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Minimizing Formation Damage To Gravel Packs: Laboratory and Field Case Studies in the Battrum Field

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ABSTRACT

Gravel packs are commonly used to minimize sand production in unconsolidated sandstone reservoirs. The migration of particulates and fines into the gravel packs often has a severely reducing effect on the permeability of the packs and the subsequent productivity of the well. Detailed laboratory studies were undertaken using 12/20 and 20/40 mesh silica gravel to ascertain the optimum gravel size to minimize formation damage to gravel packs in the Battrum field.

The Battrum field is a shallow unconsolidated sandstone reservoir located in Saskatchewan, Canada, producing a low API gravity crude oil over an area of approximately 3900 hectares with 180 active injection and production wells. Currently a large portion of the field is under enhanced recovery using a commercial scale in-situ combustion technique. The results of detailed laboratory studies, including detailed size and sieve analysis of the formation, classification of the different lithologies and detailed laboratory tests to investigate at reservoir conditions the flow of gravel and fines into different sizes of gravel packs are documented. Tests include detailed petrography and computerized petrographic image analysis on actual sections of gravel and formation sand interfaces and illustrate the mechanism of fines entrainment in the gravel packs and provide associated permeability reduction data. Details of field gravel pack treatments are also provided in the paper. Test results indicated an increased propensity for gravel pack plugging in the coarser (12/20) mesh gravel in comparison to the 20/40 mesh gravel. Simultaneous multiphase flow of both oil and water was also found to have an increasing effect on rapidity and severity of apparent plugging. The results presented provide insight into optimum gravel to sand sizing ratios for this field and have potential application to other similar reservoirs.

THE BATTRUM FIELD

The Battrum field was discovered by Mobil Oil Canada (MOCAN) in 1955 and is located in southeast Saskatchewan, Canada (Figure 1). Mobil currently operates units 1, 2 and 3 of the field. The majority of the reserves in the reservoir are produced from four distinct stratigraphic layers from sandstone facies of the Jurassic Roseray Formation.

The four layers in the Roseray formation at Battrum define an

offlapping parasequence set and have been numbered according to depositional sequence as R1, R2, R3 and R4. These layers were deposited in response to a west to east progradation of a wave dominated clastic shoreline. The layers are defined by marine flooding surfaces which document periods of relative sea level rise. The architecture of the Roseray units is determined by this origin and two episodes of post depositional erosion. Sedimentary structures indicate that the majority of the Roseray reservoir facies were deposited in a mechanical fashion by wave and/or wind generated currents. Layers R1 and R2 are the major producing units in the western portion of the field while layers R3 and R4 contain the majority of the reserves in the eastern section.

The reservoir sands are, in general, very fine to fine grained, moderately to well sorted and poorly consolidated. Reservoir quality is very much controlled by grain size with layer R2 containing the largest amount of high quality sand. Over 42% of the $39.2 \times 10^6 \text{ m}^3$ (247 million barrels) of moveable oil in place is present in this layer.

In general the better quality laminated Roseray sands (which were the subject of this study) represent moderately sorted quartzose sublitharenites with good modified primary intergranular porosity supplemented by occasional grain moldic porosity. The sandstone framework generally consists of subangular monocrystalline quartz grains with much lesser amounts of chert grains, rock fragments and detrital feldspars. There are only trace amounts of authigenic quartz cement and generally no carbonate cements.

Detrital, recrystallized and authigenic clays characterize the rock. Kaolinite clay dominates (about 4% of the bulk rock fraction) with lesser amounts of illite (2%) and smectite (1%). Quartz is the major residual constituent with trace amounts of potassic feldspar and pyrite. The high kaolinite concentration and trace smectite indicate that the Battrum matrix is potentially sensitive to fines and sand mobilization and some potential for clay swelling and sloughing. Reservoir quality and clay content vary markedly within the reservoir. Permeabilities varies in the Battrum reservoir from 500 to 3000 mD with porosities ranging from 25 to 35%.

The oil in Battrum is a medium density crude (18°API) which at the original reservoir conditions of 42°C (108°F) and 8500 kPa (1235 psi) has

an average in-situ viscosity of approximately 70 mPa•s (70 cP).

The Mobil operated Battrum units contain 180 wells over a 3900 hectare area, currently producing approximately 1030 m³/day (6480 bbl/day) of crude oil. The Mobil units are currently being exploited by a wet in-situ combustion enhanced oil recovery process, initially implemented in the late 1960's. Approximately 8.9 x 10⁶ m³ (56 million barrels) of oil have been recovered yielding a 23% recovery factor.

PRODUCTION/COMPLETION STRATEGIES IN BATTRUM

The first wells in Battrum were completed with 5.5" casing cemented to TD and perforated with casing guns at either 2 or 4 shots per foot. Most of these wells experienced severe sand inflow problems due to the highly unconsolidated nature of the Roseray sand zones. Productivity and sand control were dramatically improved when gravel packing was introduced in the mid 1960's. To accommodate the gravel packing process all wells were subsequently cased with larger 7" casing.

Although numerous sand control techniques have been tried over the years, the best producing wells exhibiting minimal sand problems in Battrum have predominately been completed with open hole gravel packs. For these wells, the current design is to drill a 12¼" hole and set 9-5/8" surface casing at approximately 500 ft. The 8-3/4" main hole is then drilled conventionally with gel chemical mud until it just penetrates the top sand layer. Seven inch (7") casing is then cemented in place. After drilling out the 7" shoe joint, the formation is drilled out to TD using 6¼" bit unless coring is requested. The open hole over the entire gross pay interval is then under-reamed to 12 inches diameter using filtered Battrum sales oil (10 micron nominal). A 5.5" O.D. wire wrapped liner is then conventionally (ie, "over the top") gravel packed in place using filtered (2 micron) 2% KCl brine and 16/30 US mesh gravel. The wells require artificial lift and a 2" insert BHP is run on a 7/8" rod string inside 2-7/8" tubing.

Unfortunately, skin damage in all gravel packed completions in Battrum has been significant. In approximately 15% of the gravel pack completions, damage was so severe it was necessary to clean out the gravel packed open hole to restore inflow. Following the removal of the gravel pack, all wells had significant increases in inflow capability. However, many times a re-gravel pack was not performed. With poor inflow from gravel packed wells, it was often more economical to produce some wells without sand control. The cost of increased rod pump changes, wellbore cleanouts and down time due to sand production could be justified. Additional rationalization for producing wells without sand control can be made due to the recent advances in progressive cavity pumps. They are vastly superior at handling sandy fluids and are performing satisfactorily in 5% of Battrum wells. However, in the majority of Battrum wells, maximum reservoir inflow capability will not be achieved without effective non-damaging sand control. To try and improve upon the results of gravel packing in Battrum, other methods of sand control were attempted. Hydraulic fracturing with proppant, resin consolidation treatments, and sandscreens have all been tried in the past with no improvement over gravel packing results.

Based on published literature, it is known that the typical procedure described above for open hole gravel packs should be providing almost unrestricted sand free production rates. Although inflow reductions in some gravel packed wells may appear worse due to the fireflood process (ie, emulsions, combustion gas) all gravel packed completions in Battrum result in excessive restrictions to flow. Over the years, various combinations of the following design parameters have not been able to improve the disappointing productivity of gravel packed completions.

- Gravel size (US mesh): 8/12, 10/12, 10/20, 16/30, 20/30.
- Under-reaming fluid: Drilling mud, gel polymers, filtered sales oil.
- Gravel pack "pre-flush's": diesel, xylene, HEC pill followed by 15% HCl

- Gravel pack fluid: produced water, 2% KCl brine (filtered and unfiltered)
- Complete well using drilling rig or service rig.

It was apparent that a design component of the Battrum completions was being overlooked which could account for the unsatisfactory gravel pack performance. A detailed field review of all gravel pack completions was initiated. However, it soon became evident that the answer would likely not become readily apparent due to the large number of interdependent variables involved. This methodology was therefore changed to see if a laboratory controlled gravel pack simulation using restored Battrum core could provide a clue to obtain improved results.

STUDY METHODOLOGY

The objectives of the laboratory special core analysis (SCAL) study were to ascertain the following:

1. Effect of gravel size on gravel pack sand retention and permeability impairment.
2. Effect of fluid velocity on gravel pack sand retention and permeability impairment.
3. Effect of multiphase flow (ie, oil and water simultaneously) on gravel pack sand retention and permeability impairment.

The tests were to be conducted utilizing actual samples of restored state Battrum reservoir core material at reservoir conditions of temperature and net overburden pressure using unoxidized, non emulsified Battrum crude oil and produced water. These conditions were utilized in order to provide the closest duplication of field operating conditions as possible.

EQUIPMENT DESCRIPTION

A schematic of the gravel pack test apparatus appears as Figure 2. A restored state core section 3.81 cm (1.5") in diameter by approximately 15 cm (6") in length is mounted in series with a 30 cm (12") long gravel pack of identical diameter. Both the gravel pack and core material were initially axially compacted to 13100 kPa (1900 psi) to ensure that homogeneous and cylindrical samples would be obtained under final overburden compaction.

The core and gravel packs were placed in a flexible lead sleeve. An internal pressure tap in the lead sleeve is located exactly at the gravel-core interface to facilitate independent permeability measurements in both the gravel and sand sections of the test stack. Pressure differential was monitored through the use of capacitance transducers. For the gravel pack a 0 to 35 kPa (0 to 5 psi) transducer having an accuracy of 0.05% was utilized and for the core section a transducer of 0 to 350 kPa (0 to 50 psi) range with comparable accuracy.

The core and injection fluids were contained in a constant temperature oven to duplicate reservoir temperature conditions with an accuracy of ±0.5°C (±1°F). Pulsation free positive displacement synchronous drive pumps were utilized to provide the variable rate displacements of both oil and water (or both simultaneously with two independent pumps) through the test stack. The pumps are capable of displacing at rates from 0.6 to 8500 cm³/hr with an accuracy of ±0.01 cm³ at pressures of up to 70 mPa (10000 psi). All injection fluids were filtered to 0.45 microns to remove any potentially plugging suspended solids.

The mounted core was contained in a bi-axially loaded Hassler type core cell capable of applying overburden pressures of up to 70 mPa (10000 psi) to the core material.

CORE AND FLUID HANDLING

Field samples of emulsified produced oil were supplied for use in the test program. The emulsified Batrum crude oil had viscosities in excess of 30,000 cP at the reservoir temperature of 42°C (108°F). Subsequent cleaning via ultracentrifuge under N₂ blanketed conditions reduced this value to the expected dead oil viscosity of approximately 190 cP. This cleaned oil was utilized in the subsequent tests which were conducted.

Core material for use in the study was selected from the Roseray pay zones in five different Batrum area wells from depths ranging from approximately 880 to 1000 meters (2890 to 3280 ft.). A total of 119 different core samples were obtained from various intervals of the selected wells. As discussed previously the Roseray sands in the Batrum field exhibit considerable variation in reservoir quality and hence the obtained core samples were classified into four distinctly different lithologic "rock types", these being:

1. Sand and clay - laminated
2. Sand and clay - bioturbated
3. Uniform sand with uniformly dispersed clay
4. Clean homogeneous sand, minimal clay content.

An extensive suite of combined wet and dry sieve analyses were conducted on multiple samples from each rock type. A statistical summary of the results for each rock type appears as Table 1.

Analysis of the data of Table 1 clearly indicates substantive differences in reservoir quality as a function of the amount and distribution of clay (primarily kaolinitic in nature). Rock type #1 was selected as the test material for the study as it exhibited the smallest median particle size and the highest fraction of finer particulates. This was based upon the supposition that this rock type would appear to represent the "worst case" scenario for potential gravel pack design problems in the Batrum reservoir.

Table 2 and Figure 3 provide a PHI scale size distribution for a typical Batrum well. Profiling of this type, conducted through a multiple array of depth correlated sieve analysis, indicates considerable variation in reservoir grain size distribution for the well, with a finer sand being observed towards the base of this particular well. This is not particularly surprising, but indicates clearly that a careful analysis of the entire exposed pay zone is essential if an accurate evaluation of gravel sizing for gravel pack design is to be made. If a single sample had been obtained from the upper, better quality core, the possibility for an inadequate gravel pack size selection for the finer sands lower in the well would have occurred.

TEST PROGRAMS

1. Core Cleaning and Wettability Restoration

The core material from the five Batrum area wells had been frozen, slabbed (1/3 to 2/3) and then thawed and placed in storage. The 2/3 slab sections were utilized as source material for the test program, but as no preservation techniques had been utilized the core material was in both a desiccated and oxidized state.

In order to obtain representative samples for testing, the core plugs were subjected to extensive flow through cleaning and wettability restoration procedures. Uniform cylindrical core samples were drilled from the slabbed core using liquid nitrogen and were mounted, while frozen, in ductile sleeves with 325 mesh 316 SS retaining screens. The core samples were pressure displaced at 42°C (108°F) with clean toluene at a low frontal advance rate (2 to 5 cm³/hr) until a colourless effluent was obtained after a 48 hour static shut in period. Several soak cycles were required. This procedure was followed by a low (2 to 5 cm³/hr) rate methanol displacement to displace the toluene and any residual salts and water from the cores. The samples were then dried by an extended nitrogen purge to volatilize any residual methanol.

Wettability restoration was conducted by evacuation of the core material to remove any residual gas saturation, followed by a pressure saturation with filtered formation water to ensure that the core microporosity was 100% saturated with brine. Cleaned produced Batrum crude oil was then slowly (2 cc/hr) displaced through the core material until the irreducible water saturation had been achieved. Displacement of unoxidized oil continued for an additional six week period to allow an equilibrium wetting condition to be established.

2. Gravel Pack Test #1, 12/20 Mesh Gravel, Single Phase Oil Flow

A gravel pack comprised of 12/20 mesh size silica gravel was utilized for the first test as it was known that this size distribution yielded a median sizing outside the range of Saucier's¹ criteria and that problems had been encountered with gravel of this size in field applications (ie, it was a deliberately damaging base reference case). The test was conducted at the reservoir temperature of 42°C (108°F) with 13100 kPa (1900 psi) of net confining pressure to simulate the net overburden pressure in the reservoir. The following procedure was employed:

- a. Flood mounted sample in reverse direction (gravel into sand) with 2% KCl to simulate near wellbore invasion by 2% KCl completion fluid normally used to complete Batrum area wells.
- b. Obtain a baseline permeability to Batrum crude in the normal flow direction (sand into gravel) at a low stable rate (10 cc/hr). Subsequently, geometrically increase oil injection rate, dropping back to base rate after each elevated rate (to eliminate potential turbulence effects) to note the effect of elevated rate flow on both core and gravel pack permeability.
- c. Quick freeze core pack (liquid N₂), remove from core holder, clean while in sleeve via toluene extraction, epoxy impregnate while still mounted, then longitudinally section resin impregnated core for thin section and petrographic image analysis of gravel-sand interface area and gravel pack.

3. Gravel Pack Test #2, 20/40 Mesh Gravel, Single and Two Phase Flow

The initial phases of gravel pack test #2 were identical to Test #1, with the exception of 20/40 mesh gravel being utilized in lieu of 12/20 gravel. Once the additional measurements with oil had been completed, an additional suite of tests were conducted in which both Batrum oil and produced water were simultaneously injected in a 1:1 ratio at a variety of geometrically increasing rates, each followed by baseline rate permeability determination to observe the effects of multiphase flow on gravel pack performance.

RESULTS OF GRAVEL PACKING TESTS

1. Test #1 - 12/20 Mesh Gravel

Table 3 summarizes the sieve analysis of the 12/20 mesh gravel pack utilized in this test. Table 4 provides a summary of the results of the multirate flow tests conducted using a baseline displacement rate of 10 cc/hr. The percentage of original permeability retained data for both the formation sand and 12/20 mesh gravel pack are plotted versus lab injection rate and appear as Figure 4. Field equivalent production rate data, based upon core cross sectional flow area, lab injection rates and given assumptions for completion diameter and net pay are also presented as a portion of this and subsequent tables. These numbers will vary widely from location to location in the field depending on gravel pack diameter and net effective pay and are presented for illustrative purposes only.

The test results indicate that the 12/20 mesh gravel pack experienced gradual reductions in permeability as injection rate increased. No reductions in gravel pack permeability were observed at relatively low rates

(<20 cc/hr), but a critical threshold rate appeared to be exceeded at 50 cc/hr. Permeability declines appeared to be relatively moderate initially with increasing rates in the 50 to 200 cc/hr range, but a massive plugging of the 12/20 mesh gravel pack appeared to occur when a rate of 400 cc/hr was achieved, resulting in only 3.1% of the initial gravel pack permeability being retained.

Core section permeability inversely mirrored the gravel pack performance initially with moderate increases in formation permeability actually being observed at injection rates of less than 200 cc/hr. This appears indicative of the motion of some material, possibly bridging kaolinitic clay or other small fines, from the formation sandpack into the adjacent gravel pack. Core permeability declined slightly at extreme rates which coincided with the severe gravel pack plugging, suggesting that the elevated interstitial velocity at 400 cc/hr apparently moved sizeable particulates both from the formation pack into the gravel pack, as well as within the formation pack itself.

Post test petrography provided interesting insight into the gravel pack damage mechanism. Thin section analysis of the gravel-core interface clearly illustrated the invasion of fine to very fine sand grains into the interstitial spaces in the gravel pack. In general, the size of the invaded particulates appeared to decrease with invasion depth, but invaded solids were still clearly visible up to 60 mm into the gravel pack. The majority of the transported material was less than 120 microns in diameter and appeared to include remnants of leached chert and feldspar grains, detrital clay mats, authigenic clay, some smaller whole sand grains and some insoluble bitumen/asphaltene particles.

Computerized petrographic image analysis of slices of core in the near gravel interface indicated a distinct migration of fine constituents (<120 microns) from the 20 mm of formation core directly adjacent to the gravel pack, into the gravel pack itself. This may explain a portion of the initial permeability increases which were observed in the core material with increasing interstitial velocity.

2. Test #2 - 20/40 Mesh Gravel - Single Phase Oil Flow

Tables 4 and 5 summarize the gravel sieve size and test analysis data for the 20/40 mesh gravel pack. The data of Table 5 have been plotted as Figure 5. These results indicate that under single phase flow the 20/40 mesh gravel pack had superior performance to the 12/20 mesh gravel pack test discussed previously. Gravel pack permeability remained virtually unaffected until velocities in excess of five times that used to cause plugging of the 12/20 mesh gravel were applied. These high velocities were evaluated out of academic interest only, as the equivalent drawdown to achieve a velocity comparable to 2000 cc/hr (about 2000 bbl/day) would not be possible in a vertical Battrum well due to the high inherent oil viscosity and limited available reservoir pressure for drawdown. Total permeability reductions in the 20/40 mesh gravel pack, even at extreme rates, were still much less severe than observed for the 12/20 mesh gravel runs.

Formation permeability also remained relatively constant over the range of injection rates evaluated indicating that the 20/40 mesh gravel pack appeared to be effective at retaining the formation fines and in general inhibiting large scale motion of the formation matrix. Some moderate increases in permeability at some of the higher injection rates suggest that some small scale internal mobilization of small fines with the formation pack may have been occurring.

3. Gravel Pack Test #2 - 20/40 Mesh Gravel - Multiphase Flow

After the conclusion of the single phase elevated oil injection rate tests discussed previously, the test procedure for the 20/40 mesh gravel pack was expanded to include a series of multiphase flow injection tests. The objective of these studies was to ascertain if simultaneous flow of both Battrum crude oil and produced water through the porous media and into

the gravel pack would cause an increased propensity for damage due to multiphase turbulence and/or wettability effects due to the motion of the water phase, which is believed to be the wetting phase in Battrum.

The results of this test are summarized in Table 7 and are plotted as Figure 6. It should be remembered that this test was conducted on the already "pre" damaged core from the preceding test. The core was subjected to multiphase oil and water flow (1:1 ratio) until stabilized initial oil and brine permeabilities were obtained. These initial stabilized values were used as the 100% permeability retained baseline values presented in Table 7.

This data indicates that no substantial change in gravel pack permeability was observed until a combined injection rate of 1000 cc/hr (500 cc/hr oil, 500 cc/hr water) was achieved. This is a lower rate than observed for the single phase test conducted previously and is much lower if strictly the flow rate of oil is considered. Also the fact that the core had been previously flowed at high velocity with oil may have biased test results, as these displacements may have already mobilized materials which may have been transported by simultaneous flow at an even lower velocity than observed in this test.

Formation pack permeability appeared to increase relatively steadily. This may be indicative of continual migration of water wetted clay particulates by the flowing wetting phase (water) in comparison to previous tests where the wetting phase remained relatively static at an irreducible saturation level.

This would appear to indicate that potential damage and sand control problems may be more severe under conditions of multiphase flow in Battrum than under single phase flow. More rigorous testing on virgin core samples with multiphase flow and at a variety of different water-oil ratios would likely be required to definitely substantiate this theory.

Post test petrographic analysis of the core and gravel pack from the 20/40 mesh tests indicated relatively little evidence of severe invasion of formation fines or clays into the gravel pack beyond 1-2 grain diameters (about 1 mm). This is consistent with the observed test results. Computerized petrographic image analysis indicated a slight buildup of smaller particulates directly at the core-gravel interface indicating that the 20/40 mesh gravel pack appeared to be acting as a retentive barrier in sharp contrast to the 12/20 mesh pack where a cleanout of small fines in the near interface region was noted.

GENERAL DISCUSSION

Table 8 summarizes the results of the rock type #1 and 12/20 and 20/40 mesh gravel pack tests with respect to various commonly used gravel sizing techniques provided by Coberly and Wagner², Hill³, Stein⁴ and Saucier¹. In general the 12/20 mesh gravel poorly satisfied all these criteria (with the exception of the Coberly and Wagner method). The 20/40 mesh gravel was in much better agreement. The 20/40 mesh gravel pack size appeared to be slightly smaller than predicted as optimum by the commonly utilized Saucier equation.

Test results indicated that the 20/40 mesh gravel performance at high velocities was substantially superior to the 12/20 mesh gravel at minimizing gravel pack plugging. From an operational point of view, this must be balanced against the much lower inherent permeability (and initial productivity) of a 20/40 mesh gravel pack than a 12/20 mesh pack. If a situation where operational pressure shocks and high drawdowns can be avoided is possible, then the coarser gravel pack may be a viable choice over the less easily damaged, but also less permeable 20/40 mesh pack.

BATTRUM FIELD EXPERIENCE

Concurrent with the laboratory SCAL studies, a technology exchange program with Mobil's affiliate in Bakersfield was established to benefit from their considerable experience in gravel packing wells in unconsolidated sands in California. These discussions indicated that a significant portion of the restricted inflow in the Battrum gravel packs may be related to formation damage caused prior to gravel packing (ie, during drilling and completion) rather than to problems directly related to improper gravel pack design and field procedures. Their field experience in using stable foam to underream the open hole had resulted in significant improvements in the productivity of wells completed near Bakersfield.

Foam underreaming was therefore conducted on a recent Battrum completion with gravel sizing results of the lab study being incorporated into the completion and gravel pack design. The completion has been deemed a success with observed inflow capability a minimum of 500% greater than adjacent wells with no indications of sand production.

CONCLUSIONS

1. The Battrum formation contains substantial quantities of mobile fines and clays and appears to be sensitive to fresh/low salinity water contact from a clay deflocculation/swelling and migration standpoint.
2. Gravel packs composed of 20/40 mesh gravel appear to be less susceptible to plugging at high differential pressure than packs composed of 12/20 mesh gravel.
3. Multiphase simultaneous flow of both oil and water appears to reduce the critical inflow rate required to damage gravel packs. It is postulated that this mechanism is a specific function of the wettability of the formation, but that further additional research needs to be undertaken in this area.
4. Saucier's equation appeared to be consistent with the results of the 12/20 and 20/40 mesh gravel tests. The 20/40 mesh gravel appeared to be slightly smaller than would be predicted by Saucier's equation, but still appeared effective.
5. Reservoir heterogeneity was illustrated to be a factor in gravel pack design and that a statistical representation of size distribution of the entire gravel pack exposed interval should be considered in gravel pack design, with consideration being given to the zones with the smallest potential mobile particulate distribution for optimum design safety.

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TABLE 1 BATTRUM ROSERAY SAND SIZE DISTRIBUTION BY ROCK TYPE				
Particle Size Range	Rock Type			
	#1 (%)	#2 (%)	#3 (%)	#4 (%)
> 500 microns	0.06	0.04	0.07	0.13
250-500 microns	1.23	2.19	0.46	5.77
177-250 microns	6.67	14.50	14.22	30.32
125-177 microns	35.41	38.48	64.14	48.78
88-125 microns	38.29	31.03	12.24	8.55
63-88 microns	8.56	5.81	2.72	1.86
44-63 microns	1.65	1.22	1.15	0.66
<44 microns	8.13	6.73	5.00	3.93
Avg (D ₅₀) Grain Size (microns)	119	132	148	165
Total % ≤ 63 (microns)	18.34	13.76	8.87	6.45
Total % ≥ 177 (microns)	7.96	16.73	14.75	36.22

TABLE 3 SIEVE ANALYSIS OF 12/20 MESH GRAVEL UTILIZED IN GRAVEL PACK TEST #1			
US Mesh Number	Micron Size	Mass Fraction Retained	Cumulative Mass Fraction
8	>2380	0.0000	0.0000
12	1680 - 2380	0.0004	0.0004
20	840 - 1680	0.9731	0.9735
Thru 20	< 841	0.0265	1.0000

D₅₀ size of 12/20 mesh gravel = 1000 microns

TABLE 2 VARIATION OF FORMATION SAND SIZE DISTRIBUTION CHARACTER IN A GIVEN WELL				
Sample #	Depth (m)	Grain Size Statistics (PHI Scale)		
		P5	P50	P95
8	916.95	2.15	2.76	4.25
9	917.20	2.24	2.81	4.52
10	917.25	2.09	2.73	4.37
10A	917.33	2.16	2.82	4.57
11	917.42	2.50	2.82	4.71
12	917.52	2.26	2.79	4.54
13	917.70	2.11	2.72	3.94
14	918.12	2.24	2.79	4.35
15	918.18	2.22	2.78	4.32
17	918.54	2.27	2.77	4.30
18	918.85	2.09	2.73	3.72
19	919.20	2.14	2.76	4.52
20	919.82	2.50	3.15	4.70
21	919.89	2.39	3.14	4.71
22	920.06	2.25	3.18	4.71
23	920.12	2.23	3.07	4.72
24	920.16	2.14	3.10	4.67
25	920.86	2.54	3.22	4.65
PHI Scale Grain Sizes		2.00 = 250 microns 2.50 = 177 microns 3.00 = 125 microns 3.50 = 88 microns 4.00 = 63 microns 4.50 = 44 microns		

TABLE 4 RESULTS OF GRAVEL PACK TEST #1 USING 12/20 MESH GRAVEL				
Flow Rate of Oil (Lab) cc/hr	Field Equivalent *		Percentage of Original Permeability Retained	
	m ³ /d	bbl/d	Core	Gravel Pack
10	1.52	9.56	100.0	100.0
20	3.02	19.00	100.2	100.0
50	7.55	47.48	112.5	77.6
100	15.11	95.03	120.2	72.6
200	30.23	190.13	137.2	68.2
400	60.47	380.32	123.8	3.1

* Based upon 22.9 cm OD completion with 10 meters of effective pay

TABLE 5 SIEVE ANALYSIS OF 20/40 MESH GRAVEL UTILIZED IN GRAVEL PACK TEST #2			
US Mesh Number	Micron Size	Mass Fraction Retained	Cumulative Mass Fraction
8	>2380	0.0000	0.0000
12	1680 - 2380	0.0000	0.0000
16	1190 - 1680	0.0000	0.0000
20	841 - 1190	0.0000	0.0000
30	595 - 841	0.2675	0.2675
35	500 - 595	0.3830	0.6505
40	420 - 500	0.3340	0.9845
50	297 - 420	0.0155	1.0000
Thru 50	< 297	0.0000	1.0000

D₅₀ size of 20/40 mesh gravel = 538 microns

TABLE 6 RESULTS OF GRAVEL PACK TEST #2 USING 20/40 MESH GRAVEL (SINGLE PHASE FLOW PHASE)				
Flow Rate of Oil (Lab) cc/hr	Field Equivalent *		Percentage of Original Permeability Retained	
	m ³ /d	bbbl/d	Core	Gravel Pack
20	3.02	19.00	100.0	100.0
50	7.55	47.48	100.1	100.0
100	15.11	95.03	100.6	98.1
200	30.23	190.13	97.6	93.8
500	75.50	474.85	99.4	107.1
**1000	151.00	949.70	106.8	100.0
2000	302.00	1899.41	114.3	58.4
4129	623.47	3921.28	100.6	50.0

* Based upon 22.9 cm OD completion with 10 meters of effective pay

** Extended period flow (5 days - 25 PV of oil) conducted at 20 cc/hr following 1000 cc/hr rate. There was no change in permeability from commencement to conclusion of this phase

TABLE 7 RESULTS OF GRAVEL PACK TEST #2 USING 20/40 MESH GRAVEL (MULTIPHASE SIMULTANEOUS FLOW) (Conducted on Same Core as Table 6)					
Flow Rate of Oil (Lab) cc/hr	Flow Rate of Water (Lab) cc/hr	Field Equivalent * Total Fluid Rate		Percentage of Original Permeability Retained	
		m ³ /d	bbbl/d	Core	Gravel Pack
10	10	3.02	19.00	100.0	100.0
20	20	6.04	38.00	98.6	111.7
50	50	15.11	95.03	101.5	111.7
100	100	30.23	190.13	123.2	99.2
200	200	60.46	380.26	126.9	89.1
500	500	151.00	949.70	128.9	57.5
1000	1000	302.00	1899.41	130.9	49.1

* Based on a 22.9 cm OD completion with 10 meters of pay

TABLE 8 COMPARISON OF VARIOUS GRAVEL SIZING CRITERIA	
<p>Saucier¹</p> <p>5 < D50 gravel/D50 formation <6</p> <p>For 12/20 gravel 1000/119 = 8.40 For 20/40 gravel 532/119 = 4.47</p>	<p>D50 gravel, 12/20 = 1000 μ D50 gravel, 20/40 = 532 μ D50 formation, = 119 μ</p> <p>(Not Satisfied) (Close to Satisfied)</p>
<p>Coberly & Wagner²</p> <p>D10 gravel ≤ 10 * D10 formation</p> <p>For 12/20 gravel 1590 ≤ 1740 For 20/40 gravel 749 ≤ 1392</p>	<p>D10 gravel, 12/20 = 1590 μ D10 gravel, 20/40 = 749 μ D10 formation, = 174 μ</p> <p>(Satisfied) (Satisfied)</p>
<p>Hill³</p> <p>D10 gravel ≤ 8 * D10 formation</p> <p>For 12/20 gravel 1590 ≤ 1392 For 20/40 gravel 749 ≤ 1392</p>	<p>(Not Satisfied) (Satisfied)</p>
<p>Stein⁴</p> <p>D85 gravel ≤ 4 * D15 formation</p> <p>For 12/20 gravel 950 ≤ 668 For 20/40 gravel 452 ≤ 668</p>	<p>D85 gravel, 12/20 = 950 μ D85 gravel, 20/40 = 452 μ D15 formation, = 167 μ</p> <p>(Not Satisfied) (Satisfied)</p>

FIGURE 1

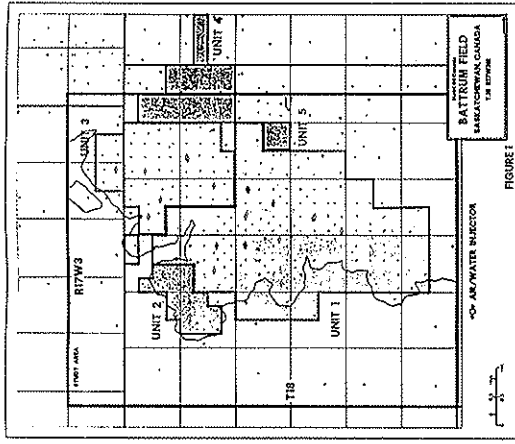


FIGURE 2
EXPERIMENTAL APPARATUS - GRAVEL PACK TESTS

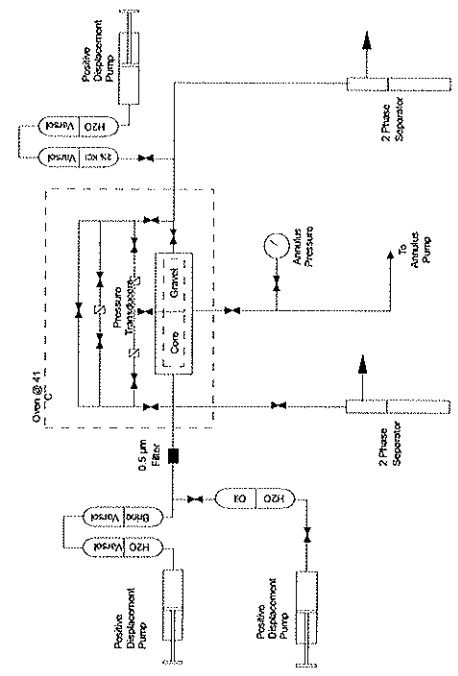


FIGURE 3
VARIATION OF FORMATION SAND SIZE DISTRIBUTION
IN A GIVEN WELL

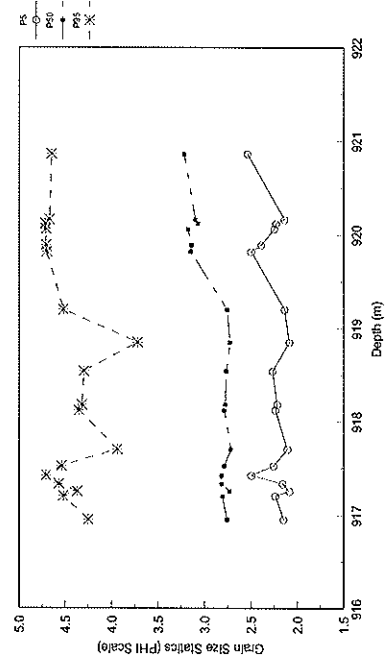


FIGURE 4
RESULTS OF GRAVEL PACK TEST #1
USING SINGLE PHASE OIL FLOW
12/20 MESH GRAVEL

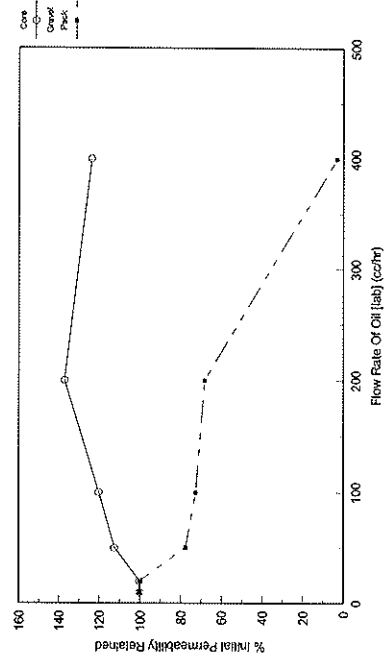


FIGURE 6
RESULTS OF GRAVEL PACK TEST #2
SIMULTANEOUS OIL & WATER FLOW
20/40 MESH GRAVEL

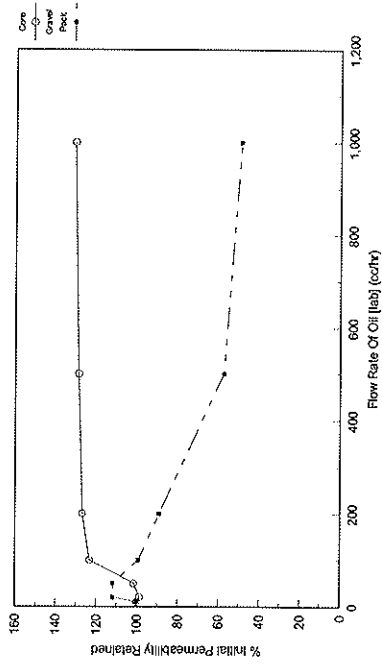


FIGURE 5
RESULTS OF GRAVEL PACK TEST #2
USING SINGLE PHASE OIL FLOW
20/40 MESH GRAVEL

