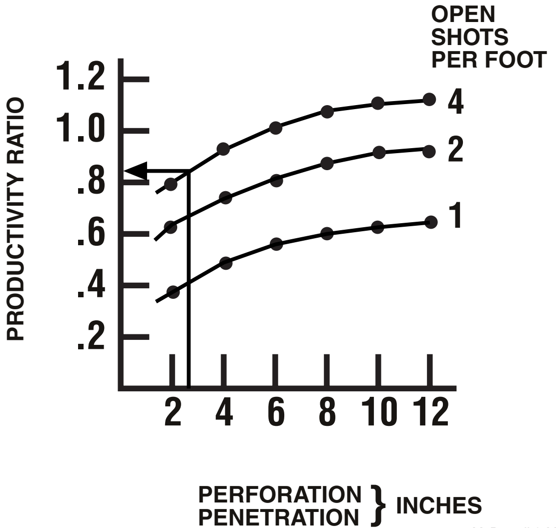


Fig 17.

McDowell & Muskat (1950)

If 60 % of the tunnels are filled completely and 40% are completely open, then there are 1.6 open shots per foot.

Productivity ratio = 0.84

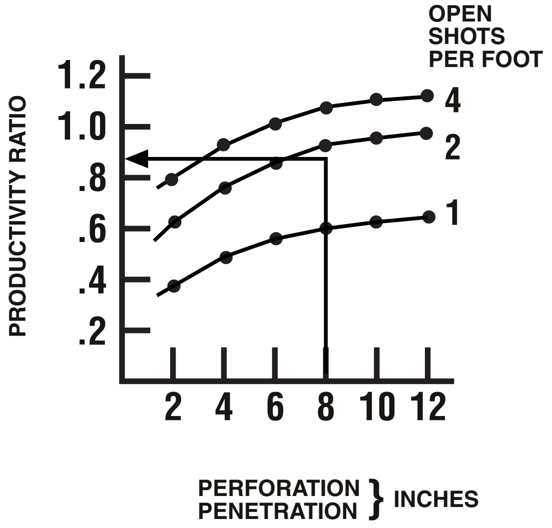


Fig 18.

McDowell & Muskat (1950)

Therefore, the actual productivity rato shoud be somewhere between both possibilities:

Estimated Ratio = 0.87

VI. APPLICATION OF PRINCIPLES TO A CASED HOLE COMPLETION

Let's look at our previous well example and change the parameters to match a cased hole completion. The potentiallly harmful effects of using dirty fluids are much more apparent than in the open hole completion.

Example: **Cased hole completion with 7" casing, a 10 foot perforated interval with 4 shots per foot, 8" perforation tunnels at 1-1/2 inches in diameter.**

During completion operations the formation and perforation tunnels were exposed to a fluid containing 500 ppm solids.

The dirty fluids resulted in reducing the permeability of the perforation crushed zone to 5% of original permeability and plugged 60% of the total perforation tunnel area.

The resulting production was 195 barrels of oil per day. (Fig 16.)

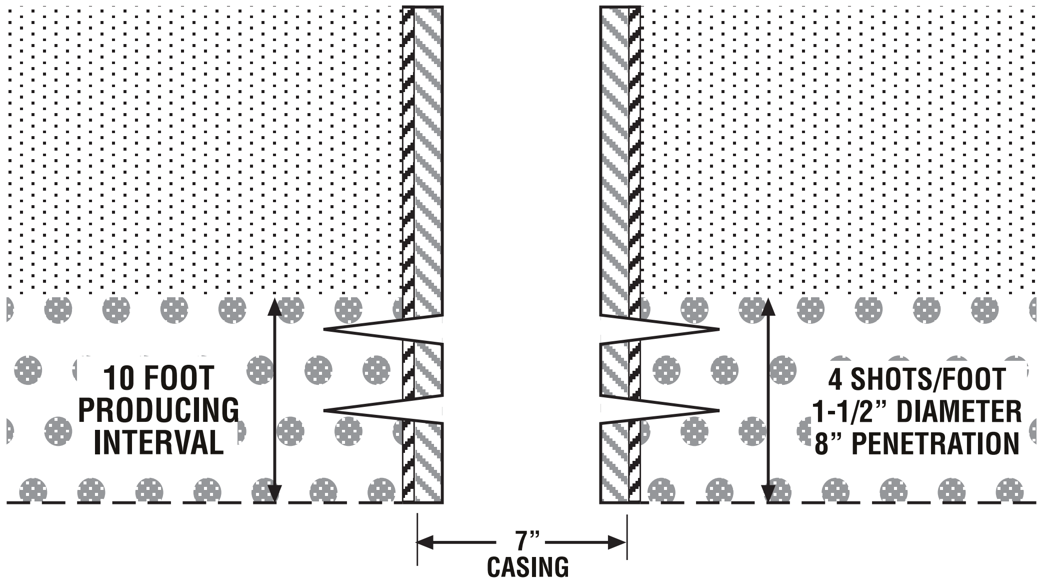


Fig 16.

What is the Loss in Production?

We must consider three separate effects to determine lost production:

a. crushed zone effect
b. plugged crushed zone effect
c. perforation plugging effect

How many solid contaminants are necessary to create the damage described in this case?

The total volume of pore space existing in the 2 inch damage zone can be estimated as follows:

Area of zone = þ(5.5")^2 - þ(3.5")^2
= (3.14) (30.25) - (3.14) (12.25)
= (3.14) (18)
= 56.52 square inches

Volume of zone = Area x Length
= (56.52) (120)
= 6782.4 cubic inches

Assume a porosity of 20%

Pore Space Volume = Zone Volume x Porosity
= (6782.4) (0.2)
= 1356.48 cubic inches

The total volume of solid contaminants in 300 barrels of a fluid having a solids content of 500 ppm can be calculated as follows:

Parts per million = milligrams per liter

300 bbl = 47,691 liters

500 ppm = (500) (47,691) = 23845500 mg
= 23845.5 grams of dirt

Assume that 1 gram of dirt occupies 1 cubic centimeter of space.

Volume of Solids = 23845.5 cc
or = 1455 cubic inches

Therefore, there are more than enough solids in 300 barrels of fluid with 500 ppm solids to completely fill the pore spaces of a 10 foot producing interval to a depth of 2 inches from the wellbore.

V. PERFORATION THEORY

A cased hole completion introduces new constraints on a producing formation that can affect its productivity. A primary area of concern is the perforation tunnel itself and how its physical characteristics make it very susceptible to plugging by solids contaminants.

Formation Shot Density

Work by McDowell & Muskat (1950) shows the relationship between perforation shot density, shot depth, and productivity. One of their basic conclusions is as follows. (Fig 9.)

> **In order for a perforated well to have the productivity equivalent to an open hole completion, there must be a minimum of 4 open shots per foot with at least 8 inches penetration.**

EFFECT OF SHOT DENSITY AND DEPTH ON RELATIVE PRODUCTIVITY

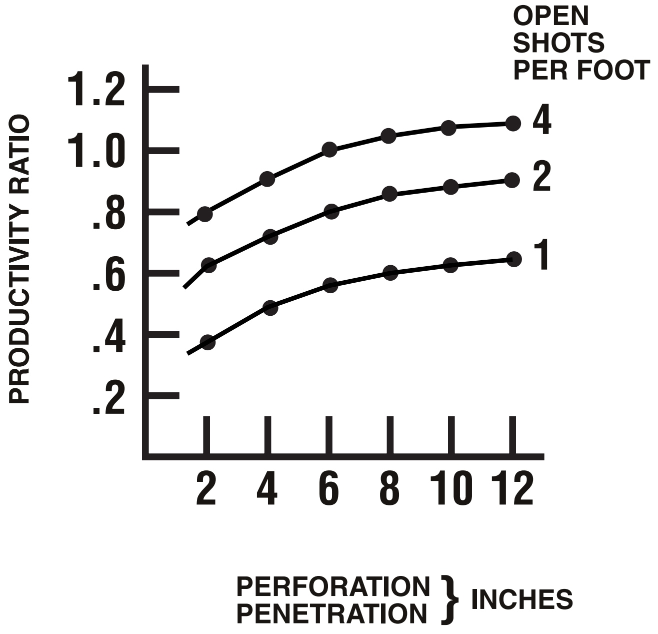


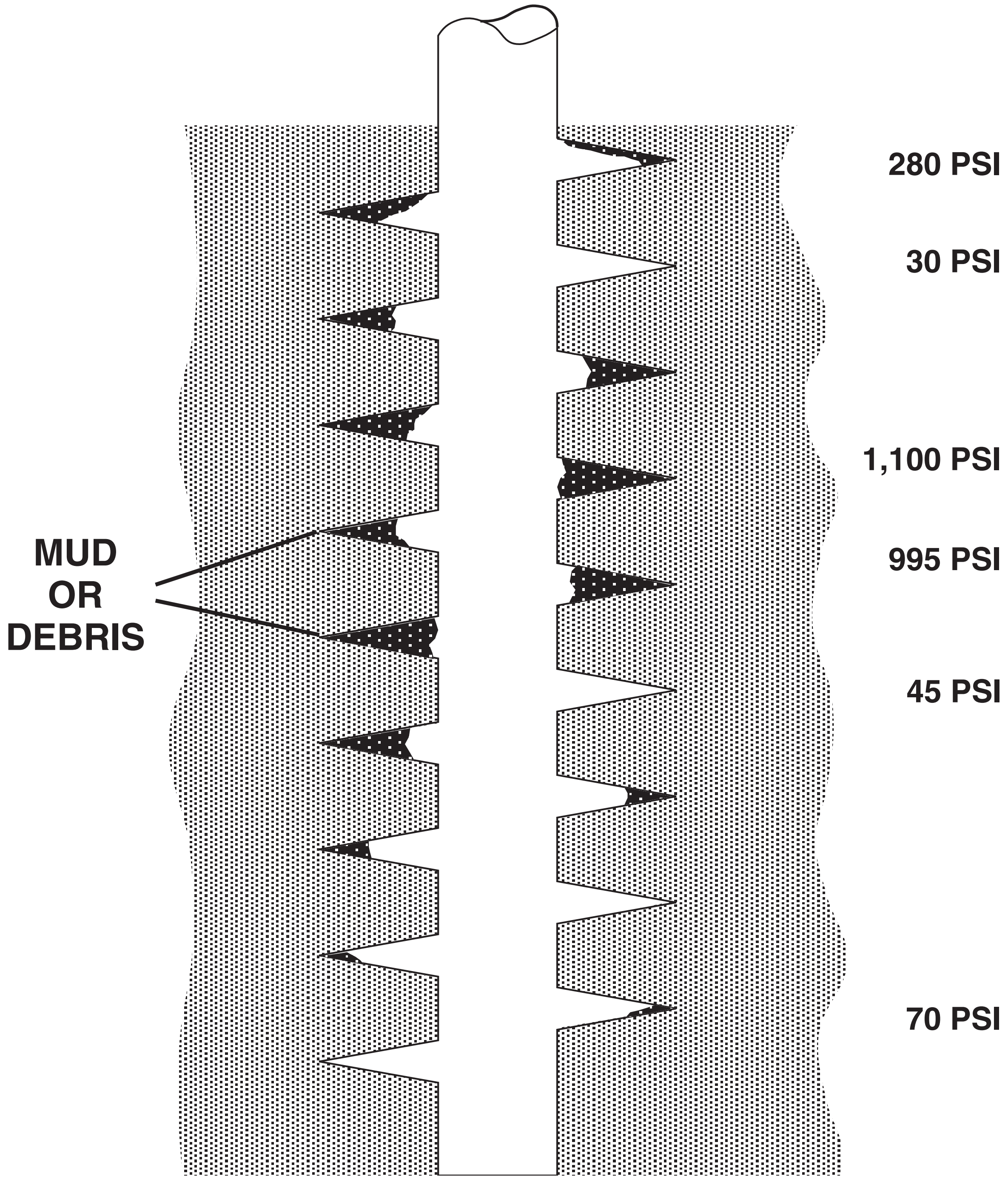
Fig 9.

McDowell and Muskat (1950)

Compacted Zone

Harry McLeod's SPE paper 10649, "The Effect of Perforating Conditions on Well Performance",
describes the crushed zone that surrounds perforations and how this small zone can dramatically affect the productivity of a well.

> **Around each perforation made in rock there exists a compacted zone with a thickness of about one half inch. The permeability of this compacted zone will vary from 10 to 25 percent of the permeability of the rock just prior to perforating. The compaction takes place when the hole is created by the impact**



PRESSURE EQUALIZATION BETWEEN WELLBORE AND FORMATION HINDERS OERFORATION UNPLUGGING

Fig 15.

It is virtually impossible for a well to clean out the plugging solids in most of its perforations through the natural flowing process of production.

Many people erroneously asume that plugging solids are easily removed from perforations by using Hydrofluoric or Hydrochloric acid. However, if a reactive acid is placed at the perforation entrance at the casing, the reaction process itself will leave by-products in the tunnel entrance and thereby insulate the remaining solids from fresh reactive fluid. (Fig 14.)

FLUID ACID "CLEANING"

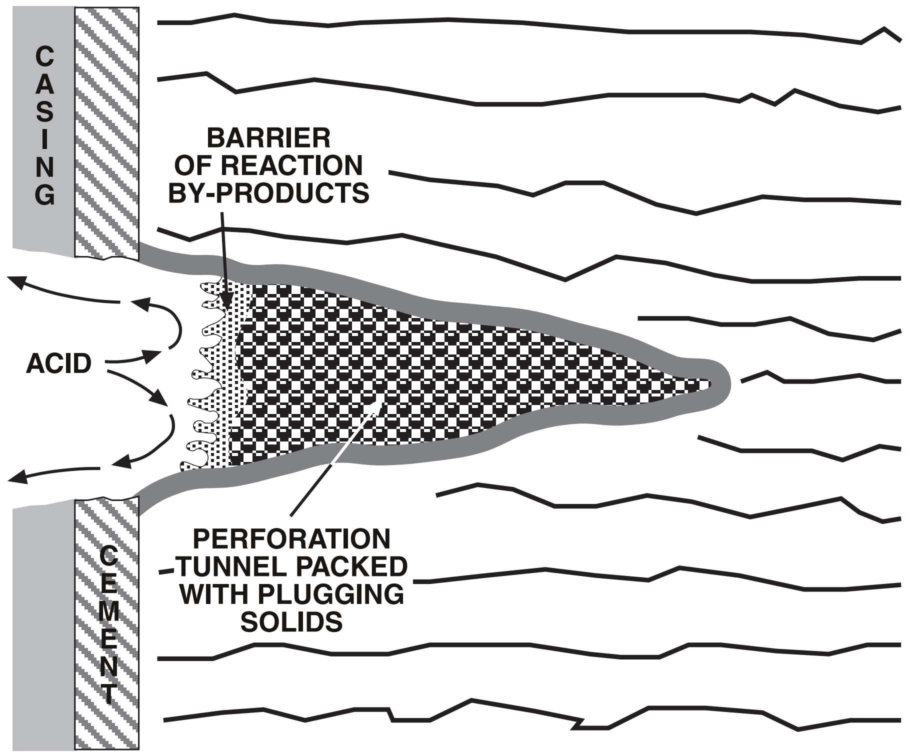


Fig 14.

Solids in perforation holes are not easily removed with acids or other solvents.

Typically a well is induced to flow by gradually reducing the fluid head in the wellbore. Flow begins when less pressure exists in the wellbore than in the formation. The amount of differential pressure required to initiate flow through any perforation depends upon the amount of plugging that exists in the tunnel. The greater the plugging, the higher the differential pressure required to start flow. The problem with getting more than a few perforations open is that a single open perforation tends to equalize pressure between wellbore and formation. Since perforations requiring less differential pressure to flow open first, those requiring higher differential pressures may never open. (Fig 15.)

TYPICAL PERFORATION TUNNEL
JET PERFORATED

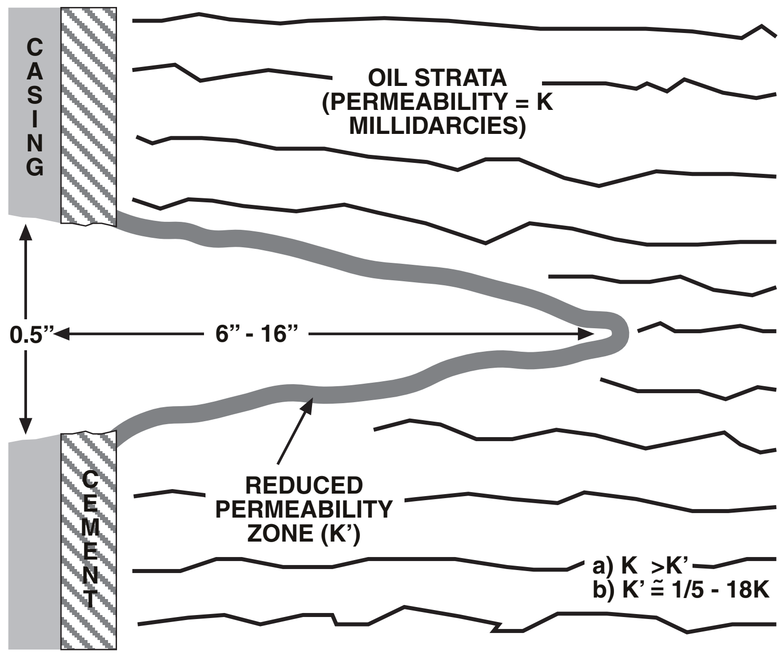


Fig 10.

The permeability of the compacted zone can be further reduced by the presence of dirty perforating fluids, particularly when pressure forces the fluid into the perforation. Permeabilities of this zone may be reduced to as little as 5% of the original permeability. (Fig 11.)

OVERBALANCED PERFORATION

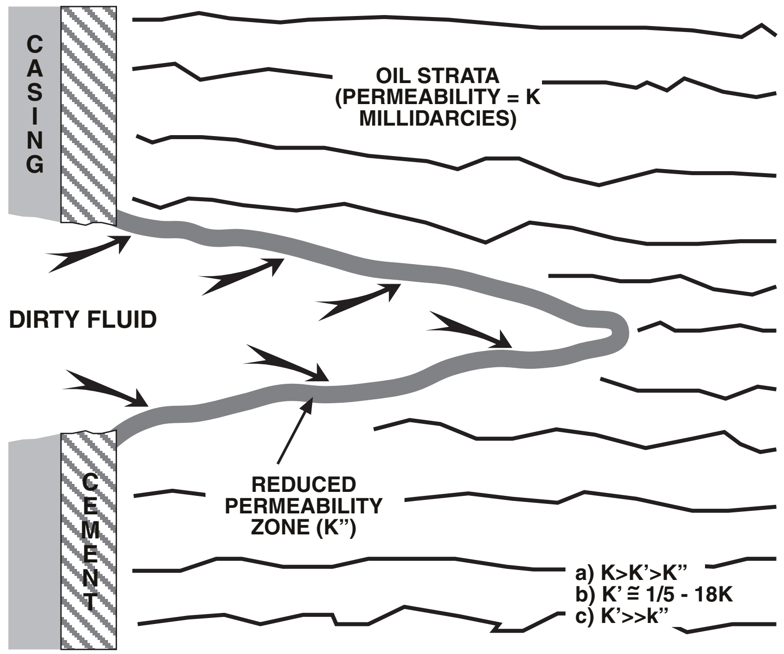


Fig 11.

The effects of the crushed zone area on well productivity were illustrated by Klotz, Krueger, and Pye in their article, "Effects of Perforation Damage on Well Productivity". Their studies indicate the following:

> **If a well is perforated with completely non-damaging fluid and if the permeability of the formation has not been impaired while driling, the permeability of the crushed zone is 20% of the original rock permeability and the well productivity is 80% of the original potential.**
>
> **If the invasion of solids into the crushed zone further reduces its permeability to 5% of original permeability, then the resulting maximum productivity that can be expected is only 45% of original potential.**

Perforation Plugging

Although the McDowell & Muskat studies showed that 4 shots per foot would give well productivities equivalent to open hole, their findings are not valid if the perforations are plugged with gun debris and solid contaminations. (Fig 12.) To achieve open hole equivalence with plugged or partially plugged perforation tunnels, it may be necessary to have substantially more than 4 shots per foot.

PERFORATION OVERBALANCED PERFORATION TUNNEL PLUGGED - VERY DIRTY FLUID

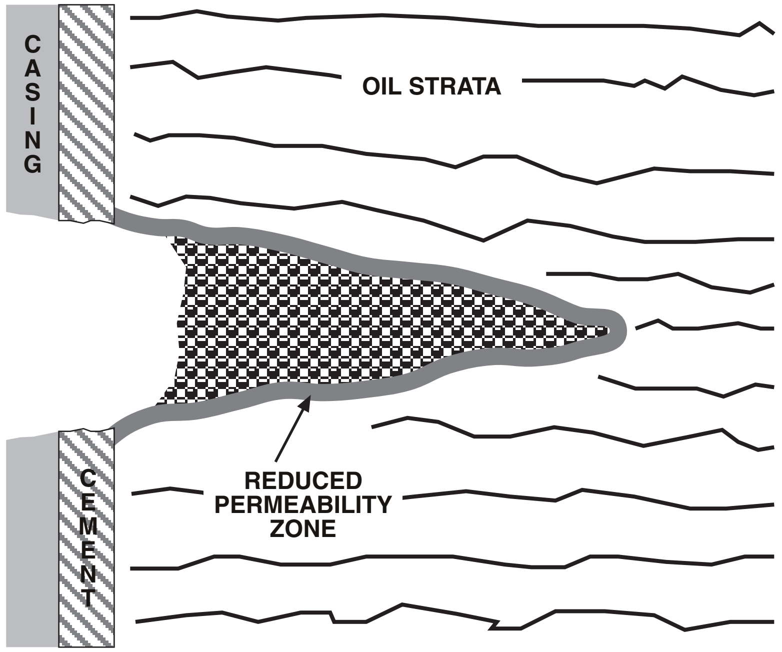


Fig 12.

J.L. Rike and T.M. Pledger discussed these problems in their SPE paper 9752, "Clean Fluids Improve Completion Results". Their basic conclusions are as follows:

The summation of all hard field evidence makes it difficult to accept any premise except one that presumes a small percentage of perforations in a given well are open and working. This hard evidence consists of:

a. Blast joints pulled from multiple completions
b. Screens recovered from sand-controlled wells
c. Pulsed-neutron logs
d. Productivity and injectivity profiles

Darcy's Law shows that the restrictions caused by plugging fines in perforation holes precludes any significant flow through the plugging fines. Therefore, plugged perforations are the po-

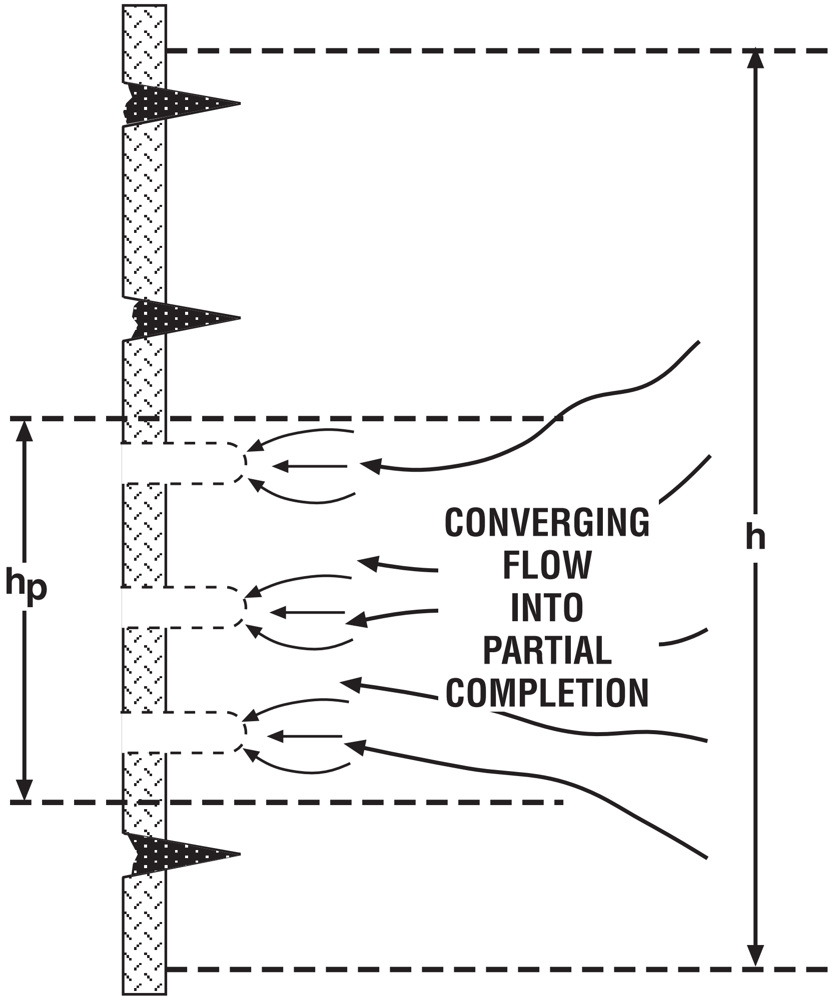


Fig 13.

h = maximum production zone
hp = actual producing zone

PLUGGED PERFORATIONS CAUSE FLOW CONVERGENCE AND REDUCED PRODUCTIVITY