Aquifer Characteristics and Hydrogeology

Kansas Geological Survey Open-File Report 94-28d

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A cooperative investigation by

The Kansas Geological Survey and
Big Bend Groundwater Management District No. 5

This report summarizes all known determinations of the permeability of the Permian bedrock underlying Groundwater Management District No. 5. Information on other hydrologic parameters of the bedrock (e.g., storativity, porosity) is also presented, as is a less exhaustive summary of the hydrogeologic characteristics of the overlying Great Bend Prairie aquifer (GBPA).

There are three general sources of data summarized in this report. First, there are previous reports of field tests of bedrock permeability (Olsen, circa 1981; Cobb et al., 1982; KCC, 1986; Gillespie and Hargadine, 1993), most of which have been previously reviewed by Young (1992). Second, a series of field tests conducted for this project; methods and the first round of test results have been reported by Butler et al. (1993). Third, a series of core samples have been analyzed with nitrogen gas permeametry by a commercial laboratory for horizontal and vertical permeability, porosity, and grain density; a copy of that laboratory report is contained in Appendix A of this report. All of the bedrock field tests used some variant of slug test methodology, but the exact techniques varied. The reader is referred to the original literature for experimental details.

Information on the hydrogeologic characteristics of the Great Bend Prairie aquifer were derived from pumping test data reported by Gillespie and Hargadine (1993), from slug test data reported by Butler et al. (1993), from a literature review summarized by Sophocleous et al. (1993), and from inverse model optimization results obtained by Sophocleous (1992).

Permian Formations and Formation Tests:

The Permian formations in the study area are layered sandstones, siltstones, and shales. They are variably but generally rather weakly cemented, and are easily fractured (see Appendix A). The coarser, less well-cemented layers tend to be more porous and permeable, and also less likely to be fully recovered in coring operations. For this reason, laboratory core permeability determinations are likely to underestimate the overall formation permeability. Slug tests can assess the integrated characteristics of a larger volume of the formation, but their validity is dependent on good well construction, especially in terms of isolating the bedrock from the overlying alluvium, and on the absence of skin effects. If the borehole provides an interconnection with the overlying aquifer of alluvial origin (which is known to occur at some wells), slug tests may overestimate the permeability of the bedrock.

The results of all available Permian formation permeability tests in both field (Kf) and lab (Kp) are summarized in Table D1. All field tests were slug tests except for one estimate based on a flowing artesian well (Gillespie and Hargadine, 1993), and all wells were completed in the upper few tens of feet of the bedrock formation. The slug test results suggest two clusters of values: one around 0.5 ft/day (0.1-1.0) and the other around 0.01 (0.004-0.04). A few values are in the 1-10 ft/day range, but two of these sites (1 and 36) are known to have well integrity problems, and the other two (5 and 10) are among the earlier installations that have generally been prone to problems.

TABLE D1. BEDROCK PERMEABILITY DETERMINATIONS

LOCATION	SITE. WELL	LAND ELEV	BR ELEV	SAMPLE ELEV	Kf (ft/day)	Kp (ft/day)	NOTES	REF
23S12W12BAAA	1.1	1827	1681	1681	14.7+			C
23S12W06BBB	5.1	1855	1674	1662	4.9			C
25S13W06BCBC	6.1	1950	1802	1734	0.03			C
					0.04			C
24S13W36DDDD	7.1	1906	1756	1676	0.2			C
					0.5			C
25S12W11AAAD	8.1	1848	1731	1611	0.35			C
24S10W06DCCC	10.1	1790	1634	1630	1			C
					9.4			C
29S14W12ADDD	14.1	1989	1751	1725		.0069+	HORIZ	A
						.017+	VERT	A
28S11W01AAAD	15.1	1725	1597	1590	0.01			C
					0.01			C
				1581		0.0012	HORIZ	A
						0.0002	VERT	A
21S12W31CCCB	16.1	1872	1652	1629	0.01			B
21S12W36DDCC	17.1	1804	1690	1675	0.0037			B
					0.009			C
21S11W07BBBA	18.1	1810	1596	1579	0.006			C
25S13W36DCCC	19.1	1901	1738	1721	0.008			C
25S13W31DDAA	20.1	1960	1762	1735		0.0007	HORIZ	A
						0.0002	VERT	A
23S10W06BBAB	25.1	1780	1682	1660		+		A
					0.044			B
23S09W01ADAA	27.1	1685	1581	1561		0.7+	HORIZ	A
						0.001	VERT	A
27S12W06BAAB	36.1	1892	1697	1682	+			B
21S12W27DACC	S-P	1840	1654	1642	0.139			B
				1637		0.017	HORIZ	A
						0.0038	VERT	A
				1615		0.96	HORIZ	A
						0.65	VERT	A
22S23W35A	NA				1.4			K
	NA				0.04			K
27S11W30CCDD	NA				0.7		FLOW	G
27S11W31ADDD	NA				0.2			G
27S11W33BBBB	NA				0.7			G
27S12W25ADDA	NA				0.5			G
27S12W25DBBC	NA				0.4			G

(+) MEASUREMENT FAILURE OR SUSPECT VALUE (PROBABLY HIGH)

SAMPLE ELEV = SCREEN FOR SLUG TEST, CORE DEPTH FOR LAB

REFS: A = APPENDIX A, B= BUTLER ET AL, G = GILLESPIE & HARGADINE, K=KCC
C = COBB ET AL.

Laboratory tests on core samples show an even greater range -- from 0.001 to 1.0 ft/day. All of the core samples were classified as muddy siltstones except for the deeper sample from the Siefkes site, which was identified as a very fine sandstone. As expected, they tend to yield somewhat lower results than the slug tests at the same wells (compare site 15 results). However, the two core samples analyzed from the Permian well at the Siefkes intensive study site (SP) show the short-range variability in the Permian beds, differing in permeability by nearly two orders of magnitude, with the higher permeability corresponding to the sandstone sample. It is interesting to note, however, that the slug test of this well yielded a result that is almost identical to the geometric mean of the two core tests. The lab results indicate that vertical permeability is lower than horizontal, but generally not by as much as an order of magnitude.

The site 17 slug test results provide a comparison between the tests conducted for this study (Butler et al., 1993) and earlier tests; the similarities (0.0037 vs. 0.009) indicate that the results of different studies can safely be combined for large-scale order-of-magnitude considerations. Beyond these general comparisons, there do not appear to be obvious patterns (e.g., with respect to test method, location, or identity of Permian formations).

Appendix A shows Permian grain densities grouped around 2.6 g/cc, and sample porosities ranging from 15.2 to 24.5%. These porosities, determined by nitrogen gas techniques, are probably closer to total porosity than to the effective porosity normally used in flow calculations.

Great Bend Prairie Aquifer Formation Characteristics:

Table D2 presents the results of selected determinations of Great Bend Prairie aquifer characteristics presented in the reports from which the Permian aquifer characteristics were assembled (see reference notes in Table D1), and results derived for the lower Rattlesnake basin by model optimization. This is by no means a comprehensive review of data available for the GBPA, but it provides a view of the direct comparisons performed by those investigators. Table D3 is a modified excerpt from the report of Sophocleous et al. (1993), summarizing available data relevant to modeling stream-aquifer interactions of the Arkansas River from Kinsley to Great Bend. It should be noted that the higher values are associated primarily with the Arkansas River alluvium, and may not be as relevant to the Mineral Intrusion study area.

The pumping tests reported by Gillespie and Hargadine (1993) yield typical values in the 150-200 ft/day range. Pumping tests are excellent large-scale tests, but because wells are normally sited and constructed to maximize access to the most productive zones of the aquifer, test results tend to produce higher K values than are appropriate for the entire aquifer formation. The other values in Tables D2 and D3 tend to confirm this. Slug test results in the mutiple GBPA wells at each of two sites show the local variability, and lower values than the pump tests, due in large part to the presence of clay layers within the

TABLE D2. GREAT BEND PRAIRIE AQUIFER PERMEABILITY DETERMINATIONS

LOCATION	SITE. WELL	BR ELEV	TEST ELEV	Kf (ft/day)	TEST TYPE	NOTES	REF
21S12W31CCCB	16.2	1652	1674	31.6	SLUG		B
21S12W31CCCB	16.3	1652	1792	56.8	SLUG		B
27S12W06BAAB	36.2	1697	1701	88.1	SLUG		B
27S12W06BAAB	36.3	1697	1746	57.9	SLUG		B
27S12W06BAAB	36.4	1697	1807	10.8	SLUG	7.8-13.8	B
27S13W21ACA1	NA			155	PUMP		G
28S11W10A	NA			200	PUMP		G
28S11W32A	NA			200	PUMP		G
28S13W26DCB1	NA			200	PUMP		G
N STAFFORD CO	NA			78	MODEL	MAX	S
N STAFFORD CO	NA			130	MODEL	MAX	S

REFS AS IN D1, S = SOPHOCLEOUS

Table D3. Hydrogeologic Properties of the Great Bend Prairie Aquifer Including the Arkansas River Alluvium (from Sophocleous et al., 1993).

Methodology	Transmissivity $T(ft^2/d)$	Hydraulic Conductivity K(ft/d)	Storativity S	Average Saturated Thickness (ft)	Source
5 aquifer tests	7,000–16,000	56–128	0.004–0.17	125	Fader & Stullken, 1978
Specific capacities of 235 irrigation wells	2,500–35,000 (ave. = 11,000)			125	Fader & Stullken, 1978
6-hr aquifer test near St. John	10,026	72	0.025	139	Cobb, 1979; 1980
8-day stream-aquifer test near Great Bend	19,404 (geom. mean)[a] 19,768 (arith. mean)[a] 4,979 (std. dev.)[a]	223 230 57	0.00056 0.000742 0.000664	87	Sophocleous et al., 1987; 1988
68 drillers' logs	6,132 (mean) 3,171 (std. dev.)	85 37	0.15 0.05	76 30	Sophocleous et al., 1993

a. Average of drawdown- and recovery-derived values of 12 observation wells.

alluvium. Sophocleous (1992) optimized permeability values against pre- and post-development groundwater levels used in a MODFLOW model of the lower Rattlesnake Creek basin. Two different approaches defined a maximum range of satisfactory fit of about 78-130 ft/day for the more productive parts of the aquifer; these are the values listed for northern Stafford County in Table D2.

The permeability contrast between the Permian and Quaternary formations is of interest from the standpoint of modeling. A "low-contrast" scenario would take the bedrock K of about 0.5 and a GBPA K of around 50 for a ratio of 100. However, values of 0.01 and 100 would be equally justified on the basis of tables D1 and D2, and this would produce a ratio of 10,000.

<u>Preliminary Head Gradient and Flux Calculations</u>:

An ultimate goal of the project is characterizing the actual and potential saltwater fluxes from the Permian formations into the GBPA on both regional and local scales. Ideally, this requires some understanding of the distributions of both heads and permeabilities, as well as of the other factors affecting hydrologic coupling between the two formations.

Water fluxes may be calculated from Darcy's equation,

$$v = \mathrm{K}(\mathrm{dH/dL}), \qquad (1)$$

where v is the specific discharge per unit area of aquifer ($ft^3/day/ft^2$), K is the permeability (or hydraulic conductivity) in ft/day, and dH/dL is the head gradient or change in hydraulic head per unit distance.

Discharge of saline water from the bedrock into the GBPA may occur along two different pathways. Predominantly horizontal down-gradient flow may move through the more permeable bedrock sandstone layers and discharge laterally when it encounters the sloping erosional surface of the bedrock. On the other hand, if there is greater pressure in the bedrock than is compensated by the potentially confining body of water in the overlying aquifer, vertical discharge may occur. If we can estimate the vertical head gradient we can therefore calculate estimates of the vertical flux of brine at each of the sites for which we have a Permian permeability estimate.

It is important to stress that the calculations undertaken here are estimates rather than rigorous determinations; the data set is sparser than we would like and a number of assumptions must be made. Nonetheless, the data sets assembled by the Mineral Intrusion project are both more extensive and arguably more accurate than anything previously available. Preparing estimates of the vertical fluxes at many of the saline sites will permit us to compare these results with salt inventories and previously calculated water budgets, and with the results of numerical modeling based on assumptions about the controlling physical principles. The outcome of the comparisons will provide guidance on the relative importance of different pathways and the validity of assumptions about mechanisms of saltwater intrusion.

Table D4 presents the results of calculations of vertical head differences, gradients, and discharge estimated on the basis of the available permeability values. These values are adjusted for density. Density adjustments are discussed generally in more detail in OFR 94-28b, but we present here a brief rationale and description of methods used to derive the density-adjusted head gradients.

For assessing the probable rate of inflow of saltwater from the Permian to the Great Bend Prairie aquifer formations, the critical head gradient is across the bedrock interface. The "confining head" of the overlying aquifer is calculated as the difference between the bedrock surface elevation and the water table elevation, multiplied by the average density of the water column determined by integrating the chloride profile (see OFR 94-28b). The result is the environmental-water head of the Great Bend Prairie aquifer. This result, based on a consistent set of recent measurements, is probably as accurate an estimate of the aquifer head at the bedrock surface as can be obtained.

The Permian head, or the pressure that can drive vertical flow of the bedrock fluids, is represented by the freshwater-equivalent head at the top-of-screen elevation in the bedrock well. To obtain the density-adjusted value, we multiply the difference between the screen and fluid level elevations by a density corresponding to the best available measurement of the chloride content of the bedrock fluid (Whittemore, 1993; see also OFR 94-28b). This approach is valid if two assumptions are met: (1) that the well has been adequately developed and is intact, so that the entire water column is of bedrock salinity, and (2) that the available water quality determination reflects conditions at the time the fluid level was measured. Both assumptions are the source of uncertainty in the Permian heads. If the first assumption is inaccurate our procedures will bias the result toward higher-than-actual Permian heads. Deviations from the second assumption could shift the result in either direction depending on the quality of the sampling and analysis and any variability in the Permian fluid.

To estimate a vertical gradient across the bedrock interface, we use the difference between the calculated freshwater head of the Permian well (H_{if}, assumed to represent the driving force for upward flow) and the environmental head at the bedrock datum (H_{in}, assumed to represent the confining pressure of the overlying water column). Hence, the hydraulic gradient (tabulated as GRAD in Table D4) is calculated as:

$$\mathrm{GRAD} = (H_{if} - H_{in})/\Delta L. \qquad (2)$$

We need to stress that the calculations reported here are merely approximations based on available data and a number of assumptions. Estimating upward flow from the Permian is complicated and is undergoing further refinements. Two sources of uncertainty in equation 2 are as follows:

TABLE D4: PERMIAN HEAD GRADIENTS AND FLUXES, 1993/1994

SITE.well	Z BR	Z SCR	DEL H93	GRAD93	DEL H94	GRAD 94	K	FLUX94	FLUX 93
1.1	146	146	0.20818		2.11953		14.7+		
SP	186	197	8.016	0.728727	9.32642	0.847856	0.14	0.1187	0.102022
4.1	129	217	99.37875	1.129304	98.79394	1.122658			
5.1	181	193	19.29349	1.607791	19.05139	1.587615	4.9+		
8.1	118.3	237	114.7107	0.966392	118.6724	0.999767			
10.1	156	160	-0.39441	-0.0986	-2.44087	-0.61022	1	-0.61022	-0.0986
11.1	208	237	16.32727	0.563009	16.9073	0.58301			
16.1	220	243	13.53518	0.588486	17.94999	0.780434	0.01	0.007804	0.005885
17.1	114	129	-18.3167	-1.22111	-17.7188	-1.18125	0.007	-0.00827	-0.00855
18.1	214	231	4.005176	0.235599	3.776692	0.222158	0.006	0.001333	0.001414
21.1	137	145	5.92004	0.740005	6.597933	0.824742			
22.1	215	231	10.51838	0.657399	12.06573	0.754108			
23.1	94	122	25.97498	0.927678	27.2474	0.973121			
24.1	123	131	4.97476	0.621845	5.871628	0.733954			
25.1	98	120	17.66877	0.803126	16.95611	0.770732	0.04	0.030829	0.032125
26.1	177	190	5.46676	0.42052	6.793272	0.522559			
27.1	104	115	10.51071	0.955519	10.80276	0.982069	0.001	0.000982	0.000956
30.1	134	155	14.60666	0.69556	15.974	0.76067			
31.1	93	108	15.38553	1.025702	15.92553	1.061702			
32.1	172	189	-26.1925	-1.54074	-22.5317	-1.32539			
36.1	195	210	17.79996	1.186664	19.13485	1.275657			
37.1	240	255	13.25598	0.883732	13.48201	0.898801			
42.1	160	178	10.57177	0.58732	13.36828	0.742682			
43.1	65	88	22.60586	0.982864	23.07462	1.003244			

(+) VALUE SUSPECT, FLUX NOT CALCULATED

HEADS ARE DENSITY-CORRECTED; SEE TEXT FOR DEFINITIONS

1) In calculating the difference between the two heads (Hif - Hin; tabulated in Table D4 as DEL H), a more appropriate solution would have used the environmental head, Hin, of the Permian (Lusczynski, 1961). The environmental head was not used because it requires a completely integrated density profile, which is not yet available for the bedrock interval.

2) The length term (ΔL) is taken as the difference in elevation between the top of the Permian well screen and the bedrock-alluvium contact. The value of the term (ΔL) is arbitrary since it depends on how deep into the bedrock the Permian well happens to be screened.

Keeping this in mind, when we multiply the hydraulic gradient (GRAD) by the hydraulic conductivity (K), the specific discharge per unit bedrock surface area is obtained, and is tabulated as FLUX in Table D4. A positive value represents upward flow of water, a negative value, downward.

Because the "Permian" well at site 1 is in contact with the GBPA we cannot calculate a credible Permian gradient at that site. At site 5, the nature of the installation has made it impossible for us to log to bedrock or confirm earlier well tests, so we do not report a flux value for that site. Both sites have substantial saltwater inventories in the GBPA, however, so it is likely that there is an upward gradient and a significant flux.

Discussion:

Estimated values such as these can be used to determine a "best" estimate value, an extreme upper or lower limit, or a "credible" upper or lower limit. The credible limits are physically reasonable estimates in which the necessary assumptions have been made to favor either the higher or the lower end of the range of possible fluxes. It is often easier to make good limit estimates than "best value" estimates, and it may be quite valuable in assessing data and models.

The estimates of flux made here are probably oriented toward the credible upper limits. As indicated above, slug test permeabilities may overestimate vertical permeability because of anisotropy or well effects. We have also noted that the density correction of the Permian heads will result in overestimation if the well is not adequately developed. Further, the calculated head gradients implicitly assume hydraulic continuity, and neglect the effects of any clay layers at the bedrock-aquifer interface. None of these assumptions are unreasonable, but errors in most cases will tend to be in the direction of a higher-than-actual calculated vertical flux. The one omission that might operate to skew results in the other direction is inability to identify regions of bedrock fracturing or surface exposure of the more permeable sandstone layers, both of which would result in higher fluxes. Special cases and alternative approaches are noted individually.

The application of these to inventory and budget considerations is discussed in OFR 94-28e. However, it should be noted that the values obtained are indeed rather high. For comparison, we note that the various estimates obtained for GBPA freshwater recharge are all less than 0.5 ft/yr, which means that the recharge expressed as a daily flux should be in the vicinity of 0.001 $ft^3/day/ft^2$. This is the lowest brine flux estimate obtained, yet because there is more freshwater than brine in the GBPA, we would normally expect the average or net Permian flux to be lower than the recharge. Possible reasons for, and implications of, this discrepancy are discussed in more detail in OFR 94-28e.

References:

Butler, J. J. Jr., W. Liu, and D. P. Young, 1993. Analysis of October 1993 slug tests in Stafford, Pratt, and Reno counties. Kansas Geol. Survey Open-File Report 93-52.

Cobb, P. M., S. J. Colarullo, and M. Heidari, 1982. A groundwater flow model for the Great Bend aquifer, south-central Kansas. Kansas Geological Survey Open-File Report 83-20, 229 pp.

Gillespie, J. B., and G. D. Hargadine, 1993. Geohydrology and saline ground-water discharge to the South Fork Ninnescah River in Pratt and Kingman counties, south-central Kansas. U.S. Geological Survey Water-Resources Investigations Report 93-4177, 51 pp.

KCC, 1986. Report of the committee concerning disposal of oil field brine into Permian formations in south central Kansas. Unpublished report by Oil and Gas Advisory Committee.

Lusczynski, N. J. 1961. Head and flow of ground water of variable density. Jour. Geophys. Res., v. 66, n. 12, pp. 4247-4256.

Olsen, M. C., circa 1981. Unpublished reports on slug test results.

Sophocleous, M. A., 1992. Modifications and Improvements on the Lower Rattlesnake Creek-Quivira Marsh Stream-Aquifer Numerical Model. Kansas Geological Survey Open-File Report 92-37, 15 pp.

Sophocleous, M. A., S. P. Perkins, and S. Pourtakdoust, 1993. Stream-aquifer numerical modeling of the Kinsley to Great Bend reach of the Arkansas River in central Kansas: final report. Kansas Geological Survey Open-File Report 93-21, 106 pp. plus appendices.

Whittemore, D.O., 1993. Ground-water geochemistry in the mineral intrusion area of Groundwater Management District No. 5, south-central Kansas, Kansas Geol. Survey Open-File Report 93-2.

Young, D. P., 1992. Mineral Intrusion: Geohydrology of Permian Bedrock Underlying the Great Bend Prairie Aquifer in South-Central Kansas. Kansas Geol. Survey Open-file Report 92-44, 47 pp.

Appendix A, KGS Open-file Report 94-28d

Report of permeability and porosity determinations of Permian core samples

ROUTINE CORE ANALYSIS

for the
KANSAS GEOLOGICAL SURVEY

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INTRODUCTION

TerraTek, Inc. received from the Kansas Geological Survey, seven (7) shallow core samples from various sites. Site descriptions and depths from which the core samples were obtained are summarized, along with the test results, in Table 1 at the end of this report. As instructed, permeability and porosity measurements were performed on each as possible. The sample from Site 25, at a depth of 128 feet, was not suitable for analysis. The remaining samples were, to varying degrees, suitable for testing.

Samples for testing were prepared from the material received. Test samples were obtained by cutting the cores with a diamond saw blade, using fresh water as blade coolant. Prior to performing the requested tests, salt, which formed as a crust on the outside of the samples, was removed by gently cleaning with methanol in a sidearm soxhlet extractor. Despite efforts to prevent sample deterioration, a certain amount of damage occurred to some of the samples during cleaning. In some cases, new samples were prepared to replace sample material which was too damaged to test. The clean samples were allowed to dry on a laboratory bench top for 48 hours prior to testing. Heated drying was avoided to prevent any further damage to the samples.

POROSITY AND GRAIN DENSITY DETERMINATION

Porosity was determined by measuring bulk volumes and grain volumes. Bulk volumes were measured by submerged weight in water using Archimedes' principle of buoyancy. Prior to measuring submerged weights, the samples were coated with bee's wax to prevent serious damage which was certain to occur if these friable samples had been allowed to come into direct contact with water. The density of the wax was measured prior to coating the samples and the weight of wax used on each sample was determined. This was done in order to calculate the volume of wax used to coat each of the samples. The volume of wax on each sample was subtracted from the total bulk volume value obtained from the submerged weight measurements so that the bulk volume of the sample material alone could be determined. Equation 1 below details the calculation of bulk volume.

$$V_B = \frac{Wt_{subm}}{\rho_{wat}} - \frac{Wt_{wax}}{\rho_{wax}} \qquad (1)$$

V_B is sample bulk volume (cm^3), Wt_{subm} is submerged weight in water of the waxed sample (gm), ρ_{wat} is the density of water (gm/cm^3), Wt_{wax} is the weight of wax coating the sample (gm), and ρ_{wax} is the density of wax (gm/cm^3).

Grain volumes were measured in a helium expansion porosimeter using Boyle's law. Before testing began, the porosimeter was calibrated using a set of six (6) aluminum billets of known volume. The calibration was performed by loading a prescribed number of the billets into the test cell, then measuring the ratio of helium pressure in a reference cell and helium pressure in the test cell containing the billets. This process was repeated four times, each time using a progressively smaller volume of billets in the test cell. The pressure relationship for each step was plotted against the volume of the billets placed in the test cell and a linear regression was performed. The grain volume tests were then performed by placing a sample in the calibrated test cell and filling as much of the free space as possible with billets. Helium was introduced in the reference cell and the pressure was recorded. The gas was then allowed to expand into the test cell. The pressure was monitored until stabilization was achieved, at which time the test pressure was recorded. The reference pressure, the test cell pressure, and the results of the linear regression analysis were used to calculate grain volume of the samples as described in Equation 2:

$$V_G = R(\frac{P_1}{P_2}) + B - V_{bill} \qquad (2)$$

V_G is sample grain volume (cm^3), R and B are linear regression coefficients, P_1 is reference cell pressure (psig), P_2 is test cell pressure (psig), and V_{bill} is the volume of billets used to fill free space in the test cell (cm^3).

Porosity was calculated using the values obtained in Equations 1 and 2 as follows:

$$\phi = \frac{V_B - V_G}{V_B} \times 100\% \tag{3}$$

Here, ϕ is porosity, V_B is sample bulk volume (cm^3), and V_G is sample grain volume (cm^3).

Measuring a dry sample weight prior to the measurements described above also allowed for the determination of grain density using the following equation:

$$\rho_G = \frac{Wt}{V_G} \tag{4}$$

ρ_G is sample grain density (gm/cm^3), Wt is dry sample weight (gm), and V_G is sample grain volume (cm^3).

PERMEABILITY DETERMINATION

Absolute permeability to nitrogen gas was measured in a pressurized Hassler core holder. Confining pressure of 400 psig was applied to prevent gas from flowing around the outside of the sample being tested. Permeability values were determined by measuring the pressure drop between the inlet end of the sample and the outlet end of the sample and by inferring a steady state flow rate at the outlet end of the sample. Back pressure was created by attaching a glass orifice tube to the gas outlet port. Flow rate through the orifice tube was previously calibrated to the outlet pressure transducer response. A constant multiplier could then be applied to the outlet pressure value to arrive at a flow rate value for the current sample. For each of the samples in this study, three measurements were performed: one vertical test and two horizontal tests. The two horizontal tests were performed at right angles to each other. Permeability values were calculated using a form of Darcy's law as follows:

$$K_a = \frac{2000 \cdot Q \cdot \mu \cdot P_B \cdot G}{(P_i + P_B)^2 - (P_{out} + P_B)^2} \qquad (5)$$

K_a is absolute permeability (md), Q is flow rate (cm^3/sec), μ is viscosity of nitrogen (centipoise), P_B is barometric pressure (atm), P_i is inlet pressure (atm), and P_{out} is outlet pressure (atm). The factor G is 1/L for horizontal flow (where L is length in cm) and L/A for vertical flow (where L is again length in cm and A is cross sectional area in cm^2).

RESULTS

Results of the tests described above are presented in Table 1.

Table 1
Core Analysis Results for
Kansas Geological Survey

TerraTek Project No. 5030 (9414)

TerraTek Sample #	Sample ID	Depth (feet)	Permeability Kmax (md)	Permeability K90 (md)	Permeability Kv (md)	Porosity %	Grain Density (gm/cc)
1	Site 27	124	437.+	73.+	0.38	15.2	2.54
2	Site 25	128	NA	NA	NA	NA	NA
3	Site 15	144	0.44	0.40	0.08	15.5	2.59
4	Siefkes (1)	203	7.0	5.2	1.4	19.4	2.64
5	Siefkes (2)	225	349.	346.	239.	24.5	2.58
6	Site 20	225	0.39	0.11	0.07	20.0	2.64
7	Site 14	264	3.5+	1.5+	6.1+	19.3	2.63

NA - No analysis performed
\+ - Fracture affecting permeability

Special caution should be exercised in interpreting results for samples #1 and #7. These two samples, in particular, exhibit cracks which developed during cleaning. The other samples, for the most part, survived the process well enough to lend confidence to the test results.