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SUBJECT: EGCR Graphite Permeability Tests: Results of Forced
Flow Experiments on EGCR Moderator-Grade Graphite

TO: Distribution

FROM: W. T. Ward and J. Truitt

ABSTRACT

Helium-permeability and porosity were determined at room temperature for specimens from a typical EGCR moderator-grade graphite block. Permeability, at a mean pressure of 2 atm, ranged from 26 to 200 (av. 86.5) millidarcys. Permeability data indicated that turbulent flow was never obtained with helium in these tests and that helium permeating the moderator graphite at EGCR operating conditions (taken to be: 600°C ; ΔP , 10 lb/in² per inch of graphite; mean P, 400 lb/in²) would be in the viscous flow region. Darcy's law and the reported constants are applicable for flow computations involving moderator graphite under these conditions. Porosity ranged from 20.6 to 29.4% (av. 23.8%), and there was no correlation between porosity and permeability variations.

The large variations encountered are believed to reflect the nonuniformity of the specimens, since

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duplicate determinations showed excellent agreement. Permeability did not change appreciably with direction of flow, and hence did not vary consistently with respect to the extrusion or any other axis. Preparation of the specimens evidently did not introduce appreciable surface effects (which could introduce serious errors in measurements on very thin samples).

INTRODUCTION

A knowledge of helium permeation rates through the various graphite components is necessary for EGCR design calculations. Components of interest are the fuel element sleeves, sleeve joints, sleeve coatings, and the large 16 in. x 16 in. x 20 ft graphite moderator columns..

The EGCR fuel sleeves are separated from the graphite moderator blocks by a 1/8-in. wide annular passage. A small flow of helium enters this passage at the bottom of each fuel channel. This helium flows up the passage, cooling both the fuel sleeve and the moderator block, then to the top plenum through a flow restrictor at the top of each column.¹

The permeability of the moderator is of concern since some of the helium which enters this coolant passage will permeate the moderator and thus starve portions of the moderator and sleeves of part of their cooling. The amount of helium which bypasses the upper part of the passage is of course dependent upon the moderator permeability.¹

Helium-permeability coefficients and porosity were determined on samples from a graphite block of a grade similar to that to be used as EGCR moderator. The region of transition from viscous to turbulent flow was ascertained experimentally using argon. "Skin" effects such as clogging of the surface pores, which might have been introduced during specimen fabrication, were investigated.

MATERIAL INVESTIGATED

All samples covered in this report were cut from the same 14 x 15 x 7 in. block of AGOT needle-coke graphite. More specifically, they were cut from a 4-in.-long piece from one end of each of three 1 x 1 x 12 in. pieces from the above block. These three pieces were numbered 1, 17, and 19. The orientation of these three pieces in the block and with respect to each other is shown in Fig. 1; that is, No. 1 was cut perpendicularly to Nos. 17 and 19, and all three were cut perpendicularly to the axis of extrusion. Four 3/4-in.-dia cylindrical specimens were then cut from each of the three pieces. The cutting direction and the manner in which they were labeled are shown in Fig. 2.

DARCY'S EQUATION AND PERMEABILITY CONSTANT

The relationship between the variables measured and the permeability constant, k , most applicable to the more permeable graphites is

$$k = \frac{Q_a P_a \mu L}{A \Delta P P_m},$$

where Q_a is the volumetric flow rate of the gas (measured at pressure P_a) which passes through a specimen of cross sectional area A and thickness L . ΔP is the pressure drop across the specimen; P_m is the absolute mean pressure; and μ is the viscosity of the gas. If μ is expressed in centipoises, the flow rate in cm^3/sec , A and L in cm^2 and cm respectively, and the pressures in atmospheres, k will be expressed in darcys.

A detailed discussion of this equation and other permeability relationships may be found in the appendix of a previously published report.²

Figure 1. Location and Orientation of Test Specimens from
14" x 15" x 7" Block of AGOT Needle Coke Graphite.

Figure 2. Specimen Orientation in 1" x 1" x 4" Piece.

RESULTS

Viscous Versus Turbulent Flow

Permeability constants of porous media are strictly valid only when viscous-flow conditions prevail, and these conditions must be determined experimentally.³ A plot of $P_m \cdot \Delta P \cdot \frac{A}{L}$ versus $Q_a P_a$ results in a line of constant slope for conditions of viscous flow. The results of helium determinations as shown in Fig. 3 indicate that these data were taken under viscous-flow conditions.

The Reynold's number Re is given by the following relationship:

$$Re = \frac{D U \rho}{\mu} = \frac{D \left(\frac{Q_m}{A} \right) \left(\frac{M W P_m}{RT} \right)}{\mu} \quad (1)$$

It is realized that a wide pore-size distribution exists; thus many values for D , A , and Q_m apply to this group. However, we shall assume that the use of a model which consists of a parallel bundle of capillaries is applicable for this discussion. D , Q_m , and A are the same for all capillaries in the bundle.

For the same gas and specimen, one may equate (at the transition point between viscous and turbulent flow)

$$\left(\frac{Q_m P_m}{A T \mu_T} \right)_{\text{critical}} = \left(\frac{Q_m P_m}{A T_{20^\circ\text{C}} \mu_{20^\circ\text{C}}} \right)_{\text{critical}} \quad (2)$$

At the critical point

$$\frac{Q_m P_m}{A} = \frac{k}{\mu} \frac{P_m \Delta P}{L} \quad (\text{Poiseuille's law}). \quad (3)$$

Also at the critical point both the Reynold's number and Poiseuille's law are applicable; thus a common solution is

$$\left(\frac{k}{\mu^2 T} \right) \left(\frac{\Delta P P_m}{L} \right)_T = \left(\frac{k}{\mu_{20^\circ\text{C}}^2 T_{20^\circ\text{C}}} \right) \left(\frac{\Delta P P_m}{L} \right)_{20^\circ\text{C}} \quad (4)$$

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Figure 3. Forced Flow Characteristics at High Flow Rates

For a given gas $\mu \propto T^{\frac{1}{2}}$, Eq. (4) becomes

$$\left(\frac{1}{T^2}\right) (Z)_T = \left(\frac{1}{T^2}\right)_{20^\circ\text{C}} (Z)_{20^\circ\text{C}}, \quad (5)$$

where $Z = \frac{\Delta P P_m}{L}$.

Once the critical value has been determined for a given piece of graphite, under one set of conditions, Eq. (5) may be used for evaluation of the critical value at any other set of conditions.

It is known that even if data were available in the transition region, it would be difficult to determine the exact transition point in porous media. However, let us consider a point B which clearly lies on the straight portion of a hypothetical curve obtained at reactor operating temperature of 600°C . If it can be shown that

$$(Z)_{\text{critical } 600^\circ\text{C}} \geq B > (Z)_{\text{max.}^* 600^\circ\text{C}} \quad (6)$$

then viscous flow conditions will prevail under reactor operating conditions.

By Eq. (5)

$$(Z)_{\text{critical } 20^\circ\text{C}} = 0.108 (Z)_{\text{critical } 600^\circ\text{C}} \quad (7)$$

when $\frac{T_{20^\circ\text{C}}^2}{T_{600^\circ\text{C}}^2} = 0.108$.

* $(Z)_{\text{max. } 600^\circ\text{C}}$ = the maximum value of Z calculated to exist under reactor operating conditions. If these conditions are assumed to be: $P_m = 400 \text{ lbs/in.}^2$, $\frac{\Delta P}{L} = 10 \text{ lbs/in.}^2 \text{ per inch}$, and $T = 600^\circ\text{C}$, then $(Z)_{\text{max.}} = 7.29 \text{ atm}^2/\text{cm}$ at 600°C , or [by Eq. (5)] $0.82 \text{ atm}^2/\text{cm}$ at 20°C .

Multiplying all terms of Eq. (6) by the temperature ratio shown:

$$\left(Z \right)_{\text{critical } 20^{\circ}\text{C}} \geq 0.108 B > 0.108 \left(Z \right)_{\text{max. } 600^{\circ}\text{C}} \quad (8)$$

Let $0.108 B$ be equivalent to point A and A' on Fig. 3; for this case A and A' are clearly on the straight portions of the curves. Then $0.108 \left(Z \right)_{\text{max. } 600^{\circ}\text{C}}$, which is calculated to be $0.82 \text{ atm}^2/\text{cm}$, is observed to be less than $\left(Z \right)_{20^{\circ}\text{C}}$ at A or $A' < \left(Z \right)_{\text{critical } 20^{\circ}\text{C}}$, and is therefore in the viscous flow region. Thus the values are applicable to flow calculations at reactor conditions.

"Skin" Effect

Previously reported data² indicated that some clogging of surface pores occurred during specimen preparation and handling. A difference in the amount of such clogging would help account for the permeability variations found in similar (even adjacent) samples. Several different methods of surfacing the areas normal to flow were tested to establish a preparation procedure resulting in a minimum of clogged pores. Enlarged photographs of these surfaced areas indicate that specimens prepared with a dry, high-speed emery wheel were the least damaged. All specimens employed in this test program were prepared by this method.

After the permeability and porosity determinations were completed, four samples were cleaned ultrasonically in acetone; then dried in a vacuum oven at 150°C for 24 hours. For three of the cleaned specimens the permeability coefficient changed very little, while for the fourth (Specimen 1 α) it approximately doubled. The value obtained for this specimen indicates that its internal structure may have been altered during the cleaning process. The results are summarized in Table 1.

Table 1. Effect of Ultrasonic Cleaning on Permeability

Specimen No.	k at 2 atm (millidarcy)				
	From Curve	Rerun of Single Point	After Cleaning	After Purposely Plugging	After Recleaning
19 α	26	25	25	22	26
1 α	62	60	112		
17 β	35	34	33		
17 Δ	200	136	145		

These results demonstrate that the method of sample fabrication reduced surface damage or "skin" effect to a minor role in the permeability of these specimens.

On one sample, the surface areas normal to flow were damaged by scraping with a knife blade until the entire surfaces appeared to be clogged. This surface damage produced a 15 percent reduction in this sample's permeability (as shown in Table 1). Subsequent ultrasonic cleaning and drying restored the original value. Although a 15 percent drop in permeability is a minor factor, it should be noted that as the sample thickness is decreased this percentage (due to surface damage) will increase. "Skin" effect or surface damage could be a major contributing factor in the permeability of very thin samples.

Permeability to Helium

Helium permeability determinations were performed on the original twelve specimens at several mean pressures, and plots of the permeability constant, k , versus the reciprocal of mean pressure were made (Figs. 4, 5, and 6). Values of k , at a mean pressure of two atmospheres, taken from these curves, are given in Table 2. A recheck of the permeability of each of the specimens was then made at a mean pressure of two atmospheres. These results are also shown in Table 2. Duplicate determinations ($P_m = 2$ atm) show good reproducibility with only two values differing by more than ten percent. The average value of the permeability coefficient corresponding to a mean pressure of two atmospheres was 86.5 millidarcys. However, eight of the samples gave values which ranged from 26 to 70 millidarcys ($P_m = 2$ atm) with an average value of 50. This agrees well with the average of 34 millidarcys found on 18 AGOT samples reported previously.² The values for the other four specimens ranged from 100-200 millidarcys which corroborates previous evidence that considerable variations exist even in the same graphite block. There appears to be no correlation between permeability variations and the orientation of the samples as cut from the block.

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Figure 4. Helium Permeability in Specimens from
1 x 1 x 4-in. Piece No. 1

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Figure 5. Helium Permeability in Specimens
from 1 x 1 x 4-in. Piece No. 17

Figure 6. Helium Permeability in Specimens from
1 x 1 x 4-in. Piece No. 19

Table 2. Permeability and Porosity of Twelve Specimens
of EGCR Moderator-Grade Graphite to Helium

Specimen No.	k at 2 atm (millidarcy)		Open Porosity (%)
	From Curve*	Rerun of Single Point	
1 α	62	60	25.9
1 β	63	64	25.5
1 γ	70	65	29.4
1 Δ	144	146	24.4
17 α	64	59	23.0
17 β	34	33	24.0
17 γ	41	44	22.3
17 Δ	200	137	23.4
19 α	26	25	20.6
19 β	40	41	21.2
19 γ	102	99	23.0
19 Δ	192	161	21.8

* Taken from curve drawn through points obtained at several mean pressures (plot of k versus $1/P_{\text{mean}}$).

Porosity

Measurements of porosity⁴ (the voids available to helium gas) were also made on these specimens. The values obtained are listed in Table 2 and averaged 23.8 percent. These porosity values do not reflect the variations in permeability.

Permeability to Argon

Argon permeability data were obtained on two of the specimens. These data are plotted on Fig. 3 where they may be compared with the helium data on the same specimens. It is apparent from the curvature of the lines that most of the argon data were obtained in the turbulent flow region.

CONCLUSIONS

1. The permeability constant, k , for helium ranged from 26 to 200 millidarcys and, in general, is in fairly good agreement with values previously reported for AGOT graphite.
2. Considerable differences in permeability may exist even in adjacent specimens from the same graphite block.
3. The variations in the permeability constant found in these specimens cannot be correlated with the direction of flow.
4. The effective porosity of the permeability samples ranged from 20 to 30% with an average value of 23.8%. There was no correlation between porosity and permeability variations.
5. Surface damage or "skin" effects, due to handling and sample preparation, contributed very little to the over-all permeability of these specimens, but it can be a major contributing factor to the permeability of very thin samples.
6. Based on the helium data and the arguments presented in the body of this report, it is estimated that the forced flow within this graphite will be viscous at reactor temperature and pressure.

REFERENCES

1. E. G. Beasley, "Acceptable Permeability for EGCR Fuel Support Sleeves," memorandum to Garland Samuels, Sept. 30, 1960.
2. N. V. Smith and J. Truitt, EGCR Graphite Permeability Tests: Results of Forced Flow Experiments on EGCR Fuel Element Sleeves and Sleeve Materials, ORNL CF-60-7-101 (July 29, 1960).
3. "Standard Procedure for Determining Permeability of Porous Media," API Code No. 27, 2nd Ed., American Petroleum Institute, Division of Production, Dallas, Texas, 1942.
4. C. G. Rall, H. C. Hamontre and D. B. Taliaferro, "Determination of the Porosity by a Bureau of Mines Method," U. S. Bur. Mines R. I. No. 5025 (July 1953).

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