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Lawrence Radiation Laboratory

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LIVERMORE

**FIELD MEASUREMENT OF THE PERMEABILITY
OF NTS ALLUVIUM**

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FIELD MEASUREMENT OF THE PERMEABILITY OF NTS ALLUVIUM

ABSTRACT

An estimate of the permeability of Nevada Test Site alluvium has been obtained by carrying out air flow tests in a partially cased emplacement hole. Downhole pressures and air flow rates were measured in quasi-steady-state experiments. Measurements were also taken of transient pressure buildup and decay. The data for the steady-state experiments have been fitted to radial (cylindrical) flow and spherical flow models and the permeability of the medium calculated. Our estimate is that the permeability of NTS alluvium is 9.5 darcies.

The grout and casing of the emplacement hole were leak checked by placing a tracer gas (Freon-12) downhole and monitoring the area around surface ground zero with a halogen leak detector. No leaks were found.

INTRODUCTION

The permeability to gas flow of the medium surrounding an emplaced device is an important factor affecting containment criteria at the Nevada Test Site. Specifically, the permeability in part determines the proper depth of burial, particularly for small devices. For small devices, preventing the flow of radioactive cavity gas through the medium to the surface and its release to the atmosphere is likely to be the governing factor (rather than cratering effects) in determining depth of burial.

To study the flow of gas under pressure through NTS alluvium, it was decided to pressurize the bottom uncased 50-ft section of a 450-ft-deep hole that had been cased to 400 ft. By pumping air into the hole, we had hoped to reach a pressure of twice overburden (about 650 psi) in 15 min and to hold this pressure for at least 5 min or until a vent to the surface could be detected using a tracer gas. It turned out, however, that the permeability of the medium was greater than expected and that the maximum pressure achieved was only 30 psig when flow rates of about 6,000 cfm were maintained for several hours.

By measuring the flow rate and corresponding downhole pressure, an estimate of the medium permeability was made. No vents to the surface within 100 ft of surface ground zero (SGZ) were detected, and it was therefore assumed that the flow of gas into the medium can be modeled by an approximately uniform flow field.

DESCRIPTION OF THE EXPERIMENT AND EXPERIMENTAL RESULTS

The emplacement hole (U10am-5)¹ used for the air injection experiments is a 450-ft-deep hole cased with a 10-3/4-in. casing to 400 ft. The casing was grouted into a 17-1/2-in.-diam hole. A Birdwell caliper log (June 21, 1969) shows that the diameter of the uncased portion of the hole varied from 10-1/2 to 18 in. Based on the caliper log, the actual volume of the uncased hole is calculated to be 49.6 ft³ and its actual surface area normal to radial flow is 160 ft². The radii of perfect cylinders (50 ft long) with the above volume and curved surface area are 0.56 and 0.51 ft, respectively. The radii of spheres with the same volume and surface area are 2.28 and 3.57 ft, respectively.

Ten compressors, each with a rated capacity of 900 cfm at 60°F at sea level, were connected to a 4-in. collecting manifold. An orifice-type flow meter with a 3-in. orifice in a 4.026-in. pipe was installed between the manifold and the well head. The flow meter provided measurements of pressure drop across the orifice, discharge pressure, and temperature. Flow calculations were made with the aid of a Sonney Orifice Computer (a circular slide rule designed for solution of the orifice formula).

The well cap and all fittings were rated at 750 psi. (This was found to be far in excess of the pressures actually developed.) The well cap provided an entrance for the main air flow and also had a fitting through which Freon gas could be placed downhole as a tracer. In addition, the cap included a valve to shut off the main air flow, electrical feed throughs for a thermistor cable, and two pressure gauges. One pressure gauge measured air pressure inside the well cap. The other gauge was attached to a 425-ft length of 5/8-in.-i.d. hose and thus measured air pressure at the uncased portion of the hole. Downhole temperatures were measured by a Fenwall thermistor.

Figure 1 is a view of all the equipment, including the bank of compressors. Figure 2 shows the well-cap.

Measurements were made with 1, 5, and 10 compressors in line. With 10 compressors in line, the differential pressure meter across the orifice pegged. Therefore, the flow rate with 10 compressors in line was estimated by extrapolation of the flow rates with 1 and 5 compressors. Downhole pressure measurements were recorded when they stabilized and an apparent steady-state situation had been reached. Table 1 gives these measurements.

Measurements were also made of transient pressure buildup and decay. The data for pressure buildup are given in Table 2. These data were taken with 10 compressors on line and the flowmeter bypassed. Since the resistance of the flowmeter was removed, the flow rate was slightly higher than the 6000 cfm reported in Table 1 and the final downhole pressure (32 psig) is also slightly higher.

¹Memorandum of D. D. Simms, NTS Engineering and Construction Group, to R. C. Emens, NTS Support Office, May 19, 1969.

Fig. 1. Air injection equipment at U10am-5.

Fig. 2. Close-up of well cap.

Table 1. Steady-state measurements.

No. of compressors	Flow rate (cfm)	Downhole pressure ^a		Air temperature (°F)	
		(psig)	(psia)	At meter	Downhole
1	815				
5	3230	17.0	29.4	124	82
10	~6000	27.0	39.4	122	94

^aThe atmospheric pressure at NTS is 12.4 psia.

A pressure decay experiment was carried out by closing, as quickly as possible, the main valve at the well cap. Table 3 gives the data.

Table 2. Pressure buildup.

Time (min)	Downhole pressure	
	(psig)	(psia)
0	27	39.4
2.5	29	41.4
6	30	42.4
12	30.5	42.9
17	32	44.4
20	32	44.4

Table 3. Pressure decay.

Time (sec)	Downhole pressure		Downhole temperature (°F)
	(psig)	(psia)	
0	24	36.4	70
5	20	32.4	
10	16	28.4	
18	13	25.4	
30	11	23.4	
45	10	22.4	

To determine if air was leaking to the surface through vents or cracks, five bottles of Freon (about 2440 ft³) were placed downhole while air was being pumped. The area about SGZ was checked with a General Electric Type H-7 audible-alarm halogen leak detector. No vents were found, and it was therefore concluded that the bond between grout and casing was not leaking gas to the surface nor were there any faults channeling gas to the surface within 100 ft of SGZ.

CALCULATIONS

Values of the permeability of the medium surrounding the emplacement hole can be estimated by using formulas for the steady flow of compressible fluids. The formula for radial (cylindrical) flow is derived in a number of texts on oil-reservoir engineering.² The formula for spherical flow is derived in the Appendix. The formula for radial flow is

²S. J. Pirson, Oil Reservoir Engineering, 2nd Ed. (McGraw-Hill Book Co., Inc., New York, 1958), pp. 392-394.

$$Q_b = 19.8 \frac{h K T_b}{\mu P_b T_h} \frac{P_h^2 - P_e^2}{\ln(r_e/r_h)} \quad (1)$$

Q_b = measured rate of flow at P_b and T_b (ft³/day)

h = length of the uncased hole (ft)

K = permeability (darcies)

μ = viscosity of air at T_h (cP)

P_b = base pressure, 12.4 psia

T_h = absolute temperature of flowing air at bottom of hole (°R)

T_b = absolute temperature of flowing air at the flowmeter (°R)

P_h = pressure of flowing air at bottom of hole (psia)

P_e = pressure of flowing air at the radius of effect (psia)

r_h = radius of the uncased hole (based on surface area of hole) (ft)

r_e = radius of effect (ft).

The radius of effect is the external radius of the flow field. For lack of better information, we assume this distance to be 425 ft (the midpoint of the uncased portion of the hole), at which distance the pressure P_e is 12.4 psi, atmospheric pressure at NTS. For radial flow, r_h is 0.51 ft. Substituting the appropriate values given in Table 1, the permeability k can be calculated by:

$$k = \frac{Q_b \mu P_b T_h}{19.8 h T_b} \frac{\ln(r_e/r_h)}{P_h^2 - P_e^2} \quad (2)$$

For example, using the data for 5 compressors ($Q = 3230$ cfm):

$$k = \frac{3230 (1440)^* (0.0185) (12.4)}{19.8 (50)} \frac{\ln(425/0.51)}{(29.4)^2 - (12.4)^2} \frac{460 + 82}{460 + 124}$$

$$k = 9.5 \text{ darcies.}$$

A similar calculation at $Q = 6000$ cfm gives $k = 9.3$ darcies.

*The factor 1440 converts cfm to ft³/day.

The formula for spherical flow is

$$Q_b = 39.6 \frac{k}{\mu P_b} \frac{P_h^2 - P_e^2}{\frac{1}{r_h} - \frac{1}{r_e}} \quad (3)$$

Here r_h (3.57 ft) is the radius of a spherical cavity with the same surface area as the actual "cylindrical" cavity. P_e and r_e are defined as before. The permeability values calculated by this equation with $r_e = 425$ ft are 9.8 and 9.6 darcies.

The close agreement between the radial and spherical flow models is fortuitous. If Eqs. (1) and (3) are compared it is seen that the geometric factors in the calculation for k are

$$F_{cyl} = \frac{\ln(r_e/r_h)}{h} \quad \text{for cylindrical flow} \quad (4)$$

and

$$F_{sph} = \frac{1}{2} \left(\frac{1}{r_h} - \frac{1}{r_e} \right) \quad \text{for spherical flow.} \quad (5)$$

In Fig. 3 these factors are plotted as a function of r_e . For the cylindrical case $h = 50$ ft and $r_h = 0.51$ ft. For the spherical case $r_h = 3.57$ ft. The two geometric factors, F_{cyl} and F_{sph} , happen to have about the same value at 425 ft, which has been taken as the radius of effect in these estimates. At smaller values of r_e the differences are larger, as high as 60%. Near the origin of flow, a radial flow pattern probably exists; and, if a pressure measurement were available at a point about 10 ft from the axis of the hole, the radial flow formula would be the one to use. At distances remote from the hole an approximately spherical flow pattern should prevail and the spherical flow formula applies.

CONCLUSIONS AND DISCUSSION

These air injection experiments lead to the result that the permeability of alluvium in the vicinity of U10am-5 is about 9.5 darcies. Both steady-state and transient (pressure buildup and decay) experiments were carried out. However, the analysis in the previous section treats the steady-state results only.

Recently, using the TRUMP heat-transfer code, Rudolf Rozsa has carried out some computer calculations on both the steady-state and transient data reported here. His results show that all the data should be treated as transients and that the pressure

Fig. 3. Comparison of radial and spherical flow equations.

decay curve, for example, depends on the length of time during which the air has been flowing. Computer calculations were able to fit the pressure buildup data with a flow rate of 7000 cfm and a permeability of 8 darcies. A detailed report on these calculations is being prepared.

Prior to the air injection experiments, some alluvium was removed from the walls of the uncased portion of the hole by undercutting. Most of the recovered alluvium crumbled, but a few coherent pieces, about 2 in. in diameter, were recovered. From these, 1-in.-diam core samples were taken and the matrix permeability measured in the laboratory.* The measured matrix permeability was about 5 millidarcies, 3 orders of magnitude smaller than the field measurements. The large difference between the in situ field measurement of gross permeability and the laboratory measurement of the matrix permeability of a consolidated sample indicates that the alluvium at U10am-5 is not typified by the consolidated sample and may contain fractures.

*By Roland Quong and Vincent La Guardia.

APPENDIX DERIVATION OF SPHERICAL STEADY-STATE FORMULA

The differential flow equation is given by the Darcy equation:

$$Q = -A \frac{K}{\mu} \frac{dP}{du}, \quad (A-1)$$

where

Q = volumetric rate of flow

A = cross-sectional area normal to the direction of flow

K = permeability of the medium

μ = viscosity of the fluid

$\frac{dP}{du}$ = pressure gradient.

For a gas that obeys Boyle's law and is flowing under steady-state conditions, the PQ product at any point in the system is the same at any other point at the same time:

$$PQ = P_h Q_h = P_b Q_b. \quad (A-2)$$

Substituting Eq. (A-1) into Eq. (A-2), one obtains

$$Q = \frac{Q_2 P_2}{P} = -A \frac{K}{\mu} \frac{dP}{du}. \quad (A-3)$$

For the radial flow case, consider a sphere whose radius r is greater than the radius of the pressurized cavity, r_h , and less than the radius of the field, r_e :

$$r_h \leq r \leq r_e \quad (A-4)$$

$$P_h \geq P \geq P_e$$

The area of the sphere normal to spherical flow is

$$A = 4 \pi r^2. \quad (A-5)$$

Substituting Eq. (A-5) into Eq. (A-3), one obtains

$$Q = \frac{Q_h P_h}{P} = -(4 \pi r^2) \frac{K}{\mu} \frac{dP}{dr}. \quad (A-6)$$

Integrating Eq. (A-6), one obtains

$$Q_h P_h \int_{r_h}^{r_e} \frac{dr}{r^2} = -4 \pi \frac{K}{\mu} \int_{P_h}^{P_e} P dP \quad (A-7)$$

$$Q_h = \frac{2 \pi k}{\mu P_h} \frac{\frac{P_h^2}{r_h} - \frac{P_e^2}{r_e}}{\frac{1}{r_h} - \frac{1}{r_e}}. \quad (A-8)$$

In practical units, Eq. (A-8) becomes

$$Q_h = \frac{39.6 k}{\mu P_h} \frac{\frac{P_h^2}{r_h} - \frac{P_e^2}{r_e}}{\frac{1}{r_h} - \frac{1}{r_e}}, \quad (A-9)$$

where

Q is in ft^3/day

k is in darcies

μ is in cP

P_h and P_e are in psia

r_h and r_e are in ft.

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