Appendix 1

Modeling - 4-6 Proppant Transport by Thin Fluids

Introduction

Modeling of proppant transport has highlighted the need for quantitative data on the transport of materials in the fracture by thin fluids. The Hydraulic Fracturing Monograph (1994) refers to experiments done by Kerns, Perkins, and Wyant (1959). Results of these experiments suggest that up to 50 lbs/min of sand can be transported by water with velocities of between 4.5 and 6.5 ft/s. The results are scattered over a range of velocities and it was decided to repeat these experiments to determine the cause of the scatter and to better understand the processes involved in sand transport by water and other thin fluids.

Methods

An apparatus was constructed so that the transport of sand in a horizontally oriented slot could be observed. Sand can be added at a constant rate and water flowed through the slot at a constant rate. The pressure required to maintain constant sand and fluid rates was monitored. A schematic of the apparatus is presented in Figure 1.

Sand and water enter the 5/16 inch wide slot through an open end that is 1 foot tall. The sand and water then move through the 8 foot length of the slot where they exit via three 5/16 inch perforations spaced 3 inches apart on the 1 foot tall end of the slot. The rate of sand or water added could be varied up to 16 lbs/min and 5 gal/min, respectively. 20/40 Ottawa and 16/30 Carbolite proppants were used with water (60 to 68°F). Observations were recorded and portions of the experiments were video taped.

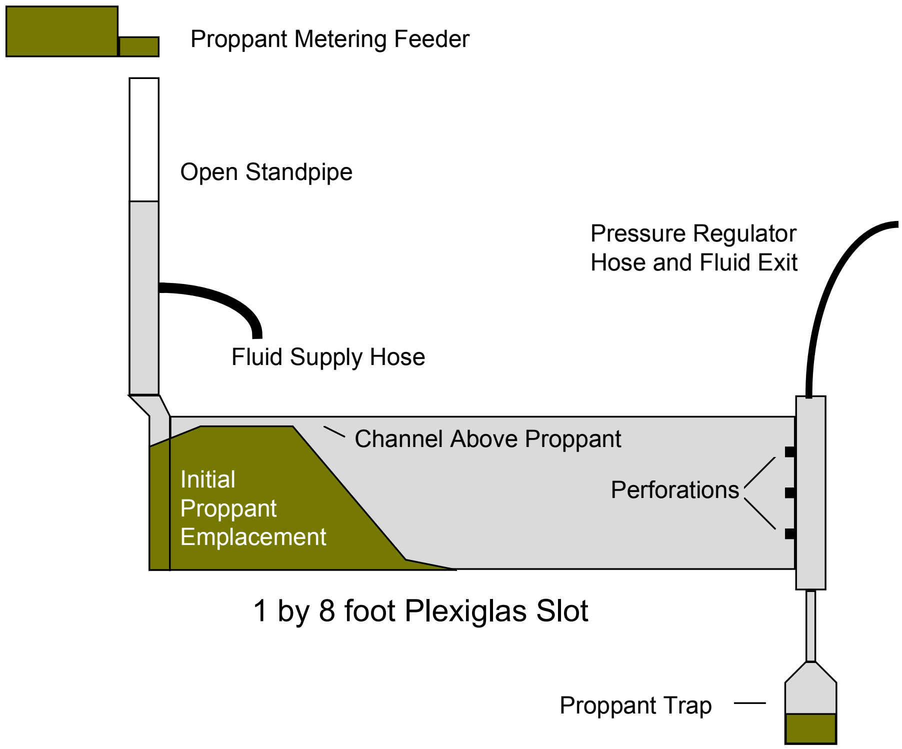


Figure 1 - Diagram of the device used in the experiments described. Proppant and fluid are added at the left where they enter over the full height of the slot. Materials exit at the right through perforations. Pressures were measured by noting the height of fluid in the stand pipe.

Proppant Transport

Velocity profile

Moving water exerts a shear stress on its bounding surfaces. Resistance to shearing controls the velocity profile of the moving fluid. In a fracture the velocity is reduced to zero or near zero at the sides and top of the fracture as the fluid transports proppant. The base of the moving fluid is confined by a permeable proppant pack. This proppant pack conducts some fluid and therefore the boundary velocity is greater than zero at the base (Figure 2).

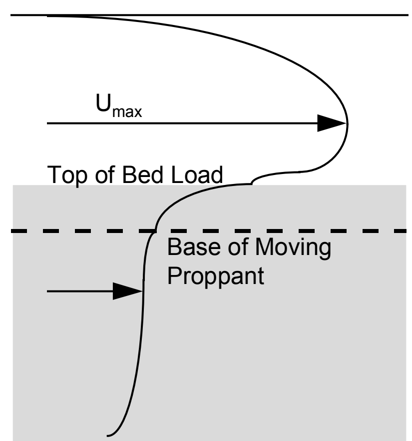


Figure 2 - Diagram of the velocity profile in the channel above the proppant pack and in the proppant pack. The upper portion of the proppant pack also moves as bed load.

Bed load and suspended load

Enough shear on the proppant causes it to move with the fluid. There is also a velocity profile for the moving proppant grains with the greatest velocity at the top and a rapid reduction in velocity to a nonmoving boundary in the proppant pack. This moving bed of proppant is called the bed load of the fluid. Grains are lifted by Bernoulli forces and these, along with inertia, lift individual grains to a laminar-turbulent boundary in the fluid. When the grain encounters this boundary it is propelled forward in a ballistic path. When this grain strikes another grain there is a cascade effect, other grains move by rolling and sliding forward.

The bed load is different from any suspended load that may also exist in a moving fluid. Particles are held in suspension by upwardly directed components of turbulent flow.

Capacity

The amount of bed load that a moving fluid can carry is a function of at least these variables:

- Grain diameter
- Grain sphericity
- Grain roughness
- Grain density
- Fluid density
- Fluid viscosity
- Fluid turbulence
- Fluid velocity profile
- Amount of suspended load
- Acceleration due to gravity

For a given fluid - proppant system the bed load is directly related to the local bulk velocity of the moving fluid. Once the relation is known between velocity and bed load, they could be used interchangeably.

Moving fluid with a given velocity will transport the same bed load, if available, either by carrying proppant that is added or eroding proppant from the underlying proppant pack.

Channel above proppant pack

When water transports proppant into a fracture, the proppant is conducted into the open fracture then immediately settles out as the velocity suddenly decreases. The sand that drops out builds toward the top of the fracture until only a small channel is present. The sand then builds forward in a series of foreset beds until the fracture is filled. The open channel remains at the top of the sand however (Figure 1).

Velocity and power

Determining the velocity of fluid transporting proppant in a fracture is a difficult exercise. In general, the bulk of the fluid is traveling in a channel above the proppant pack, though a small amount is also traveling through the proppant pack and is being lost through leak-off in the fracture walls. The bulk fluid velocity is approximately the bulk fluid rate divided by the cross sectional area of the open channel at the top of the proppant pack. The minimum sized area would give the greatest velocity for a given flow rate and would be measured to the top of the moving bed load. The maximum sized area would be measured to the base of the moving bed load. Because the flow is partitioned between these and other zones and there is a velocity profile in the open channel and the proppant pack, it is difficult or impossible to measure an exact velocity to associate with a given bed load. We avoided this problem in part by simply recording minimum and maximum bulk velocities.

Velocity is also determined by the rate of fluid forced into the fracture. A higher velocity can be obtained by increasing the rate, but this will require a greater pressure. Since higher sand delivery rates equate to higher velocities, it follows that higher sand delivery rates will require higher pressures as well. The product of fluid velocity and shear stress is defined as stream power. Power can also be thought of as being generated by rate and pressure.

Experimental results

For each experiment performed the following data were recorded:

- Water flow rate
- Sand delivery rate
- Pressure head
- Height of channel to top of bed load
- Height of bed load

These data are in tables at the end of this report and are summarized in figures.

Relation of proppant and fluid rates

Figure 3 shows proppant delivery rate versus maximum and minimum velocities calculated from the top and base of the bed load for 20/40 Ottawa sand. Figure 4 is a similar graph for 16/30 Carbolite proppant. The trends of these graphs show the relation between bed load and velocity for these two proppant types in water and for 16/30 Carbolite in a 20 lb guar fluid.

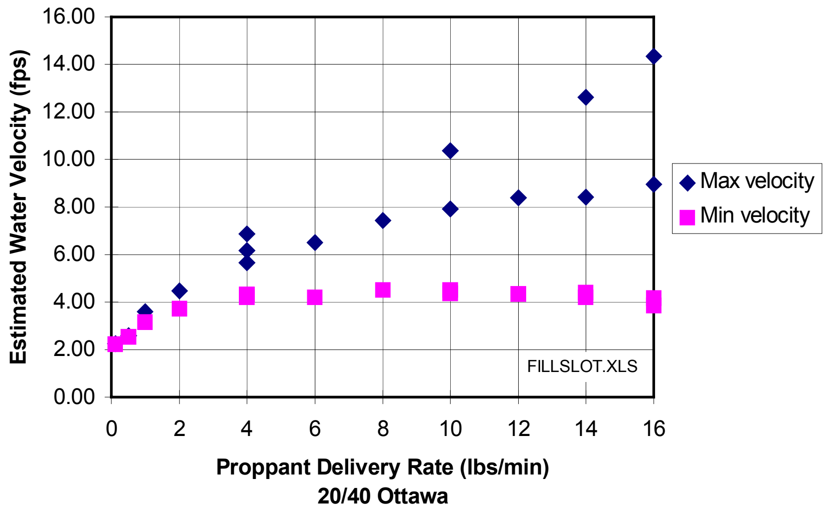


Figure 3 - Proppant delivery rate versus calculated fluid velocity for experiments with 20/40 Ottawa proppant. Fluid velocities are average velocities calculated on the cross sectional area of the open channel above the bed load for maximum velocity and for the cross sectional area of the channel and moving bed load for the minimum velocity. The effective velocity is somewhere between these two extremes.

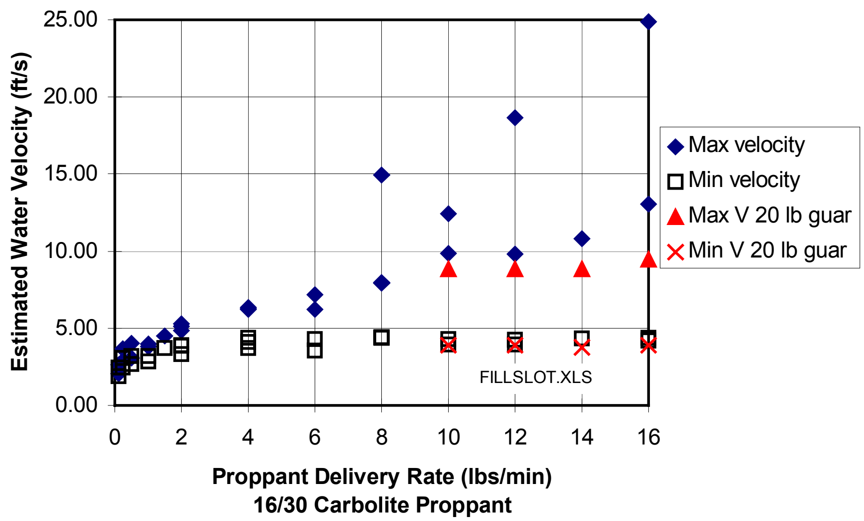


Figure 4 - Proppant delivery rate versus calculated fluid velocity for experiments with 16/30 Carbolite proppant. Fluid velocities are average velocities calculated on the cross sectional area of the open channel above the bed pack for maximum velocity and for the cross sectional area of the channel and moving bed load for the minimum velocity. The effective velocity is somewhere between these two extremes.

The velocity at a proppant delivery rate of zero corresponds to the minimum velocity required to move the proppant at the top of the proppant pack. This velocity is near 2 ft/s for nearly all types of proppants.

As sand is added, the channel height above the sand decreases and the bed load height increases. Decreasing channel height translates to a higher velocity since the flow rate is constant. Increasing height of bed load is reflected in the flattening of the minimum velocity points in Figure 3 and Figure 4. At high proppant delivery rates, the channel height was very small. That means that a small difference (1 or 2 mm) in measurement is a large proportion of the total channel height and produces a large difference in calculated velocity. The precision of the velocity number decreases with increasing velocity.

Addition of guar to increase the fluid viscosity had a small effect on the velocity required to move proppant. Figure 4 shows that both the maximum and minimum calculated velocities are slightly lower than for water. This suggests that increased viscosity increases the shear transmitted to the bed load.

Relation of proppant rate and bed load height

Figure 5 shows the proppant delivery rate versus the height of the bed load. Recall that the proppant delivery rate is directly related to fluid velocity. The bed load height varies only a little between the two proppant varieties tried. 16/30 Carbolite generally has a thicker bed load development for a given proppant delivery rate. This graph also shows that to deliver 16 lbs/min of proppant requires a bed load height of 1.75 to 2 cm. This is an important concept in understanding screen out.

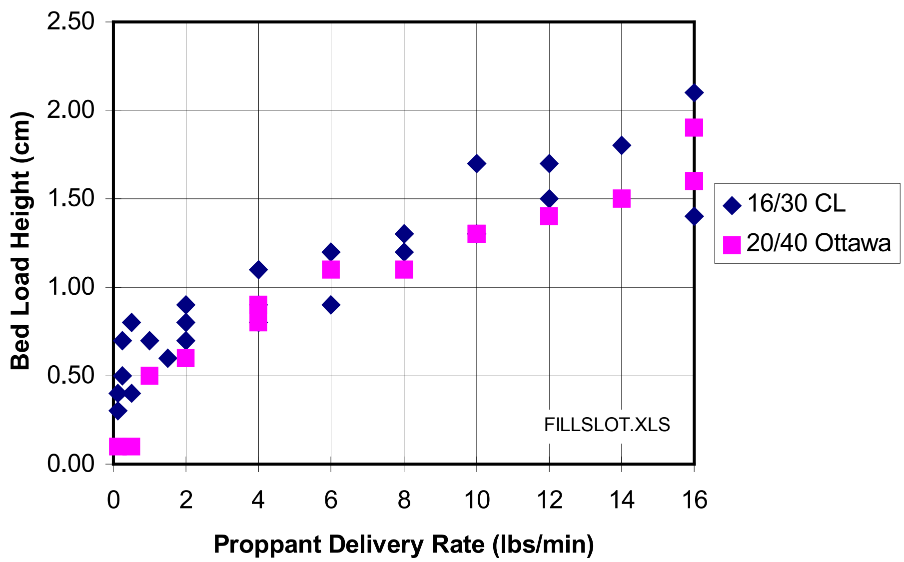


Figure 5- Proppant delivery rate versus height of bed load for all experiments. Proppant delivery rate is equivalent to effective velocity in that a single velocity is required to achieve a single proppant delivery rate for a given fluid-proppant system.

Relation of proppant delivery rate to fluid pressure

We monitored the pressure head at equilibrium proppant and fluid rates. The proppant delivery rate (equivalent to velocity) is plotted against excess pressure in Figure 6. Excess pressure is the pressure greater than that required for 1/8 lb/min at a given flow rate and sand type. As expected, to achieve a higher proppant rate (fluid velocity) requires a higher pressure.

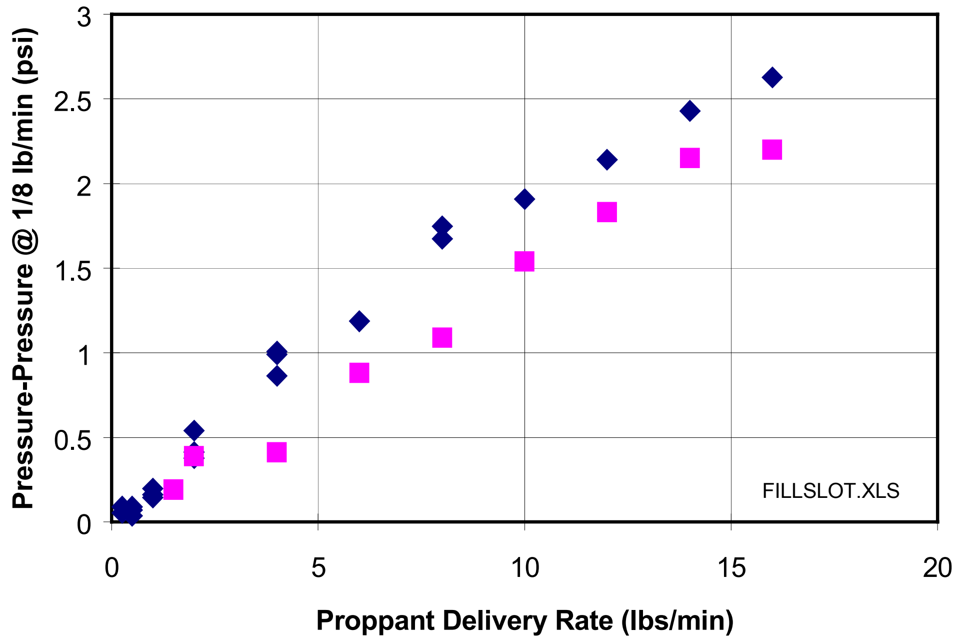


Figure 6 - Proppant delivery rate versus pressure greater than that measured in the experimental system for proppant delivery rates of only 1/8 lb/min. This shows the increasing pressure required to maintain a high velocity.

Discussion

Thin fluids transport proppant grains by traction at the top of the proppant pack. At nearly any sand and fluid rate, sand is transported through the perforation and into the fracture. This sand builds up immediately near the well until it reaches nearly to the top of the fracture. As the proppant buildup approaches the top, it restricts the flow, and velocity through the channel increases. The increase in velocity transports sand through the channel and out into the fracture. As the proppant continues to build, the channel lengthens into the fracture.

Any specific combination of fluid pressure and rate translates to a given stream power and ability to maintain a velocity. A certain fluid power is able to maintain a velocity (bed load) but can be overloaded at higher bed loads unless pressure also increases. We now see the interplay of pressure, fluid rate and proppant rate for thin fluids.

One limit on pressure may be the fracture extension pressure. If the channel increases in height, velocity will immediately decrease and sand delivery will decrease. This may cause screen out near the well or in the tubing. Any other decrease in pressure will have the same effect on velocity and the ability for the fluid to carry sand as bed load.

Another limit may be from leak-off or other diversion of the flow into the proppant pack. As fluid rate in the channel above the proppant pack decreases, velocity decreases. This means less velocity downstream and causes a potential for less sand delivery potential downstream. Screen out away from the well may occur by this mechanism.

In our slot model, proppant delivery rates of 8 lb/min require velocities of 4 to 8 ft/s. Proppant rates of 16 lb/min require 6 to 14 ft/s. A typical fluid rate in a frac job is 40 bbl/min (1680 gal/min) with 1 lb/gal of proppant (1680 lbs/min). Extending our data show that at these rates the bed load thickness is 12 cm (Figure 7) and the excess pressure would be around 100 psi (Figure 8).

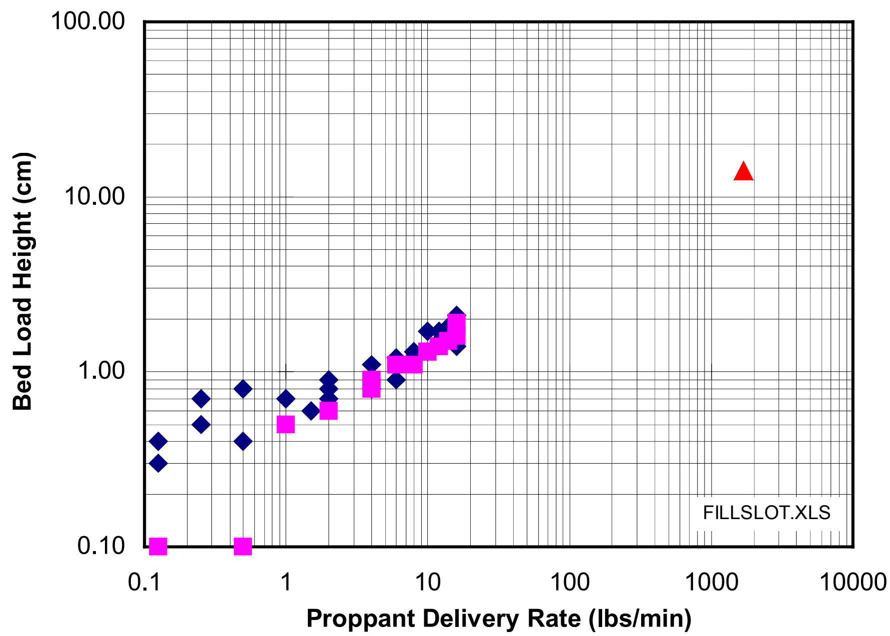


Figure 7 - Extrapolation of data trend to frac job rates showing the point where 1 lb/gal proppant with 40 bbl/min fluid rate plots (triangle). The expected bed load height in the fracture would be near 20 cm (8 in).

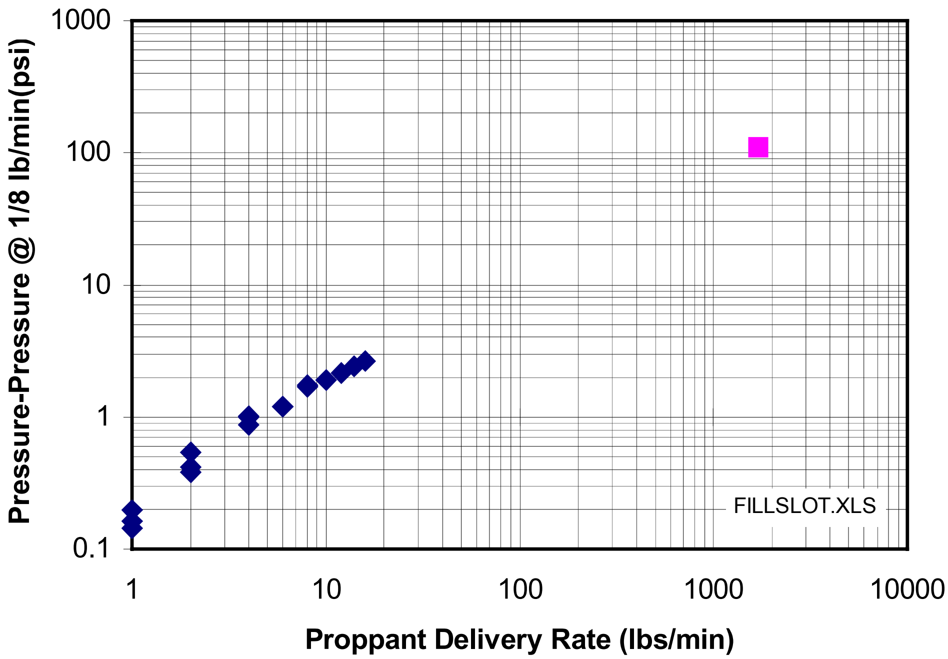


Figure 8 - Extrapolation of excess pressure required to achieve necessary effective velocity. The square shows a typical frac job rate of 1 lb/gal proppant with 40 bbl/min fluid. Excess pressures required to maintain the necessary velocity are not great (100 psi).

Appendix 1 (a)

The following table contains the raw data analyzed in this discussion

Prop Rate lbs/min	Fluid Rate gpm	P-P @ 1/8 lb/min	Base Channel (cm)	Base Moving Proppant (cm)
16/30 Carbolite – Water				
16	5		1	3.1
14	4.98		1.2	3
12	4.89		1.3	3
10	4.92		1.3	3
8	4.9		1.6	2.9
6	4.95		1.8	3
4	5.05		2.1	3.2
2	5.09		2.6	3.4
1.5	5.01		2.9	3.5
16/30 Carbolite – Water				
4	2.86		1.2	2
6	2.86		1.2	2.1
8	2.86		0.5	1.7
10	2.86		0.6	1.9
12	2.86		0.4	1.9
16	2.86		0.2	1.7
16/30 Carbolite – Water				
8	4.86	1.746	1.6	2.9
4	4.87	0.864	2	2.9
2	4.85	0.378	2.6	3.3
1	4.91	0.144	3.2	4
0.5	4.93	0.036	3.2	4
0.25	4.93	0.09	3.5	4.2
0.125	5.01	0	5	5.3
16/30 Carbolite - Water				
2	3.05	0.54	1.5	2.4
1	3.07	0.198	2.1	2.8
0.5	3.07	0.09	2.6	3
0.25	3.1	0.054	2.80	3.3
0.125	3.1	0	3.9	4.3
20/40 Ottawa Sand - Water				
4	4.97	0.99	2.1	3
12	4.83	2.142	1.5	2.9
4	4.99	1.008	2.3	3.1
16	4.81	2.628	1.4	3
14	4.84	2.43	1.5	3
10	4.85	1.908	1.6	2.9
8	4.85	1.674	1.7	2.8
6	5	1.188	2	3.1
2	4.98	0.414	2.9	3.5
1	4.97	0.162	3.6	4.1
0.5	4.96	0.072	5	5.1
0.125	4.94	0	5.7	5.8
Cont.				

20/40 Ottawa Sand - Water				
14	3.87		0.8	2.3
16	3.85		0.7	2.6
10	3.97		1	2.3
4	3.96		1.5	2.4
16/30 Carbolite – 20 lb gel				
16	5.08		1.4	3.4
14	5.08		1.5	3.5
12	5.08		1.5	3.4
10	5.08		1.5	3.4

References

Howard, G.C. and Fast, C.R.: 1994, "Propping Agents for Hydraulic Fracturing," Monograph, *Hydraulic Fracturing,* New York, Dallas, (1970)2,.89.

Kern, L.R., Perkins, T.K., and Wyant, R.E.: 1959, "The Mechanics of Sand Movement in Fracturing," *JPT* (Oct. 1959) 216, 403-405.

Appendix 2

4.9 Large-Scale Single-Phase Flowback Evaluation in Vertical Slots

4.9.1 Introduction

A series of experiments were performed to investigate proppant flowback in water. Three slot models and miscellaneous other devices were used with a range of proppants. Goals of these tests are to describe the processes active during flowback in a fracture system and to develop equations to predict the initiation and amount of proppant flowback for a given set of conditions.

4.9.1.1 Definition of flowback

In general, this report uses the term flowback as the transfer of proppant from the fracture to the well bore. Flowback is the result of three processes, erosion, transport, and shearing of the grain bed. These three processes may act simultaneously in different parts of the fracture. Since there are multiple processes and areas where they work, proppant flowback may be too general of a term and should be qualified if the process or zone where flowback is occurring is known. Control of proppant flowback can be accomplished by inhibiting either shearing, erosion, or transport in the perforation or fracture.

4.9.1.2 Conditions of tests

Tests were done using a variety of fracture and perforation models. The fracture slot models are constructed of Plexiglas and metal sheets separated by spacers. One slot is 5/16 inch wide, 1 foot tall, and 8 feet long. Another is 3/16 inch wide, 6 feet tall, and 0.5 feet wide, and the third is 7/16 inch wide, 36 inches tall, and 10 inches wide. A range of proppant sizes and types were used.

4.9.2 Divisions of the fracture-perforation system

The fracture model shows three distinct zones. In each zone there is a unique process of proppant movement. These areas have been categorized as Zones I, II, and III and are described below. By analogy, these three zones are proposed to be present in a fractured well. Data for each zone is first summarized and then discussed in increased detail.

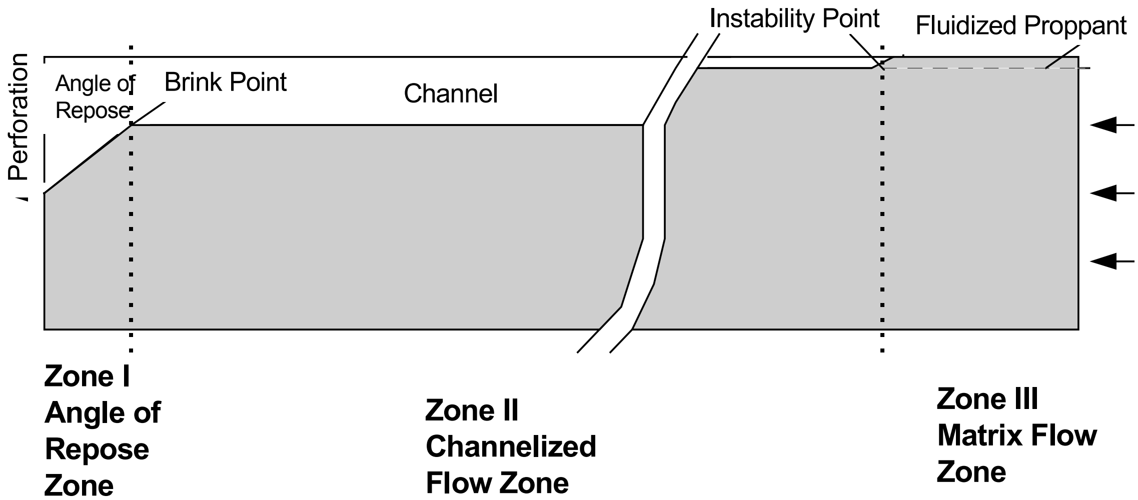


Figure 0-1 The major features discussed in the text are identified in this view of the fracture slot model. Fluid enters along the entire height at the right and exits through a single 5/16 inch diameter perforation at the left. The figure shows an example of Zone III at the right. This zone only exists for a short time at the beginning of the experiment.

4.9.2.1 Zone I - Angle of repose

Zone I includes the perforation and the fracture near the perforation. The lateral dimensions of this zone are defined by the angle of repose of the proppant in the fracture and the height of the proppant in the fracture. Zone I extends from the perforation up to the brink point at the angle of repose. The submerged angle of repose, measured for a variety of proppant grains ranges from 30° to 39°.

A separate set of experiments were performed to investigate the origin of proppant production from the perforation. After the angle of repose is established however, proppant moves in Zone I by slumping or grain flow to the angle of repose.

4.9.2.2 Zone II - Channelized flow

Zone II is defined by the presence of a channel, or proppant-free conduit, above the proppant pack. This zone comprises most of the length of the model and probably is also the dominant zone in a fractured well. Proppant moves in response to the shear stress generated by the moving fluid in the channel. In summary, the channel base is eroded until an equilibrium height is reached for a given velocity. If velocity decreases, the channel is stable. If velocity increases, the channel depth increases.

Most sand erosion and transport is from this zone.

4.9.2.3 Zone III - Matrix flow zone and instability point

Zone III contains proppant all the way to the top of the fracture model. This zone is only stable at very low flow rates in the slot model. Once velocities and pressure differentials are high enough, a thin channel rapidly forms and generally propagates the entire length of the fracture model. Proppant at the propagating end of the channel is very unstable and this division between Zones II and III is called the instability point in this report.

Zone III may not exist in a real world fracture due to compaction and inability to place a grain of proppant in a channel if the channel is only as tall as the diameter of a proppant grain. If Zone III exists in a well, it would only be present for a short time during initial production or would be located distally from the well bore. Initial proppant movement appears to be in a thin fluidized bed that forms at the top of the proppant pack, where streamlines of flow in the proppant converge at the instability point and where maximum pressure drop occurs.

The instability of Zone III is enhanced with a single fluid phase, the conditions examined in this report. If gas and liquid are present, Zone III will be more stable and Zones I and II, as defined here, may not exist.

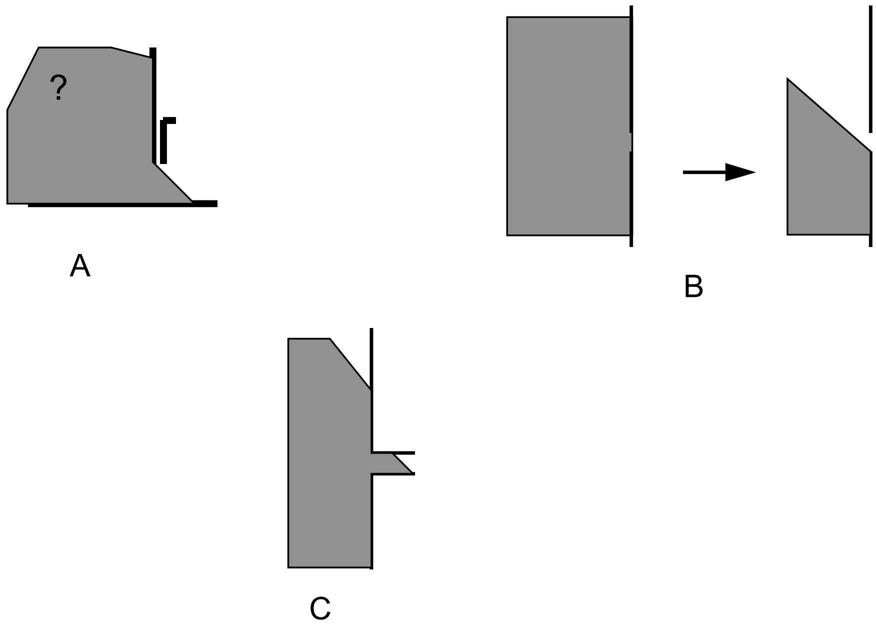
4.9.3 Zone I

When the experiment begins the slot is full of proppant and saturated with water. There is no flow or differential pressure through the proppant pack. What initiates or inhibits spontaneous flowback of proppant at the perforation at this point in time?

4.9.3.1 Spontaneous flowback and the angle of repose

Cohesionless grains will flow out of a reservoir until their angle of repose is reached. This angle is independent of the amount of material in the reservoir. Consider the model shown. If you open a gate at the base of the reservoir of proppant, can you tell how much proppant is in the reservoir by the appearance of the material that forms the slope at the base?

If there is no floor for the proppant to establish an angle of repose in front of the perforation, proppant will spontaneously flow out until the angle of repose is reached behind the perforation. If the perforation is of adequate length for an angle of repose to develop within the perforation tunnel spontaneous flow of proppant will be arrested.



Illustrations of the importance of the formation of an angle of repose at the perforation to inhibit spontaneous flowback of proppant. A) The amount of material that forms the angle of repose is independent of the amount of material in the reservoir. B) If there is no platform on which to develop an angle of repose the material will spontaneously flow out until and internal angle of repose develops at the base of the perforation. C) If an angle of repose can form in the perforation tunnel proppant production is arrested independent of the amount of proppant behind the perforation.

Angles of repose were measured in Zone I during flowback tests. They ranged from 30 to 39° depending of the proppant, but were constant to within ±1° throughout each test. The measurements are tabulated below by proppant type. Temperature (fluid viscosity) did not affect the angle of repose, but no attempt was made to predict the angle for given proppants.

Angle of repose for proppant types used in tests.

Mesh Size	Proppant	Diameter (mm)	Angle of Repose(°)
40/60	Badger	0.3	33
18/20	Bauxite	0.95	35
20/40	Ottawa	0.6	34
12/20	Badger	1.1	39
16/20	Carbolite	1	30
16/30	Ottawa	1	30

4.9.3.2 Effect of closure on spontaneous flowback

An experiment was performed to evaluate the effect of closure on the initiation of spontaneous flowback. Dry sand was placed between 100 in^2 platens oriented vertically. The sand was held in the device by sealing the margins with tape. Closure up to 4000 psi was then placed on the platens. After closure pressures were established a small "perforation" was made in the tape near the base of the slot. Sand flowed out of the "perforation" until it established an angle of repose on a small platform positioned in front of the perforation.

The experiment is complicated by crushing of the proppant near the center of the platen, but clearly shows that proppant near unconfined margins is free to move by the force of gravity to its angle of repose.

4.9.3.3 Fluid movement through the perforation

Observations of the slot model with a visible cross section of a perforation shows that there is always a small channel at the top of the perforation. Since this channel is more conductive than the proppant pack, flow is concentrated along the top of the perforation. This is illustrated in the video. Concentration of flow increases the impact of even small flow rates and decreases the effect of perforation diameter.

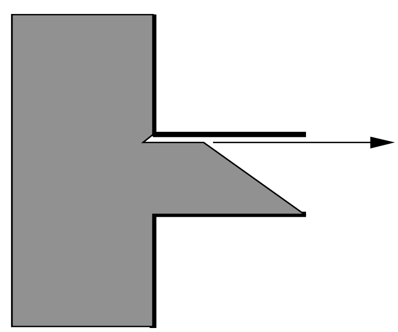


Illustration of the channel at the top of the perforation and the location of flow through this channel illustrated by the arrow.

As proppant is produced from the top of the perforation, grains move into that space from the reservoir of proppant in the fracture. The proppant column then collapses near the perforation. Collapse is nearly vertical at first and the collapsing column only widens about 1 inch for every 24 vertical inches.

4.9.3.4 Initiation of flowback at the perforation

Introduction - Two slot models and one other device made of pipe were used to investigate the initiation of proppant movement at the perforation. One slot model is made of two pieces of Plexiglas six feet tall one-half foot wide, separated by a 1/4 inch spacer. A 1/4 inch hole was drilled in the spacer to simulate a perforation. This model was used to evaluate whether the height of the proppant pack influences the initiation of flowback.

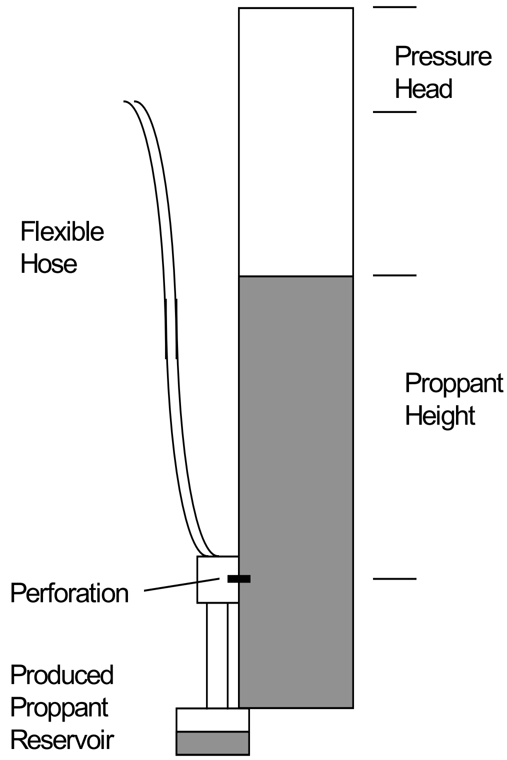


Diagram of the 6 by 0.5 foot slot model. Pressure head is adjusted by the height of the flexible hose on the low pressure side of the perforation. A constant water level is maintained on the high pressure side of the slot. Proppant heights up to 4 feet are possible in this apparatus.

The second slot model is made of two sheets of Plexiglas separated by 7/16 inch spacers. The spacers separate the slot into two halves connected by a 7/16 inch space simulating a perforation. This slot was made to be able to see what is taking place in a perforation and to compare initiation flow rates between proppant types.

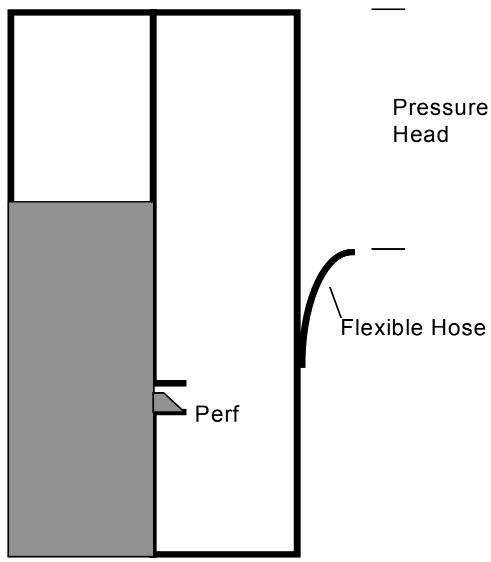


Diagram of the 36 by 10 inch slot model. When the critical flow rate is reached through the perforation, proppant flow is visible.

A device was constructed to compare proppant flow through a variety of perforation sizes and shapes. A 2 inch diameter stand pipe is attached to an elbow. Various inserts simulating different perforation types can be placed in the elbow. The flow rate is adjusted by varying the height of a flexible outlet tube.

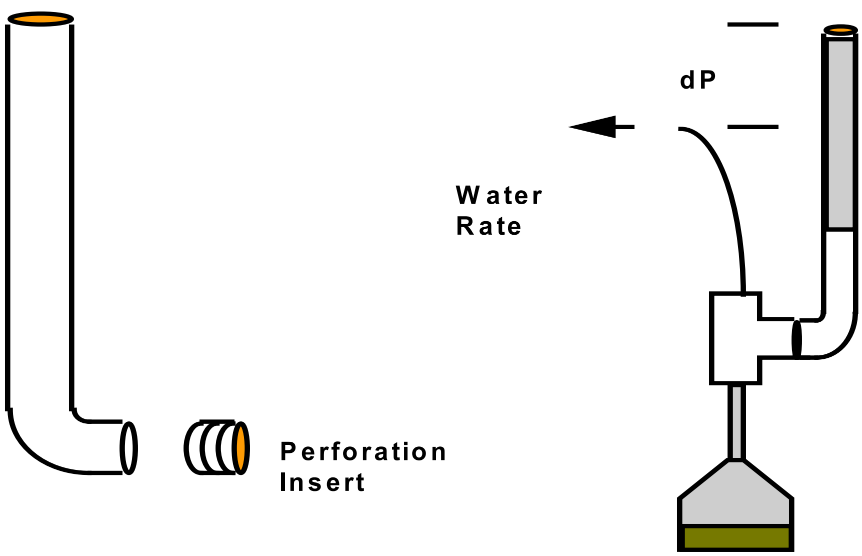


Diagram of the pipe model. Inserts consist of various sizes and shapes of pipe epoxied into a short nipple and screwed into the elbow at the base of the standpipe.

Summary - These models show the physical processes that characterize and control flowback through and near the perforation tunnel. In summary:

1) Spontaneous flowback is controlled by the presence of a stable angle of repose. If the floor of the perforation tunnel is too short for an angle of repose to develop, proppant will spontaneously fall out of the perforation.

2) The models show that flowback through the perforation mostly depends on flow rate (actually shear velocity) and depends little on the differential pressure developed in the proppant pack.

3) It can be seen that proppant movement in the perforation tunnel is due to shear forces of fluid flowing through a small channel at the top of the perforation.

4) Since most of the flow rate is at the top of the perforation, the highest velocities are also there. The velocity profile in the perforation tunnel is complex and not well understood at this point. Perforation shape has a great effect on the velocity distribution in the perforation.

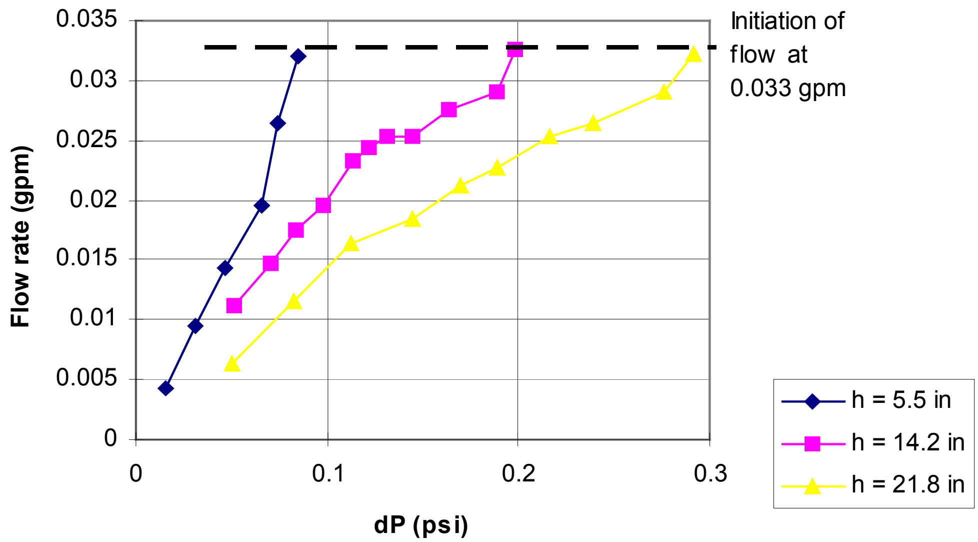
5) The flow rate required to initiate proppant movement through a perforation is around two times that required to maintain proppant movement.

6) Flow rates required to initiate proppant movement depend on the proppant type and size, but generally increase with increasing diameter.

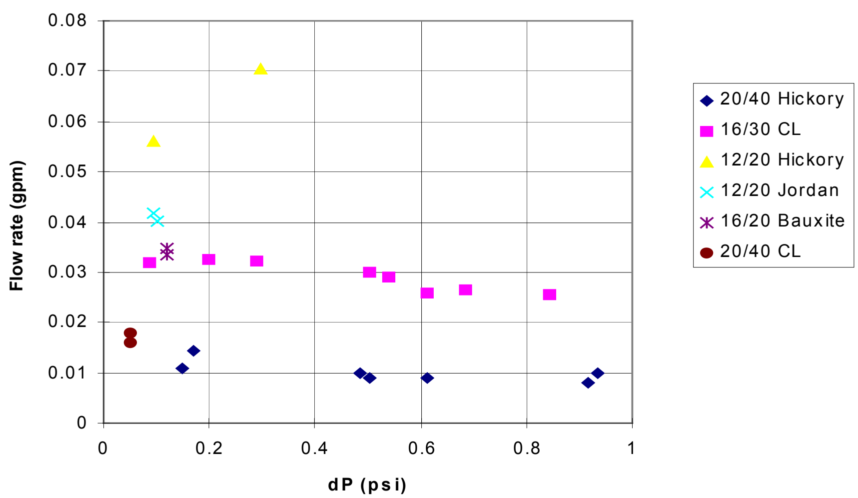
Relative effects of differential pressure and flow rate - Several tests were performed to determine the relative importance of fluid pressure differential and flow rate in the initiation of flowback at the perforation. Proppant was loaded to different heights in the 36 inch high and 6 foot high slot models and the differential pressure and flow rates measured for a number of steps until flowback occurred. These results are shown. The graphs show that the initiation of flowback occurs at nearly the same flow rate for each height of proppant, but that the differential pressure required to achieve that flow rate varied. This supports the conclusion that the initiation of flowback is dominantly dependent on flow rate (velocity) and is only slightly influenced by differential pressure developed in the proppant pack.

A steady pressure head was established by adjusting the height of the water column on the exit side of the perforation. The flow rate was sampled over a 30 second interval and recorded for that constant differential pressure.

Most sand types give fairly consistent results between runs. The least consistent initiation rates were with 12/20 Hickory, which also had the highest required rates for initiation of movement.



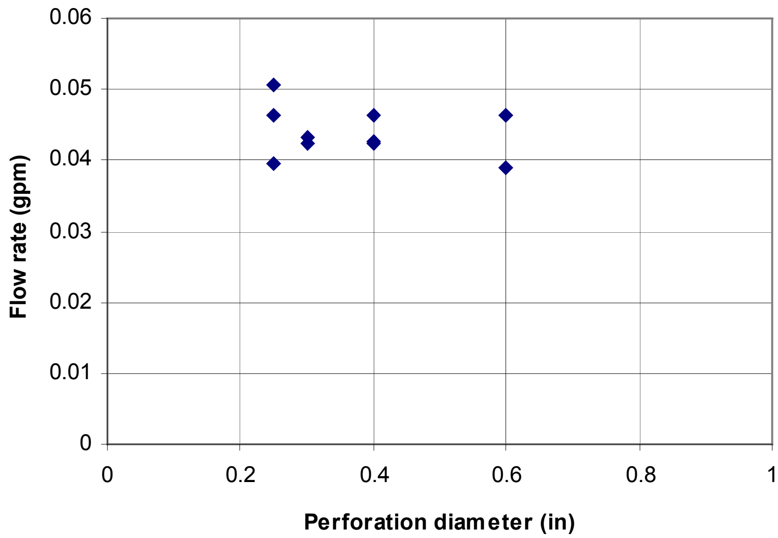
Graph of dP through the proppant pack versus flow rate for flow through three heights of 16/30 Carbolite proppant in the test slot. Each point represents a stable pressure head-flow rate measurement up to the point of initiation of flowback. The three curves illustrate that flowback is dominantly rate (velocity) dependent rather than pressure dependent.



Graph of dP through the proppant pack versus flow rate for several types of proppant. Different pressures are generated by varying the height of proppant in the slot. Points with pressures greater than 0.4 psi are data for a 1/4 inch round perforation. Points below 0.4 psi are for a 7/16 inch square perforation. The trends suggest there is a slight decrease in required flow rate with increasing dP.

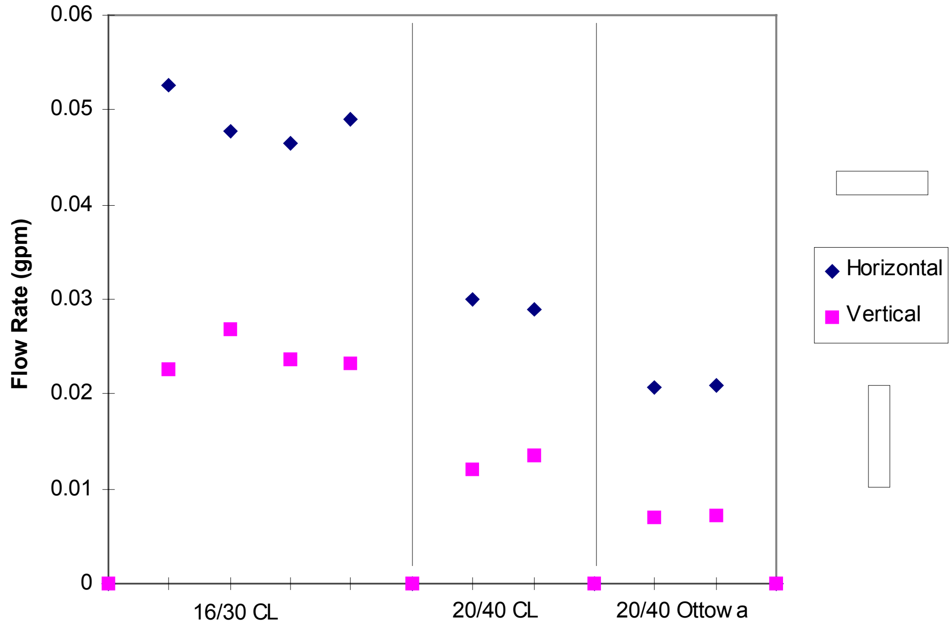
Independence of initiation flow rate to perforation size and length - Four perforation diameters were compared using the pipe device. Each diameter gave a similar rate for a given proppant type.

Flow rates for the pipe device are slightly higher than for the slot models. The higher rates are interpreted to be due to the greater difficulty in maintaining a constant pressure head in the pipe device.



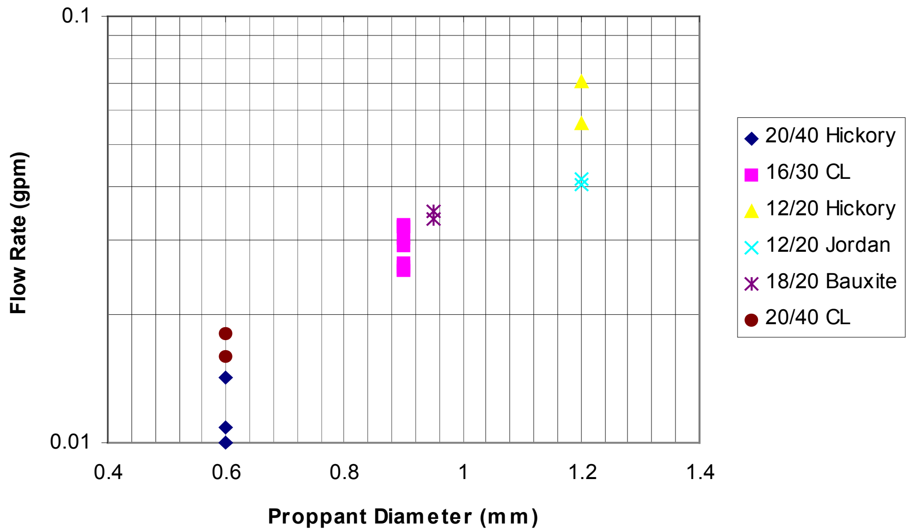
Initiation flow rates for four sizes of perforations for 16/30 Carbolite proppant in the pipe device. These rates are in a narrow and low range and are similar between perforation sizes.

<u>Dependence on perforation shape -</u> While differences in diameter have little effect on the flowback initiation rates, the shape of the perforation does affect initiation. To test this effect an insert was made for the pipe device that consists of a "perforation" that is a rectangle 1.5 by 0.2 inches in size. The rectangular opening was oriented vertically and horizontally and the initiation flow rates measured. A horizontal orientation requires over two times the bulk flow rate that a vertical orientation does. The vertical orientation is similar to that of a circular shape opening.



Flow rates for the initiation of flowback at the perforation for horizontally and vertically oriented rectangular "perforation". Three sand types are shown.

<u>Dependence on proppant diameter -</u> Data from the experiments on the initiation of flowback in the perforation tunnel shows that there is a general increase in the flow rate required to initiate proppant movement that depends on proppant diameter and to a smaller degree on the type of proppant. This dependence is interpreted to exist because, larger proppant grains result in a larger channel at the top of the perforation so more flow is possible at a lower velocity. Results are plotted below.



Average proppant diameter versus flow rates for initiation of proppant movement in the perforation tunnel. Data labels show proppant types and mesh sizes.

Application to petroleum production - Based on these experiments, the initiation of flowback at the perforation requires a rate of about 0.033 gpm per perforation for 16/30 proppant. Rates to maintain flowback are difficult to measure accurately, but are about one-half of that required to initiate proppant movement. This means that a typical frac job that is flowed back at 1 bbl/min (42 gpm) would require over 1200 perforations to reduce the average rate below the threshold of initiation. For 20/40 proppant it would take over 2500 perforations. These are clearly more perforations than are typically present.

As Zone I develops its angle of repose however, some perforations are exposed and will take a much larger proportion of the flow rate. In some situations, flow rates at perforations covered by proppant may fall below initiation rates. These numbers still suggest that if proppant is covering a perforation it will normally be produced and an angle of repose will form in the fracture in Zone I

4.9.3.5 Angle of repose zone in the fracture

Stable Configuration - Zone I exists near the perforation. The proppant lies at its angle of repose and extends from the perforation up to where it intersects with the channel at the brink point or the top of the fracture. The angle of repose is constant through time for a given proppant. Angles measured in the simulated fracture vary from 30 to 39° depending on proppant density, sphericity, and grain roughness.

Processes - The term brink point is used to mark where the angle of repose intersects with a channel floor. This also marks the point of flow separation for fluid that has been traveling through the channel. Velocity suddenly decreases as water depth increases. Grains that have been transported along the channel floor (Zone II) by shear forces now move in Zone I by gravity driven slumping to the perforation and out into the well bore.

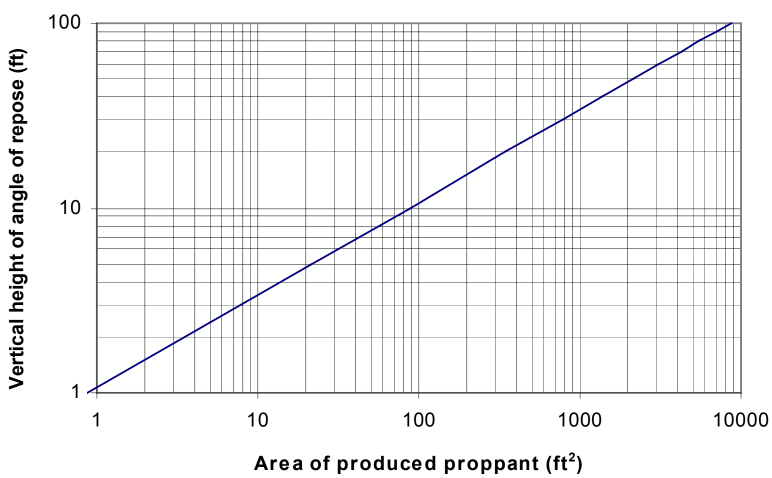
The configuration of Zone I comes to equilibrium early during the production history. After the angle of repose is established, for every grain that is transported to the top of the slope, one grain leaves through the perforation.

The angle of repose appears to be independent of sand delivery rate and flow rate. Dye shots in coarser proppant showed that some fluid moves through the proppant pack and exits the proppant pack through the angle of repose surface. This should decrease the angle of repose slightly due to additional buoyant forces, but these effects were not measurable in the model and are considered to be negligible.

Initiation of flowback in zone I - When a certain flow rate is reached, a small amount of proppant is produced through the perforation. Proppant then collapses vertically to fill this void. Production and collapse continues until a stable angle of repose is reached.

Application to petroleum production - Zone I always forms first. Based on the model observed, if proppant is being produced with single phase fluid flow, for any significant length of time, a stable Zone I has been established.

The volume of proppant produced from Zone I can be easily calculated if you assume the proppant extends at its angle of repose from some perforation to the top of the original sand level in the fracture .



Relation between the wall area of produced proppant to the vertical height of the angle of repose at 30°. The area times proppant loading gives the pounds of proppant produced assuming the entire zone is cleared of proppant.

Some questions arise when considering the geometry of and processes in Zone I. Is the anchor corner of the angle of repose always at the lowest perforation? The model used had only one perforation. Previous work with models with multiple perforations suggests that flowback would occur from each perforation until the angle of repose is anchored at the lowest perforation. It may be possible that the upper perforations could easily handle the produced fluids and reduce velocity and differential pressures to low enough levels that proppant would not be produced from lower perforations.

At high flow rates would fluid flow back into the slip face and stabilize those grains or would there be more flow out of the slip face to destabilize it? In tests for this report, such a small proportion of flow was through the proppant pack that it had little apparent effect on the angle of repose. Minor flow both into and out of the slip face at different flow rates and similar rates were observed using dye shots.

Does closure affect the geometry or processes in Zone I? Our experiments with proppant between vertical plates suggest that closure has no significant effect on uncrushed proppant near boundary of the proppant pack. Crushing of proppant does alter its grain size and shape so that its angle of repose is affected due to the increased internal angle of friction in angular grains and the effect of electrostatic forces between small particles.

4.9.4 Zone II

4.9.4.1 Introduction

After proppant is emplaced it is stable in Zone II as long as there is no spontaneous flowback and fluid production rates are very low. As fluid begins moving faster, it removes proppant from the top of the perforation tunnel and allows proppant near the well bore to be produced until the angle of repose is reached for the proppant in the fracture that is near the well bore. Fluid movement will also erode proppant from the top of the proppant pack. Once a channel forms above the proppant pack, nearly all of the flow is diverted away from the proppant pack to the channel. This flow continues to erode proppant grains from the top of the proppant pack until an equilibrium channel height is established for a given flow velocity. The channel height can be predicted in the slot model from the bulk flow rate. The 2 by 8 foot slot was used to describe channel development in Zone II.

All tests were run by flowing water through water saturated proppant. Only a single liquid phase was used. Any air bubbles that appeared in the slot were vented from the top of the model. The proppant was packed as densely as possible by loading the proppant into a water-filled slot, with simultaneous mechanical vibration.

Tests were run using the following proppants and test conditions.

Proppant types, size, and water temperatures used in the flowback tests to determine relation of channel height to flow rate

Proppant	**Mean Size (mm)**	**Density (g/cc)**	**Water Temperature (°F)**
40/60 Badger	0.3	2.65	60
20/40 Ottawa	0.6	2.65	60
20/40 Beads	0.6	1.05	57
16/30 Ottawa	0.9	2.65	69
18/20 Bauxite	0.9	3.56	65
16/20 Carbolite	1.0	2.71	70
16/20 Carbolite	1.0	2.71	175
12/20 Badger	1.2	2.65	70

4.9.4.2 Channelized flow zone

Definition - Zone II has an open channel across the top through which most fluid travels. A channel is a conduit with walls formed by the subparallel sides of the fracture or fracture model and base formed by the proppant grains. It is located at the top of the accumulation of water saturated proppant (proppant pack). The top of the channel is a smooth spacer in the model. In an actual fracture, the top boundary is unknown but presumably is formed when the fracture walls narrow together and meet.

In its stable configuration, the proppant bed is a planar surface with no additional erosion or no sand movement. Channel height is most strongly controlled by flow velocity for normal proppant sizes and densities.

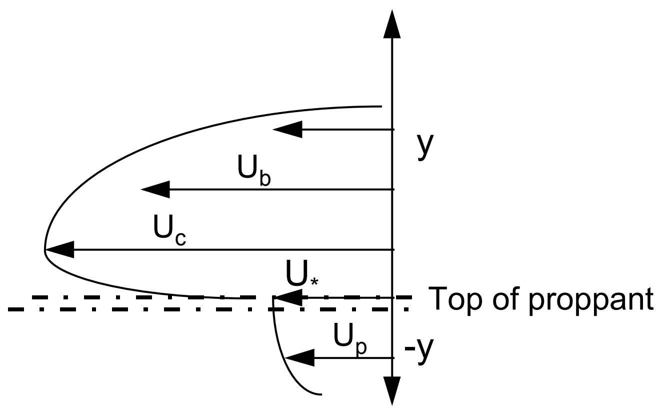
Processes - If proppant grains can be moved (eroded) from the channel base they will be transported down the channel and out the perforation. Sand added to the channel will also be transported out. Erosion occurs if the shear stress (T_o) of the moving fluid can move a proppant grain on the bed. The critical shear stress parameter can be converted to a more easily conceptualized threshold velocity (U_*). Threshold velocity can be related to bulk velocity (production rate) and channel height (h) by an understanding of the velocity profile in the fracture.

At stable flow rates (constant velocity) the pressure force of the fluid being produced is equal to the drag (shear force) on the perimeter of the fracture. This drag produces a complex velocity profile with minimum velocities along the perimeter and maximum velocities in the lower center of flow channel.

The height of the channel where no proppant will be eroded can be calculated if three parameters are known: 1) critical velocity for the proppant-fluid system 2) velocity profile for the fluid-fracture system and 3) the fracture width.

Threshold of grain movement - critical velocity - Initiation of grain movement on a planar bed of loose grains depends on grain and fluid density ratio; kinematic fluid viscosity; and grain diameter, shape, and surface texture. Values for the threshold of movement are shown in the Shields' diagram. These values are empirical, but have been related to Shields' β and the Boundary Reynolds number. The shear stress (T_o) required to move a given class of proppant can be determined from the Shields' diagram and easily converted to a critical velocity (U_*). Determination of U_* for a given set of fluid and proppant conditions is discussed below.

Velocity profile - Most work on velocity profiles are for open channels or pipes. Fractures differ from these systems in having a different (tall and narrow) configuration and a permeable base. Most of the shear stress is produced by the fracture walls in a narrow fracture, but the spacing between the walls (fracture width) defines the hydraulic radius parameter. It follows that the velocity profile will be mostly controlled by the nature of the fracture walls, the spacing between them, and the permeability of the proppant pack at the base of the channel. The walls comprise most of the area the shear force acts over. The velocity profile also depends on whether flow is laminar or turbulent. From dye shots, the velocity profile in the slot model has a generalized shape shown below in.



Velocity profile in a channel and in the underlying proppant in Zone 2. U_* is the threshold velocity. U_c is the maximum forward velocity and occurs in the lower third of the channel. U_b is the average or bulk velocity which occurs near the base and about one-third of the way up the channel. U_p is a velocity in the proppant pack

Turbulent flow - Fluid flow in the fracture over the range of normal well production rates is turbulent. Turbulence is induced by the rough walls and high velocities. Dye shots in the fracture model also show the flow is turbulent in the channel. Literature suggests flow over a sand-rough surface should be turbulent.

Bedforms at the base of the channel - If the velocity through a channel is increased, proppant is eroded from the base. The moving bedload of proppant forms a predictable sequence of bedforms as it is transported down the channel. The general sequence through time as proppant is removed is from upper plane beds to sand waves or ripples to lower plane beds to no movement. When equilibrium is reached, the channel floor is planar.

Bed load layer - The proppant is transported in a thin layer (bed load) immediately above the interface. Proppant was not observed to be transported as a suspended load. This bed load layer ranges from 0 to 10 mm in thickness in the slot model. Literature suggests this zone marks a change from turbulent to laminar flow near the boundary. The most unstable grains are lifted from the bed by Bernoulli forces and rise to the top of the boundary layer due to lift and inertia, where they are accelerated forward in a ballistic path. Their impact with the surface downstream causes more grains to move in a cascade effect (surface creep). If the flow is far faster than equilibrium, the bed load layer is thicker and appears to move continuously.

Buoyancy and vertically directed flow - A vertical component of flow from the proppant pack into the channel would be expected to make it easier for proppant grains to be eroded from the base of the channel. Dye shots show there is complex, but minimal, flow of fluid between the channel and the proppant pack across the proppant-fluid boundary. The complexity increases as proppant pack permeability increases and if any bedforms are present. Minor flux in both directions was observed. Most of this flow occurs near the fluid proppant interface. Away from the interface, flow through the proppant pack is fairly uniform and shows a nearly vertical velocity profile.

Flow from the channel into the proppant pack will stabilize the surface and flow from the matrix into the channel will destabilize grains at the surface. Though the flux observed is low compared to the flow in the channel, this effect may be more important in an actual fracture where fluid is being added from the fracture walls. The slot model does not simulate a natural fracture very well in this aspect.

4.9.4.3 Initiation

Velocity increase - If velocity (flow rate) is increased, erosion of the base of the channel occurs until a new equilibrium depth is attained. Proppant grains are transported to the brink point between Zones I and II as a traction carpet at the base of the channel.

When the slot model is first prepared, it is completely filled with water saturated proppant grains. As flow rate increases a thin (<1cm thick) and planar-based channel quickly propagates from the brink point back into the proppant pack. The processes occurring are not clear, but it is hypothesized that the pressure drop is greatest at the shortest flow path from source to developing channel. Flow through the proppant pack is concentrated at this instability point When some energy threshold is exceeded, the grains are suspended in a turbulent, fluidized grain flow and are transported to the channel in Zone II.

Understanding the initiation of channeling is critical to extending flowback models to multiphase conditions and to predicting how far into the fracture flowback will continue. In a real fracture, there is probably always an initial channel at the top of the proppant pack, due to settling and incomplete transport.

Bedform transitions - If there is a significant flow rate increase (factor of 2 or more) initial sand erosion and transport forms upper flow regime plane beds and appears as a smooth surface. These plane beds transition to sand waves and then ripples as channel depth increases. Most of the volume of proppant removed occurs by the migration of these bedforms. If the flow rate is only increased slightly, ripples or lower plane beds may be the first bedforms produced. In summary, moving proppant forms a predictable sequence of bedforms as equilibrium height is approached.

4.9.4.4 Calculating Channel Height (h) From Flow Rate

One goal of these tests was to predict the amount of proppant flowback for a given set of conditions. This goal can be restated as determining the dimensions of the volumes above the angle of repose in Zone I and above the channel base in Zone II. Examination of the slot model has indicated the channel height in Zone II can be predicted from flow rate in fluid saturated systems. The use of a variety of flow rates; proppant densities and sizes; and two fluid viscosities showed that channel height is mostly controlled by the flow rate and is relatively insensitive to other parameters over normally encountered conditions.

Knowledge of three parameters will allow prediction of channel height from flow rate: 1) critical velocity for the proppant-fluid system 2) fracture width and 3)velocity profile for the fluid-fracture system. The velocity profile is the most difficult item of these three to obtain. Use of these parameters is described below.

4.9.4.5 Determining Shields' β and Threshold Velocity U_*

Determining the energy required to initiate movement of a given proppant grain is the first task described. This number depends on the properties of the fluid and proppant; density, kinematic viscosity, and diameter. Shields' β is obtained from the graph below and is used to determine the critical shear stress and velocity required to initialize movement of proppant grains in the specified system on a flat cohesionless bed.

The beginning of particle movement is related to particle size d, submerged specific weight of the particle and fluid $g(\rho_s-\rho)$ or (Y_s-Y), the shear stress acting of the basal layer of grains T_o, and the dynamic and kinematic fluid viscosities, μ andν.

Required parameters are:
T - temperature to determine ν and ρ
d - grain diameter
Y_s - $\rho_s g$ for proppant
Y- ρg for fluid
ν- kinematic viscosity

The force required to move a proppant grain is a function of these parameters:

$$f[d,(Y_s-Y),T_o, \mu,\nu ,\rho] = 0$$

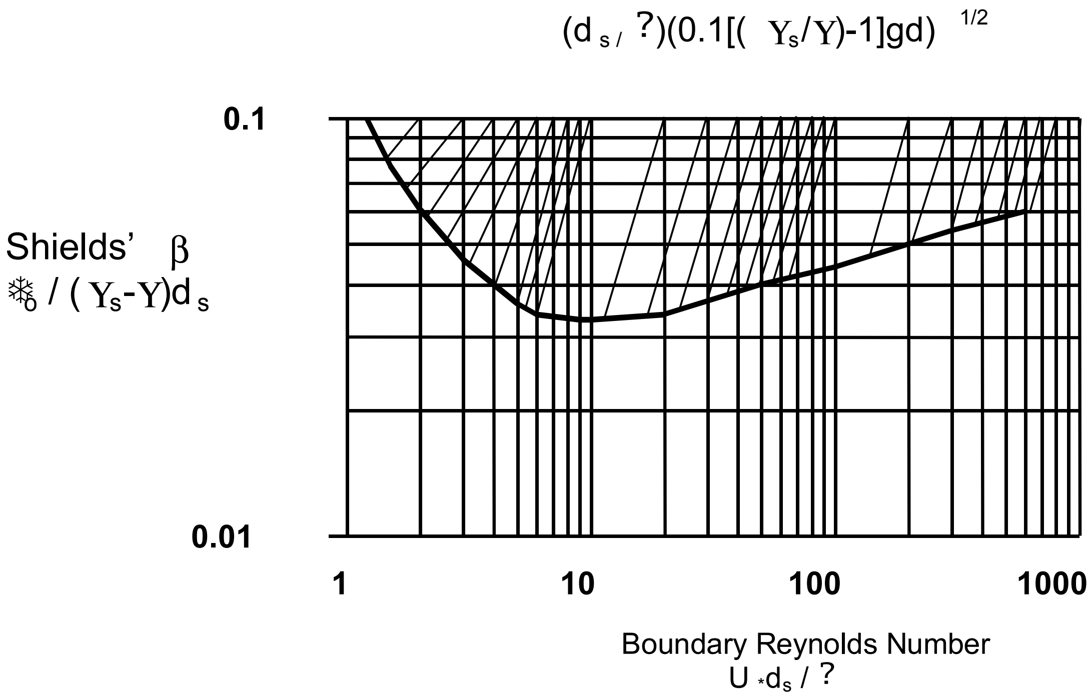
Relating these variables by dimensional analysis yields the Shields' equation

$$T_o/(Y_s-Y)d = f(dU_*/\nu)$$

where $U_* = (T_o/\rho)^{1/2}$

The left hand side of the Shields' equation is Shields' β and is the ratio of the shear stress on the bottom to the weight of the grains on the bottom. The right hand side of the equation is a "boundary Reynolds number." It is the ratio between grain size and the average thickness of the "viscous sublayer."

The graph below can be used to calculate the shear stress required to move a given sediment. The shear stress is greater at higher temperatures because the kinematic viscosity of water is reduced. Upwardly directed components of fluid flow within the proppant pack will reduce the apparent Y_s value.



Shields' diagram for obtaining U_* for given proppants and fluids. There is a small range of values for most typical proppants. To calculate the shear stress required to move a given sediment, calculate $(d/\nu)(0.1[(Y_s-Y)-1]gd_s)^{1/2}$, locate this value along the top margin of the graph, find the intersection of the Shields' curve with the projection of this value along the diagonal lines on the diagram and read off the value of β on the ordinate (from Blatt, Middleton, and Murray, 1980).

4.9.4.6. Typical Values for U_*

The range of critical velocity for water-proppant systems is not great and typical values are given in table 4.9.4.6 below. For typical proppant diameters from 0.5 to 1.5 mm the Shields' curve is at its flattest shape. Velocities given below are threshold velocities at the proppant-channel interface and may be very different from bulk velocities.

Typical U_* values in cm/s for given proppant and fluid combinations. Not all of these combinations of proppants, fluids, and temperatures were run in our experiments

		Diameter	(screen /	mm)
Proppant / Fluid	40/60 0.3 mm	20/40 0.6 mm	16/30 0.9 mm	12/20 1.2 mm
Sand (2.65 g/cc) / Water (70°F)	1.38	1.74	2.16	2.53
Carbolite (2.71 g/cc) / Water (70°F)	1.40	1.76	2.20	3.39
Bauxite (3.56 g/cc) / Water (70°F)	1.65	2.16	2.65	4.22
Sand (2.65 g/cc) / Water (180°F)	1.25	1.94	2.48	2.88
Carbolite (2.71 g/cc) / Water (180°F)	1.26	1.97	2.53	2.94

4.9.4.7. Fracture width and hydraulic radius

Fracture width is required to convert flow rate to a velocity. In the slot model the width is fixed at 5/16 inch. A fracture in a well is of course more complex and width and height may vary along its length. The flow rate volume is divided by the width and height (cross sectional area) of the fracture to determine a linear flow velocity. Fracture width also influences the velocity profile discussed in the next section.

Reynolds number is $R = \rho UL / \mu$. L is hydraulic radius which for a narrow and tall fracture is fracture width (w) divided by 2 to 4 (w/2 to w/4).
Hydraulic Radius (L) = A/P (area/perimeter). For a triangular fracture L=1/2wh / w+2h if w<<h then L = 1/2wh / 2h or L = w/4

4.9.4.8. Velocity profile

To predict the channel height, the vertical velocity profile in the fracture must be known. Shear stresses on the walls and top of the channel reduce the near wall velocities to near zero. Since there is some flow through the proppant pack, there is less drag at the base of the channel and the velocity at the top of the proppant pack is not zero. This displaces the height of maximum velocity down towards the top of the proppant.

It also follows that more permeable (conductive) proppant packs will have higher interstitial fluid velocities and have maximum flow velocities displaced more towards the top of the proppant pack. This will produce greater threshold velocities for a given flow rate and channel height. Since coarser proppants generally have higher conductivities, the change in velocity may offset the higher critical velocities needed to move larger proppant grains. Mathematical modeling of velocity profiles is underway.

4.9.4.9. Experimental Data

In the slot model, flow was established through the slot, causing proppant to erode from the top of the pack and a channel to form. Once a channel formed above the proppant it was allowed to equilibrate at least until the lower plane bed bedforms dominated the length of the slot. If necessary, the flow rate was then reduced until no there was no movement of proppant in the channel. When no proppant movement was detected along the channel base, the flow rate, channel height, differential pressures, and temperatures were recorded. The flow rate was then increased and the procedure repeated to generate the data below. Temperature, flow rate and channel height are summarized in the table below.

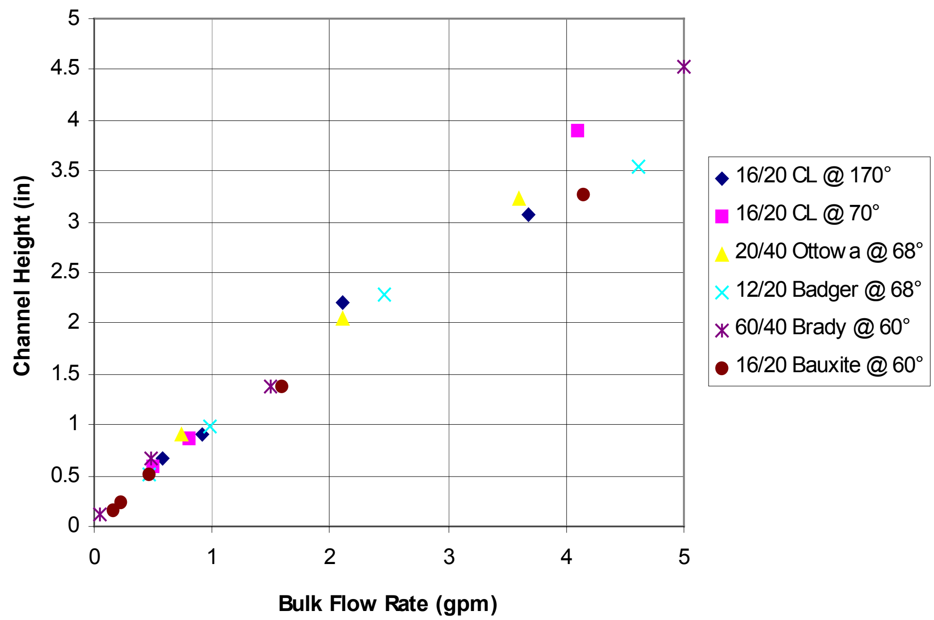
Measured flow rates and corresponding channel heights for tests for the sand type and water temperature listed.

Proppant	Temperature (°F)	Flow Rate (gpm)	Channel Height (cm)
60/40 Brady	60	0.583	1.7
		0.924	2.3
		2.113	5.6
		3.687	7.8
20/40 Ottawa	68	0.738	2.3
		2.110	5.2
		3.607	8.2
20/40 Neutral Density Beads	60	0.125	1.4
		0.165	2.0
		0.506	3.9
		2.036	8.5
		3.586	12.0
16/20 Carbolite	70	0.5	1.5
		0.8	2.2
		4.1	9.9
16/20 Carbolite	175	0.583	1.7
		0.924	2.3
		2.113	5.6
		3.687	7.8
16/30 Bauxite	60	0.167	0.4
		0.220	0.6
		0.462	1.3
		1.596	3.5
		4.150	8.3
12/20 Badger	68	0.459	1.3
		0.985	2.5
		2.460	5.8
		4.610	9.0

All of the test results except for the neutral density beads, plot on a similar trend. The linearity of the results suggests that differences between proppants have only a minor effect compared to the effect of flow rate. For the slot model it is possible to predict channel height from flow rate by:

$h = 0.83\ Q + 0.17$ where h = channel height in inches and Q = flow rate in gallons per minute.

Data points from all tests except the neutral density bead grains. Channel depth versus threshold flow



rate (with no visible sand movement). A first order line fit to these data can also be expressed by h = 0.83Q + 0.17.

4.9.4.10. Discussion

The section above discussed the forces required to move proppant grains. It may not be possible to obtain all the necessary parameters for an actual fracture, but an understanding of the processes involved will help in selecting empirical solutions and using rules of thumb solutions. In our water saturated slot models the channel always formed at the top of the proppant pack. We did have observations of gas bubbles and partially saturated proppant at the top of the slot though. Anything in the top of the channel will displace the channel to a lower position. This could include trapped gas bubbles or partially saturated proppant grains (see video).

Channel height may also be affected by reduction in channel width. Channel walls may collapse as proppant is removed. Collapse decreases width (increases velocity) and channel height directly and re-initiates erosion at the base to equilibrate flow.

Increasing flow rates cause only a slight and temporary increase in delta P in the proppant pack measured between the ends of the slot model.

Flow in the channel can and will transport any proppant introduced into it in order to maintain a stable height.

Fluid input from the fracture walls rather than the end of the channel will affect the system differently than this model shows. Fluid input would be expected to destabilize the proppant and make it easier to erode. Near the well bore however, most flow is expected to be from the end of the fracture. Fluid input will also increase the flow rate and velocity downstream. Channel height would be expected to be greater near the well due to flow convergence alone.

4.9.4.11. Application to petroleum production

Our flow rates went up to 5 gpm (171 bbl/day) for a channel height of just over 4 inches. Using the relation generated would give channel heights of 12 and 29 inches for flow rates of 500 and 1000 bbl/day respectively. It is unlikely that the fracture would remain open, unsupported as a channel 29 inches high. An equilibrium height can be expected where the velocity in the channel causes no additional erosion of proppant.

4.9.5 Matrix Permeability Zone

4.9.5.1. Stable Configuration

By definition, the matrix permeability zone is always in a stable condition. Exceptions in an actual fracture may be from compaction of the proppant. This zone is dominated by matrix flow, but its "stability" is critical. Small changes in flow rate can quickly cause instability and the onset of channel formation.

4.9.5.2. Zone III studies

The slot model used in these tests is not a very good design to study Zone III. We do not know if this zone actually exists in any real-world situation. It seems that settling and the geometry of subparallel fracture walls would always leave some sort of initial channel at the top of the proppant pack.

4.9.6 Discussion

Based on observations from the slot model, proppant flowback will continue until equilibrium is established in all three zones.

In zone I, with even minor flow rates, proppant will be produced until the angle of repose is reached and is anchored on the lowest open perforation. No additional proppant will be produced from Zone I if flow rates are increased.

In Zone II, proppant is produced until the channel depth is reached where the critical velocity is attained. If flow rates are increased, additional proppant will be transported to Zone I until a new equilibrium depth is achieved. Proppant transport is initially at its maximum rate and decreases as bedforms transition.

In Zone III, the proppant pack is stable by definition. It is always at a critical point of transitioning to a channel and extending Zone II however, unless the flow rate is decreased.

Since the height of the channel in Zone II is always greater than the height of the channel above the sand in the perforation tunnel, flowback is controlled by the velocity of the fluid in the channel in Zone II. Processes in Zone I are important to understand, but are not the limits to proppant production in the system described.

Because processes active in Zone II control the amount of flowback, strategies to prevent flowback must concentrate on this zone as well.

4.9.7 Future studies

Future studies should address the following topics:

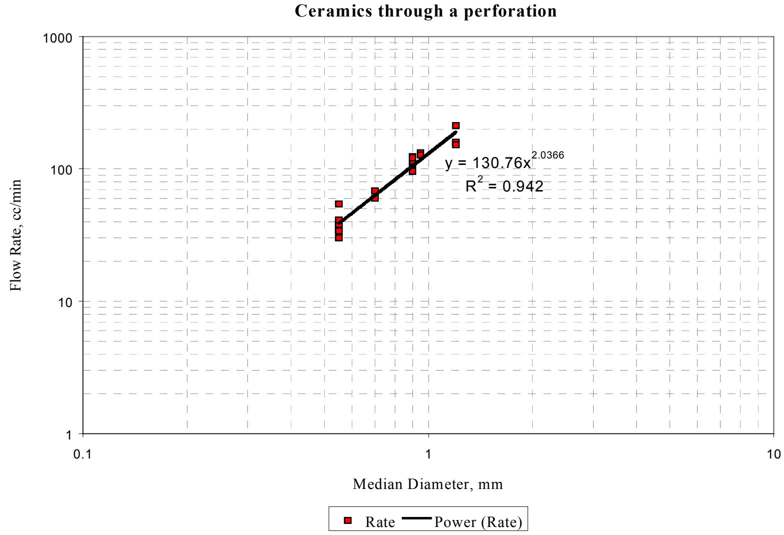
- Modeling of the velocity profile in a proppant floored channel
- Effect of interstitial gelled fluids on processes in Zones I and II during initial and continued fluid production
- The magnitude and effect of cohesive forces, that dominate partially saturated proppant packs, on flowback processes
- The effect of crushed material added to the proppant pack on flowback. Crushed material is the most likely product of closure stresses.

4.10 Initiation of Flow Back in Single Phase Water Flow Condition

What is the driving force to initiate proppant flow back has been the goal of our study. This is directly related to the prediction of the initiation of proppant flow back. From the discussion in section 4.9 we know that in order to let a proppant move, a minimum shear velocity is required. This velocity is determined by Shields' correlation. What does Shields' β factor mean? It means that the ratio of the shear force generated by the fluid velocity to the gravitational force acting to the particle must exceed certain value to start moving a particle with particular diameter and density. Therefore, the fluid velocity flowing around the particle generates the necessary force to initiate the flow back.

If we plot the data of velocity or flow rate versus proppant diameter for Carbo-lite obtained shown in section 4.9, we get Fig. 4.10-1.

Fig. 4.10-1 Median diameter vs flow rate to initate flow of Ceramics through a perforation



A correlation between the flow rate and the diameter of the proppant can be obtained that has a slope of 2. This means that the velocity (since the perforation geometry is constant) is proportional to the second power of the diameter of the proppant. As we know, in transition to turbulent flow regime, the drag force acting on a particle is a function of the particle diameter to the power of 1.5 to 2. Our question is how to convert the flow rate to the interstitial velocity to calculate the drag force.

We tabulated the most recent single phase water flow back test data in Table 4.10-1. In the table, the proppant size, concentration, closure, flow rate to initiate flow back, dP at the flow back rate, and the superficial fluid velocity at the flow back rate. The purpose of summarizing the test data is to investigate the trend of the velocity as function of proppant size and other parameters.

Table 4.10-1 Single phase water flow back test data

Sample	Mesh	Load	Closure	Rate, ml/min.	ΔP, psi/5"	size, mm	Vw, cm/s.
CL	12/20	2	1000	290	0.148	1.3	2.23
	12/21	2	1500	224	0.462	1.3	1.715
	16/20	2	1000	280	0.47	0.949	2.088
	16/20	2	4000	202	0.7	0.949	1.506
	16/20	3	4000	130	0.35	0.949	0.969
	20/40	2	1000	70	0.283	0.71	0.54
	20/40	3	500	80	0.15	0.71	0.386
	20/40	3	1000	60	0.54	0.71	0.29
	20/40	3	2000	70	0.25	0.71	0.338
	20/40	3	3000	68	0.2	0.71	0.2
	20/40	3	4000	75	0.19	0.71	0.36
Jordan	12/20	2	500	100	0.245	1.099	0.769
	12/20	2	1000	160	0.33	1.099	1.23
	12/20	3	500	60	0.12	1.099	0.289
	12/20	3	1000	130	0.23	1.099	0.627
	16/30	2	500	80	0.262	0.728	0.599
	16/30	3	500	80	0.401	0.728	0.383
	20/40	2	500	60	0.465	0.584	0.46
	20/40	2	1000	67	1.044	0.584	0.515
	20/40	3	500	60	0.193	0.584	0.289
	20/40	3	1000	58	0.4	0.584	0.28
Hickory	12/20	2	250	360	0.593	1.2	2.6
	12/20	2	1000	800	0.226	1.2	5.93
	12/20	3	500	230	0.182	1.2	1.145
	16/30	1.5	2000	100	0.35	0.83	0.99
	16/30	2	1000	105	0.51	0.83	0.75
IP+	16/20	2	500	280	0.74	0.959	2.192
	16/20	2	1000	270	0.938	0.959	2.133
	16/20	2	4000	230	0.926	0.959	1.904
	20/40	2	1000	110	0.53	0.662	0.933
	50	3	500	27	0.45	0.297	0.326
	50	3	1000	29	0.38	0.297	0.350
	50	3	2000	28	0.42	0.297	0.338
	40/70	1	1000	15	0.4	0.344	0.272
	40/70	2	1000	50	0.75	0.344	0.453
	40/70	3	1000	40	0.312	0.344	0.242

If we plot all the data as function of proppant size, we get Fig. 4.10-2a. The trend of the effect of proppant size on the flow rate and superficial velocity can be observed clearly. The relationship is very similar to the one in Fig. 4.10-1.

Since most of the test was done under 1000 psi closure, it is worth to plot the flow back rate and velocity versus proppant diameter for different concentrations at 1000 psi closure. Fig. 4.10-2b is a plot of 2 lb/ft^2 proppant at 1000 psi and Fig. 4.10-2c is a plot of 3 lb/ft^2 proppant at 1000 psi closure. These plots show a monotonous increase in flow rate or velocity with the increase in proppant diameter. The same trend as seen in Fig. 4.10-1 can also be observed.

Fig. 4.10-2a Flow back rate and velocity vs. proppant size

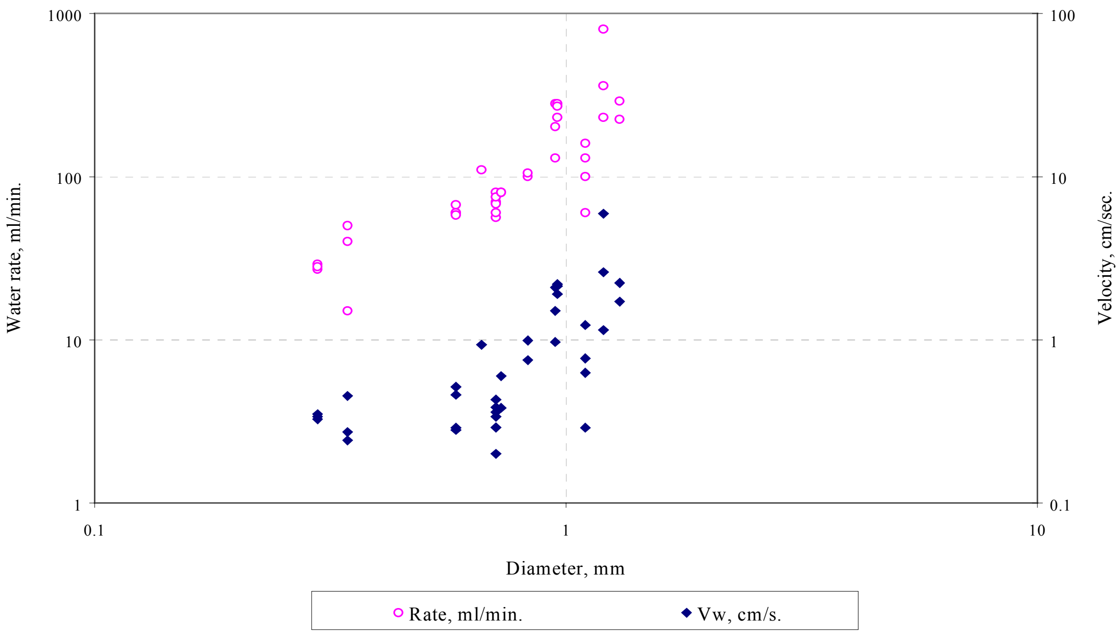


Fig. 4.10-2b Flow back velocity vs. diameter, 2# 1000 psi

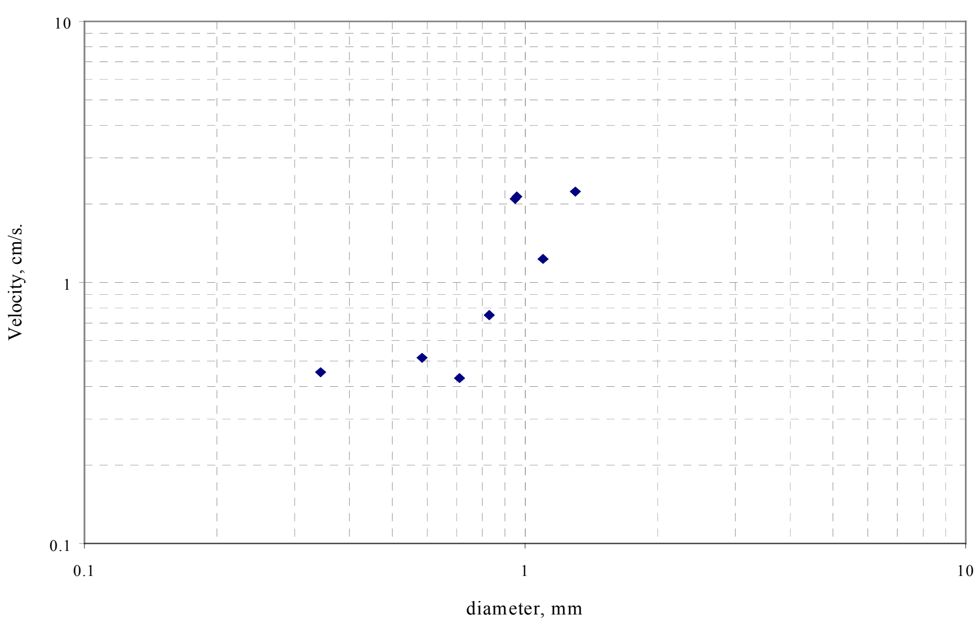
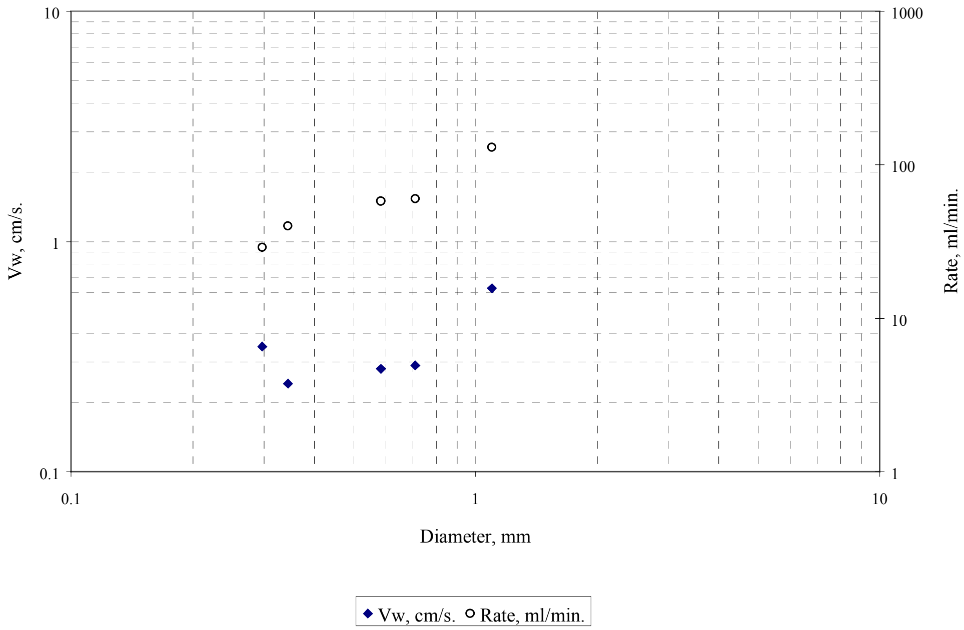


Fig. 4.10-2c Flow back Vw vs. diameter, 3# 1000 psi



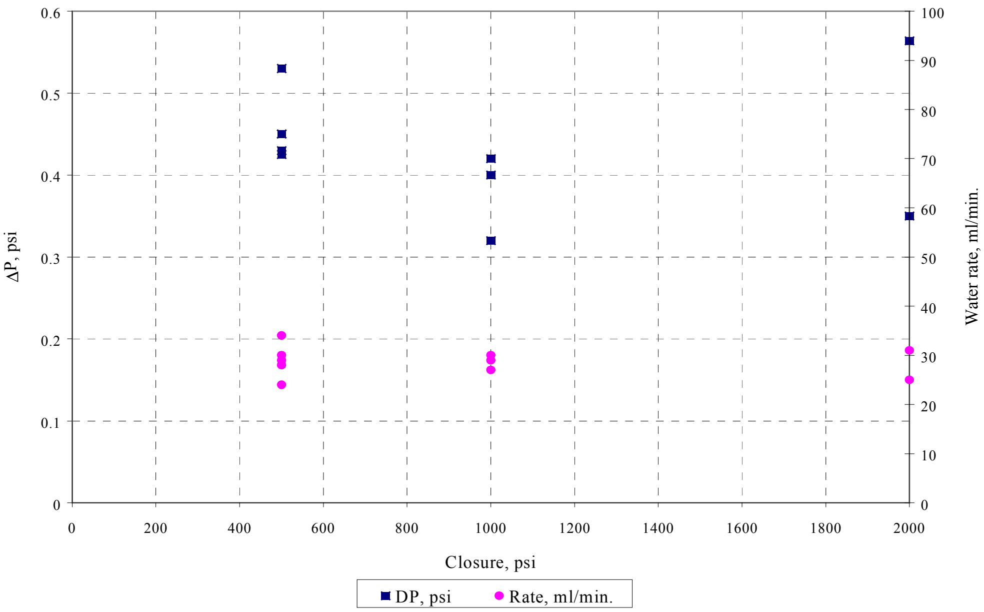
A special series of test was designed to investigate the influence of the closure variation at 500 to 2000 psi with single sized particles (50 mesh). The proppant IP+ was chosen for this test. The load was fixed at 1.5 lb/ft^2. Several tests were carried out to see the reliability or repeatability of the tests. The tests were run at room temperature. Table 4.10-2 summarizes the tests. The results are plotted in Figure 4.10-3. The variation of the data within the same closure pressure can be quite large. But from engineering point of view, a trend can be seen.

Table 4.10-2 Summary of flow back test with IP+ proppant

Size mesh	Load lb/ft^2	Closure psi	?P psi/5"	Rate ml/min.
50	1.5	500	0.45	29
50	1.5	500	0.43	34
50	1.5	500	0.53	28
50	1.5	500	0.45	30
50	1.5	500	0.425	24
50	1.5	1000	0.4	29
50	1.5	1000	0.42	27
50	1.5	1000	0.32	30
50	1.5	2000	0.564	31
50	1.5	2000	0.35	25
40/70	1	1000	0.4	15
40/70	2	1000	0.75	50
40/70	3	1000	0.312	40

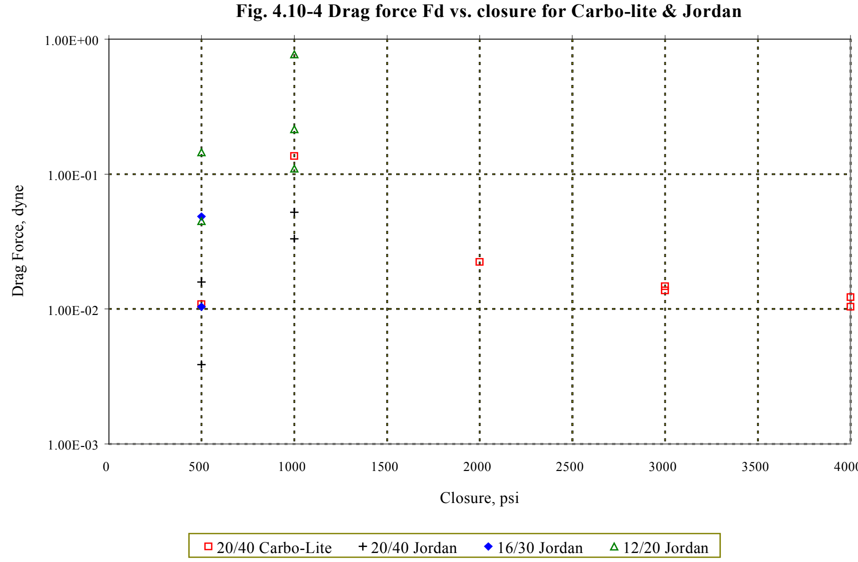
A similar type of test was performed with 40/70 IP+ by varying the concentration of the proppant with a fixed closing pressure (1000 psi). The concentration range was from 1 to 3 lb/ft^2. This seems to partially support the conclusion that if the width of the proppant pack is greater than 6 layers of proppant particle, the flow rate will not be sensitive to the closure. If the main force to initiate the flow back is the drag force generated by the fluid flow, then the velocity of the fluid around the proppant particle is the most important parameter to look at.

Fig. 4.10-3 Flow back vs. Closure, 50 mesh IP+



Effort has been paid to investigate the drag force acting on the proppant particles due to fluid flow through the proppant pack. In the investigation, the friction factor as well as the calculated drag force on a single particle were obtained. A fairly good trend was found as shown in Fig. 4.10-4 for example. This method has been used to evaluate both single phase and multi-phase flow back tests. Work continues to clarify the relationship of closure and concentration versus proppant diameter.

Fig. 4.10-4 Drag force Fd vs. closure for Carbo-lite & Jordan



Concept of Flowback Initiation Diagram

After examining the available data, a relationship is taking shape that predicts the flowback initiation velocity from the diameter, the concentration and the closure. A t low concentrations the velocity required to mobilize proppant increases rapidly as closure increase, while at higher concentrations the velocity is virtually independent of closure. There appears to be a closure at which each concentration experiences a maximum pressure to initiate flow. This concept is shown in Figure 3 4.10-5. The peak closure appears to decrease as concentration decreases.

The objective of future work in this area will be to compile the available data in this manner and perform experiments to define the relationship for various concentrations and diameters.

Fig 4.10-5 Concept of flowback velocity vs Concentration Diagram