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In Situ Permeability Measurements for the Event in U1-C

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MASTER

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by

Carl Keller
Dale Engstrom
Francis West

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MASTER

IN SITU PERMEABILITY MEASUREMENTS FOR THE
EVENT IN U1-C

by

Carl Keller, Dale Engstrom, and Francis West

ABSTRACT

Test apparatus was designed for the measurement of the in situ permeability in the vicinity of the 1100-ft U1-C shaft at NTS. A very reasonable approximation to a one-dimensional flow geometry was obtained. Measurement of gas injection flow rates and pressures allowed the determination of the effective permeability of the medium around the U1-C shaft to be from 1 to 10 darcys with the major exceptions at depths of less than 200 ft where the permeability was greater than 40 darcys. However, permeability results were seen to vary with source pressure and, therefore, must be used with discretion.

I. PURPOSE

A need for permeability data has grown out of the basic question: where does the gas go which is generated in a nuclear explosion cavity? In particular, there is a question of whether the emplacement hole is the path of least resistance for cavity gases. Before flow calculations can be performed for gas flow in the medium or emplacement hole stemming materials, permeabilities of the various materials have to be measured.

Other related questions which require permeability data are:

1. Are cased holes better than uncased holes?
2. Will collapse occur before leakage to the surface?
3. What are the best stemming materials?
4. What gas pressures can be expected below impermeable plugs in the hole?

There are many other containment questions which require permeability data for quantitative answers.

This report does not attempt to answer the above questions. Rather, a somewhat unique set of

permeability measurements is presented for the geologic medium around the U1-C shaft. The measurements are unique in that the shaft allows direct access to the medium for visual inspection, core extraction, and in situ permeability measurement. The test apparatus is simple and the permeability results are obtained with a minimum of inference. Hopefully, the results will permit quantitative answers to the above questions.

II. THE GEOLOGIC SITUATION

The shaft, U1-C, is located in the Yucca Flat area of the Nevada Test Site. The alluvium is about 2100 ft deep at the shaft site and the underlying rock is tuff. Table I gives the USGS interpretation of the composition of the alluvium. The content of clay size material, sand, and pebbles is shown on the middle graph of Fig. 1. Water and CO₂ content are shown on the left-hand graph of Fig. 1 as X's and horizontal bars, respectively; and sonic velocity data are on the right-hand graph. The water table is at about 1570 ft from the surface.

TABLE I
USGS LITHOLOGIC LOG OF U1-C SHAFT, NEVADA TEST SITE

Unit description	Thickness (ft)	Depth interval (ft)
Alluvium		
Sand and gravel Pebble- and cobble-sized fragments in sandy tuffaceous matrix; few boulders, up to a maximum diameter of 2 ft (observed in tailings); includes silty material; fragments largely tuff, angular and sub-rounded, with some Paleozoic rock clasts, commonly rounded. Poorly to partly indurated, degree highly variable; poorly bedded, with irregularly spaced gravelly zones alternating with more sandy zones; much gravel at the 800-foot level; calcareous throughout, with scattered thin caliche bands; tannish-gray-----	1,020	0- 1,020
Tuffaceous sandstone and conglomerate Sand and pebble-sized fragments, some cobbles, some thin siltstone layers; largely reworked tuffaceous material (nonwelded, air-fall), with much pumice and some welded fragments; sparse Paleozoic rock fragments. Indurated and bedded, commonly with gentle dips and a maximum observed dip of 28°; calcareous; reddish-brown in upper 50 feet becoming tan-gray below-----	205+	1,020- 1,250

Generally, cores from U1-C are quite similar to, but somewhat more indurated than, the alluvium in Area 3.

From the standpoint of material competence and sonic velocities, the two units recognized above by the USGS are quite similar and no radical change is apparent in their physical properties.

Generally, the medium is dry, gravelly to sandy and more or less indurated (i.e., cemented) depending upon the bed.

III. CALCULATIONAL MODEL AND ASSUMPTIONS

Permeability is defined as a property of the medium, but unlike many medium properties, it does not depend to any great extent upon the actual mass of the medium (i.e., the mineralogy, density, etc.) but rather upon how the mass is arranged in a sample volume. Therefore, pea gravel, sand, and volcanic ash may all have the same void fraction, bulk density, and water content but drastically different

permeabilities. The shaft shows that the medium is a heterogeneous mixture of gravel, sand, clay, and caliche. Any permeability measured in such a medium is defined as an effective or average permeability.

Whereas petroleum engineers recognize a difference in vertical and horizontal permeability for a small sample of reservoir rock due to the microscopic grain arrangement, the vertical and horizontal permeability of the medium is probably much different on a macroscopic scale because of the various beds.

Fig. 1. U1-C shaft.

The first major assumption of the measurements is that the medium can be described as homogeneous and infinite. Or, the effect of the heterogeneities is negligible. One defense of that assumption is that for seepage calculations, one is not interested in the detailed permeability but rather the effective permeability.

One must realize the difference between the model necessary for measuring permeability in a small part of the world and the model used to calculate gas flow from the shot cavity to the surface.

The first model is best one-dimensional for converting experimental data to permeability values. The second model should be two-dimensional.

The derivation of the equations relating flow and pressure measurements to permeability is included in the Appendix. The assumptions are that a point gas source will generate a spherically symmetric pressure field about the source and that the pressure field has achieved a steady-state distribution.

The result is

$$K = \frac{\mu (R/mw) T M \left(\frac{1}{r_o} - \frac{1}{r} \right)}{2\pi (P_o^2 - P^2)},$$

where K is the permeability, μ is the gas viscosity, R is the gas constant, mw is the average molecular weight of the gas, T is the absolute temperature, M is the rate of mass flow from the central source, r_o is the radius of the central source, P_o is the source pressure, and P is the pressure at a point r from the source center.

In principle, by injecting gas at a known pressure and rate into the medium in spherical geometry and measuring the pressure at a distance r from the source, the permeability can be determined. The apparatus used in the shaft is sketched in Fig. 2. The actual cylindrical source was spherized for calculational purposes by defining the spherical source radius as

$$r_o = \frac{(2r_h \ell + r_h^2)^{1/2}}{2},$$

where r_h is the hole radius, and ℓ is the open hole length. The approximation conserves source area rather than volume.

The orifice flow meter was calibrated over the flow range of 50 to 75 scfm such that the flow Q (scfm) was given by

$$Q = 11.92 (\sigma \Delta P)^{.3631}.$$

ΔP is the pressure drop across the orifice in psi. σ is a function of inlet pressure, P_ℓ .

$$\sigma = \frac{35.3 \cdot P_\ell \text{ (PSIA)}}{460 + T(^{\circ}\text{F})}.$$

T is the gas temperature.

Q (the volume flow rate) is related to M (the mass flow rate).

$$Q(\text{scfm}) = \frac{(mw) 2.83 \times 10^4 \times M(\text{gm/sec})}{22,400 \cdot 60}.$$

Fig. 2. Permeability test apparatus.

Combining the above expressions for our geometry, K is

$$K = \frac{197 (P_\ell \cdot \Delta P)^{.3631}}{(P_o^2 - P^2)},$$

and Q is

$$Q = 4.48 (P_\ell \cdot \Delta P)^{.3631}.$$

Note, our gas temperature is 60 - 63°F., and our r_o is 6.35 cm (.21 ft). The probe-source separation is a constant 4 ft for all tests.

The experimental data consist of

1. the orifice inlet and outlet pressure, P_ℓ and P_f ,
2. the source pressure, P_o ,
3. the probe pressure, P (i.e., the pressure at r), and
4. the probe-source separation, r .

From these are obtained Q , P_o , P , and r for the above equations. The permeability values calculated are given in Table II through Table XVII at each level in the shaft.

TABLE II
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 500' below the surface on 6-22-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.2	13.6	17.0	15.3	15.22	14.45
17.0	14.05	23.1	17.3	26.0	12.8
19.0	14.6	32.0	19.5	39.5	11.7
21.0	15.15	42.0	22.4	50.3	10.5
23.1	15.8	53.4	25.1	64.0	9.90
25.25	16.3	66.6	28.5	77.0	9.12
27.3	16.8	78.9	32.0	88.7	8.41

NOTE: All pressures are in psia.

TABLE III
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 600' below the surface on 6-23-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.0	13.05	15.0	14.7	7.7	6.2
16.8	13.1	17.0	16.6	9.0	3.6
18.9	13.1	19.0	18.6	9.4	2.2
23.0	13.15	24.4	22.7	17.0	2.1
27.8	13.2	31.0	27.7	24.0	1.8
33.0	13.32	38.2	32.6	31.0	1.5
38.0	13.48	46.0	37.4	39.0	1.4
42.7	13.6	54.6	42.0	48.0	1.3

NOTE: All pressures are in psia.

TABLE IV
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 700' below the surface on 6-24-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.2	13.1	15.3	15.0	7.8	9.89
18.0	13.35	18.7	18.0	11.0	3.44
23.0	13.7	24.9	22.9	14.0	1.85
28.0	14.15	32.0	28.0	26.0	1.96
32.6	14.6	39.1	32.7	33.0	1.72
42.8	15.85	57.8	42.6	53.0	1.46

NOTE: All pressures are in psia.

TABLE V
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 400' below the surface on 6-30-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.0	13.1	16.0	14.95	12.5	10.0
18.0	13.25	22.4	17.6	24.0	7.3
23.0	13.4	35.2	22.7	41.0	5.1
28.0	13.65	49.5	27.95	56.0	4.1
33.0	13.9	64.75	33.7	71.0	3.5
37.8	14.0	75.0	38.0	80.0	2.8
41.9	14.15	82.8	42.25	85.0	2.4

NOTE: All pressures are in psia.

TABLE VI
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 800' below the surface on 6-30-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.2	13.1	15.4	14.95	9.0	6.7
18.0	13.15	18.75	17.80	13.0	3.7
23.0	13.22	25.5	22.60	21.0	2.7
27.65	13.40	32.5	27.30	29.0	2.2
32.7	13.55	41.3	32.2	39.0	1.9
37.6	13.78	51.1	36.8	49.0	1.8
42.4	14.00	63.0	41.6	61.0	1.7

NOTE: All pressures are in psia.

TABLE VII
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 900' below the surface on 6-30-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.25	13.05	15.3	15.05	7.3	5.15
15.35	13.1	15.4	15.1	7.8	5.4
18.0	13.2	18.0	17.75	7.7	2.27
23.0	13.43	23.1	22.8	9.0	1.14
27.8	13.62	27.9	27.75	7.5	.56
32.95	13.85	33.0	32.8	8.9	.44
37.8	14.2	38.1	37.75	11.4	.41
42.5	14.5	42.8	42.5	11.3	.31

NOTE: All pressures are in psia.

TABLE VIII
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 1000' below the surface on 6-30-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.1	13.15	15.25	14.8	9.0	7.2
18.2	13.45	19.00	18.00	13.0	3.8
23.0	14.1	26.0	22.8	22.0	3.0
27.8	14.8	33.25	27.50	30.0	2.4
33.0	15.6	43.6	32.75	42.0	2.2
37.9	16.65	54.40	37.3	54.0	2.0
43.0	17.6	67.6	42.3	67.0	1.9

NOTE: All pressures are in psia.

TABLE IX
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 1050' below the surface on 6-30-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.1	13.15	15.2	14.95	7.28	5.81
18.1	13.22	18.1	17.95	6.4	1.85
23.0	13.5	23.1	12.85	8.5	1.07
28.0	13.92	28.3	27.9	11.0	.80
33.0	14.45	33.2	32.95	9.7	.48
37.8	15.18	38.6	37.75	15.9	.58

NOTE: All pressures are in psia.

TABLE X
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 100' below the surface on 7-1-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.0	13.25	52.1	20.2	66.0	59.0
14.85	13.28	51.7	20.0	66.0	65.0
16.8	13.32	101.3	38.8	107.5	45.0

No measurements were made at higher pressure because flow was limited by the air line.

NOTE: All pressures are in psia.

TABLE XI
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 200' below the surface on 7-1-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_ℓ	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.0	13.05	15.0	14.75	7.2	5.8
14.95	13.08	15.0	14.75	7.2	6.1
18.15	13.1	18.5	17.9	11.0	3.0
23.15	13.22	24.7	22.95	18.0	2.1
27.7	13.3	30.8	27.6	24.0	1.8
32.55	13.4	38.0	32.25	32.0	1.6
37.0	13.55	45.6	36.55	40.0	1.5
42.6	13.75	58.6	42.15	54.0	1.5

NOTE: All pressures are in psia.

TABLE XII
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 300' below the surface on 7-1-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_F	Flow Rate Q (scfm)	Permeability K (darcys)
15.05	13.08	15.1	14.8	7.8	6.1
15.0	13.1	15.1	14.8	7.8	6.4
18.1	13.13	18.6	17.9	11.0	3.2
22.75	13.25	24.8	22.45	20.0	2.5
27.9	13.4	33.0	27.5	30.0	2.17

Leak around input hole

NOTE: All pressures are in psia.

TABLE XIII
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 200' below the surface on 8-18-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_F	Flow Rate Q (scfm)	Permeability K (darcys)
15.4	13.1	16.0	15.1	12.0	7.9
18.0	13.2	20.3	17.8	19.0	5.5
23.0	13.3	31.7	23.0	34.0	4.3
28.0	13.5	43.3	28.7	60.0	3.4
33.5	13.7	60.5	34.5	65.0	3.1
38.0	13.9	77.0	40.5	80.0	2.8
38.1	14.0	77.5	40.8	80.0	2.8
43.0	14.2	98.0	48.0	98.0	2.6
45.5	14.4	109.5	50.2	102.0	2.6
46.4	14.4	113.0	51.5	111.0	2.5

NOTE: All Pressures are in psia.

TABLE XIV
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 300' below the surface on 8-18-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.4	13.1	16.0	15.2	11.0	7.6
18.0	13.15	19.2	17.8	15.0	4.3
22.5	13.3	27.7	22.5	27.0	3.6
27.9	13.6	42.5	28.0	46.0	3.4
South wall began sloughing sand					
31.5	14.0	63.0	33.2	69.0	3.8
35.2	14.3	93.5	41.0	98.0	4.16
37.0	14.6	109.0	45.2	111.0	4.2
33.0	14.3	89.0	38.8	95.0	4.7
23.0	13.7	40.0	23.4	47.0	6.1

NOTE: All pressures are in psia.

TABLE XV
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 400' below the surface on 8-18-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_f	Flow Rate Q (scfm)	Permeability K (darcys)
15.5	13.1	16.8	15.4	14.0	9.0
18.0	13.2	21.5	18.0	21.0	5.8
23.0	13.4	34.0	23.2	38.0	4.81
28.0	13.6	48.0	28.6	54.0	3.9
33.0	13.8	63.5	34.3	69.0	3.4
37.8	14.0	79.5	40.3	83.0	3.0
43.0	14.3	101.0	46.7	102.0	2.7
46.3	14.4	111.0	50.6	110.0	2.5
18.0	13.2	22.2	18.0	23.0	6.8
23.1	13.4	35.5	23.4	40.0	5.0
28.2	13.6	50.7	29.3	57.0	4.1
33.0	13.8	66.0	34.8	72.0	3.5
38.0	14.1	83.0	41.0	87.0	3.1
42.2	14.2	97.5	46.3	99.0	2.7
45.8	14.4	111.6	50.6	110.0	2.6

NOTE: All pressures are in psia.

TABLE XVI
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 100' below the surface on 8-18-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_F	Flow Rate Q (scfm)	Permeability K (darcys)
15.3	13.2	66.0	27.0	78.0	57.0
17.0	13.4	111.5	43.7	115.0	46.0
14.0	13.15	31.5	15.5	43.0	82.0
15.0	13.2	61.5	24.5	74.0	64.0
16.0	13.3	88.0	35.0	96.0	53.0
16.9	13.35	111.5	43.8	115.0	47.0

NOTE: All pressures are in psia.

TABLE XVII
PERMEABILITY MEASUREMENTS IN SHAFT NUMBER U1-C

At 775' below the surface on 8-19-71

Source Pressure P_o	Probe Pressure P	Orifice Inlet Pressure P_L	Orifice Outlet Pressure P_F	Flow Rate Q (scfm)	Permeability K (darcys)
18.0	13.0	18.0	17.85	6.4	1.8
23.0	13.2	23.9	23.0	14.0	1.7
28.0	13.3	30.0	28.0	20.0	1.4
33.0	13.5	37.1	33.4	27.0	1.3
38.0	13.6	44.2	38.0	34.0	1.2
43.2	13.78	52.5	43.1	41.0	1.1
47.7	14.0	59.5	47.7	48.0	1.0
53.0	14.2	68.7	52.7	57.0	.96
58.0	14.4	78.0	57.6	65.0	.91
63.0	14.7	88.0	63.2	73.0	.86
23.6	13.2	24.8	23.6	15.0	1.8 (with N_2 bottle)

NOTE: All pressures are in psia.

The adjacent lithology is sketched for each test hole.

Generally, the pressure on the hole was increased at 5-min intervals. Since the gauge pressures were not changing much after 2 min, it was assumed that a steady state had been nearly established. The gauges were read at the end of each 5-min interval. Stepping the pressure down rather than up showed that the effect of prepressurizing the medium before testing at subsequent pressure levels had very little, if any, effect.

Some of the test holes were rerun for a wider range of pressures. The results are presented in chronological order to aid in determining if the sequence of testing a given hole produces a difference in the results. The possible effect of testing a hole may be erosion, moisture buildup in the medium, etc.

IV. RESULTS AND CONCLUSIONS

An outstanding feature of the measurements is the decrease of the effective permeability with an increase in flow rate (and also source pressure). At first one would suspect that erosion of the fine material would clog the medium farther from the source and give the same effect. However, retesting the hole at a lower pressure again yields approximately the same result as the original test. Also, when the order of testing was reversed, the dependence upon pressure (or flow) was still seen. One exception was the test on 8/18/71 at 300 ft. As the pressure was increased, the effective permeability also increased. But, for that particular test it was observed that sand was falling off the south wall of the shaft (the test hole was 20 ft deep in the east wall) just when the effective permeability began to increase with pressure. Very probably, a path had been eroded from the source to the south wall. That test was the only one showing such a phenomenon.

Apparently, the character of the flow changes with the flow rate so as to reduce the permeability as it's defined. The trend is in the right direction when one considers the effect of increasing the flow rate.

At a sufficiently slow flow velocity (a parameter very dependent upon the geometry of the porosity) the flow should be laminar. As the velocity

increases, turbulent flow will develop and therefore an increase in pressure will not produce a corresponding increase in flow. As the pressure is increased, a larger fraction of the momentum and energy of the gas is transferred to the porous medium.

Figure 3 shows the variation of the permeability, k , with the source pressure, P_o , for several locations. Figure 4 shows the variation of K with the flow rate, Q . Both plots imply a change in the flow character at a very low pressure (or flow). Such a change in permeability with flow rate should exaggerate the concavity of the pressure distribution from the source to the probe.

The variation of the permeability with depth from the surface is shown in Fig. 5 for source pressures of 15 psia and 25 psia. The relative permeability does not seem to change with the possible exception of that at 775 ft. The very high permeability near the surface is compatible with drilling experience.

In conclusion, one is forced to accept the fact that permeability, as defined by Darcy's law, is a function of pressure. The chief value of the permeability measurements is to establish the relative permeability of various materials. The permeability

Fig. 3. Permeability vs source pressure.

Fig. 4. Permeability vs flow rate.

measurements made in the shaft (U1-C) are not sufficiently pressure independent to make precise computer calculations of gas flow rates through the medium. However, since cavity pressures are higher than those used for the permeability measurements and since the permeability decreases with a pressure increase, computer calculations should be useful as conservative bounds for gas flow through the medium.

Two-dimensional gas flow calculations by Rudi Rozsa at Lawrence Livermore Laboratory (private communication) show that the effect of the shaft on the permeability measurements is negligible for such low permeabilities.

Fig. 5. Permeability of U1-C medium at a source pressure of ~25 psia & ~15 psia.

These results may raise as many questions as they answer. The idea of a pressure dependent permeability is incompatible with the model for Darcy flow. The spherical test geometry further complicates the interpretation of the data because the gas flux is a function of the radial distance from the source. Perhaps more simple one-dimensional plane geometry tests would be useful in examining the region between laminar and turbulent flow conditions. In any case, one must be careful when comparing material permeability values.

APPENDIX

STEADY-STATE COMPRESSIBLE FLUID FLOW IN A PERMEABLE MEDIUM

In a homogeneous, isotropic medium with permeability K , the flow of a compressible gas of viscosity μ is thought to be adequately described by Darcy's equation for the flow velocity.

$$\vec{v} = -\frac{K}{\mu} \nabla P,$$

where P is the pressure and x is the space coordinate. The flow velocity is defined as the volumetric flow rate, Q , divided by the flow area, A :

$$v \equiv Q \text{ (cc/sec)} / A \text{ (cm}^2\text{)}.$$

The mass flux across any area, A , in the medium is

$$\vec{v} \cdot \vec{A} \rho = F,$$

where $\vec{A} = A\vec{n}$ with $\vec{n}$ as the normal to the area.

In any one-dimensional geometry (plane, spherical, or cylindrical) the vector notation can be dropped. Even though 2-D results are more useful, the immediate need for permeability measurements can be satisfied by a 1-D analysis if a check on the necessary assumptions (listed later) shows them to be valid.

For this first pass treatment, we will assume that the gas has a viscosity μ and an ideal equation of state:

$$PV = nRT$$

or

$$\rho = \frac{P}{(R/mw) T} ,$$

where R is the gas constant, mw is the molecular weight, and T is the absolute temperature.

Therefore, the flow rate (gm/cm^2 sec) is

$$F = v\rho = - \frac{K}{\mu} \frac{\partial P}{\partial x} \cdot \frac{P}{(R/mw) T} .$$

The total mass flow is

$$M \equiv \int_A F dA .$$

The only difference between the various 1-D geometries is the definition of A .

In Plane Geometry: (e.g., flow up a pipe)

$$x = x$$

$$A = \pi r^2$$

where r is the radius of a pipe perpendicular to A ,

$$\text{hence } M = \int_A F dA = - \frac{K}{\mu} \frac{\pi r^2}{(R/mw) T} P \frac{dP}{dx} .$$

From this relationship, one can determine P as a function of x by separation of variables and integrating

$$\int_0^L M dx = \int_{P_0}^{P_L} - \frac{K \pi r^2}{\mu (R/mw) T} P dP$$

or

$$ML = \frac{K \pi r^2}{2 \mu (R/mw) T} (P_0^2 - P_L^2) ,$$

where L is the length of the pipe, P_L is the outlet pressure, and P_0 is the source pressure.

More generally,

$$P \text{ at } \ell = \left[P_0^2 - \frac{2 \mu (R/mw) T M \ell}{K \pi r^2} \right]^{1/2}$$

$\ell \equiv$ the distance up the pipe from $x = 0$.

Note: By measuring P_L (the outlet pressure), the coefficient

$$2 \mu (R/mw) T M / K \pi r^2$$

can be determined and the shape of the pressure gradient is a function of P_0 and P_L alone. Another way to say it is: if the outlet pressure is the ambient pressure, the pressure distribution in the pipe is the same regardless of the permeability. The parameter affected by a change in permeability is the mass flow, M , such that M/K is a constant.

In Spherical Geometry: (e.g., infinite medium)

$$x = r$$

$$A = 4 \pi r^2$$

$$\text{hence, } M = \int_A F dA = - \frac{K}{\mu} \frac{4 \pi r^2}{(R/mw) T} P \frac{dP}{dr}$$

or

$$\int_{r_0}^r M \frac{dr}{r^2} = \int_{P_0}^P - \frac{K 4 \pi}{\mu (R/mw) T} P dP$$

or

$$M \left(\frac{1}{r_0} - \frac{1}{r} \right) = \frac{4 \mu K}{\mu (R/mw) T} \frac{(p_0^2 - p^2)}{2}$$

$$p = \left[p_0^2 - \frac{\mu (R/mw) T M}{2} \left(\frac{1}{r_0} - \frac{1}{r} \right) \right]$$

Note: At $r \gg r_0$, $p \approx p_{\text{ambient}}$

hence
$$\frac{M}{r_0} \approx \frac{4 \pi K (p_0^2 - p_{\text{ambient}}^2)}{\mu (R/mw) T}$$

In Cylindrical Geometry: (e.g., a drill hole pump test)

$x = r$ (radius)

$A = 2 \pi r L$, $L \equiv$ length of the cylinder

hence
$$M = \int_A F dA = - \frac{K}{\mu} \frac{2 \pi r L}{(R/mw) T} p \frac{dp}{dr}$$

or

$$\int_{r_0}^r M \frac{dr}{r} = \int_{p_0}^p - \frac{K 2 \pi L}{\mu (R/mw) T} p dp$$

or

$$M \ln \left(\frac{r}{r_0} \right) = \frac{K \pi L}{\mu (R/mw) T} (p_0^2 - p^2)$$

$$p = \left[p_0^2 - \frac{\pi (R/mw) M T}{K \pi L} \ln \left(\frac{r}{r_0} \right) \right]^{1/2}$$

The permeabilities can be determined from each of the three geometries as:

Plane

$$K = \frac{2 \mu (R/mw) T M L}{\pi r^2 (p_0^2 - p_L^2)}$$

Spherical

$$K = \frac{\mu (R/mw) T M \left(\frac{1}{r_0} - \frac{1}{r} \right)}{2 \pi (p_0^2 - p^2)}$$

where P is the pressure at radius r .

Cylindrical

$$K = \frac{\mu (R/mw) T M \ln \left(\frac{r}{r_0} \right)}{\pi L (p_0^2 - p^2)}$$

where P is the pressure at r .