Some Considerations in the Selection and Installation of Gravel Pack for Oil Wells

By C. J. Coberly* and E. M. Wagner,* Members A.I.M.E.

(Los Angeles Meeting, October, 1937)

Sand produced with the oil in many fields is one of the major causes of wear and down time on pumps, tubing, gas anchors and other equipment. Arresting this production of sand at its source would materially increase the life of such equipment and reduce production costs.

It is possible to materially reduce or eliminate sand trouble in some fields by the judicious selection of the openings in perforated liners. However, in other fields this is impossible because of fineness of the sand, poor compaction of the formation, low bottom-hole pressures, or other conditions. In such cases, gravel packing seems to offer a practical and relatively simple solution of the problem.

Gravel packing of wells, especially water wells, is not new. However, the selection and placing of the gravel have heretofore not been given sufficient study, and for that reason the results often have been unsatisfactory. An analysis of the problem is presented herein, with the hope of showing that gravel packing can be put on a rational basis and made a practical method of correcting a condition that has been a constant source of trouble to the oil industry. Three problems are considered: (1) selection of the proper mesh "gravel" to hold the formation in question, (2) proper placing of the gravel, (3) selection of a properly perforated liner to hold the gravel.

Selection of Liner

The third problem named is the most readily solved. It would seem that a perforated liner that will hold back all of the gravel should be selected. In this way the pack will remain permanently intact. This will require a slot having a width equal to or less than the diameter of the smallest grains in the gravel pack. While a slot with a width twice the grain size at the ten percentile of the gravel pack would hold the gravel in the accepted sense, the small quantity produced during the period the slot bridge is being built up might be enough to cause the pack to settle, allowing the production of sufficient formation sand to brand the installation a failure.

Manuscript received at the office of the Institute Oct. 1, 1937; revised July 1, 1938.

* Kobe, Inc., Huntington Park, California.

Copyright, 1938, by the American Institute of Mining and Metallurgical Engineers, Inc.

Petroleum Technology, August, 1938. Printed in U. S. A.
Selection of Gravel

Experiments with Steel Balls

The selection of the proper mesh of gravel to hold the given formation sand is a question requiring more careful study. Idealizing the gravel pack as spheres of a single size, it is found that there are two possible patterns in which they may arrange themselves—hexagonal, as shown in Fig. 1, and cubical, as shown in Fig. 2. Steel balls poured at random into a glass beaker show that the predominant arrangement is hexagonal, both horizontally and vertically, when the dimensions of the container are large compared to the size of the spheres. Even where the packing is cubical
in one layer, the opening in layers behind lead eventually to the hexagonal shape. This being true, the governing opening for the bridging of the formation sand will be the triangular shape between spheres (Fig. 1). The circle that can be inscribed within the surrounding spheres will be used as a criterion on which to base the selection of a "gravel" to hold a given sand. For hexagonal packing the diameter of this circle is \(0.1547D\), and for cubical packing \(0.4142D\), where \(D\) is the diameter of the spheres.

To determine the relation of the size and shape of openings to be bridged to the size of the bridging particles in ideal cases, a number of tests were made using steel balls. Round holes were first investigated. It was found that a satisfactory bridge is formed when the hole size is not more than three times the diameter of the balls, and that a bridge can be formed on holes 3.25 times the ball diameter. However, the bridge in the latter case is very unstable. A bridge seldom forms on openings larger than 3.25 times the ball diameter.

### Table 1.—Bridging of Formation Sand on Openings between Grains
SMALL STEEL BALLS ON LARGER STEEL BALLS

<table>
<thead>
<tr>
<th>(\Delta^a)</th>
<th>Hexagonal Packing</th>
<th>Cubical Packing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Limit of Bridging</td>
<td>Stable Bridge</td>
</tr>
<tr>
<td></td>
<td>(D)</td>
<td>(R)</td>
</tr>
<tr>
<td>(\frac{1}{4})</td>
<td>1(^b)</td>
<td>2.47</td>
</tr>
<tr>
<td>(1\frac{1}{4})</td>
<td>2.63</td>
<td>(1\frac{3}{4})</td>
</tr>
<tr>
<td>(\frac{3}{4})</td>
<td>1(^b)</td>
<td>2.48</td>
</tr>
<tr>
<td>(\frac{3}{8})</td>
<td>2.32</td>
<td>(\frac{3}{8})</td>
</tr>
</tbody>
</table>

\(\Delta^a\) The size container and depth of small balls used affects the results on limits of bridging. Not enough \(\frac{3}{8}\) and \(\frac{3}{4}\)-in. balls were available to duplicate results obtained with \(\frac{1}{4}\)-in. balls.

\(D\) = diameter of large steel balls, representing gravel, in inches.

\(\Delta\) = diameter of small steel balls, representing formation sand, in inches.

\(R\) = ratio (diameter of circle inscribed in figure formed by large balls)/\(\Delta\).

\(^b\) Occasionally bridges.

\(^c\) Seldom bridges.

To investigate the bridging of formation sand on the openings between grains of a gravel pack, some experiments were performed with steel balls arranged in forms to confine them in contact as in hexagonal and cubical packing. Smaller balls were then placed in the forms, and their action in bridging the triangular and square openings formed by the larger balls noted. Various combinations of small balls, representing formation grains, and large balls, representing grains in the gravel envelope, were tried. Results are shown in Table 1. The following conclusions are reached from an examination of this table:
1. A stable bridge is formed over the opening between balls arranged in hexagonal packing when the inscribed circle in the opening does not exceed twice the diameter of the smaller balls.

2. A stable bridge is formed over the opening between balls arranged in cubical packing when the inscribed circle in the opening does not exceed 2½ times the diameter of the smaller balls.

3. It is possible, with both hexagonal and cubical arrangements of the large balls, to form a bridge when the diameter of the inscribed circle is as much as 2½ times the diameter of the small balls. However, the bridge is very unstable and of no practical significance.

**Experiments with Graded Sands**

After completing the work with steel balls, the bridging action of sorted sand grains was investigated. The sand used in all experiments was a Monterey Beach sand whose grains were quite angular, with well rounded corners. The larger sand grains did not approximate spheres very closely.

A stable bridge was formed on round holes three times the diameter of the grains. However, the range of bridging extended to holes having diameters as much as 4 to 4½ times the grain size. Bridging was very unstable on these large-diameter holes. The extension of the range of bridging seemed to be due to the angularity and shape of the sand grains.

The bridging of sorted sand grains of various sizes on beds of larger grains, or "gravel," was investigated by placing 2-in. beds of various small grains on different 3-in. beds of large grains held on a screen in a glass tube. The tube was then filled with gasoline to a height of 24 in. over the sample, and the gasoline drawn through the sands by connecting the bottom of the tube to a vacuum of 12 to 13 lb. per sq. in. (Fig. 3). Action of the grains under the flow of fluid was noted. Bubbles of gasoline vapor forming continually in the sand because of the high vacuum helped simulate well conditions. Results of these tests are shown in Table 2.

The largest grains used (-6+8) approached the limit in size for consistent results for the particular tube used. (Inside diameter of the tube was 15½ in.) The small grains had a tendency to flow down the sides of the tube at the boundary between the large grains and the tube, especially in the -6+8 size.

Examination of Table 2 leads to the following conclusions: Stable bridging of the small grains over the spaces between the large 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 grains, assuming the large grains to be arranged in hexagonal packing. In determining this relation, the diameter of the large grains was assumed as that of the width of the opening in the screen through which these grains passed, and the diameter of the small grains in the overlying bed
Fig. 3.—Method of examining the bridging of sorted sand grains and core sands.
was assumed as that of the opening in the screen on which these grains were held. This is the worst condition in the bed, the smallest fine grains bridging on the largest coarse grains. If rectangular packing at the point

**Table 2.—Migration of Graded Small-diameter Grains into Beds of Graded Large-diameter Grains**

<table>
<thead>
<tr>
<th>Classification Size of Bed of Large Grain, Mesh</th>
<th>Classification Size of Overlying Bed of Fine Grains, Mesh</th>
<th>Ratios ( \frac{d_1}{\Delta_1} \quad \frac{d_2}{\Delta_2} \quad \frac{d_3}{\Delta_3} \quad \frac{d_4}{\Delta_4} \quad \frac{D_1}{\Delta_1} )</th>
<th>Type of Packing of Grains Assumed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-in. bed — 6 + 8.</td>
<td>65 + 100</td>
<td>3.5 2.5 2.1 1.7 2.5 23</td>
<td>H</td>
<td>Goes through readily</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.3 6.6 6.6 4.7 6 22</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48 + 65</td>
<td>2.5 1.7 1.7 1.2 1.7 16</td>
<td>H</td>
<td>Makes considerable sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.6 4.7 4.7 3.3 4.7 16</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35 + 48</td>
<td>1.7 1.2 1.2 0.88 1.2 11</td>
<td>H</td>
<td>Makes trace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.7 3.3 3.3 2.3 3.3 11</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 + 10</td>
<td>100 + 150</td>
<td>3.5 2.5 2.5 1.7 2.5 23</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.4 6.6 6.6 4.6 6.6 23</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5 1.8 1.7 1.2 1.7 16</td>
<td>H</td>
<td>Hardly trace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.6 4.7 4.6 3.3 4.7 16</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 + 14</td>
<td>150 + 200</td>
<td>3.5 2.5 2.5 1.7 2.4 22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.3 6.6 6.6 4.6 6.6 22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.6 1.7 1.7 1.2 1.7 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.5 4.6 4.6 3.3 4.6 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14 + 20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a* All grains classified according to Tyler screen scale.

*b* \( d_1 \) = diameter of inscribed circle in opening formed between large grains. Grains assumed to be spheres of diameter \( D_1 \) equal to width of openings in screen through which sand passes.

\( d_2 \) = diameter of inscribed circle in opening formed between large grains. Grains assumed to be spheres of diameter \( D_1 \) equal to width of openings in screen on which sand is held.

\( \Delta_1 \) = diameter of small grains assumed equal to width of openings in screen through which sand passes.

\( \Delta_2 \) = diameter of small grains assumed equal to width of openings in screen on which sand is held.

\( a \) = average grain size small grains.

\( d_4 \) = diameter of inscribed circle in opening formed between large grains. Grains assumed to be spheres of diameter equal to average width of opening of screen through which sand passes and on which sand is held.

\( \Delta_4 \) = diameter of inscribed circle in opening formed between large grains. Grains assumed to be spheres of diameter equal to average width of opening of screen through which sand passes and on which sand is held.

\( H \), hexagonal packing; \( C \), cubical packing.

of stable bridging is assumed, the size of openings between the grains is found to be beyond that for stable bridging as determined in the experiments with steel balls. These results indicate that a type of packing resembling hexagonal is predominant and is the controlling factor determining the openings to be bridged in the sand grains. This checks the observation made with steel balls in a large container. Of course,
neither hexagonal packing nor cubical packing was strictly possible with the grains used, because of their variation from the spherical shape.

Experiments with Core Sands

The next step was to place some actual core sands over coarse beds of graded grains to determine the "gravel" size that would hold them. It is a well established fact that twice the diameter of the grain size at the ten percentile is the approximate upper limit of the width or "mesh" of the openings in perforated or screen casing on which a stable bridge is formed. The ten percentile grain size was therefore assumed to be the effective grain size of the core sands for bridging on the coarse "gravel" bed. Results of tests on several cores are shown in Table 3. Analyses of the cores used are shown in Figs. 4, 5, 6 and 7.

<table>
<thead>
<tr>
<th>Core</th>
<th>Classification Size of Gravel Bed, Mesh</th>
<th>Grain Size at Ten Percentile = δ</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Type of Packing of Grains Assumed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brimm No. 1...</td>
<td>- 8+10</td>
<td>0.0085</td>
<td>1.7</td>
<td>11</td>
<td>1.2</td>
<td>H</td>
<td>Forms satisfactory bridge.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.110</td>
<td>4.5</td>
<td>11</td>
<td>3.2</td>
<td>C</td>
<td>Makes little sand. Can use this grain size.</td>
<td></td>
</tr>
<tr>
<td>Brimm No. 1...</td>
<td>-10+14</td>
<td>0.110</td>
<td>1.2</td>
<td>8</td>
<td>0.84</td>
<td>H</td>
<td>Makes no sand. No appreciable drop in flow as compared with -8+10</td>
<td></td>
</tr>
<tr>
<td>Carson No. 8...</td>
<td>- 3+4</td>
<td>0.022</td>
<td>1.9</td>
<td>12</td>
<td>1.3</td>
<td>H</td>
<td>Bridges, but makes considerable sand.</td>
<td></td>
</tr>
<tr>
<td>Carson No. 8...</td>
<td>- 4+6</td>
<td>0.290</td>
<td>4.9</td>
<td>12</td>
<td>3.5</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carson No. 8...</td>
<td>- 4+6</td>
<td>0.290</td>
<td>1.3</td>
<td>8</td>
<td>0.92</td>
<td>H</td>
<td>Forms satisfactory bridge; makes some sand.</td>
<td></td>
</tr>
<tr>
<td>Balboa 61......</td>
<td>- 8+10</td>
<td>0.0095</td>
<td>1.5</td>
<td>10</td>
<td>1.1</td>
<td>H</td>
<td>Forms satisfactory bridge; makes little sand.</td>
<td></td>
</tr>
<tr>
<td>Lakeviewb......</td>
<td></td>
<td>0.431</td>
<td>0.033</td>
<td>4.1</td>
<td>10</td>
<td>2.8</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The cores from California were used merely as examples of actual mixtures of grains that might be encountered. Their use here in no way indicates that the wells they are from are having sand trouble. The samples as used were broken down to their ultimate particle size in order to insure that results could be repeated. No allowance has been made for the possible effects that consolidation of the samples or cementing of the grains in groups might have under actual conditions.
- Lakeview core indicates a $D_1$ of 0.431 in., based on gravel of 13 times the ten percentile grain size. This diameter was beyond the limits of the apparatus used. However, it illustrates the fact that large gravel should be used only on relatively coarse sand.
- The grains available in this range were a poor selection. They did not approach spheres. Most of the grains had an elongated shape. The -4+6 grains were somewhat better, but in both cases the openings found were larger than if grains more nearly spherical had been available.
- All grains classified according to Tyler screen scale.
- Based on 13 times the ten percentile grain size.

Table 3 indicates that selection of gravel for gravel packing can be made on the basis that the opening bridged, assuming hexagonal packing, will be twice the diameter of the ten percentile grain size. The opening assumed is that between grains equal in diameter to the openings in the screen through which the grains in the coarse bed pass. The above
statement holds only when a bed of grains of a single classification is used. Beds of grains of more than one grain classification were not investigated.

A different statement of conclusions reached can be made as follows: The diameter of the largest grains in a single classified sand suitable for gravel packing is approximately 13 times the grain size at the ten percentile analysis of the formation sample. This applies to sand classified by Tyler screens.

The conclusions as stated are for gravel grains of the maximum size that could be used to form a stable bridge. It is not desirable in most
cases to use this maximum grain size. Grains that are one or possibly two screen sizes (Tyler scale) smaller would provide an additional factor of safety. Possibly 10 times the grain size of the core at the ten percentile might prove to be a good practical basis for the largest grains in the gravel pack.

**Permeability of Gravel Pack**

The question of the permeability of the gravel pack itself also enters into the selection of the gravel. It was found that a tightly compacted bed of classified sand of 8 to 10 grain size had a permeability of approxim-
SELECTION AND INSTALLATION OF GRAVEL PACK FOR OIL WELLS

mately 2500 darcys; of 10 to 14 grain size, 1500 darcys. In view of the high permeability of the gravel bed as compared to the formation no material difference in the total pressure drop would result from decreasing the grain size from the maximum (the 13 times rule) as recommended above.

Where a “gravel” pack made up of grains of more than one classification is used, the governing opening should probably be taken as that between the largest grains of the biggest classification in the mixture. Mixtures of more than three classifications should probably not be used, as the porosity decreases rapidly as the spread in grain sizes increases. It would not be economical, however, to limit the pack to grains of a single classification.

There was some question as to whether the permeability of the interface between the formation sand and the graded sand might not be less than that of the formation sand itself, and thus restrict production. A special investigation of this point was made.

The permeability of a bed of grains from a sample of the Wilcox zone similar in analysis to Brimm No. 1 (Fig. 4) was found to vary from 13 to 50 darcys, the permeability varying with degree of compaction of the bed. The permeability of the same sand on a bed of 8 to 10 grain classified sand varied from 20 to 50 darcys. Therefore it was concluded that the interface between the formation sand and the gravel will have substantially the same permeability as the formation sand.

Placing of Gravel

The proper gravel for the formation under consideration having been selected, the problem of placing this gravel presents itself. This involves consideration of the following points:

1. The gravel must be transported to the point of placement in such a manner that the possibility of “bridging” or clogging is reduced to a minimum.

2. The gravel must be placed in such a manner that the possibility of bridging during placement in the annular space surrounding the screen will be reduced to a minimum.

3. The angle of repose of the gravel must be small, so that the gravel may fill all crevices and pockets in the formation as fully as possible.

4. The method of placing should be such that if any interruption occurs placing of the gravel may be resumed without serious difficulty.

5. Any material mixed with the gravel to facilitate placing should be easily removable by washing, natural flow of the oil, etc. It should preferably be soluble in the produced oil or in some treating agent.

6. Provision should be made for the placing of additional gravel later if the bed settles or if the original filling of the cavity is incomplete.
7. The gravel should preferably be placed from below; that is, the flow of gravel should be from the bottom of the hole upward, in order to reduce to a minimum the production of cavings during the placing of the gravel and to reduce the possibility of a portion of the hole remaining filled with original formation sand.

All of these conditions appear to be best fulfilled by mixing the gravel with a viscous fluid and placing it in the state of a pressure-mobile mixture in the well cavity. This mixture being pressure-mobile will also have the advantage that it may be handled as a fluid—that is, it may be pumped through tubing.

A method and possible equipment for placing the gravel-fluid mixture are illustrated in Fig. 8. A liner with the proper mesh screen to hold the gravel selected will be set with a packer-type hanger in the water string after the well has been thoroughly reamed and cleaned to bottom. (Where the liner is short and where there is no danger of heaving, it may be set on bottom. However, in general the liner will be located more centrally in the hole when hung.) The liner has a special shoe containing a left-hand thread for landing the wash pipe through which the fluid-gravel mixture is to be pumped, and a ball check valve through which the mixture will flow into the well, but which will prevent it from backing into the wash pipe from the well. The wash pipe could also be landed in a socket or a long close fit instead of screwed into the left-hand thread. After landing the wash pipe, a quantity of the fluid that is to be mixed with the gravel is pumped into the cavity, providing a “slug” of heavy fluid at the bottom of the well, the purpose of which is to protect the fluid in the gravel mixture from contamination by mixture with the well fluid.

The fluid-gravel mixture is placed from the surface either by pumping from a closed tank into the wash pipe when there is considerable formation pressure, or by pouring the fluid-gravel mixture into the wash pipe if the formation pressure is low. Placing of the gravel would be continued until the cavity is full. This would be indicated by excessive pumping pressure where the mixture is being pumped in, or by the tubing filling up to the surface if the mixture is being poured in. This condition could also be checked by sounding the level of the mixture in the tubing in cases where the gravel is being poured in. After the cavity has been filled, the tubing is unscrewed and removed from the well. The well is then bailed clean of the excess gravel, which ran from the tubing when it was pulled and the well put on production.

Until the viscous fluid mixed with the gravel, and as much of it as may have been forced into the formation, has been displaced, the production rate may be low. This fluid will eventually be “cut” by the well fluid (if the carrier fluid is oil-soluble). Occasionally it may be desirable
Fig. 8—Placing gravel-oil mixture through wash tube.

a, method; b, coupling check valve.
to force distillate or other solvent into the gravel pack to hasten removal of this carrier fluid.

The question of whether the wash tube may become sanded in when it is released from the shoe in the liner naturally arises. The fluid-gravel mixture is extremely mobile, and it is believed that the possibility of sanding in the wash tube with the gravel that will fill the liner when the wash tube is withdrawn is quite remote. Then too, the size of the grains to be used in the envelope is relatively small, which reduces the possibility of bridging the grains and sticking the wash tube. Usually when speaking of gravel packing, gravel of \( \frac{1}{4} \) or \( \frac{3}{8} \) in. or larger is thought of. The work done for this paper indicates that the largest size "gravel" that would ordinarily be used would be 6 to 8 grain size. Ordinarily it should be possible to control sand in wells requiring gravel larger than this by setting the proper screen casing.

When a liner is extremely long, or when there are alternate blank and perforated zones, it will be desirable to place a special coupling like that shown in Fig. 8 in the liner at the proper points. This coupling contains check valves through which gravel may be placed. With long liners, gravel is placed through the shoe until it ceases to flow. The wash tube is then removed and a special fitting with opposed basket packers is run on the end of the wash pipe. By landing the wash pipe so that the packer straddles the special collars, gravel can be placed through these couplings at successively higher points in the liner. The procedure would be the same with alternate blank and perforated pipe, special couplings being placed at the top and bottom of each set of perforations. If it is desired to run a flush-joint liner, a special coupling that is substantially flush inside and out could probably be devised containing valves similar to those shown in Fig. 8.

The slots in the liner should have a mesh that will prevent gravel from entering from the inside of the casing; otherwise, when the packers with the gravel in between are being moved through the casing the slots will become plugged. Liners with fine-mesh slots may be set without affecting the production, owing to the high permeability of the gravel envelope. It will thus usually be possible to select an undercut slot which will not plug when gravel is placed against the inside of the slots.

If the well makes sand when put on production, the probability is that the cavity was not completely filled, or that the gravel has settled. In such a case, the tubing can be rerun with the opposed packers and sufficient gravel placed through the highest special coupling to fill the cavity. Procedure would be the same as in the first run.

In some wells where gravel packing has been tried, the space between the liner and the water string has been used as a reservoir for gravel to take care of settling of the bed. The volume that can be so stored is negligible, especially when a liner of the maximum possible diameter
is being set, as is desirable in most instances. The provision of means for placing of additional gravel after the original pack has been made thus seems to be important.

APPLICATION OF FINDINGS TO FIELD CONDITIONS

The Oklahoma City field has been selected as an example of a situation where a good deal of sand trouble is being experienced.

There are two principal producing zones in the Oklahoma City field, the Simpson and the Wilcox. The Simpson sand is fairly well consolidated, and comparatively little sand trouble is experienced in wells producing from this zone. However, wells producing from the Wilcox zone experience considerable sand trouble. The Wilcox zone is almost continuous sand from top to bottom. The sand occurs in layers of varying hardness due to different binders, different amounts of binder, different degrees of compaction of the formation, or other conditions. Typical variation in the strength of the different layers is shown in Fig. 9.
Crushing strengths of the cores from this well vary from 60 to 2100 lb. per square inch.

When the Oklahoma City field was drilled, many wells were produced open hole. As a consequence most of these wells made large quantities of sand during the flowing and gas-lift periods. Therefore many of the wells now have cavities of considerable size in the producing zone. However, when tools are run evidence of hole of approximately the original bore is still found. This leads to the conclusion that sand has been produced from the softer zones, leaving the harder strata, and that there remains a structure of alternate shelves and cavities.

Most of the wells in the field are now pumping or are soon to be placed on the pump. Sand difficulties continue during pumping, their magnitude depending on the age of the well, its present production, length of period of natural flow, length of period of gas lift, gas-oil ratio, well location, and any other factors that have affected or may still affect the size of the cavity around the well and the ability of the oil to carry sand from the present producing face to the bore of the well. In the newer section of the field, the natural flowing life of the wells was shorter, and their present pumping rate is higher than in the older parts of the field. This means that a smaller cavity is likely to surround the wells, and the oil comes into the well at higher velocities than in the older sections. Both of these conditions tend toward the production of more sand during pumping. In fact, sometimes if a well is shut down for a short period the pump becomes sanded in because of the settling of the large percentage of sand carried by the oil in the production tubing.

Bottom-hole conditions in Oklahoma City are rather unique. Bottom-hole pressure is of the order of 20 to 50 lb. per sq. in. (October 1937), but production rates as high as 2000 bbl. per day are not uncommon, even with this low formation pressure. Such production rates are possible because of the high permeability of the Wilcox sand, which varies from 1 to 3 darcys, with only a few streaks of cemented sand having a permeability as low as 0.1 darcy. These high permeabilities are due to the low uniformity coefficient of the sand, which is approximately 1.5 to 1.75. The uniformity coefficient of a sand of uniform size would be 1. The usual range of the uniformity coefficient for cores is from 2.5 to about 7.5.

The Wilcox sand has a characteristic screen analysis throughout the field, as shown in Figs. 4, 10 and 11. These samples represent the maximum variation from well to well found in the samples analyzed. The curves show a grain size of from 0.008 to 0.0095 in. at the ten percentile, indicating that the proper mesh for a perforated liner to hold this sand is from 0.016 to 0.019 in. If a perforated liner that would hold the sand back were hung in one of these wells, a filter bed of approximately the
permeability of the original Wilcox sand would gradually be built up around it. The equation for the pressure at any point around a perforated liner during flow into it from the surrounding formation is as follows:

\[ \Delta P = \frac{V_1 R_1}{K} \log_e \frac{R_x}{R_1} \]

\[ \Delta P = C \log_e \frac{R_x}{R_1} \]
where $\Delta P =$ pressure, atmospheres,
$R_1 =$ radius of outside diameter of liner, cm.,
$R_2 =$ any radius, cm.,
$V_1 =$ velocity of fluid through cylindrical surface of radius $R_1,$
\[ \text{cm. per sec.}, \]
$u =$ viscosity of fluid, centipoises,
$K =$ permeability of formation, darcys.

The pressure drop for a production of one barrel per day per foot of active formation for a 6%\(^{-}\)in. liner with oil having a viscosity of 4.75 centipoises at 126° F. for formation permeabilities of 0.1, 0.8, 1.3 and 3.0 darcys has been worked out, and is shown in Fig. 12 plotted as a function of the radius from the axis of the well. The conditions correspond to bottom-hole conditions in Oklahoma City. These curves show that it is unlikely that many of the production rates obtained would be possible if the formation were filled in around the liner. This is especially evident when it is considered that the pressure drop will be greater than the curves show by a factor to take care of the convergence of the flow of the oil into the slots. The simple expedient of setting a perforated liner of the proper mesh thus seems inadequate as a solution for the sand problem in this particular field. Field results check these conclusions.

![Figure 12](image-url)
As pointed out above, typical screen analyses of cores from the Wilcox zone indicate a grain size at the ten percentile of 0.0080 to 0.0095 in. For a proper gravel pack a grain size of 0.110 to 0.146 in. is required, using the rule of the largest grains being 13 times the ten percentile core analysis. This corresponds to a sand falling between 6 and 8 mesh. If 10 times the ten percentile is used, the largest gravel size becomes 0.080 to 0.095 in., or minus 8 mesh. Tests checked this selection (Table 3), little sand being produced. However, gravel beds of -10+14 sand (approximately two meshes less than that selection by the 13 times rule) allowed absolutely no Wilcox sand to be produced during formation of a bridge.

Selection of the fluid to mix with gravel for packing a well in Oklahoma City was made on the following considerations:

1. The fluid should be miscible with the well oil in all proportions.

2. If a hydrocarbon derivative is used, it should preferably be refined from the same crude that is present in the formation to be gravel-packed. This will insure that no detrimental compounds will be formed on mixture with the well fluid. It should not obtain its viscosity from compounds added during refining, but should be naturally viscous.

<table>
<thead>
<tr>
<th>Table 4.—Oils Used in Flow Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tests</td>
</tr>
<tr>
<td>125° F. 26 A.P.I.</td>
</tr>
<tr>
<td>Specific gravity</td>
</tr>
<tr>
<td>Flash point, open cup</td>
</tr>
<tr>
<td>Fire point, open cup</td>
</tr>
<tr>
<td>Pour point S.S.U. at 210° F</td>
</tr>
<tr>
<td>150 sec.</td>
</tr>
<tr>
<td>Topped crude treated at 60° F.</td>
</tr>
</tbody>
</table>


3. The viscosity of the fluid should be as high as is practical. The gravel will stay in suspension better if the fluid viscosity is high. The more viscous the fluid, the longer it will take to mix with the well oil during placement of the gravel and the less will be the effect of such mixing on the viscosity of the fluid used as the vehicle.
In view of these considerations, oil known as S.R. stock from Oklahoma City crude seems to best fill the qualifications of the fluid in which to suspend gravel to place in wells in Oklahoma City.

Flow tests were made of gravel mixed with oils having the properties shown in Table 4. The lighter of the two oils was mixed with 8 to 10 grain graded sand like that found satisfactory to hold core samples from Brimm No. 1. A quantity of well saturated sand mixture was placed in a long U-tube. When 25 cm. of oil was added to one leg of the tube, the gravel-oil mixture flowed readily around the bend in the tube. It was concluded from this that oil moving at practically any velocity will carry the gravel with it (test at 60° F.). When heated to 130° F. (bottom-hole temperature, Brimm No. 1) with a head of 25 cm. as above, gravity alone caused the oil to migrate through the sand, but velocities only slightly greater caused the sand to flow with the oil. This test leads to the conclusion that the heavier oil, marked B, would be better suited to placing gravel at Oklahoma City.

Tests on the angle of repose of the dry gravel and samples of gravel mixed with just enough oil to thoroughly wet them yield the following results:

- Dry sand (-8 +10 classified beach sand. Well rounded angular grains) ............................................ 33°
- Wetted with oil A (60° F.) ............................................ 5½°
- Wetted with oil B (60° F.) ............................................ 7½°

These tests demonstrate the fact that a mixture of gravel and steam-cylinder oil can be expected to fill any crevice or fissure in its entirety.

The method proposed for placing gravel is suited only for wells that have been produced long enough to clean the drilling mud from the walls of the bore, and that have a cavity around the bore in the producing zone with dimensions suitable for the proper placing of the gravel. Modifications, such as methods of underreaming and means for removing mud from the face of the producing zone, must be introduced to make its application universal.

No consideration has been given in this paper to the increased production that may be expected incidental to the underreaming necessary to gravel-pack a well. This is an advantage obtained in a gravel-packed well in addition to the control of sand production and caving, and in itself may more than pay for the cost of gravel packing. The advantages of increased well diameter in the producing zone have been fully covered in the literature. A few pertinent references are included.

**Selected Bibliography**


