**Use of Capillary Pressure to
Estimate Permeability
in a Drill Cutting Sample
Lansing "C' Zone, Ashley #1
NE/4 Section 5 T17S R8W
Ellsworth County, KS**

by

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Subject

Drill cuttings from the Ashley #1, Lansing "C' Zone, Ashley #1, NE/4 Section 5 T17S R8W, Ellsworth County, KS were submitted for analysis to determine permeability from principal pore throat diameter as measured by mercury capillary pressure intrusion analysis. Wireline logs and core were unavailable for the well and only cuttings were obtained. Thin-section photomicrographs were provided. Analysis included routine porosity, mercury capillary pressure analysis and permeability calculation from principal pore throat diameter.

Experimental Methods

Sample Preparation

Nine cuttings from the Lansing "C' zone measuring from 0.25-0.5 inches in size were submitted. Upon receipt the cuttings were vacuum/ pressure saturated with methyl alcohol and soxhlet extracted with a toluene/methyl alcohol azeotrope to remove any remnant oil and salts. The cuttings were then dried in a vacuum oven at 70 ^{o}C to a constant weight within $\pm$ 0.002 gm.

Porosity and Grain Density

Ambient Helium porosity was determined using a Boyle's Law technique. Dry sample weights were measured to ±0.001 gm. Bulk volume was determined by mercury immersion to an accuracy of ±0.01 cc. Accurate porosity measurement for this composite sample was complicated by the large moldic pore size, the presence of large pores on the exterior of the cuttings, and the small cutting sample volumes. Mercury entry into large exterior pores limited bulk volume measurement to exclude all exterior pores. Ambient Helium porosity was measured to an accuracy and precision of better than $\pm$ 2 porosity percent. Grain density was measured to an accuracy and precision of better than +0.03 g/cc. Accuracies for these measurements were less than typical for core analysis due to the small sample size.

Air-Mercury Capillary Pressure

To obtain better resolution of the capillary pressure properties and a better understanding of the pore size distribution and pore entry throat sizes mercury intrusion capillary pressure analysis was performed. All nine cuttings were transferred to the capillary pressure instrument and evacuated to a pressure of less than 0.01 torr for a period of 5 minutes. The sample was subjected to increasing mercury injection pressures ranging from 1 to 10,000 psi. At each pressure, equilibrium was assumed to have been established when the volume of mercury injected was less than 0.2% of the pore volume for a one minute period. Injected mercury volumes were corrected for system and mercury compressibility effects. Results are presented in the following table and figures. Accuracy and precision vary with sample pore volume and outer pore sizes and surface roughness. Pump injection volumes are readable to 0.001cc. Based on a pore volume of 0.11 cc, estimated precision for the measurement is 2% for pore sizes less than 150um.

<div align="center">**Results**</div>

Petrography and Cuttings Description

Thin section photomicrographs were provided by Kent Operating Company (Figure 1) for cuttings from the same interval as the samples analyzed in this report. The cuttings comprise oomoldic-rich, bioclast lime packstone to grainstone. The samples are moderate to poorly sorted with ooids and oomolds ranging in size from 0.25-1.0 mm and exhibiting moderate to low sphericity. Ooids and oomolds appear to be lined with early isopachous cement. Interparticle porosity is occluded by finely crystalline calcite with no significant observable porosity. Highly oil-productive Lansing-Kansas City oomoldic limestones often exhibit crushing and fracturing of the matrix, providing connection between moldic pores, but this is not evident in these samples. Approximately half of all ooids were removed by dissolution.
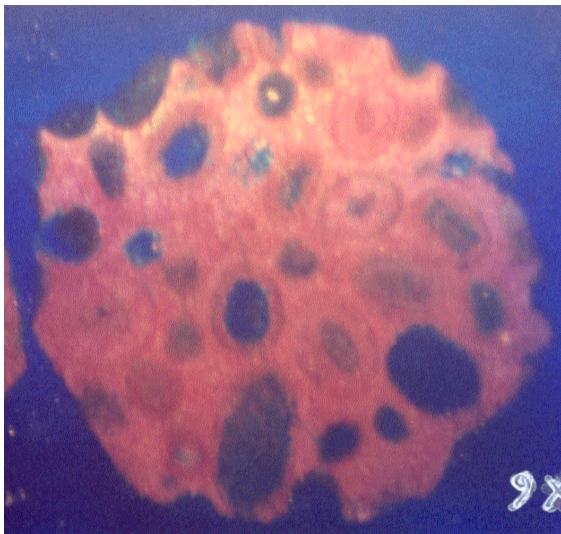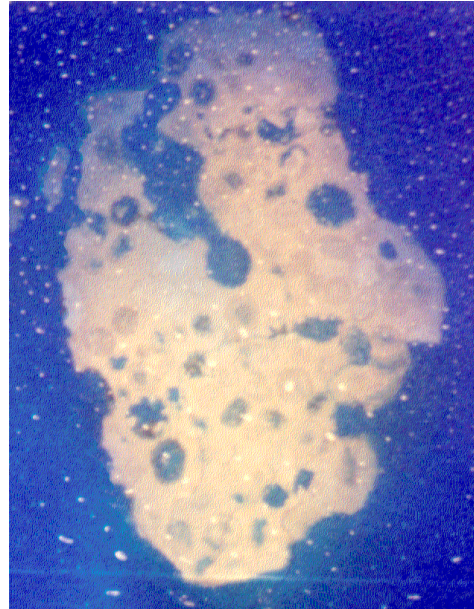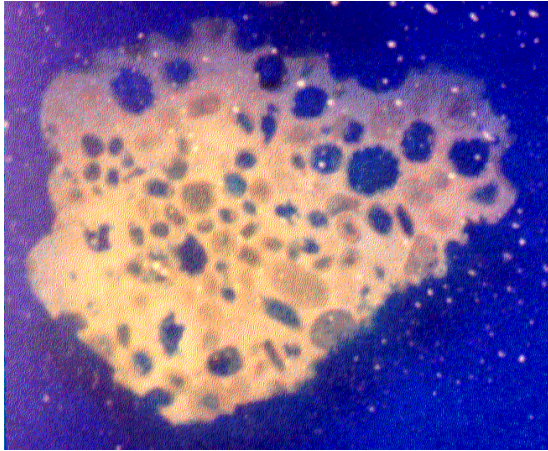

Figure 1. Thin-section photomicrographs provided by Kent Operating Company of Ashley #1 Lansing "C" zone cuttings. Samples exhibit moderate to poor sorting, ~50% dissolution of ooids, interparticle porosity filled by finely crystalline calcite cement. No fabric crushing or fracturing is evident. No scale bar – largest oomolds are ~1mm in diameter.

Porosity and Grain Density

Measured helium porosity for the composite eight cuttings is 11.1% with a grain density of 2.71 g/cc. Individual cuttings porosities estimated from thin-section photomicrographs provide by Kent Operating Company (Figure 1) range from 10 to 20%. Assuming thin-section photomicrographs provided represent the Lansing "C" interval in the Ashley #1 then average porosity may be near 10-15%. Differences between thin-section and helium porosities are within the error of each measurement and possible differences in the samples analyzed.

Mercury Capillary Pressure Analysis

The accompanying tables and figures summarize the intrusion analysis performed. Initial desaturation from 100% to approximately 70% wetting-phase saturation is likely to be highly influenced by the presence of large pores near the sample surface that are directly accessible or accessible through pore throats that would not have had access to desaturation in larger samples. This effect of sample size on capillary pressure curve shape has been previously documented (Morrow, 1976) and is pronounced in rocks with large pores and small sample size like these cuttings. A further problem with capillary pressure analysis of small composite samples is that the single curve represents the combined intrusion of many different samples. Desaturation at low pressures may reflect the influence of large exterior pores but may also represent desaturation of a single good sample that contains large pore throats but which volumetrically represents a fraction of the combined cuttings pore volumes. Capillary pressure data are presented both as measured and with the initial desaturation for pore throats greater than 20 microns removed and the total pore volume renormalized to equal only the pore volume accessible at air-mercury injection pressures greater than 20 psia.

Pore Entry Throat Diameter

Permeability is conventionally shown cross-plotted with porosity. However, the principal variables that exert greater influence on permeability are pore size and pore throat size distribution. From the air-mercury capillary pressure analysis, pore throat diameters were calculated using the Washburn relation:

$$Pc = 4CTcos\theta/d$$

Where Pc = capillary pressure (psia), C = conversion constant (0.145), θ = contact angle (deg), T = Interfacial tension (dyne/cm), d = Pore entry diameter (microns). This relation assumes that the non-wetting phase is entering cylindrical shaped pores. In reality, the pores of rocks can differ considerably from perfect cylinders. In addition, larger pore bodies are frequently "bottle-necked" by smaller pore throats so that the pore size distribution measured by mercury intrusion is actually a reflection of the volume accessed by the smaller pore throats. These operational definitions resulting from the measurement of pore size, as well as variation in the contact angle with surface roughness and mineralogy, results in pore sizes which can may vary by as much as $\pm$ 50% from the pore sizes derived from the Washburn relation above. Based upon the difficulty of adequate topologic description of pore geometry, it is considered sufficient for comparative purposes to

present the generalized pore entry throat sizes based upon the original Washburn relation.

Larger pore throats, in the 65-86 micron diameter range have not been observed in Lansing-Kansas City rocks and are unlikely to exist in these samples except as exterior pores. Though pore throats in the 20-40 micron diameter range have been observed and reported, samples exhibiting these pore throat sizes exhibit significantly coarser matrix than these samples. The probably range of pore throat diameters range from 0.6 to 8.6 microns, based on the sample lithology, and the distribution of pore throat diameters and volumes, and assuming that these cuttings accurately represent the relative proportion of pore types in the L-KC "C" zone interval in the Ashley #1. Over 65-75% of the pore volume is accessed through pore throats of less than 3 microns.

Permeability Calculation from Porosity and Pore Throat Diameter

Figure 2 illustrates the correlation between porosity and permeability for Central Kansas Uplift Lansing-Kansas City oomoldic limestones. For the 11% porosity exhibited by the composite cuttings samples estimated permeability ranges from 0.01 md to 0.2 md. Assuming a possible range in porosity of 10-15% the estimated permeability ranges from 0.01 md to 2 md.
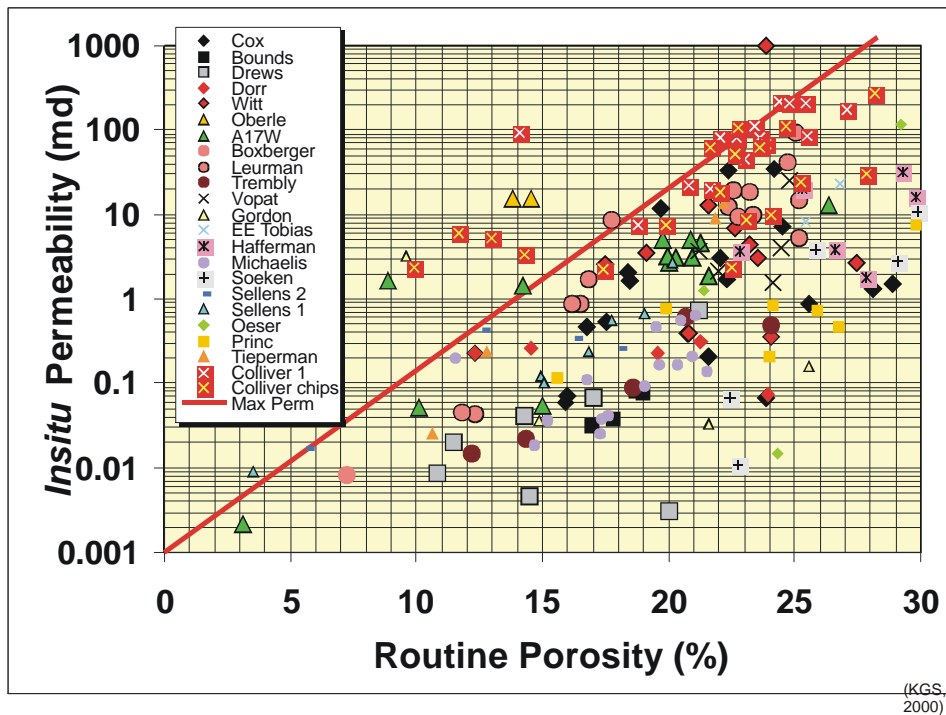
Figure 2. Cross-plot of *in situ* Klinkenberg permeability versus routine helium porosity for oomoldic limestones from the Central Kansas Uplift region.

(KGS, 2000)

Figure 3 illustrates the correlation between principal pore throat diameter and permeability for many sandstone and carbonates (Byrnes, 2001) and for the Lansing-Kansas City Formation in Kansas. The equation relating pore size to permeability for the L-KC can be expressed:

$$\text{PPETD} = 4.725\,ki^{0.448}$$

where PPETD is the principal pore entry throat diameter (microns) and *ki* is the *in situ* Klinkenbrg permeability (millidarcies, md).
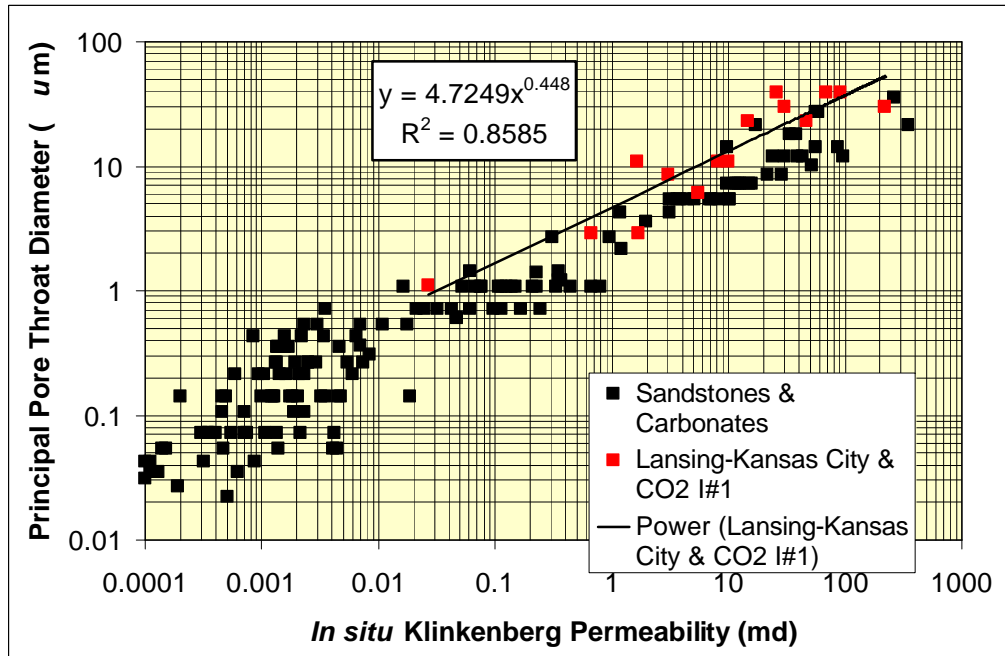
Figure 2. Permeability versus pore throat diameter for U.S. sandstones and carbonates (black square) and for L-KC rocks in Kansas (red square).

Based on the above equation, the permeability of the rocks analyzed is dependent on assumptions concerning the presence of larger pores. For a sample exhibiting pore throat diameters up to 14 microns (and assuming that larger pore throats are not directly accessible in larger samples), permeability could be estimated to range from 0.01 to 2 md. For a sample with pore throats diameters generally less than 3 microns, the estimated permeability ranges from 0.01 to 1 md.

Estimated permeabilities of 0.01 to 2 md for the lithologies evident in Figure 1 are consistent with other L-KC reservoir rocks of similar lithology, oomold size, oomold packing, and porosity (Byrnes and others, 2000).

Comparison of the capillary pressure curve for the data renormalized to remove the volume associated with pore throats greater than 20 microns (Figure 3), with another central Kansas Uplift L-KC sample exhibiting 1.7 md shows that the cuttings sample exhibits higher entry pressures indicating that their permeability is lower than the comparison sample.

Height Above Free Water Level
Gore Leurman #7 3057 ft - 1.7 md

Figure 3. Comparison of capillary pressure curves for the cuttings and another L-KC where capillary pressure is translated to height above free water shows that the cutti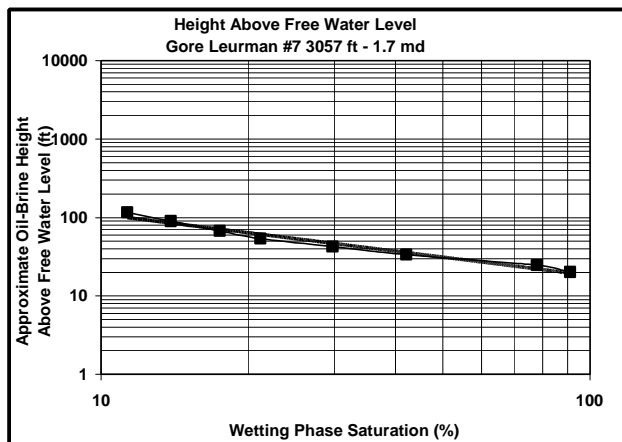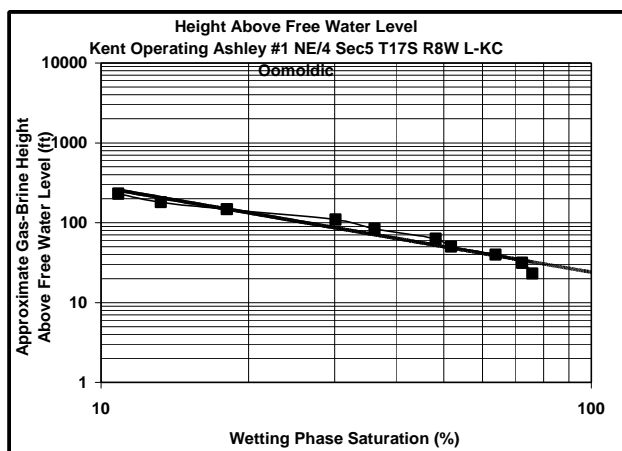ngs analyzed have high entry pressures and therefore lower permeabilities. Cuttings trend was defined using renormalized volume data for which volume for pores throats greater than 20 microns was removed and saturation renormalized to reflect remaining pore volume.

Height Above Free Water Level
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC

Summary

The cuttings samples provided from the Ashley #1 Lansing "C" zone exhibit porosity in the range of 10-20%. Assuming the cuttings are representative of the Lansing "C" interval, the average interval porosity is 10-15%. This is consistent with both thin-section and helium porosity analysis.

Permeability for these rocks lies in the range of 0.01 md to 2 md. This range is predicted using correlation of both porosity and mercury intrusion pore throat diameter analysis.

It is important to note that the cuttings samples provided may not be fully representative of the reservoir. High permeability oomoldic Lansing-Kansas City can be friable and may not be preserved in cuttings. However, the low energy depositional environment indicated by the lithology of these cuttings samples is not consistent with the higher energy environments often characteristic of better oomoldic reservoirs.

References

Morrow, N.R., 1976, "Effect of scale on capillary pressure curves of carbonate samples", J. Can. Pet. Tech., July-Sept, p. 75-79.

Byrnes, A.P., 2001, Dec. 2001 Quarterly Report Field Demonstration of Carbon Dioxide Miscible Flooding in the Lansing-Kansas City Formation, Central Kansas http://www.kgs.ukans.edu/CO2/Reports/DE-AC26-00BC15124_QR123101.pdf
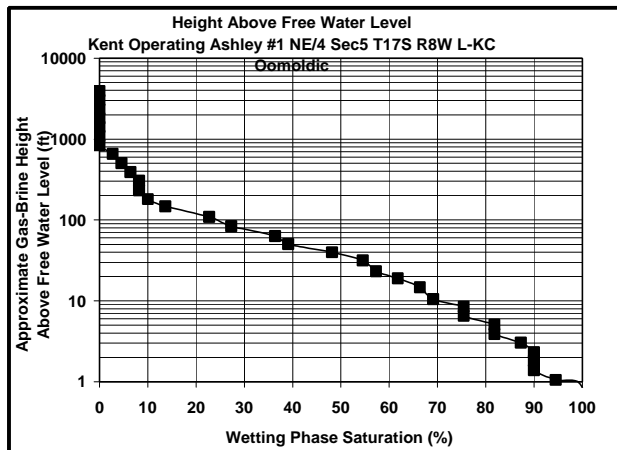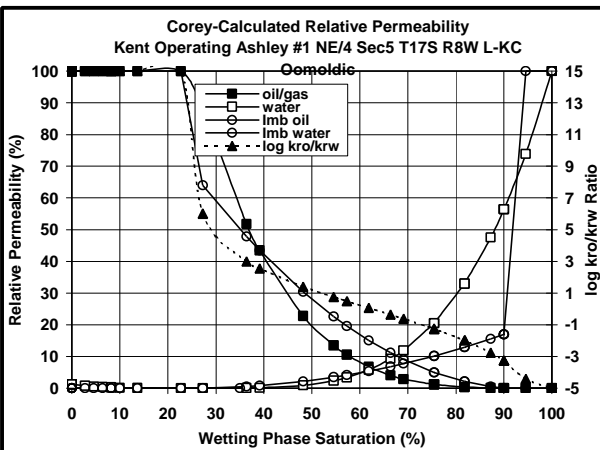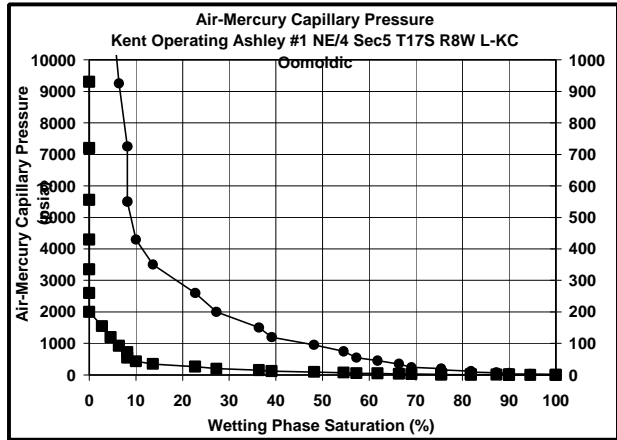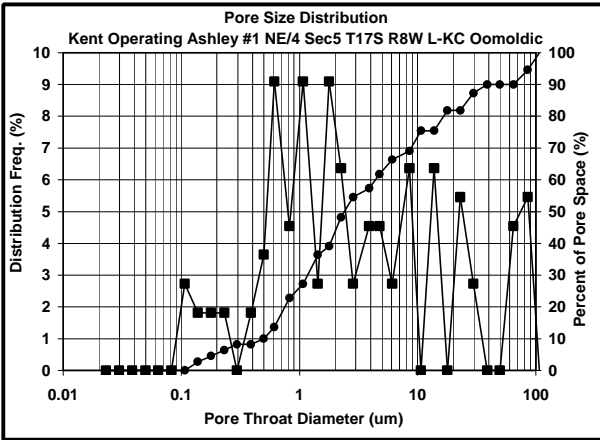
Mercury Injection Capillary Pressure Analysis
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic
(Includes complete intrusion analysis)

Estimated Permeability from Pore Throat Diameter = 0.2 - 4 md
Sample consisted of cuttings exposing large volume of exterior pores

Mercury Injection Capillary Pressure (psia)	Approx. Pore Entry Diameter (um)	Cumulative Wetting Phase Saturation (% pore vol)	Pore Size Distribution Frequency	Cumulative Surface Area (m2/g)	Approx. Gas-Water Height Above Free Water Level (ft)	Approx. Oil-Water Height Above Free Water Level (ft)	Honarpour *et al*. Imbibition Carbonate Oil Relative Permeability (%)	Water Relative Permeability (%)	Corey Calculated Oil or Gas Relative Permeability (%)	Water Relative Permeability (%)	Log Oil/Brine Kro/Krw Ratio
		100.0	0.0	0.000	0.1	0.1	0.0	100.0	0.0	100.0	-5.0
2.0	107	100.0	0.0	0.000	0.8	0.8	0.0	100.0	0.0	100.0	-5.0
2.5	86	94.5	5.5	0.000	1.0	1.0	0.0	100.0	0.0	73.9	-4.4
3.3	65	90.0	4.5	0.000	1.4	1.3	0.0	17.0	0.0	56.4	-3.3
4.3	50	90.0	0.0	0.000	1.8	1.7	0.0	17.0	0.0	56.4	-3.3
5.5	39	90.0	0.0	0.000	2.3	2.2	0.0	17.0	0.0	56.4	-3.3
7.2	30	87.3	2.7	0.000	3.0	2.8	0.5	15.6	0.1	47.5	-2.8
9.3	23	81.8	5.5	0.001	3.9	3.6	2.1	12.9	0.3	32.9	-2.0
12.0	18	81.8	0.0	0.001	5.0	4.7	2.1	12.9	0.3	32.9	-2.0
15.5	14	75.5	6.4	0.002	6.5	6.1	5.0	10.2	1.1	20.5	-1.3
20	11	75.5	0.0	0.002	8.4	7.8	5.0	10.2	1.1	20.5	-1.3
25	8.6	69.1	6.4	0.003	10.5	9.8	9.1	7.7	2.9	11.9	-0.6
35	6.1	66.4	2.7	0.003	15	14	11.1	6.8	4.0	9.3	-0.4
45	4.8	61.8	4.5	0.005	19	18	15.1	5.4	6.7	5.8	0.1
55	3.9	57.3	4.5	0.007	23	22	19.6	4.1	10.5	3.4	0.5
75	2.9	54.6	2.7	0.009	31	29	22.6	3.5	13.5	2.4	0.7
95	2.3	48.2	6.4	0.013	40	37	30.4	2.1	22.8	0.9	1.4
120	1.8	39.1	9.1	0.022	50	47	43.5	0.8	43.5	0.1	2.5
150	1.4	36.4	2.7	0.016	63	59	47.8	0.5	51.8	0.1	3.0
200	1.1	27.3	9.1	0.030	84	78	64.0	0.0	88.4	0.0	6.0
260	0.82	22.7	4.5	0.039	109	102	100.0	0.0	100.0	0.0	15.0
350	0.61	13.7	9.1	0.064	147	137	100.0	0.0	100.0	0.1	15.0
430	0.50	10.0	3.6	0.076	180	168	100.0	0.0	100.0	0.2	15.0
550	0.39	8.2	1.8	0.084	231	215	100.0	0.0	100.0	0.3	15.0
725	0.30	8.2	0.0	0.084	304	284	100.0	0.0	100.0	0.3	15.0
925	0.23	6.4	1.8	0.097	388	362	100.0	0.0	100.0	0.4	15.0
1200	0.18	4.6	1.8	0.113	504	470	100.0	0.0	100.0	0.6	15.0
1550	0.14	2.7	1.8	0.135	650	607	100.0	0.0	100.0	0.8	15.0
2000	0.11	0.0	2.7	0.177	839	783	100.0	0.0	100.0	1.2	15.0
2600	0.08	0.0	0.0	0.177	1091	1018	100.0	0.0	100.0	1.2	15.0
3350	0.06	0.0	0.0	0.177	1406	1312	100.0	0.0	100.0	1.2	15.0
4300	0.05	0.0	0.0	0.177	1804	1683	100.0	0.0	100.0	1.2	15.0
5550	0.04	0.0	0.0	0.177	2329	2173	100.0	0.0	100.0	1.2	15.0
7200	0.03	0.0	0.0	0.177	3021	2819	100.0	0.0	100.0	1.2	15.0
9300	0.02	0.0	0.0	0.177	3902	3641	100.0	0.0	100.0	1.2	15.0

All Hg calculations assume air-mercury T=484 dyne/cm, contact angle=140deg.

Oil/Gas-Brine Pc assumes insitu o/g-brine Tcos0=	64.0000	22.0000	dynes/cm
Oil/gas-Brine height assumes o/g density gradient =	0.0866	0.3464	psi/ft
Oil/gas-Brine height assumes brine density gradient =	0.4980	0.4980	psi/ft
Swi assumed for relative permeability =	25.0	25.0	%
Sorw assumed for relative permeability =	10	10	%
In situ Gas/Oil & Brine Density (g/cc)=	0.200/0.80	1.15	g/cc

Mercury Injection Capillary Pressure Analysis
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic

Pore Size Distribution
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic

Air-Mercury Capillary Pressure
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC
Oomoldic

Corey-Calculated Relative Permeability
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC
Oomoldic

- oil/gas
- water
- lmb oil
- lmb water
- log kro/krw

Height Above Free Water Level
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC
Oomoldic

Mercury Injection Capillary Pressure Analysis
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic
(Large Pores Removed and Pore Volume Renormalized)

Estimated Permeability from Pore Throat Diameter = 0.2 - 4 md
Sample consisted of cuttings exposing large volume of exterior pores

Mercury Injection Capillary Pressure (psia)	Approx. Pore Entry Diameter (um)	Cumulative Wetting Phase Saturation (% pore vol)	Pore Size Distri-bution Fre-quency	Cumula-tive Surface Area (m2/g)	Approx. Gas-Water Height Above Free Water Level (ft)	Approx. Oil-Water Height Above Free Water Level (ft)	Honarpour et al. Imbibition Carbonate Oil Relative Permea-bility (%)	Water Relative Permea-bility (%)	Corey Calculated Oil or Gas Relative Permea-bility (%)	Water Relative Permea-bility (%)	Log Oil/Brine Kro/Krw Ratio
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Oil/gas-Brine height assumes brine density gradient =	0.4980	0.4980 psi/ft
Swi assumed for relative permeability =	25.0	25.0 %
Sorw assumed for relative permeability =	10	10 %

Mercury Injection Capillary Pressure Analysis
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic

Pore Size Distribution
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic

Air-Mercury Capillary Pressure
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic

Corey-Calculated Relative Permeability
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic

Height Above Free Water Level
Kent Operating Ashley #1 NE/4 Sec5 T17S R8W L-KC Oomoldic