Boundary Effect on Porosity Measurements and Its Resolution by Method and Mathematical Means

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Abstract: The evidence at hand indicates that significant changes in porosity test results occur when different test methods are employed. These differences are directly related to the surface boundary established by the particular method used. This paper will explore these boundary effects in order to identify the most accurate measurement method, and will introduce mathematical formulas that can be applied for the correction of erroneous pore volume that occurs at the test plug surface.

It is established that porosity measurements at ambient conditions yield greater values than their actual in situ value in the subsurface. Considerable effort has gone into reproducing these overburden conditions in order to evaluate the effect on porosity. In this study it becomes apparent that not all reduction in porosity is due to rock compressibility under confining pressure. The degree of porosity change is a function of grain size cementation, surface texture, and sleeve conformance.

To investigate this problem, experiments are performed on solid metal cylinders in which the surfaces are altered to produce pore volume. Also, extensive investigations are carried out on Aramco clastic and carbonate cores. This includes extensive full diameter versus plug comparisons. Also included are studies from six Berea and five Aramco northern area reservoir sandstone samples. These samples are tested and their porosities are calculated in six different ways. Employed are Boyle's Law, helium injection, hydrocarbon resaturation, displacement, and caliper techniques. Two individual mathematical approaches are implemented for result correction. The formulas are constructed based on the premise of distorted pore and bulk volumes at the plug surface, and are worked to establish an empirical boundary within the test plug. Mercury injection drainage capillary pressure curves are utilized as a tool to check the extent of distorted pore volume at the rock surface.

INTRODUCTION

The fluid storage potential of a rock formation is described as its porosity. Porosity is the ratio of void space to solids in a given volume of material and is described as a percentage or fraction of the whole (1). The void space is referred to as pore volume. A sample taken from such a porous media is comprised of three measurable volumes: bulk volume, grain volume, and pore volume (2). Although all three can be measured independently, they are only meaningful (in terms of fluid storage) as a whole. It is in the method of combining any two of these parameters when calculating porosity that substantial differences in result will occur.

As porosity is defined as the ratio of pore volume to the bulk volume to a given total volume, there must be a boundary established that defines the limits of this total volume, referred to as bulk volume. It is in the establishment of this boundary that erroneous pore volume may be created. The problem of boundary establishment arises every time a sample is taken from its place in situ.

Furthermore, the reduction of porosity as a function of simulated overburden pressure is not entirely due to matrix compressibility throughout the entire sample volume. Rather, it is a result of sleeve conformation along the plug surface boundary. The rapid reduction in pore volume that occurs between initial and approximately 700 psig often attributed to compressibility is in fact the elimination of both false and possible true pore volume at the test plug wall surface, plus the reorientation and packing of damaged grain material at the plug surface. This is particularly true in the case of friable-to-unconsolidated material. The extent of these surface effects depends greatly on rock characteristics (grain size, sorting, cementation, texture, and its true porosity). The method and skill of taking the plug is also a contributing factor.

Laboratory methods employed for direct measurement of pore volume are liquid resaturation and Boyle's Law gas expansion in a Hassler-type holder. For bulk volume, the methods employed are caliper measurement, liquid displacement, and Archimedes' principle weight displacement. For grain volume, the methods employed are Boyle's Law of gas expansion (matrix cup), and liquid displacement following sample desegregation.

BOUNDARY EFFECT ON POROSITY MEASUREMENTS

Six Berea and five Aramco Northern Area sandstone samples were selected. All samples used in this study were cleaned and dried cylinders, 1½ inch in diameter and two inches in length. Their grain and pore volumes were determined using helium at an injection pressure of 100 psig and applying the principles of Boyle's Law. The grain volumes were measured in a matrix cup (no confining pressure), and pore volumes were measured at a confining pressure of 200 psig in a Hassler-type holder. Bulk volumes were determined by length and diameter caliper measurements. Also, pore and bulk volumes of each sample were measured by resaturation methods using kerosene as a saturant (dry and saturated weight difference

Table 1: Calculated porosities based on different techniques.

Sample	Length (cm)	Diam. (cm)	Grain vol. (cc)	Pore volume (cc) He inj. in Hassler	Pore volume (cc) Resaturate with kerosene	Bulk volume (cc) Caliper	Bulk volume (cc) $PV_{He} + GV$	Bulk volume (cc) Resaturation
				Berea sandstone				
1.	5.06	3.89	48.2	11.0	11.09	60.14	59.2	59.31
2.	5.03	3.89	47.4	11.5	11.56	59.78	58.9	59.05
3.	5.00	3.81	46.3	10.3	10.33	57.01	56.6	56.59
4.	5.00	3.89	47.7	10.9	11.01	59.42	58.6	58.77
5.	5.03	3.89	47.9	11.1	11.14	59.78	59.0	59.21
6.	5.00	3.81	46.2	10.3	10.33	57.01	56.5	56.56
				Aramco sandstone				
7.	4.95	3.73	37.6	14.2	13.70	54.09	51.8	51.94
8.	4.85	3.71	35.4	14.5	14.07	52.43	49.9	50.16
9.	4.93	3.73	37.9	14.0	13.95	53.87	51.9	52.32
10.	5.03	3.73	38.2	14.3	14.02	54.96	52.5	52.80
11.	4.85	3.73	37.0	13.4	13.01	53.00	50.4	50.60

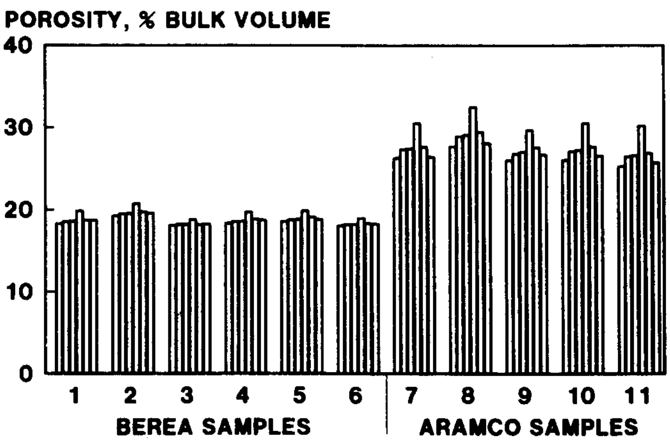

Figure 1: Porosity bar chart as a function of different techniques.

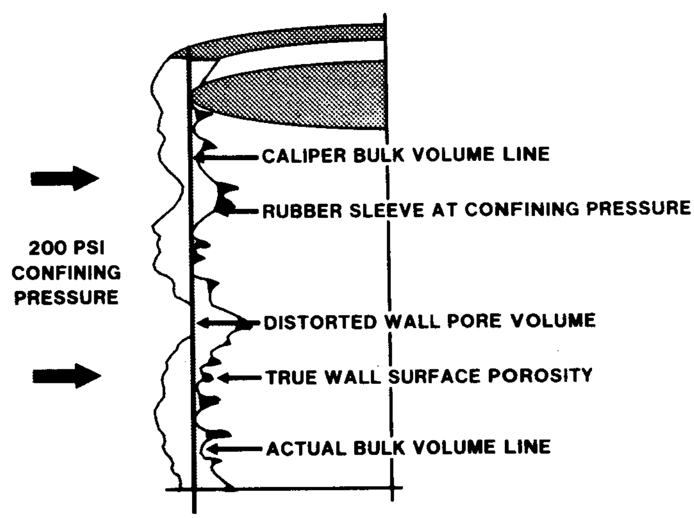

Figure 2: Direct pore volume measurement in Hassler-type core holder.

and volume displacement weight gravity corrected). Using the resulting data, the porosity of each sample was calculated six different ways (see Table 1). A porosity bar chart illustrates the range of differences that occur between calculation methods (see Figure 1). Both Berea and Aramco samples show the same result: a minimum porosity value was obtained when direct pore volume by helium injection in a Hassler-type holder was divided by a caliper-obtained bulk volume. Conversely, a maximum porosity resulted when the pore volume was obtained by subtracting the matrix cup grain volume from the caliper bulk volume. The average porosity difference between these two methods was found to be 1.2 porosity units or 6.6% for Berea sandstone samples, and 4.4 porosity units or 16.8% for Aramco sandstone samples.

In the direct pore volume measurement method, only the internal pore volume is measured and the surface pore volume eliminated (see Figure 2). Because the bulk volume equation is for a true cylinder, it yields the highest value. In combining the lowest pore volume with the highest bulk volume, a porosity that is lower than actual porosity is derived. In the case of high porous coarse grain sandstones, such as are found in Aramco Northern Area reservoirs, this method can lead to serious errors. The highest porosity values are obtained when a pore volume, which is calculated as the difference between a calipered bulk volume and a matrix cup grain volume, is combined with a caliper-measured bulk volume. The reason for this is that the calipered bulk volume includes false as well as true surface porosity (see Figure 3).

In an attempt to describe what is actually happening to the surface porosity, and therefore obtain a more ac-

Table 1: Continued.

Porosity (%)						Grain density (g/cc)
ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	
			Berea sandstone			
18.29	18.55	18.58	19.85	18.73	18.70	2.67
19.24	19.48	19.52	20.71	19.73	19.58	2.65
18.07	18.20	18.20	18.79	18.18	18.25	2.66
18.34	18.55	18.60	19.72	18.84	18.73	2.67
18.57	18.75	18.81	19.87	19.10	18.81	2.67
18.07	18.21	18.23	18.96	18.32	18.26	2.67
			Aramco sandstone			
26.25	27.34	27.41	30.49	27.61	26.38	2.71
27.66	28.91	29.06	32.48	29.43	28.05	2.70
25.99	26.76	26.98	29.65	27.56	26.66	2.69
26.02	27.08	27.24	30.49	27.65	26.55	2.69
25.28	26.48	26.59	30.19	26.88	25.71	2.69

$\phi_1 = PV_{He}/BV_{cal}$
$\phi_2 = PV_{He}/BV_{ker}$

$\phi_3 = PV_{He}/(PV_{He} + GV)$
$\phi_4 = (BV_{cal} - GV)/BV_{cal}$

$\phi_5 = (BV_{ker} - GV)/BV_{ker}$
$\phi_6 = PV_{ker}/BV_{ker}$

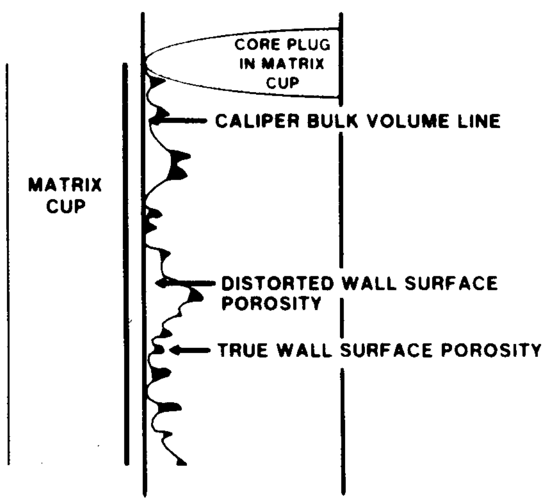

Figure 3: Indirect pore volume measurements in matrix cup.

curate porosity value for the test sample, two equations were developed, based on two different approaches to provide an approximate correction.

I. By definition,

$$\phi = \frac{PV}{BV}. \tag{1}$$

Assume

Σ_1 = correction for pore volume, and
Σ_2 = correction for bulk volume.

Therefore, the true porosity is

$$\phi = \frac{PV + \Sigma_1}{BV + \Sigma_2}, \tag{2}$$

or it can be expressed as

$$\phi = \frac{PV}{BV} + \frac{\Sigma_1}{BV} - \left[\frac{\Sigma_2^{2n-1}PV}{BV^{2n}} + \frac{\Sigma_1\Sigma_2^{2n-1}}{BV^{2n}} - \frac{\Sigma_2^{2n}PV}{BV^{2n+1}} - \frac{\Sigma_1\Sigma_2^{2n}}{BV^{2n+1}}\right]_{n=1}^{n=i}. \tag{3}$$

If $BV = PV + GV$, and if pore volume is corrected by true surface pore volume, Σ, then $\Sigma_1 = \Sigma_2 = \Sigma$, and Equation (3) becomes

$$\phi = \frac{PV}{PV + GV} + \frac{\Sigma}{PV + GV} - \left[\frac{1}{(PV + GV)^{2n}} \cdot \left(\Sigma^{2n-1}PV + \Sigma^{2n} - \frac{\Sigma^{2n-1}PV}{(PV + GV)} - \frac{\Sigma^{2n+1}}{(PV + GV)}\right)\right]_{n=1}^{n=i}. \tag{4}$$

To provide a practical determination of the true surface pore volume, samples were placed in the mercury injection pump chamber and a low vacuum, on the order of 20 micrometers of mercury pressure, was applied to remove air. Once the low vacuum was obtained, pressure was applied to the mercury covering the sample in increasing increments. The volume of mercury as a function of pressure was measured with a volume changer piston, which has an accuracy of ±0.002 cc. The typical pressure increments were 4 cm Hg. Figures 4 and 5 show the pressure versus volume of mercury injected into the samples for Berea and Aramco sandstone, respectively. It is assumed that change in the slope shows mercury intrusion

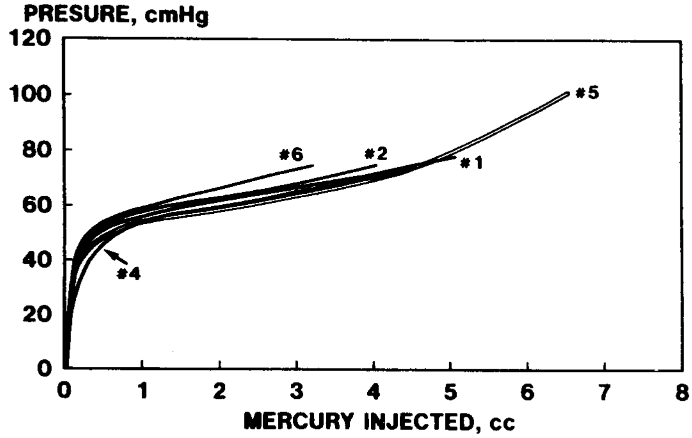

Figure 4: Pressure versus injected mercury (Berea samples).

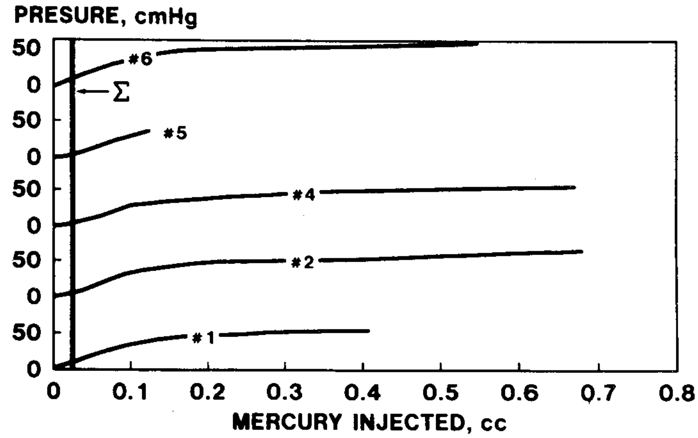

Figure 6: Pressure versus injected mercury (Berea samples).

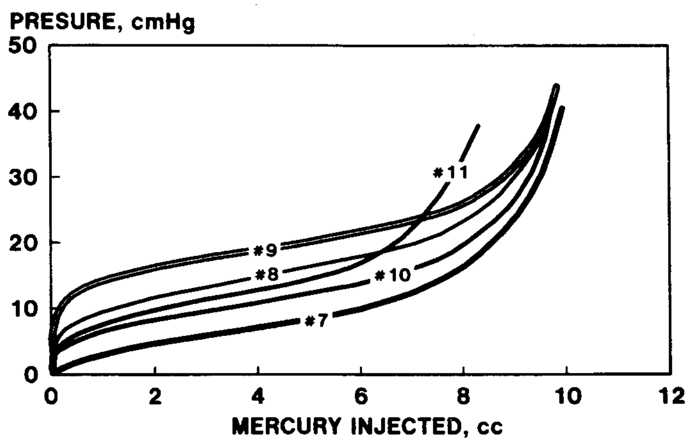

Figure 5: Pressure versus injected mercury (Aramco sandstone samples).

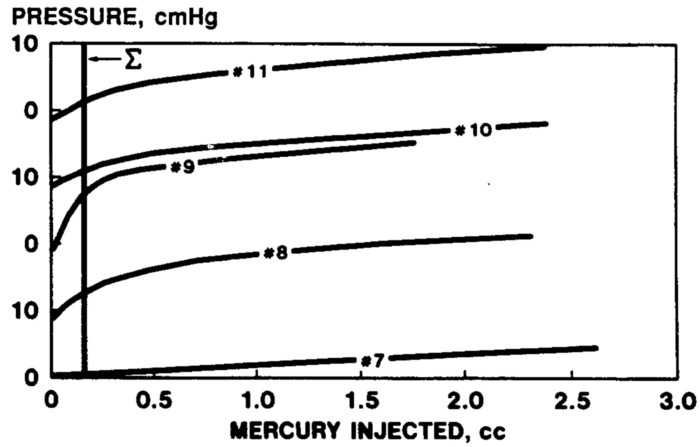

Figure 7: Pressure versus injected mercury (Aramco sandstone samples).

into the sample. Figure 6 shows that mercury has started to intrude into the rock sample at 0.025 cc for Berea sandstone samples. In other words, 0.025 cc is the value of true surface pore volume in Equation 4 for Berea samples. Similarly, surface pore volume is found as 0.15 cc for Aramco samples in Figure 7.

II. Caliper bulk volume of the test plugs is defined as

$$BV = \pi r^2 \times L. \tag{5}$$

The difference between caliper bulk volume and grain volume plus internal pore volume will be equal to surface pore volume around the core plug (Figures 2, 3, and 8):

$$\Delta V = \pi r^2 L - (GV + PV). \tag{6}$$

Furthermore, this volume consists of true and false surface pore volume:

$$\Delta V = \Sigma_F + \Sigma_T. \tag{7}$$

The true porosity of the core plug is

$$\phi = \frac{PV + \Sigma_T}{\pi r_2^2 \times L - \Sigma_F}. \tag{8}$$

Also, the true porosity around the core plug is

$$\phi = \frac{\Sigma_T}{\pi(r_2^2 - r_1^2) \times L - \Sigma_F}, \tag{9}$$

where r_1 is the radius of ideal porous media and r_2 is the caliper measured radius of the plug. From Equations (8) and (9),

$$(PV + \Delta V - \Sigma_F)\,[\pi(r_2^2 - r_1^2) \times L - \Sigma_F] = (\pi r_2^2 L - \Sigma_F)(\Delta V - \Sigma_F)$$

or

$$a\Sigma_F + b = 0. \tag{10}$$

The value of inner radius for ideal porous media depends on the grain size and cementation characteristics of the rock sample. Berea sandstone grain size ranged from 88 to 125 micrometers and these grains are well cemented. The depth of the damaged surface can reasonably be assumed as 1½ maximum grain size, which is 188 microns. Therefore, the inner radius for Berea sandstone is

$$r_1 = (r_2 - 0.0188) \text{ cm}. \tag{11}$$

Aramco sandstone grain size ranged from 350 to 500 micrometers and thin-section studies showed these grains to be poorly cemented. The grain size and cementation characteristics lead us to assume the depth of the destroyed surface as one maximum grain size, which is 500 micrometers. Then,

$$r_1 = (r_2 - 0.0500)\ \text{cm} \quad (12)$$

for Aramco sandstone. Table 2 shows calculated porosities and their corrected values based on Equations (4) and (10) for Berea and Aramco sandstones.

BOUNDARY EFFECT ON FULL-DIAMETER VERSUS PLUG ANALYSIS COMPARISONS

Throughout the industry, full-diameter core analysis is performed in a Hassler-type core holder at confining pressures of 200–300 psig. Pore volumes in full-diameter core analysis are measured directly by expanding helium into the pores and connecting capillaries. This constitutes a direct pore volume measurement. Again, bulk volume for full-diameter core is calculated by caliper measurement. The combining of these two measurements will systematically yield a lower porosity, as illustrated previously, due to the fact that the caliper bulk volume measurement includes distorted wall porosity as well as true wall porosity. The Hassler-type holder sleeve at 200 psig confining pressure, on the other hand, eliminates this distorted wall pore volume by establishing a boundary along the surface wall. The higher bulk volume divided by the lower pore volume yields an erroneously low porosity value (see Figure 2).

In the case of core plug analysis, the most common practice is to measure grain volume by means of a matrix cup, then subtract this result from the caliper-derived bulk volume, to arrive at a pore volume. As the bulk

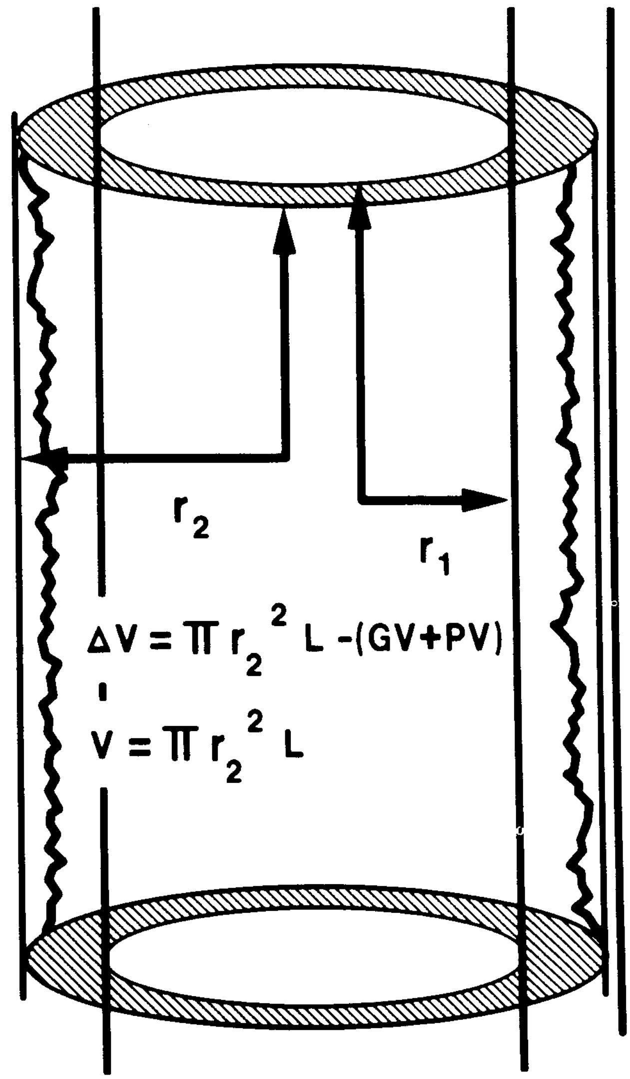

Figure 8: Bulk volume boundaries for porosity correction.

Table 2: Calculated porosities and their corrected values.

Sample	Measured porosity (%)						Corrected porosity (%)	
	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_I	ϕ_{II}
				Berea sandstone				
1.	18.29	18.55	18.58	19.85	18.73	18.70	18.72	18.66
2.	19.24	19.48	19.52	20.71	19.73	19.58	19.63	19.62
3.	18.07	18.20	18.20	18.79	18.18	18.25	18.31	18.43
4.	18.34	18.55	18.60	19.72	18.84	18.73	18.71	18.70
5.	18.57	18.75	18.81	19.87	19.10	18.81	18.92	18.93
6.	18.07	18.21	18.23	18.96	18.32	18.26	18.34	18.43
				Aramco sandstone				
7.	26.25	27.34	27.41	30.49	27.61	26.38	27.76	27.72
8.	27.66	28.91	29.06	32.48	29.43	28.05	29.36	29.21
9.	25.99	26.76	26.98	29.65	27.56	26.66	27.27	27.44
10.	26.02	27.08	27.24	30.49	27.65	26.55	27.52	27.47
11.	25.28	26.48	26.59	30.19	26.88	25.71	26.88	26.70

Table 3: Statistical data comparison whole core versus plug analysis (Aramco central area limestone).

		N	$\bar{x}$	SD	Range
Porosity Reservoir 1	Full diameter core	9	17.89	6.47	20.2
	Plug core	52	18.62	7.36	30.7
	Difference	52	0.73	0.89	10.5
Porosity Reservoir 2	Full diameter core	68	17.55	7.82	26.9
	Plug core	401	19.56	8.75	35.2
	Difference	401	2.01	0.93	8.3
Grain density Reservoir 1	Full diameter core	9	2.69	0.0523	0.19
	Plug core	52	2.74	0.0433	0.17
	Difference	52	0.05	0.0090	0.02
Grain density Reservoir 2	Full diameter core	68	2.68	0.0595	0.25
	Plug core	401	2.75	0.0471	0.28
	Difference	401	0.07	0.0124	0.03

volume boundary includes distorted wall pore volume, the porosity results obtained by this method will be higher than the true porosity.

In the grain density determination, the same condition holds true. In the case of a full-diameter core, the grain volume value is derived by subtracting a directly measured pore volume (gained by Hassler-cell) from a caliper-measured bulk volume that is higher than actual volume. This results in a higher than actual grain volume (as false pore volume at the surface is counted as grain volume). Because grain density is calculated by dividing the weight of the sample by its grain volume, the results will be a lower than actual grain density.

In the case of core plug grain density determinations, the grain volume is measured directly. The result is a true apparent grain density. The term "apparent" is applied because only interconnected pore spaces are accounted for.

In the course of another study on two Aramco Central Area reservoirs, 77 full-diameter core samples were prepared and tested. Six vertical plugs were then taken, three from the top and three from the bottom of each sample, totaling 450 plugs. The routine porosity plug results of these, when compared with full-diameter results, showed a higher core plug porosity and/or grain density relative to full-diameter core porosity and/or grain density (Table 3).

Although these differences may be explained as matrix heterogeneity, in what would otherwise appear to be a homogeneous sample, it must be maintained that surface boundary effect is a contributing factor. Although its effects may rise and diminish in magnitude, depending on the lithology and/or wall surface preservation, we are aware that this condition exists and that it is always slanted in the same direction. It is conceded that surface pore volume in carbonate lithologies is more complicated than in clastics.

BOUNDARY EFFECT ON PORE COMPRESSIBILITY STUDIES

In the establishing of porosity at overburden conditions, a typical laboratory procedure is to test and record

Table 4: Porosity change versus O.B. pressure (Aramco sandstone).

Sample no.		Overburden pressure (psi)							
		100	150	200	400	800	1,600	2,500	3,000
1.	Bulk volume	54.40	54.05	53.90	53.60	53.30	53.20	53.10	53.05
	Grain volume	38.60	38.60	38.60	38.60	38.60	38.00	38.60	38.60
	Pore volume	15.80	15.45	15.30	15.00	14.70	14.60	14.50	14.45
	Porosity (%)	29.0	28.6	28.4	28.0	27.6	27.4	27.3	27.2
2.	Bulk volume	53.60	53.20	53.00	52.60	52.40	52.20	52.00	52.00
	Grain volume	37.50	37.50	37.50	37.50	37.50	37.50	37.50	37.50
	Pore volume	16.10	15.70	15.50	15.10	14.90	14.70	14.50	14.50
	Porosity (%)	30.0	29.5	29.3	28.7	28.4	28.2	27.9	27.9
3.	Bulk volume	52.80	52.30	52.10	56.70	51.40	51.20	51.10	51.05
	Grain volume	38.00	38.00	38.00	38.00	38.00	38.00	38.00	38.00
	Pore volume	14.80	14.30	14.10	13.70	13.40	13.20	13.10	13.05
	Porosity (%)	28.0	27.3	27.1	26.5	26.1	25.8	25.6	25.6

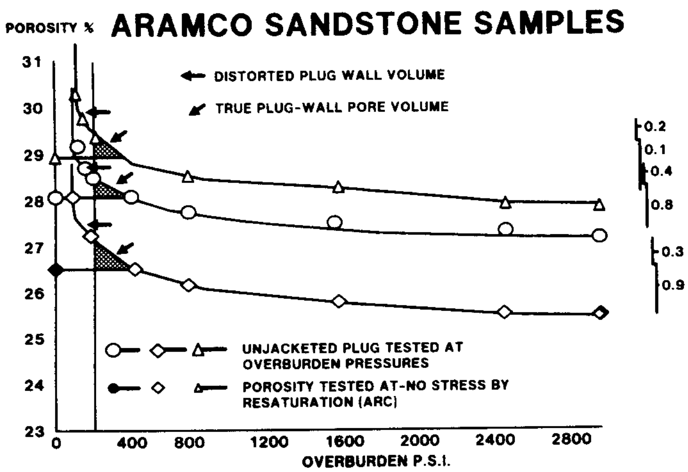

Figure 9: Porosity reduction versus overburden pressure (Aramco sandstones).

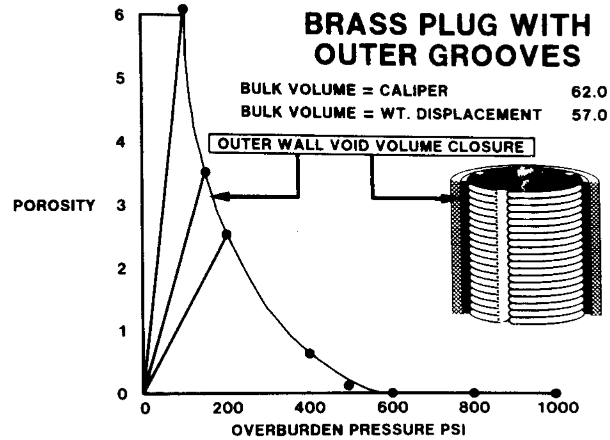

Figure 10: Surface porosity reduction versus overburden pressure.

porosity changes as the rock sample is subjected to confining pressures starting at an initial pressure that is increased incrementally to a predetermined net overburden pressure. Table 4 and Figure 9 are typical illustrations of this porosity change versus confining pressure. The core samples used here are from an Aramco sandstone reservoir, and as such are typical in behavior. The porosity versus pressure curve drops abruptly at the early lower confining pressure, then slopes out at 400–700 psi. A very gentle decline continues to the net overburden pressure point. If further stress is applied, another drop may occur. This is attributed to matrix deformation. It becomes apparent that not all of this reduction in porosity, especially at the lower pressures, is due to rock compressibility resulting in the reduction of pore space. It is, in fact, due to the limitation of pore volume created by the setting of the boundary, which establishes the bulk volume of the test sample.

In order to validate the preceding statement, the following controlled experiment was conducted using a solid brass plug, which of course has no measurable porosity or compressibility. Its surface was machined in such a manner as to provide an uneven surface in which vertical channels were cut to allow helium to pass along the threaded wall. After preparing this surface, the plug's bulk volume was established by both caliper measurement and Archimedes' principle. These two measurements yielded considerably different results due to boundary effect. The plug was then placed in a Hassler-type core holder and confining pressure applied starting at 150 psi and increasing in increments of 50 psi to 600 psi. Pore volumes were measured at each point. Figure 10 vividly illustrates a rapid reduction of pore volume as the sleeve pressure is applied, coming to the zero line at 600 psi. The reduction of porosity as a function of overburden pressure in this experiment is totally due to the elimination of the distorted surface pore volume by sleeve conformation to the plug wall surface, as there is no compressibility or internal pore volume to account for.

CONCLUSIONS

In comparing calculated porosities with mathematically corrected porosities, it becomes apparent that serious errors occur where caliper bulk volume measurements are used. In direct pore volume measurements, as a percentage of actual porosity, the average porosity is 2% less for Berea and 5% less for Aramco sandstones when compared with mathematically corrected porosities. In the case of the grain volume measurement, the calculated porosities were 5% and 11% higher, respectively, for Berea and Aramco sandstone as compared to mathematically corrected porosity results, illustrating that caliper bulk volume measurements should be avoided. Bulk volume determinations should be performed by liquid displacement or by adding a directly measured grain volume (matrix cup) to a directly measured pore volume (Hassler-type holder). In the case of full-diameter versus plug analysis, it is imperative that the measurement techniques for both be the same. Again, caliper bulk volume determinations must be avoided for both full-diameter and plug samples.

For pore compressibility or porosity at net overburden pressure studies, the elimination of false surface porosity at the early stages of pressure must be taken into account and corrected for when developing overburden correction factors.

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