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FIELD MEASUREMENTS OF FRACTURE PERMEABILITY IN GRANODIORITE*

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Introduction

The Piledriver Event, fired June 2, 1966, was a DOD underground nuclear shot in granodiorite at NTS. Depth of burst was 463.1 meters and the yield was 61 ± 10 kt.(1) Three "NX" (3" diameter) exploratory holes were drilled by K Division during July and August, 1969 to determine the extent of rock fracture caused by the event, to obtain core samples, and to more accurately determine the cavity radius. These holes were drilled from an alcove at the end of the tunnel used to emplace the Piledriver device. (See Figure 1.). It was proposed(2) that permeability measurements be made in these holes to check previous granodiorite permeability measurements on the Hardhat Event (3) and to compare scaling from the smaller (5 kt) Hardhat yield to that of the 60 kt Piledriver yield.

Abstract

Field measurements of fractured granodiorite were made August 6-7, 1969, in hole "B" of the main drift of the tunnel used to emplace the Piledriver device (see Fig. 1). Measurements were made by isolating 5 foot sections of the 3" diameter hole with "straddle packers" and flowing air into the isolated region. A schematic of the equipment is shown in Figure 2. The experiment

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

was abruptly terminated when the prototype straddle-packer shaft became inextricably lodged in the hole, probably due to a cave-in. Measurements were made for the first 50 feet of the hole and are summarized in Table I. The data were obtained by a flow method and a pressure decay method. Both these methods seem to agree and give valid results, however the premature termination of the experiment prevented enough data to be taken to provide positive proof.

Equipment and Procedure

A new approach was taken to measure the permeability of the NX core holes. This necessitated the design of new equipment, the major piece being called a straddle-packer shaft. This shaft was a 12 ft length of 1" stainless steel tubing modified so that packers on either end could be inflated, pressure could be read in the center section, and air could be pumped into the center section (see Fig. 2). Each of the packers was made of three layers of bicycle inner tubes which were clamped at the ends so that an air-tight seal around the shaft was obtained. A test of this configuration in a 3" pipe showed that the packers, inflated to a pressure of 80 psig, would resist a center pressure of 100 psig. Imperial Eastman nylon hose, 1/8" i.d. was used to connect the packers to a high pressure nitrogen cylinder and to connect the center-section pressure port to a Heise gage. Imperial Eastman K-310, 5/8" i.d. hydraulic hose was used to connect the shaft to a compressed air source (in this case a large Gardner-Denver compressor which also ran the drilling rig). The velocity of the compressed air was measured by a Hastings type S-22A probe inserted in a 3" pipe which was connected between the compressed air source and the 5/8" i.d. hose. The probe connected to a Hastings model B-22 Velometer.

Two types of methods were used to determine the permeability: one a pressure-decay method, the other a constant flow method. The shaft was lowered into the hole and the packers pressurized. For the pressure-decay method, the center section of the shaft between the packers was pressurized to a given value and then the air flow was cut off. The time interval for the pressure to decay to another value was recorded. The flow method was similar only that flow was measured rather than cut off. When both pressure and flow reached what appeared to be a steady state condition (usually within five minutes) these "steady state" values were recorded and the shaft moved to another position in the hole.

On 5 August 1969, the equipment was set up in the main drift of the tunnel used to emplace the Piledriver device. On 6 August 1969, permeability measurements began using the pressure-decay method. Eight runs were made at a depth of 10 ft. (Runs made any closer to the top of the hole would be meaningless due to the fact that the hole was cased for the first eight feet.) When the shaft was moved to the 15' location, the bottom packer ruptured on inflation. Examination of the rupture showed a long gash rather than a small puncture. Extra inner tubes were brought along for this eventuality and runs were begun again that afternoon, but at reduced packer and operating pressures. After the first afternoon run (at the 10' mark) the field under study was pressurized for several minutes. When subsequent runs showed markedly different values than previously obtained, the pressurization was repeated several more times in between a total of 22 afternoon runs. All of these pressurizations were observed to affect the decay times. Nine runs were made at the 10' mark, eleven at the 15' mark and two at the 20' mark. On the third run at the 20' mark the top packer ruptured. This was about the same spot that the 15' mark bottom packer ruptured, also it was the same type longitudinal tear. This packer was replaced and runs were begun again the next day.

The pressure-decay method was abandoned in favor of the flow method which allowed still lower packer and operating pressures and is better suited to a high permeability field. During the 13 flow method runs made on 7 August, it was discovered that, after a while, the medium would leak air back into the hole. This was evidently the cause of the anamolous readings observed the day before. Therefore, before each run, the hose was disconnected and the air (which was at very low pressures) allowed to bleed out. The 12th and 13th runs were made near a zone which the drillers said had to be redrilled after each "trip". Therefore it was decided not to enter this area, but to rerun the length of hole just measured. The shaft was pulled up a few feet and then refused to budge. A cable hoist of the type frequently used to lift engines out of automobiles was pressed into service, but could not move the shaft. Various combinations of pressurizing-depressurizing and pulling did not free the shaft and therefore the effort was abandoned.

Results and Discussion

The apparent cave-in of the 3" hole on top of the probe ended the experiment before much relevant data were taken. The data which were taken are shown in Appendix A (Piledriver Permeability Data). The computational methods are shown in Appendicies B (Calculations for Flow Method), C

(Derivation of Pressure-Decay Formula), and D (Calculations for Pressure-Decay Method). The results of the computations are shown in Tables I (Selected Summary of Data), II (Summary of Data, Flow Method), and III (Summary of Data, Pressure-Decay Method). Although all data taken and results calculated are presented, Table I contains the results considered most accurate and reliable. The reasons for these choices are as follows:

Most of the data taken on 6 August 1969, (the pressure-decay data) were affected by back-pressure from gas already injected into the media during preceding runs. This was noticed after run B-1 when a large amount of air had been run through the equipment. The following run (B-2) showed an immediate and obvious change in decay rate. The average permeability of these subsequent runs (B-2 to B-9) is 18 md while the average of the runs previous to this (runs A-1 to A-8 and B-1) is 47 md, nearly a factor of three difference. Therefore, because of various pressurizations made in order to investigate and understand the back-pressure phenomenon, only the pressure-decay runs up to and including B-1 are considered valid. These runs, all at the 10 ft zone are presented in Table I.

When the data were taken by the flow method (Table II) the back-pressure effect was minimized by allowing the pressure to decay to ~ 0 psig before each run. However, a different trend in the data was noticed: if high and low pressure runs were made at the same location, the high pressure run had the higher permeability. Since this may have been caused by leakage past the straddle-packers, the runs at lower pressures are considered more accurate. Table I contains the flow-method results which are considered best.

The selected data from the pressure-decay method are all at the 10' point, but their average of 47 md compares well with the 58 md measured at the 10' mark by the flow method (run C-2). Also seen in Table I is the higher permeability around the 15' depth (run C-4). Since two straddle-packers ruptured here, it seems that a large crack might connect to, or intersect the hole in this region, thereby increasing its permeability.

Discussion of Method of Calculation

Both computational methods used in this report and that used by Boardman and Skrove[3] are based on the steady-state, isothermal, radial-flow equation for ideal gases,[4] (equation (B-1), Appendix B). This equation involves the assumption of a value for r_e, the radius to the external boundary - also called the radius of effect, and radius of drainage. Boardman used a value of $r_e = 50$ft, pointing out that the permeability is rather insensitive to changes in r_e. The permeabilities calculated in this report are also based on $r_e = 50$ purely for comparison with Boardman's numbers. If $r_e = 5$, all permeabilities would be lower by a factor of 0.615. However, the radius of drainage can be calculated by the following formula:[5]

$$r_e = \left[\frac{\gamma K P_o t}{\mu \phi \tau}\right]^{1/2} \qquad (1)$$

where:

r_e = radius of drainage, ft.

γ = dimensionless constant $\cong$ 2.24

K = permeability, md

P_o = mid-formation pressure, psia

t = time, days

μ = gas viscosity, cp

ϕ = porosity, dimensionless

τ = dimensionless time, 0.00633

One problem with using this equation is making a correct choice for the time. When the pressure-decay runs were made, the time interval in which the system was brought up to pressure was not measured. If one uses just the decay time interval for a run, the result would represent a minimum value for r_e. Applying equations (1) and (B-1) for Run A-1 and for solving K and r_e by simultaneous equations, the radius of effect would equal 400 ft. This gives a permeability of 0.0457 d., or a factor of 1.34 times the reported value of Run A-1. Thus it is seen that varying r_e from 5 ft to 400 ft changes permeability values by a factor of two. This factor of two then is probably the accuracy of the absolute value of the permeabilities presented in this report.

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Conclusions

1. It is possible to measure permeability using the experimental method described.

2. The packers on the straddle-packer should be tougher.

3. The computational methods used are better for relative permeability measurements and are not as good for absolute values.

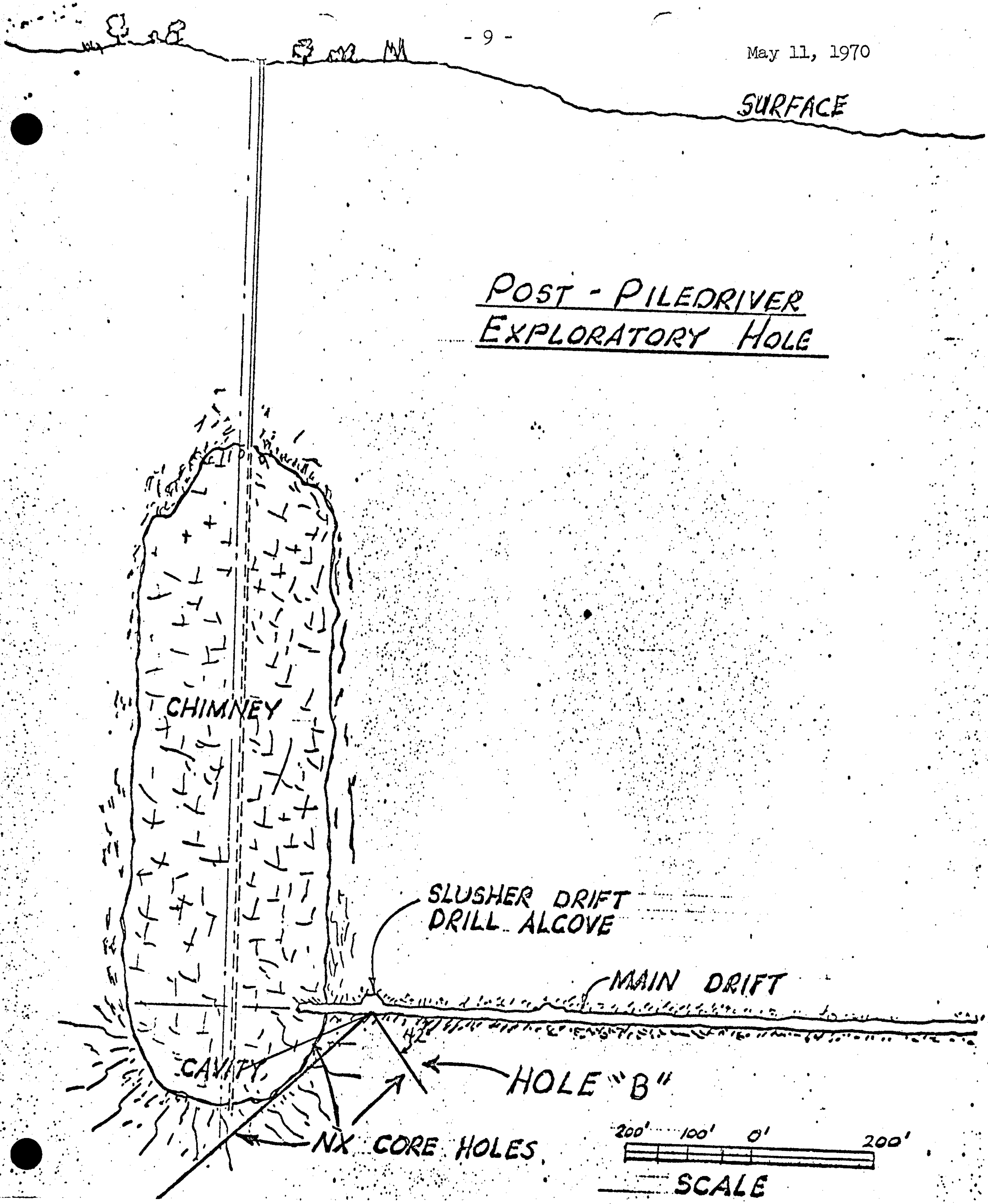

Figure 1. Vertical Cross-Section of the Piledriver Event[6]

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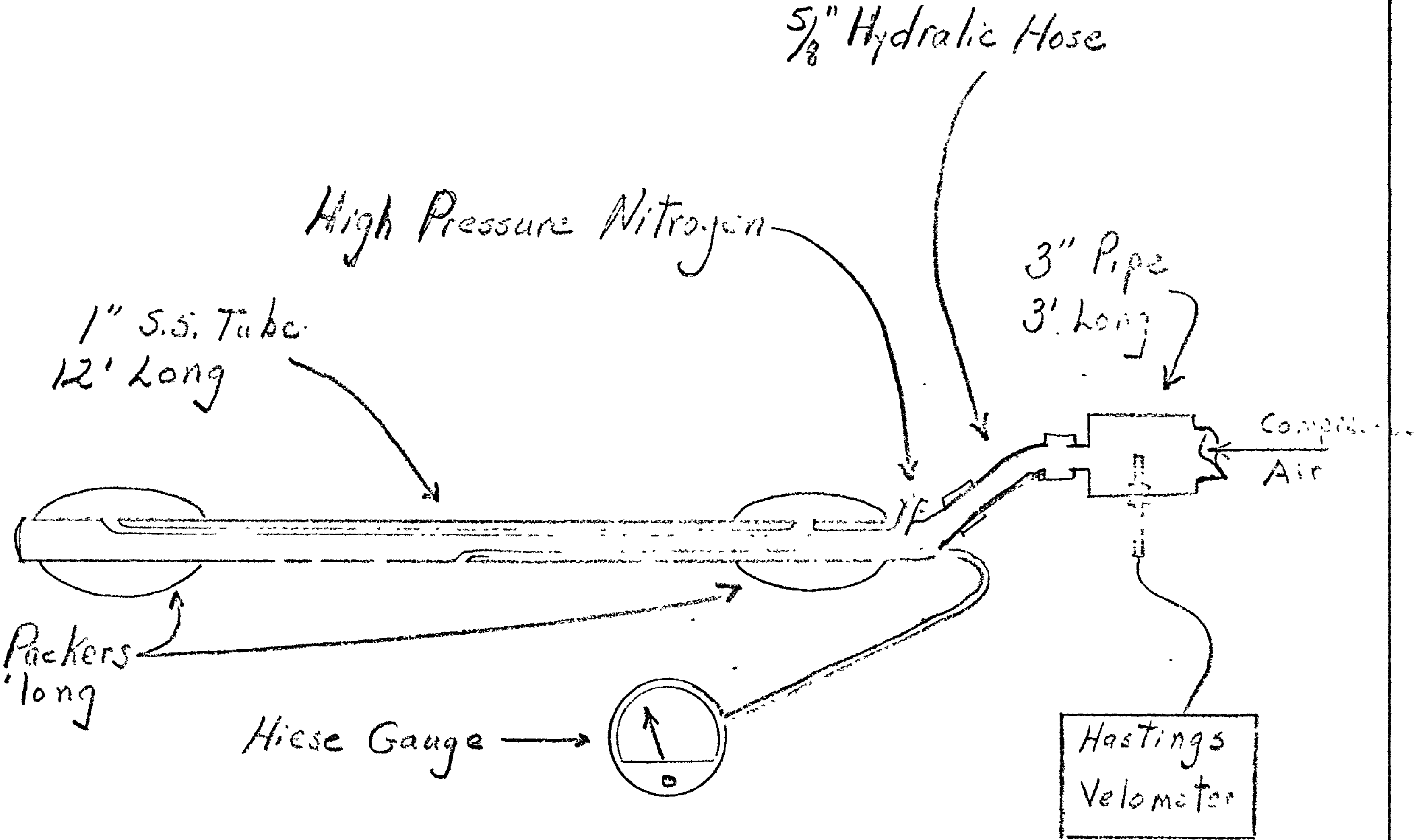

Fig 2 Cross-section of Straddle-Packer Shaft

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Table I

Selected Summary of Data

Flow Method Data

Run No.	Position in Hole B (ft from main drift)	Hole Pressure (psig)	Permeability millidarcies
C-2	10	10	58
C-4	15	10	110
C-6	30	13	14
C-10	45	14	19
C-13	48.5	12	5.5

Pressure-Decay Method

Run No.	Position in Hole B	Hole Pressure Initial	Hole Pressure Final	Permeability millidarcies
A-1	10	40	2.6	34
A-2	10	40	10	51
A-3	10	40	10	49
A-4	10	40	10	38
A-5	10	40	10	51
A-6	10	40	10	48
A-7	10	40	10	51
A-8	10	40	10	55
B-1	10	25	5	43
Average				47

Table II

Summary of Data, Flow Method

Run No.	Position feet	Hole Pressure (psig)	Flow 1000 cf/day	Perm. Darcies
C-1	10	18	79	0.11
C-2	10	10	20	0.058
C-3	15	15	73	0.13
C-4	15	10	36	0.11
C-5	30	23	25	0.025
C-6	30	13	7	0.014
C-7	35	28	20	0.014
C-9	40	14	10	0.019
C-10	45	14	10	0.019
C-11	45	21	32	0.035
C-12	48.5	21	9	0.010
C-13	48.5	12	2	0.0055

Packer pressure at 30 psig.

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Table III

Summary of Data, Pressure-Decay Method

Run No.	Position feet	Hole Pressure Initial (psig)	Final	Permeability Darcies
A-1	10	40	2.6	0.0341
A-2	10	40	10	0.0511
A-3	10	40	15	0.0495
A-4	10	40	15	0.0381
A-5	10	40	10	0.0511
A-6	10	40	10	0.0485
A-7	10	40	10	0.0511
A-8	10	40	10	0.0547
A-9	15	Bottom Packer Ruptures		
B-1	10	25	5	0.0435
B-2	10	25	10	0.0127
B-3	10	25	10	0.0169
B-4	10	25	10	0.01802
B-5	10	25	10	0.01995
B-6	10	25	10	0.01745
B-7	10	25	10	0.0186
B-8	10	25	10	0.0186
B-9	10	25	10	0.01926
B-10	15	25	10	0.0215
B-11	15	25	10	0.02232
B-12	15	25	10	0.0294
B-13	15	25	10	0.03105
B-14	15	25	10	0.0349

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Table III (cont'd)

Run No.	Position feet	Hole Pressure Initial (psig)	Final	Permeability Darcies
B-15	15	25	10	0.0399
B-16	15	25	10	0.02059
B-17	15	25	10	0.02232
B-18	15	25	10	0.0215
B-19	15	25	10	0.02539
B-20	15	25	10	0.02059
B-21	20	25	10	0.0349
B-22	20	25	10	0.0372
B-23	20			
C-8	35	25	13.5	0.00294

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Appendix A

Piledriver Permeability Data

6 August 1969, Hole "B", Morning Run

Pressure Decay Method

Run No.	Position	Packer Press.	Decay Press.	Time
A-1	10 ft mark	60 psig	40 - 2.6 psig	55 sec
A-2	10'	60	40 - 10	15
A-3	10'	60	40 - 15	10
A-4	10'	60	40 - 15	13
A-5	10'	60	40 - 10	15
A-6	10'	60	40 - 10	16
A-7	10'	60	40 - 10	15
A-8	10'	60	40 - 10	14
A-9	15'	Bottom Packer Ruptures		

6 August 1969, Afternoon Run (after repair)

B-1	10'	36.5	25 - 5 psig	25 sec
	Pressure held constant for several minutes			
B-2	10'	36.5	25 - 10	44
B-3	10'	36.5	25 - 10	33
B-4	10'	36.5	25 - 10	31
B-5	10'	36.5	25 -10	28
	Pressure held constant for several minutes			
B-6	10'	36.5	25 - 10	32

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Appendix A (cont'd)

Run No.	Position	Packer Press.	Decay Press.	Time
B-7	10 ft mark	36.5	25 - 10	30 sec
B-8	10'	36.5	25 - 10	30
B-9	10'	36.5	25 - 10	29
B-10	15'	40	25 - 10	26
B-11	15'	40	25 - 10	25
B-12	15'	40	25 - 10	19
B-13	15'	40	25 - 10	18
B-14	15'	40	25 - 10	16
B-15	15'	40	25 - 10	14
	Pressure held constant for several minutes			
B-16	15'	40	25 - 10	27
B-17	15'	40	25 - 10	25
B-18	15'	40	25 - 10	26
B-19	15'	40	25 - 10	22
B-20	15'	40	25 - 10	27
B-21	20'	40	25 - 10	16
B-22	20'	40	25 - 10	15
B-23	20'	40	Top Packer Ruptures	

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Piledriver Permeability Data

7 August 1969 - Flow Method

Run No.	Position	Packer Press.	Flow Press.	Flow
C-1	10 ft mark	30 psig	18.1 psig	960 ft/min
C-2	10'	30	10.4	320
C-3	15'	30	15.1	990
C-4	15'	30	10.2	490
C-5	30'	30	23	270
C-6	30'	30	13.1	101
C-7	35'	30	28.5	180
C-8	35'	30	25-13.5 in 2 minutes*	
C-9**	40'	30	14.0	138
C-10	45'	30	14.0	139
C-11	45'	30	21.3	360
C-12	48.5'	30	21.0	101
C-13	48.5'	30	12.1	35

Probe stuck in hole - moves 5 ft, then resists ~ 500 lb pull.

* Pressure Decay Method.

** Pressure Backflow from hole noticed, waited until it decayed away.

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Appendix B

Calculations for Flow Method

$$K = \frac{q \mu P_b \ln (r_e/r_n)}{19.88 h (P_h^2 - P_e^2)} \qquad \text{(B-1)}$$

K = permeability, darcies

q = volume flow rate in ft^3/day at P_b

μ = viscosity of air, 0.0195 cp

P_b = tunnel pressure, 12.4 psia

r_e/r_n = radius of effect = 400

h = hole length in ft = 5.5 ft

P_e = absolute pressure at r_e, 12.4 psia

P_h = absolute pressure in hole, psia

$\ln r_e/r_n = \ln 400 = 5.99$

Sample Calculation

Run C-1

P_h = 18.1 psig + 12.4 = 30.5 psia

$q = 960 \text{ ft/min } (0.0233 \text{ ft}^2)(30.5/12.4)(1{,}400 \frac{\text{min}}{\text{day}}) = 79{,}100 \text{ cf/day}$

$$K = \frac{(79{,}100)(0.0195)(5.99)}{19.88 (5.5)(30.5^2 - 12.4^2)} = 0.1089 \text{ darcies}$$

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Appendix C

Derivation of Pressure-Decay Formula

In each of the pressure decay experiments, pressure in the section of drill hole being measured was allowed to drop by a factor of 2 or 3. Therefore, the instantaneous rate of flow changed by an even greater factor during the period of measurement, and an integrated form of the flow equation must be used.

The steady-state, isothermal, radial flow equation for ideal gas is,

$$q = \frac{19.88\ hk\ (P_h^2 - P_e^2)}{\mu\ P_b\ \ln (r_e/r_h)} \qquad \text{(C-1)}$$

where q = volume rate of flow in ft^3/day at base pressure, P_b

h = hole length, ft.

k = permeability, darcies

P_h = absolute hole pressure, psia

P_e = absolute pressure at r_e

r_e = radius of effect

r_h = radius of the hole

μ = viscosity of air, cp

P_b = tunnel pressure, psia

Let $A = \frac{19.88\ h}{\mu\ P_n\ \ell n\ (r_e/r_h)}$ (C-2)

then (C-1) can be rewritten:

$$q = Ak\ (P_h^{\ 2} - P_e^{\ 2})\ . \qquad \text{(C-3)}$$

If dV = volume of gas which has leaked out of the hole in time dt, then

$$q = dV/dt \qquad \text{(C-4)}$$

and

$$dV = Ak\left[P_h^{\ 2} - P_e^{\ 2}\right]dt \qquad \text{(C-5)}$$

The relation between the volume of gas which has leaked out of the hole and the corresponding pressure drop is,

$$dV = -\frac{V_h}{P_b}\,dP \qquad \text{(C-6)}$$

where Vh = volume of the pressurized section of hole, in ft^3.

Combining equations (C-5) and (C-6), and integrating:

$$\frac{V_h}{P_b}\int_{(Ph)_i}^{(Ph)_f}\frac{dP}{\left[P_h^{\ 2} - P_e^{\ 2}\right]} = -\int_0^t Ak\ dt \qquad \text{(C-7)}$$

or

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$$\frac{V_h}{P_b} \; \frac{1}{2P_e} \; \ln \frac{(Ph)_f - P_e}{(Ph)_f + P_e} \times \frac{(Ph)_i + P_e}{(Ph)_i - P_e} = - Akt \qquad \text{(C-8)}$$

where $(Ph)_f$ = final hole pressure, psia

$(Ph)_i$ = initial hole pressure, psia

t = time in days

The following numerical values can be substituted:

h = 5.5 ft

μ = 0.0195 cp

P_b = 12.4 psia

r_e = assume 50 ft

r_h = .125 ft.

V_h = 0.27 ft^3

P_e = 12.4 psia

Converting t in days to t in seconds

1 day = 8.64×10^4 seconds

$$k = -\frac{1}{t} \; (1.002) \ln \frac{(Ph)_f - 12.4}{(Ph)_f + 12.4} \times \frac{(Ph)_i + 12.4}{(Ph)_i - 12.4} \qquad \text{(C-9)}$$

where t = time in seconds

$(Ph)_f$ = final hole pressure, psia

$(Ph)_i$ = initial hole pressure, psia

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Appendix D

Calculations for Pressure Decay Method

$$k = -\frac{1}{\tau}(2.309)\log\frac{(P_h)_f\ (P_h)_i + 24.8}{(P_h)_i\ (P_h)_f + 24.8} \qquad \text{(D-1)}$$

τ = time in seconds

$(P_h)_f$ = final hole pressure, psig

$(P_h)_i$ = initial hole pressure, psig

k = darcies

Derivation of this formula is shown in Appendix "C".

Sample Calculation

Run No. A-2 $\tau = 15,\ P_{h_f} = 10,\ P_{h_i} = 40$

$$K = -\frac{1}{15}(2.309)\log\frac{10\ (64.8)}{40\ (34.8)}$$

$$K = -(.154)\log .466$$

$$K = (-0.154)(-0.332) = 0.0511$$

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