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O.E.C.D. HIGH TEMPERATURE REACTOR PROJECT

DRAGON

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Dragon Project Report

THE FUEL ELEMENT GRAPHITE

by

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1. INTRODUCTION

The main requirements of a fuel element graphite for reactors based on the Dragon concept may be listed as follows:

(i) Low transmission coefficient for fission products.

(ii) Dimensional stability under service conditions.

(iii) High strength.

(iv) High thermal conductivity.

(v) High purity.

(vi) High resistance to oxidation.

At the inception of the Dragon Project the overriding requirement was for effective control over fission product diffusion since without this, the primary circuit would become grossly contaminated. With the graphites available it was evident that the diffusion coefficients for the highly active gaseous species made the containment quite inadequate. Using a system in which the interspace between the fuel and graphite can was purged by the coolant flowing through the graphite fuel cans, it was found that by using conventional reactor grade graphite the fission product gases could be swept-back and acceptable apparent diffusion coefficients thus obtained (i.e. $< 1 \times 10^{-6}$ cm^2/sec). However, in these circumstances the amount of gas flowing through the graphite fuel tubes into the clean-up system is comparable with the total primary circuit coolant flow and therefore unacceptable. By choosing the only low permeability fine grain graphite (Morgan Crucible EY 9) which was available in the sizes required, it was found that the purge flow could be reduced to an acceptable level. Unfortunately, however, because of the fine pore structure of this material fission products can readily back-diffuse against the coolant flow through the pores (see Section 4).

At the time of the signing of the Dragon Project agreement in 1959 a considerable amount of work had been carried out on impregnating the EY 9 family of materials to reduce the permeability to such a level that the gaseous fission product diffusion requirement could be satisfied. This work, which was reported at the Dragon Graphite Symposium in November 1959 [1] indicated that EYX 60 graphite, a progeny of EY 9, could be impregnated in a variety of ways to yield very low gas permeabilities. In particular, full sized fuel tubes had already been successfully impregnated using the furfuryl alcohol process and it became evident early in 1960 that this route was the most expedient for producing the initial change of fuel elements for the Dragon Reactor within the very limited time available.

In the two years which have elapsed since this decision a considerable amount of information has accumulated concerning the likely behaviour of graphites in high temperature reactor systems, particularly data on dimensional stability under irradiation. The influence of this new knowledge on the development of fuel element graphite within the Dragon Project is discussed in detail in Section 4 of this paper.

2. PROVISION OF FUEL ELEMENT GRAPHITE FOR THE INITIAL CHARGE OF THE REACTOR EXPERIMENT

2.1 Introduction

Although a number of different routes are being developed to supply material for the Reactor Experiment the route which has been most actively pursued since the end of 1959 revolves around the treatment of fine grain graphite produced by Morganite Carbon Ltd. Difficulties which have been met with in following this route are reported in this section while the development of alternative materials is discussed in Section 4.

2.2 Base Material

2.2.1 Supply of EYX 60 and Variants

As mentioned in the Dragon Graphite Symposium in 1959, difficulties with the impregnation of EY 9 type graphite had led to the selection of EYX 60 for further studies.

Until this time high purity graphite had not been a pre-requisite for the Reactor Experiment. The main requirement had been that the boron content should be less than 1.5 ppm. Experiments which the Morgan Crucible Company had carried out in 1958, for their own information, had led them to expect that a mean boron content of 5 ppm was a production possibility. In order to see if a better figure could be achieved a large production trial was initiated using as clean conditions as practicable. An examination of the boron content at the various stages of the manufacturing process yielded the following information [2]:-

Process Stage	Mean Boron Content (ppm)
Ground raw material	1.1
Mixed	1.2
Rods after kilning	1.6
Rods after graphitisation	3.6

The results quoted for the kilned rods are taken from drillings at one end. There was an uneven distribution of boron with up to 10 ppm on the skin. The heterogeneity of the boron content increased on graphitisation with the skin having as much as 20 ppm.

It was the uneven distribution as much as the level of boron which made this material unacceptable. The Project therefore negotiated with the Morgan Crucible Company for the purchase of the ungraphitised version of EYX 60, i.e. CY 119 so as to allow its subsequent graphitisation or purification elsewhere.

Supply of CY 119 commenced in June 1960. A radiographic examination of samples of the first deliveries of CY 119 revealed the presence of large inclusions which were subsequently identified as iron. This led to an extensive radiographic examination of the CY 119 stock. The most striking result of this survey was the appearance of long streaks and many spots (Fig. 1) which indicated the presence of impurities of higher density than graphite. Analysis showed that iron was present in the darkest and most definite spots while rare earths were found in the streaks. Cracks were also found (Fig. 2) but to detect them it was estimated that the direction of the X-ray beam must be within 20° of the plane of the crack [3].

During the survey 347 rods, 3¼" diameter, 79" long, were inspected, a single radiograph being taken of a one foot length in the centre of the bar since preliminary experiments had indicated that impurities were homogeneously distributed along the length of the rods. An indication of the degree of contamination is given by the following summarised results:-

Rods with heavy inclusions along the central section	11.5 %
" " medium " " " " "	44.5 %
" " light " " " " "	44.0 %
Rods showing cracks	9.2 %

These findings were made known to Morganite Carbon Ltd., and as a result a "cleaned-up" version of CY 119 was produced, this being designated CYX 150. The pore spectra of both these materials are shown in Figs 3 and 4. After producing only a small quantity of this material, Morganite Carbon Ltd., stated that because of difficulties in achieving a sufficiently low permeability aggravated by heavy losses during processing it was necessary to further modify the manufacturing conditions. This further development led to the grade designated CYX 165 which is purchased by the Dragon Project to a specification which is summarised in Table 1. We believe CYX 165 to be essentially similar to the original CY 119.

2.2.2 Graphitisation and Purification

With the decision to purchase baked material first in the form of CY 119, then as CYX 150 and finally as CYX 165 the Project undertook the responsibility of graphitising and, if necessary, purifying. Trial graphitising runs were carried out by three companies:-

Skandinaviska Grafitindustri Aktiebolaget, Trollhättan, Sweden.
Société Le Carbone - Lorraine, Paris, France.
Compagnie Pechiney, Haute Savoie, France.

Measurement undertaken both at AERE, Harwell and by Compagnie Pechiney, France, showed that the shrinkage occurring during the graphitisation of CY 119 was important, (see Fig. 5), but not such as to require special control of the heating rate during treatment.

The results of the graphitisation undertaken in Sweden indicated a tendency to homogenise the impurity distribution between different rods

Table 1

Summary of Specification for the Supply of Baked Carbon Rods Grade CYX 165

Test Property	3¼" diameter rod	2" diameter rod	1½" diameter rod	1" diameter rod
Minimum length (in)	79	49	48	48
Diameter (in)	3.43-3.57	2.04-2.17	1.56-1.[illegible]	1.10-1.18
Maximum bow (in)	0.188	0.126	0.126	0.126
External cracks	None	None	None	None
Permeability coefficient (cm^2/s)	1-3	1-3	Not applicable	Not applicable
Porosity (%)	14.0-17.5	13.0-16.0	do	do
Apparent density (g/cm^3)	Not applicable	Not applicable	1.60-1.70	1.60-1.70
Spurious impurities				
- on 12" long sample radiograph, no sample to contain more than the following amounts of high density areas				
0.3-0.5 mm dia	40	10)	Not applicable	Not applicable
0.5-1.0 mm dia	5	2)		
greater than 1.0 mm dia	Nil	Nil		

but did not bring any important decrease in impurity levels:-

	Ash	Iron	Vanadium	Silicon	Calcium	Boron	
Rod 1	1000	138	9	150	280	8	
Rod 2	1080	89	18	175	300	6	Contents in ppm
Rod 3	970	41	9	100	250	7	

Sufficient material was graphitised in Sweden to allow work within the Project requiring fuel element components to continue (Dummy Mark I and II and Seven Element Rig). Some measurements made before and after graphitisation are reported in Table 2.

It was clear however that to satisfy the purity requirements for the Reactor Experiment itself, it would be necessary to purify the material during graphitisation.

In June 1960 the Project had been informed that Société Le Carbone - Lorraine, France, had developed a new graphitising process and that they were interested in graphitising and/or purifying Dragon material. Accordingly a small number of full size rods of the Morgan grade CY 119 was sent for treatment. A summary of the results obtained is given in Table 3. These control tests were carried out on small samples cut from the ends of rods and may not, therefore, by fully representative.

X-ray diffraction measurements carried out by **Le Carbone - Lorraine** indicated that the CY 119 rods supplied were either graphitised or, more likely, contained a graphite component. A second component (possibly carbon black) did show slight increase of crystallinity during heat treatment. It was suggested by Le Carbone - Lorraine that the existence of graphite in the baked material was the cause of incomplete purification, samples of their own material processed between two of the CY 119 rods having yielded a total ash content of 6-10 ppm with a boron content less than 1 ppm.

A preliminary attempt by Compagnie Pechiney, France showed that Morgan EYX 60 graphite was able to be purified by the industrial process used by this firm. The ash and boron contents were substantially reduced:-

	Ash	Boron	Iron	Vanadium	
Sample 1	176	0.15	15	47	
Sample 2	186	0.15	10	52	Contents in ppm
c.f. typical graphitised unpurified	1000	7	90	12	

Purification of the rods, $3\frac{1}{4}$" dia, 79" long, destined for fuel tubes posed serious problems. The ratio of diameter to length is quite different from normal graphite electrode production and hence suitable furnaces are not normally available. Additionally the total quantity of rods required to be processed is small as also are the numbers available at any one time. Thus the Project required a manufacture who was in steady production of nuclear graphite, who operated a purification process and who was capable and willing to accept small batches of material occupying much less than the total volume of a furnace.

Table 2

Graphite for Dummy Mk II Fuel Elements - Test Results on
Morgan CY 119 and CYX 150 Graphitised by Skandinaviska
Grafitindustri Aktiebolaget

1. Results on CY 119 Samples (mean and spread on 5 samples)

	Length (mm)	Diameter (mm)	Weight (kg)	Apparent Density (g/cm^3)	Resistivity (microhm-cm)	Overall Bow (mm)
Before graphitising	2071.5 2068-2078	88.96 88.6-89.35	20.87 20.71-21.19	1.616 1.609-1.624	2285 2197-2341	3.2 2-4
After graphitising	2034-9 2029.5-2041.5	86.38 86.0-86.9	20.56 20.38-20.80	1.720 1.703-1.737	2147 2039-2236	4.2 3-5

2. Results on CYX 150 Samples (mean and spread on 15 samples)

	Length (mm)	Diameter (mm)	Weight (kg)	Apparent Density (g/cm^3)	Resistivity (microhm-cm)	Overall Bow (mm)
Before graphitising	2085.7 2055-2128.5	88.89 88.3-89.45	21.27 21.03-21.70	1.643 1.621-1.664	2308 2176-2481	2.7 1-5
After graphitising	2053.1 2021.5-2098.5	86.31 85.7-87.2	20.90 20.58-21.40	1.740 1.696-1.770	1947 1836-2244	4.0 1-6

Table 3

Graphitisation and Purification Trials by Société Le Carbone - Lorraine, France

Property	Test Results		
	As received (as Morgan CY 119)	After graphitising	After purification and graphitising
Apparent Density (g/cm^3)	1.62-1.64	1.66-1.69	1.73-1.74
Resistivity $\perp$ (ohm-cm)	0.00400	0.00400	0.00360
Breaking Strength (Kg/cm^2)	300-360	210-260	210-250
Hardness (Shore Scleroscope)	49-53	40-45	39-42
Ash	0.1-0.2%	200-350 ppm	30-60 ppm
Boron (ppm)			1-2

At the end of 1961, when initial deliveries of CYX 165 for the First Charge of the Reactor Experiment commenced, the only known manufacturer who could satisfy the Project's requirements was Compagnie Pechiney, France.

A trial purification of a mixed batch of CYX 150 and CYX 165 rods showed that the boron content could be reduced to 0.11-0.50 ppm and the ash content to between 56 and 200 ppm (see Tables 4 and 5). Subsequent purification runs have been carried out bimonthly and results to date are given in Tables 6-9. In addition to the properties listed in these tables, samples are taken from each purification run for the determination of pore spectrum and also thermal neutron adsorption cross-section in the French pile oscillator ZOE. The cross-section results to date given in Table 10, indicate that values of about 3.85 mb have been attained. Typical pore spectra are given in Fig. 6.

A possible limitation of the present method of purification is that the vanadium content is increased from about 20 ppm to 50 ppm. The increase appears to correlate with an increased tendency for the graphite to exhibit pitting corrosion [4] and it has stimulated work within the Project on the purification of graphite with halogen gases [5]. Similar work at Hanford has recently been reported [6].

2.2.3 Grading System for EYX 60 and its Variants

As it will be appreciated from the events described above, a situation developed in which a number of grades of graphite of widely differing purity were being used by the Project. To avoid confusion the following grading system was introduced:-

Type of Material	DRAGON Grade No.
Morgan CY 119 graphitised by Morganite Carbon Ltd. (M), i.e. EYX 60	1
Morgan CY 119 graphitised by Skandinaviska Grafitindustri (SGA)	2
Morgan CY 119 graphitised and purified by Compagnie Pechiney (P)	3
Morgan CYX 150 graphitised at M (i.e. EYX 85)	4
Morgan CYX 150 graphitised at SGA	5
Morgan CYX 150 graphitised and purified at P	6
Morgan CYX 165 graphitised at M	7
Morgan CYX 165 graphitised at SGA	8
Morgan CYX 165 graphitised and purified at P	9

2.2.4 Possible Composition of Dragon Grade 1 Graphite

Because the Project has carried out a considerable amount of work in the field of fine grain graphite and also because it has test data on CY 119 before and after graphitising, it has been possible to make deductions concerning the composition of Dragon Grade 1. The

Table 4

Results of Purification of First Shipment of Live Fuel Element Graphite

(comprising both Grade-6 and Grade-9 Graphite)

Measurements on Whole Bars

	Before Graphitisation and Purification			After Graphitisation and Purification			Change After Graphitisation and Purification		
	A	B	C	A	B	C	A	B	C
Diameter (mm)									
mean	89.4	89.1	54.0	87.2	86.7	52.5	-2.2	-2.4	-1.5
spread	88.3-90.3	88.6-89.4	53.6-54.6	86.1-87.9	86.1-87.3	52.0-53.0			
Length (mm)									
mean	2098	2089	1233	2072	2058	1211	-26	-31	-30
spread	2081-2121	2078-2106	1228-1237	2053-2092	2048-2074	1204-1216			
Resistivity (micro ohm- cm)									
mean	2298	2356	2240	2149	2372	1944	-149	+16	-296
spread	2021-2498	2168-2630	1986-2576	1851-2400	2125-2663	1712-2203			
Bow: arc to chord (mm)									
mean	1.24	0.38	1.03	2.63	1.85	1.86	+1.39	+1.47	+0.83
spread	0.6-2.5	0.3-1.8	0.3-2.4	0.7-7.5	0.5-4.4	0.3-3.6			
Apparent Density (g/cm^3)									
mean	1.632	1.618	1.662	1.711	1.707	1.753	+0.079	+0.089	+0.091
spread	1.61-1.68	1.60-1.64	1.63-1.70	1.68-1.77	1.68-1.74	1.71-1.79			

A = bars of Dragon Grade-6, 3¼" diameter, 79" long, results on 11 samples.
B = bars of Dragon Grade-9, 3¼" diameter, 79" long, results on 11 samples.
C = bars of Dragon Grade-6, 2" diameter, 48" long, results on 36 samples.

Table 5

Results of Purification of First Shipment of Live Fuel Element Graphite
(comprising both Grade-6 and Grade-9 Graphite)

Summary of Test Results on Sample Bars After Treatment

Material	Dragon Grade-6	Dragon Grade-6	Dragon Grade-9	No. of Samples	No. of Measurements per sample
Bar dimensions					
Diameter	2"	$3\frac{1}{4}$"	$3\frac{1}{4}$"		
Length	48"	79"	79"		
Ash (ppm)				6	3
mean	101	141	161		
spread	56-220	113-190	110-200		
Boron (ppm) by chemical analysis				6	1-3
mean	0.20	0.40	0.40		
spread	0.11-0.46	0.19-0.52	0.23-0.50		
Mean thermal expansion coefficient ($\times 10^{-6}/^{\circ}C$) over range 0-500°C				6	2
∥	2.03	2.09	2.29		
⊥	4.80	4.92	4.82		
Mean Young's modulus (kg/mm^2) at room temperature				6	2
∥	1347	1623	1454		
⊥	572	661	670		
Mean electrical resistivity (microhm - cm) at room temperature				6	2
∥	1942	1920	2126		
⊥	3823	3825	4005		

∥ represents a measurement made on a sample cut parallel to the axis of extrusion
⊥ represents a measurement made on a sample cut perpendicular to the axis of extrusion

Table 6

Results of Purification of Second Shipment of Live Fuel Element Graphite

(Dragon Grade-9)

Measurements on Whole Bars

Rod Size	State	Diameter (mm)	Length (mm)	Apparent density (g/cm^3)	Electrical resistivity (microhm-cm)	Bow: arc to chord (mm)
3¼" dia 79" long	As received	89.3 89.0-89.9	2045 2018-2062	1.614 1.59-1.63	2421 2240-2605	1.5 0.3-3.6
	After graphitisation and purification	86.7 86.4-87.2	2011 1999-2122	1.706 1.69-1.73	2287 2111-2491	2.4 1.0-4.7
2" dia 49" long	As received	54.4 54.1-54.8	1251 1249-1253	1.632 1.60-1.66	2286 2030-2665	1.8 0.9-3.4
	After graphitisation and purification	52.7 52.5-53.1	1228 1227-1231	1.727 1.69-1.79	2157 1948-2596	1.5 0.6-3.2
1½" dia 48" long	As received	40.8	1251	1.661	2103	1.6
	After graphitisation and purification	39.5	1228	1.749	2019	1.9
1" dia 48" long	As received	29.1	1232	1.677	2022	1.6
	After graphitisation and purification	28.2	1210	1.753	1987	2.4

NOTE: The values quoted above are the mean of the following numbers of rods:

3¼" dia	16	1½" dia	10
2" dia	36	1" dia	24

Table 7

Results of Purification of Second Shipment of Live Fuel Element Graphite

Summary of Test Results on Sample Bars after Treatment

Material	Dragon Grade-9			
Bar dimensions - diameter	1"	1½"	2"	3¼"
length	48"	48"	49"	79"
Ash (ppm)				
mean	145	134	114	132
spread	133-160	113-150	93-133	120-140
No. of samples	2	2	6	2
No. of measurements/sample	3	3	3	3
Boron by chemical analysis (ppm)				
mean	0.19	0.21	0.16	0.23
spread	0.13-0.26	0.14-0.30	0.10-0.31	0.14-0.32
No. of samples	2	2	6	2
No. of measurements/sample	1 & 3	1 & 3	1 (3 in one case)	1 & 3
Mean thermal expansion coefficient ($\times 10^{-6}/^{\circ}C$) over range 0-500°C				
∥	2.18	2.22	2.17	2.30
⊥	Not determined	Not determined	4.88	4.87
Mean Young's modulus (kg/mm^2) at room temperature				
∥	1590	1419	1464	1376
⊥	Not determined	Not determined	655	680
Mean electrical resistivity (microhm-cm) at room temperature				
∥	1777	1921	1921	2116
⊥	Not determined	Not determined	3657	3711

∥ represents a measurement made on a sample cut parallel to the axis of extrusion.

⊥ represents a measurement made on a sample cut perpendicular to the axis of extrusion.

Table 8

Results of Purification of Fourth Shipment of Live Fuel Element Graphite

Comprising Dragon Grade 9

Measurements on Whole Bars

	Before Graphitisation and Purification		After Graphitisation and Purification		Change After Graphitisation and Purification	
	A	B	A	B	A	B
Diameter (mm)						
mean	89.5	29.2	86.7	28.3		
spread	88.9-90.4	28.8-29.6	86.2-87.8	28.1-28.4	-2.8	-0.9
Length (mm)						
mean	2030	1225	1992	1202		
spread	2020-2040	1225-1226	1982-2003	1201-1204	-38	-23
Resistivity (micro-ohm-cm)						
mean	2374	2204	2114	2013		
spread	2182-2698	2111-2326	1932-2412	1931-2086	-260	-191
Bow. arc to chord (mm)						
mean	1.2	1.1	4.7	1.9		
spread	0.9-2.0	0.7-1.5	2.0-8.3	1.4-2.7	+3.5	+0.8
Apparent Density (g/cm^3)						
mean	1.569	1.649	1.718	1.741		
spread	1.555-1.584	1.611-1.682	1.686-1.735	1.725-1.747	+0.149	+0.092

A = Bars of Dragon Grade 9 $3\frac{1}{4}$" diameter 79" long, results on 14 specimens.

B = Bars of Dragon Grade 9 1" diameter 48" long, results on 12 specimens.

Table 9

Results of Purification of Fourth Shipment of Live Fuel Element Graphite

Summary of Test Results on Sample Bars after Treatment

Material	Dragon Grade 9	
Bar dimensions - diameter length	1" O.D. 48" long	3¼" O.D. 79" long
Ash (ppm)		
mean	220	243
spread	213-240	203-300
No. of samples	2	4
No. of measurements/sample	3	3
Boron by spectrographic analysis (ppm)		
mean	0.21	0.27
spread	0.16-0.26	>0.43-0.12
No. of samples	2	4
No. of measurements/sample	6	18
Mean thermal expansion coefficient ($\times 10^{-6}/^{\circ}C$) over range 0-500°C		
∥	2.13	2.19
⊥	not determined	2.53 ?
Mean Young's modulus (Kg/mm^2) at room temperature		
∥	1563	1294
⊥	not determined	611
Mean electrical resistivity (microhm-cm) at room temperature		
∥	1749	2021
⊥	not determined	4047

∥ represents a measurement made on a sample cut parallel to the axis of extrusion.

⊥ represents a measurement made on a sample cut perpendicular to the axis of extrusion.

Table 10

Thermal Neutron Absorption Cross-Section Measurements on Graphites Purified Industrially by Compagnie Pechiney

Sample	Apparent Density	Thermal Neutron Absorption Cross-Section (measured in ZOE-(mb))	
1st (trial) batch			
- sample 1	1.75	3.78	± 0.05
- sample 2	1.73	3.86	
2nd batch	1.75	3.89	
3rd batch	1.73	3.82	
4th batch	1.74	3.89	

important points to note are:-

(i) The X-ray diffraction data indicate that CY 119 contains graphite while still only "baked". Furthermore it also contains a poorly crystalline component at the baked stage which does not graphitise significantly.

(ii) The electrical resistivity is relatively low at the baked stage but hardly changes on graphitisation (see Tables 2 and 3).

(iii) The room temperature thermal conductivity is relatively low (0.16-0.17 cal/cm/°C/sec).

(iv) The pore spectrum commences near 1 micron.

(v) The maximum particle size visible in photomicrographs is about 150 micron diameter, such particles being highly striated.

These observations suggest that Dragon Grade 1 has a graphite - black filler with a fairly high loading of carbon black (graphite to black ratio probably near 2:1). The graphite powder is likely to be through 200 mesh. The comparatively low apparent density of Grade 1 (1.67-1.70 g/cm^3) probably results from the use of a binder with a lower coking yield than pitch (e.g. a pitch/tar mixture) possibly allied to a higher binder content than, for example, HX 10 [7]. This higher binder content could have arisen from the use of carbon black finer than the medium thermal black used in HX 10.

2.3 Machining

The original procedures for the machining of the fuel element graphite were worked out by the U.K.A.E.A. in their Graphite Workshop at Bracknell.

When larger numbers of components were required, it was necessary to promote an industrial firm into this field. It was eventually decided, after competitive tendering, to place the machining of the first charge of the Reactor Experiment with the Graviner Manufacturing Company Ltd., Gosport, England.

The sequence of operations used by this firm when machining the fuel tube is given in Table 11. The main innovation (as compared with the U.K.A.E.A. procedure at Bracknell) is the use of a multiple broaching tool (see Fig. 7).

2.4 Impregnation

In order to satisfy the activity level requirements in the primary circuit it is necessary to achieve diffusion coefficients of less than 10^{-6} cm^2/sec for fission products moving through the fuel tube. This value is ultimately fixed by the leak rate of the primary circuit and by limitations involving fission product deposition within the circuit. In addition, in making design calculations it is always assumed that no decay in fission product activity occurs during transit through the fuel tube.

Table 11

Machining Operations for Fuel Tube
To Drawing CD 33990

Operation Number	Operation
1.	Rough turn rods to 3" diameter.
2.	Bore 1.750" and 1.255" diameters on boring rig, holding with 3 jaw chuck and steady mounted on table.
3.	Inspect.
4.	Drill 7/16" diameter true to bore.
5.	Inspect.
6.	Turn outside diameter of tube to 2.750" diameter, turn 2.299" diameter and 5° angle.
7.	Inspect.
8.	Form hexagonal outer profile using broaching machine* (see Fig. 7).
9.	Inspect.
10.	Face, turn thread diameter and undercut. Form angles and cut thread, drill, ream and undercut bores. Tap 9/16" B.S.F.
11.	Inspect.
12.	Face to length. Form counterbore, angles and undercut. Cut thread.
13.	Inspect.

*Patent applied for - Graviner Mfg. Co. Ltd.

For the highly active noble gas fission products which move by gaseous diffusion through the pore structure it turns out that this leads to a permeability requirement of approximately 10^{-5} cm^2/sec if this is achieved by the impregnation of an initially fine pored material such as the EY 9 family, (see Section 3.1).

Laboratory scale work on the impregnation of Morgan EY 9 graphite using furfuryl alcohol was carried out by the Royal Aircraft Establishment, Farnborough, U.K. and by the Hawker Siddeley Nuclear Power Co. Ltd., U.K., prior to the signing of the Dragon Project Agreement. Development of the furfuryl alcohol process continued until early 1961. It then became necessary to finalise the process specifications in order to ensure a supply of fuel element components for the Reactor Experiment particularly through the need to supply material for testing which was representative of the type which would constitute the initial charge.

Difficulties on this work associated with the variable nature of the pore structure in EY 9 graphites were discussed during the Dragon Project Graphite Symposium in November 1959 [1]. These difficulties continued even with EYX 60 graphite in which a special attempt was made by Morganite Carbon Ltd., to achieve the pore spectrum which was apparantly best suited for impregnation with furfuryl alcohol. The work on impregnation which was carried out during 1960 has been reported and impregnation processes have been outlined for the fuel element components which lead to the most acceptable results in terms of achieving the desired reduction in permeability [8]. In the case of the fuel tubes the process chosen involves forcing the furfuryl alcohol impregnant through the fuel tube by the application of pressure to the resin contained within the tube. With the development of fission product retaining fuels and the consequent elimination of the fuel box from the current design of the fuel element, subsequent work has centered around this process.

In an attempt to obtain a more uniform deposition of impregnant coke through the wall of the fuel tube, experiments were carried out using different methods of impregnation. In particular many trials were carried out in which impregnation through the outer or inner faces of the fuel tube was performed in alternate impregnations. Some results are given in Table 12 which show that in every case spalling occurred on subsequent heat treatment.

It was therefore decided to finalise on a process of impregnation through the inner face of the fuel tube and a complete charge for the Seven Element Rig was processed in this way. The results of this work are given in Table 13. After an initial pressure test to determine the starting permeability (during which it was found that some fuel tubes burst due to the presence of internal defects) each tube received two impregnation treatments. It became evident that since in many cases the required permeability reduction was not achieved in two impregnations, any process specification for the Reactor Charge itself would have to make provision for re-impregnation. The experiment was however, considered to have produced a satisfactory result particularly since no losses occurred due to spalling during baking. Subsequently the complete charge was vacuum degassed at 1500°C in an 800 KVA furnace which was available at that time at the Hawker Siddeley Nuclear Power Company's Plant and no losses occurred due to spalling during this operation. Fig. 8 shows the fuel tubes assembled into the graphite loading stand prior to insertion into the degassing furnace.

Table 12

Trial Impregnation of Dragon Fuel Tubes

Number	1	2	3	4	5	6	7	8	9	26	43	48	59	54
Wt g	4835	4945	4990	4875	4870	4785	4940	4942	4785	4958	4898	4924	4880	4936
K cm^2/sec (p_m = 52 psi	4.6 x 10^{-2}	2.8 x 10^{-2}	4.6 x 10^{-2}	Burst under internal pressure of 90 psig.	4.6 x 10^{-2}	4.6 x 10^{-2}	4.6 x 10^{-2}	2.8 x 10^{-2}	4.6 x 10^{-2}	2.3 x 10^{-2}	3.1 x 10^{-2}	2.8 x 10^{-2}	4.4 x 10^{-2}	2.0 x 10^{-2}
Type of impregnation	Internal Pressure	Internal Pressure	Internal Pressure		Total Immersion	Total Immersion	Total Immersion	Total Immersion	Total Immersion	Internal Pressure	Internal Pressure	Internal Pressure	Internal Pressure	Internal Pressure
Viscosity of impregnant cp	80	80	350		10	10	10	10	10	10	10	10	10	10
Catalyst	2%	by weight of phosphoric acid specific gravity 1.75 g/cc →												
Impregnation Pressure psig	100	100	100	-	nil	nil	nil	nil	nil	100	100	100	100	100
Impregnation Time	100 m	90 m	19 hr	-	16 hr	16 hr	23 hr	18 hr	16 hr	30 m	30 m	30 m	30 m	30 m
Wt after impregnation g	5255	5353	5640	-	5212	5163	5296	5300	5154	5255	5249	5305	5253	5295
Wt % impregnant pick-up	8.7	8.3	15.3	-	7.0	7.9	7.2	7.3	7.7	6.0	7.2	8.0	7.6	7.3
Time of air airing	73 hr	73 hr	24 hr	-	4 days	66 hr	24 hr	48 hr	72 hr	96 hr	46 hr	48 hr	120 hr	120 hr
% wt loss of imp. on air airing	1.2	1.9	-	-	1.5	1.6	0.8	1.5	2.4	-	-	-	-	-
Wt after carbonizing to 1000°C	5045	5147	5200	-	5035	4968	5115	5119	4960	5093	5066	5120	5070	5125
Yield of carbon from resin %	49.9	48.5	41.4	-	48.3	51.0	49.0	49.5	47.5	45.0	47.0	45.0	51.0	49.0
K cm^2/sec (p_m = 52 psi)	4.0 x 10^{-6}	2.5 x 10^{-6}	1.9 x 10^{-4}	-	2.5 x 10^{-3}	4.6 x 10^{-4}	4.5 x 10^{-4}	1.3 x 10^{-4}	2.7 x 10^{-4}	5.6 x 10^{-3}	8.8 x 10^{-3}	3.2 x 10^{-4}	2.1 x 10^{-4}	4.2 x 10^{-3}
Pick up of carbon % wt	4.15	4.10	6.4	-	3.4	4.0	3.5	3.6	3.7	2.7	3.4	3.6	3.9	3.8
2nd Impregnation : type	Internal Pressure	Internal Soak	Internal Pressure	-	Internal Pressure	Internal Pressure	Total Immersion	Inside Evacuated	Internal Pressure	Inside Evacuated	Inside Evacuated	Inside Evacuated	Inside Evacuated	Internal Pressure
Viscosity of impregnant	10	10	10	-	10	10	10	10	10	10	10	10	10	10
Catalyst	2%	by weight of phospheric acid specific gravity 1.75 g/cc →												
Impregnation Pressure psig	100	nil	100	-	100	100	nil	15	100	15	15	15	15	100
Impregnation Time	7 hr	7 hr	7 hr	-	7 hr	5 hr	47 hr	18 hr	13 hr	3 hr	3 hr	3 hr	3 hr	24 hr
Wt after impregnation	5064	5164	5620	-	5105	5002	5225	5259	4977	5298	5345	5175	5120	5135
Wt % impregnant pick-up	0.38	0.38	1.15	-	1.4	0.69	2.14	0.77	0.34	4.0	5.5	1.4	0.99	0.19
Wt after carbonizing to 1000°C	5045	5150	5220		5070	4972	5150	S	4965	S	S	S	S	5122
Total wt % carbon pick-up	4.15	4.15	6.7		4.1	3.95	4.25	-	3.8	-	-	-	-	3.8
K cm^2/sec (p_m = 7.5 psi)	1.6 x 10^{-6}	2.6 x 10^{-7}	7.10^{-7}		1.10^{-5}	1.2 x 10^{-7}	1.3 x 10^{-7} S	-	1.6 x 10^{-6}	-	-	-	-	2.9 x 10^{-7}

Notes (i) S indicates that spalling occurred during carbonization.

(ii) Carbonization rates were 5°C/hr in the range 200-550°C and 30°C/hr from 550-1000°C except for the 1st cycles on tubes 26, 43, 48, 59 and 54 which were heated at 15°C/hr.

(iii) All final permeability figures were determined using air as the test medium. Nitrogen was the test gas in measurements made before and after the 1st impregnation

Table 13

Impregnation of Fuel Tubes for the Second Charge of the Seven Element Rig

INITIAL DATA			FIRST IMPREGNATION					SECOND IMPREGNATION				
No.	Wt. in grms	K cm^2/sec @ pm = 3.6×10^6 d/cm^2 (Nitrogen)	Resin Viscosity cp	Penetration time in mins	Resin uptake % by weight	Carbon gain % by weight	K cm^2/sec @ 3.6×10^6 d/cm (Nitrogen)	Resin Viscosity cp	Resin uptake wt. %	Total carbon gain wt. %	K cm^2/sec @ pm = 3.6×10^6 d/cm^2 (Nitrogen)	K cm^2/sec @ pm = 0.5×10^6 d/cm^2 (vac. test) (Air)
3	4890	4.6×10^{-2}	350	16 hours	20.0	6.3	1.9×10^{-4}	25	1.0	5.7	$< 10^{-5}$	7.0×10^{-7}
10	4895	2.5×10^{-2}	80	40	[illegible]	3.7	1.5×10^{-3}	25	1.9	4.5	2.6×10^{-4}	
11	4812	7.0×10^{-2}	80	[illegible]	8.9	4.1	[illegible]	25	[illegible]	5.3	0.15×10^{-4}	3.5×10^{-6}
12	4918	[illegible]	80	75	7.8	3.7	0.4×10^{-3}	25	0.55	5.9	0.8×10^{-4}	
13	4853	7.0×10^{-2}	80	55	8.7	3.7	28.0×10^{-3}	25	5.3	6.0	3.5×10^{-4}	
14	4860	4.6×10^{-2}	80	35	8.7	4.0	6.0×10^{-3}	25	4.1	5.9	2.2×10^{-4}	
15	4732	7.0×10^{-2}	80	30	9.4	4.3	10.0×10^{-3}	25	4.3	5.1	1.7×10^{-4}	
16	4920	3.5×10^{-2}	80	65	8.9	4.0	1.7×10^{-3}	25	1.5	4.6	0.5×10^{-4}	
17	4827	7.0×10^{-2}	80	40	9.8	4.2	15.0×10^{-3}	25	5.6	6.7	0.1×10^{-4}	[illegible]
18	4839	4.6×10^{-2}	80	50	[illegible]	3.7	10.0×10^{-3}	25	4.4	5.7	0.4×10^{-4}	4.9×10^{-6}
19	4831	7.0×10^{-2}	80	30	[illegible]	3.7	10.0×10^{-3}	25	5.5	6.0	0.3×10^{-4}	
20	4944	1.5×10^{-2}	120	165	7.7	3.7	1.6×10^{-4}	25	0.61	4.0	$< 10^{-5}$	4.6×10^{-7}
21	4912	1.9×10^{-2}	120	105	8.5	3.7	1.1×10^{-4}	25	0.41	4.0	$< 10^{-5}$	[illegible]
22	4839	4.6×10^{-2}	120	90	9.7	4.6	17.0×10^{-4}	25	2.5	5.9	$< 10^{-5}$	3.2×10^{-6}
23	4899	2.8×10^{-2}	120	120	8.5	4.0	0.1×10^{-4}	25	0.41	4.3	$< 10^{-5}$	5.0×10^{-7}
24	4919	4.6×10^{-2}	120	75	9.3	4.3	5.1×10^{-4}	25	0.82	4.8	$< 10^{-5}$	1.0×10^{-6}
25	4846	7.0×10^{-2}	120	60	10.0	4.6	17.0×10^{-4}	25	2.0	5.7	$< 10^{-5}$	3.9×10^{-6}
26	4858	7.0×10^{-2}	120	50	9.8	4.6	21.0×10^{-4}	25	2.3	5.8	$< 10^{-5}$	2.6×10^{-6}
27	4841	4.6×10^{-2}	120	45	9.0	4.1	17.0×10^{-4}	25	1.7	5.2	$< 10^{-5}$	1.6×10^{-6}
28	4878	7.0×10^{-2}	120	35	9.7	4.5	43.0×10^{-4}	25	3.3	6.2	3.5×10^{-5}	
29	4932	1.9×10^{-2}	120	105	7.7	3.7	1.3×10^{-4}	25	0.51	4.0	$< 10^{-5}$	1.2×10^{-6}
30	4927	2.8×10^{-2}	120	90	8.3	3.9	2.5×10^{-4}	25	0.59	4.2	$< 10^{-5}$	1.2×10^{-6}
31	4842	7.0×10^{-2}	120	60	9.8	4.6	31.0×10^{-4}	25	3.9	6.5	$< 10^{-5}$	3.3×10^{-6}
32	4881	3.5×10^{-2}	120	34	9.7	4.7	4.9×10^{-4}	25	1.2	5.2	$< 10^{-5}$	2.6×10^{-6}
33	4895	3.5×10^{-2}	120	75	9.3	4.5	3.5×10^{-4}	25	0.84	4.9	$< 10^{-5}$	9.0×10^{-7}
34	4899	4.6×10^{-2}	120	105	9.0	4.3	18.0×10^{-4}	25	1.9	5.2	$< 10^{-5}$	4.4×10^{-6}
35	4815	7.0×10^{-2}	120	75	10.5	5.3	9.3×10^{-4}	25	2.1	7.2	$< 10^{-5}$	1.8×10^{-6}
36	4838	7.0×10^{-2}	120	60	9.7	4.7	18.0×10^{-4}	25	2.3	5.8	$< 10^{-5}$	1.5×10^{-6}
37	4874	4.6×10^{-2}	120	45	8.5	3.9	18.0×10^{-4}	25	3.2	5.5	7.7×10^{-5}	
39	4880	2.8×10^{-2}	120	165	8.8	4.3	2.8×10^{-4}	25	0.72	4.8	$< 10^{-5}$	7.9×10^{-7}
40	4943	2.0×10^{-2}	120	165	7.7	3.7	2.5×10^{-4}	25	0.61	4.0	$< 10^{-5}$	2.2×10^{-6}

Table 13 (continued)

Sheet 2

	INITIAL DATA			FIRST IMPREGNATION					SECOND IMPREGNATION				
L.P. No.	No.	Wt. in grms	K cm^2/sec @ pm = 3.6×10^6 d/cm^2 (Nitrogen)	Resin Viscosity cp	Penetration time in mins	Resin uptake % by weight	Carbon gain % by weight	K cm^2/sec @ 3.6×10^{-6} d/cm (Nitrogen)	Resin Viscosity cp	Resin uptake wt. %	Total carbon gain weight %	K cm^2/sec @ pm = 3.6×10^{-6} d/cm^2 (Nitrogen)	K cm^2/sec @ pm = 0.5×10^{-6} d/cm (vac. test) (Air)
	41	4885	2.9×10^{-2}	80	105	9.0	4.7	8.5×10^{-5}	Fresh F/A	0.58	4.9	$< 10^{-5}$	1.9×10^{-6}
	42	4869	3.5×10^{-2}	80	135	12.5	7.0	2.8×10^{-4}	"	0.19	6.2	1.15×10^{-5}	
	43	4812	5.8×10^{-2}	80	90	9.2	4.6	2.3×10^{-3}	"	1.65	5.2	2.3×10^{-4}	
	44	4877	3.5×10^{-2}	80	150	10.2	5.4	3.8×10^{-4}	"	1.00	5.9	1.55×10^{-5}	
	45	4932	2.9×10^{-2}	80	180	8.2	4.1	1.5×10^{-4}	"	0.27	4.2	$< 10^{-5}$	4.4×10^{-6}
	46	4792	7.0×10^{-2}	80	30	10.4	4.9	9.8×10^{-3}	"	4.20	7.0	1.0×10^{-3}	
	47	4996	1.7×10^{-2}	80	150	7.9	3.9	6.5×10^{-5}	"	0.17	3.9	$< 10^{-5}$	3.2×10^{-6}
	48	4887	5.8×10^{-2}	80	60	9.1	4.5	1.4×10^{-3}	"	0.94	4.7	$< 10^{-5}$	
	49	4815	7.0×10^{-2}	80	105	9.0	4.5	3.8×10^{-4}	"	2.40	5.7	8.3×10^{-5}	
	50	4867	7.0×10^{-2}	80	90	14.5	8.2	1.6×10^{-3}	"	2.10	8.8	2.1×10^{-4}	
	51	4843	5.8×10^{-2}	80	105	15.7	8.3	1.0×10^{-2}	"	2.90	9.7	1.0×10^{-3}	
	52	4875	7.0×10^{-2}	80	120	10.2	5.6	1.8×10^{-3}	"	0.78	5.6	6.6×10^{-5}	
	53	4832	FAILED TO HOLD INITIAL PRESSURE - BURST AT 50 P.S.I.										
	54	4877	5.8×10^{-2}	80	90	8.9	4.4	1.7×10^{-3}	"	1.60	7.1	3.9×10^{-5}	
	55	4947	2.0×10^{-2}	80	135	8.5	4.5	2.4×10^{-4}	"	0.85	4.6	$< 10^{-5}$	1.0×10^{-6}
	56	4820	5.8×10^{-2}	80	105	12.9	7.3	7.0×10^{-4}	"	0.98	7.3	5.7×10^{-5}	
	57	4940	1.7×10^{-2}	80	90	7.3	3.4	4.6×10^{-4}	"	0.76	3.8	3.0×10^{-5}	
	58	4893	5.8×10^{-2}	80	70	11.5	6.2	7.0×10^{-4}	"	2.30	7.0	1.0×10^{-5}	
LP 11	59	4992	3.5×10^{-3}	80	90	8.1	3.1	2.5×10^{-3}	"	1.00	3.1	$< 10^{-5}$	1.3×10^{-6}
	60	5044	2.8×10^{-2}	80	120	7.9	3.1	9.2×10^{-4}	"	0.52	3.1	$< 10^{-5}$	4.1×10^{-6}
LP 8	61	5035	2.8×10^{-2}	80	90	7.6	3.0	1.7×10^{-3}	"	2.00	3.6	1.0×10^{-3}	
	62	5027	2.8×10^{-2}	80	90	7.4	3.1	3.5×10^{-3}	"	1.30	3.3	5.3×10^{-4}	
9295 LP13	63	5029	2.8×10^{-2}	80	115	7.5	3.0	3.5×10^{-3}	"	1.80	3.6	$< 10^{-5}$	2.6×10^{-6}
LP 12	64	5000	3.5×10^{-2}	80	55	7.0	2.5	4.8×10^{-3}	"	3.00	3.6	$< 10^{-5}$	2.3×10^{-6}
LP 13	65	5025	2.8×10^{-2}	80	60	7.3	2.6	3.1×10^{-3}	"	2.30	3.4	$< 10^{-5}$	3.2×10^{-7}
LP 12	66	5005	2.8×10^{-2}	80	100	7.8	3.1	6.2×10^{-4}	"	2.30	3.1	$< 10^{-5}$	4.0×10^{-6}
LP 13	67	5030	2.8×10^{-2}	80	70	8.5	3.3	2.6×10^{-3}	"	1.80	3.8	BROKEN	
LP 9	68	5053	2.9×10^{-2}	80	105	8.2	3.3	8.8×10^{-4}	Fresh F/A	0.70	3.4	$< 10^{-5}$	4.6×10^{-7}
	69	4990	5.8×10^{-2}	80	120	8.9	3.1	5.3×10^{-4}	"	0.89	3.4	2.2×10^{-5}	
	70	4805	FAILED TO HOLD INITIAL PRESSURE - BURST AT 70 P.S.I.										

Table 13 (continued)

	INITIAL DATA			FIRST IMPREGNATION					SECOND IMPREGNATION			
L.P. No.	No.	Wt. in grms	K cm^2/sec @ $pm_2 = 3.6 \times 10^{-6}$ d/cm^2 (Nitrogen)	Resin Viscosity cp	Penetration time in mins	Resin uptake % by weight	Carbon gain % by weight	K cm^2/sec @ 3.6×10^{-6} d/cm (Nitrogen)	Resin Viscosity cp	Resin uptake wt. %	Total Carbon gain wt. %	K cm^2/sec @ pm = 3.6×10^{-6} d/cm^2 (Nitrogen)
LP 8	71	5007	5.8×10^{-2}	80	60	7.9	2.8	2.6×10^{-3}	"	2.60	3.8	2.6×10^{-3}
30 LP 11	72	5030	4.3×10^{-2}	80	120	8.2	2.8	3.1×10^{-4}	"	0.33	3.0	2.7×10^{-4}
	73	4915	8.8×10^{-2}	80	70	10.8	5.5	3.3×10^{-4}	"	1.25	5.9	1.2×10^{-4}
XVIII LP 13	74	4995	5.8×10^{-2}	80	90	7.5	2.5	2.6×10^{-3}	"	2.30	3.2	1.7×10^{-4}
XI LP 12	75	4975	5.8×10^{-2}	80	105	7.7	2.2	1.1×10^{-3}	"	1.20	3.0	9.6×10^{-4}
29 LP 11	76	4993	5.8×10^{-2}	80	75	7.3	2.1	4.5×10^{-3}	"	4.60	4.2	7.3×10^{-5}
LP 13	77	5005	5.8×10^{-2}	80	150	8.4	2.8	5.5×10^{-4}	"	0.52	3.7	5.8×10^{-5}
	78	5018	8.8×10^{-2}	80	70	8.8	3.2	1.3×10^{-3}	"	1.00	3.5	4.9×10^{-5}
LP 12	79	5012	5.8×10^{-2}	80	110	5.1	2.9	4.2×10^{-4}	"	1.00	3.1	1.3×10^{-5}
IX LP 13	80	5068	FAILED TO HOLD INITIAL PRESSURE - BURST AT 70 P.S.I.									
	81	5045	5.8×10^{-2}	80	20	7.9	2.8	6.8×10^{-3}	"	5.30	5.4	5.1×10^{-5} initially impregnated with thin resin
	82	4985	5.8×10^{-2}	80	45	7.7	2.3	3.1×10^{-3}	"	3.00	3.5	8.3×10^{-5} initially impregnated with thin resin
LP 14D	83	5085	3.4×10^{-2}	80	BURST UNDER IMPREGNATION PRESSURE AT 40 P.S.I.							
LP 14	84	5065	3.4×10^{-2}	80	30	3.2	0.8	6.8×10^{-3}	"	6.00	2.8	7.3×10^{-5}
LP 14C	85	5057	5.8×10^{-2}	80	25	8.0	2.9	3.8×10^{-3}	"	4.70	5.0	1.6×10^{-5} initially impregnated with thin resin
	86	5000	5.8×10^{-2}	80	45	8.2	2.5	3.0×10^{-3}	"	2.50	3.5	3.5×10^{-4}
	87	5029	5.8×10^{-2}	80	40	7.9	2.8	2.6×10^{-3}	"	2.80	4.0	5.9×10^{-4} initially impregnated with thin resin
LP 118	88	5044	5.8×10^{-2}	80	BURST UNDER IMPREGNATION PRESSURE AT 78 P.S.I.							
28 LP 11	89	5007	3.4×10^{-2}	80	130	7.7	2.8	3.3×10^{-4}	"	0.60	2.8	6.8×10^{-5}
LP 11	90	5042	4.3×10^{-2}	80	30	7.9	2.8	3.1×10^{-3}	"	4.30	4.7	1.6×10^{-4} initially impregnated with thin resin
LP 8	91	4996	8.8×10^{-2}	80	75	7.5	2.3	4.2×10^{-3}	"	4.00	4.0	2.2×10^{-4}

In addition to this large scale experiment other work was carried out in which an attempt was made to improve the process by varying the conditions of impregnation. The results of these trials in which single fuel tubes were impregnated, covering a number of process variables suggested than an increase in the duration of the second impregnation led to significant improvements in final permeability (compare Process 1 with Process 3 in Table 14). Further experiments carried out by Morganite Carbon Ltd., working under contract to the Project did not confirm this (see Table 15). The results of this latter work did confirm, however, that the process of impregnation previously used only during the work carried out by Hawker Siddeley was workable and produced satisfactory results. During this time additional trials of the process by Anglo Great Lakes Corp. Ltd., also proved successful, the bulk of the impregnation work required in producing specimens for irradiation and other tests being carried out under this latter contract.

In early 1962 a process specification was prepared for the impregnation of the fully machined components for the initial change of the Reactor Experiment. This specification is given in Appendix 1. A series of unavoidable circumstances at this time led to a situation in which there was no opportunity to carry out full trials of the specification on the actual material which was being purified for the Reactor Experiment. It was therefore necessary to go out to tender for the impregnation of the initial charge without the support of such work. After competitive tender action in which eight European firms were approached the contract was awarded to Sigri Kohlefabrikate G.m.b.H. Meitingen über Augsburg, W. Germany in May, 1962.

The deliveries of the fully machined fuel tubes and end plugs made to Sigri up to mid-December, 1962 are shown in Table 16. Measurements made of the nitrogen permeability prior to impregnation at a mean pressure of approximately 3.6×10^6 dynes/cm^2 show values of between 2×10^{-1} and 2×10^{-2} cm^2/sec. There is a general relationship between the permeability and the weight of the components as shown in Figs. 9 and 10.

Following the previous experience on the treatment of the Seven Element Rig some fuel tubes have been destroyed on the application of surprisingly low internal pressures. In certain cases cracks have been found during the course of this test and some of these are shown in Figs. 11 and 12.

The preparation of the furfuryl alcohol impregnant for the initial impregnation presents no undue difficulties provided the bulk of impregnant being mixed in any one container is limited so as to prevent uncontrolled polymerisation. In practice the controlled condensation is performed in a thermostated tank in which several 10 litre batches of impregnant are prepared simultaneously. Graphs indicating the increase of viscosity with time at various temperatures are shown in Fig. 13.

Fig. 14 illustrates the impregnation rigs used for the fuel tubes and end plugs. Three four-point rigs are used for the fuel tubes and ten-point rigs for the end plugs. Each rig is fed with impregnant through a central reservoir, the impregnant entering at the base of each component through a valve. After filling the subsidiary reservoirs above each component and closing the inlet valve, pressure is applied to the resin through a common control valve at the head of each rig. Control of the initial impregnation is exercised by noting the penetration of liquid through the component while the

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Table 14

Impregnation of Fuel Rods Showing Effect of Varying Treatment Conditions

Specimen Number	Process Number	1st Impregnation		2nd Impregnation		3rd Impregnation		K* (cm^2/s)
		Resin Pick-up %	Carbon Pick-up %	Resin Pick-up %	Carbon Pick-up %	Resin Pick-up %	Carbon Pick-up %	
6/79/1	01	8.3	2.5	-	-	-	-	10^{-4} approx.
/2								10^{-4} approx.
/3								10^{-4} approx.
6/82/1	1	8.6	2.8	0.45	0.1	-	-	1.9×10^{-6}
/2								1.2×10^{-6}
/3								3.7×10^{-7}
6/78/1	2	11.7	4.7	1.4	0.5	0.48	0.04	9.0×10^{-7}
/2								3.4×10^{-7}
/3								2.4×10^{-7}
6/79/A1	3	8.3	2.5	3.0	1.0	-	-	6.9×10^{-8}
A2								9.7×10^{-9}
A3								4.9×10^{-8}
6/80/1	04	7.6	2.9	-	-	-	-	1.3×10^{-5}
/2								3.0×10^{-5}
/3								1.8×10^{-5}
6/81/1	4	8.5	3.4	1.3	0.6	-	-	3.9×10^{-7}
/2								1.8×10^{-8}
/3								4.7×10^{-7}
6/80/A1	5	7.6	2.9	1.6	0.9	-	-	1.25×10^{-7}
A2								3.2×10^{-8}
A3								2.8×10^{-7}

* K was measured on three sections cut from the fuel rod.

KEY to Process Numbers:

Process No.	1st Impregnation		2nd Impregnation		3rd Impregnation	
	Impregnant viscosity cP	Impregnation time	Impregnant viscosity cP	Impregnation time	Impregnant viscosity cP	Impregnation time
01	120	To penetration	none	none	none	none
1	"	"	10 approx.	7 h	"	"
2	"	"	"	"	10 approx.	7 h
3	"	"	"	40 h	none	none
04	240	"	none	none	"	"
4	"	"	10 approx.	7 h	"	"
5	"	"	"	40 h	"	"

Table 15

Impregnation of Fuel Tubes and Plugs
(Morganite Carbon Ltd.)

Fuel Tube No.	Initial Perm. † (cm²/s)	1st Impregnation Visc. (cP)	Impreg. time (min)	Resin pick-up (%)	Carbon pick-up (%)	Permeability (cm²/s) †	2nd Impregnation Visc. (cP)	Impreg. time (h)	Resin pick-up (%)	Carbon pick-up (%)	Pressure Perm. † (cm²/s)	Vac. Perm. †† (cm²/s)
GX200	1.5×10^{-2}	120	95	8.5	4.2	1.1×10^{-4}	7.5	7	0.4	0.0	4.2×10^{-6}	7.0×10^{-8}
GX301	6.5 "	116	60	9.2	3.2	6.3×10^{-4}	7.5	7	0.9	0.5	$<10^{-6}$	4×10^{-7}
GX187	3.9 "	116	60	8.1	2.7	4.9×10^{-4}	7.5	7	0.7	0.4	$<10^{-6}$	2.2×10^{-7}
GX212	6.2 "	116	-	7.0	4.5	4.9×10^{-4}	5	6½	1.8	0.9	$<10^{-6}$	1.3×10^{-6}
BD47	4.9 "	160	75	8.5	3.0	3.0×10^{-4}	8	7	1.1	0.5	$<10^{-6}$	9.5×10^{-8}
GX294	3.2 "	160	90	8.1	2.9	1.7×10^{-4}	8	6	0.9	0.4	$<10^{-6}$	1.9×10^{-7}
BD31	4.5 "	116	60	9.2	3.2	2.7×10^{-4}	4.5	7	0.4	0.3	$<10^{-6}$	5.6×10^{-7}
BD5	3.4 "	112	65	7.6	2.8	Damaged during kilning		-	-	-	-	-
GX90	1.6 "	320	120	8.1	2.6	6.3×10^{-4}	8	6	2.3	1.1	$<10^{-6}$	1.8×10^{-7}
GX205	7.8 "	200	75	7.8	2.8	1.1×10^{-4}	5	15½	4.6	3.2	2.1×10^{-6}	1.1×10^{-6}
BD40	2.5 "	129	50	8.4	2.9	1.4×10^{-4}	4.0	20	0.4	0.1	$<10^{-6}$	3.4×10^{-7}
BD64	6.2 "	122	65	8.9	2.0	4.3×10^{-4}	9.5	40	0.8	0.4	4.3×10^{-6}	7.9×10^{-7}
BD72	4.9 "	129	50	8.5	2.8	1.3×10^{-3}	8.0	24	0.9	0.5	1×10^{-4}	1.4×10^{-5}
GX321	4.9 "	129	40	6.8	1.2	4.3×10^{-3}	9.5	80	0.1	-	$<10^{-6}$	2.0×10^{-7}
BD60	9.0 "	116	55	9.4	3.3	3.7×10^{-4}	3.5	80	0.4	0.2	7.2×10^{-6}	1.4×10^{-7}
GX190	9.0 "	137	65	9.3	3.4	3.4×10^{-4}	7.0	7	0.1	-	1.7×10^{-4}	(a)
GX192	7.3 "	137	55	8.2	2.8	3.4×10^{-3}	7.0	4	0.8	0.4	2.4×10^{-4}	(a)
GX104	1.5 "	137	85	7.3	2.7	7.7×10^{-5}	5.0	7	0.7	0.3	1.0×10^{-6}	2.7×10^{-7}
BD36	1.8 "	137	95	7.2	2.6	2.9×10^{-4}	5.0	7	1.1	0.5	2.1×10^{-6}	8.0×10^{-7}
GX61	4.0 "	137	45	7.7	2.9	2.7×10^{-4}	7.0	7	0.7	0.2	Spalled*	(a)
BD21	4.0 "	124	35	7.7	2.8	5.3×10^{-4}	7.0	7	0.5	-	"	"
GX108	2.5 "	137	55	8.3	2.8	7.5×10^{-4}	7.0		0.1	-	3.7×10^{-5}	"
GX183	3.9 "	137	40	8.4	3.0	1.2×10^{-4}	7.0	7	0.2	0.1	3.3×10^{-5}	"
BD54	1.8 "	137	80	7.1	2.7	3.7×10^{-4}	5	15½	2.2	-	Spalled*	"
GX350	2.3 "	137	65	7.7	2.7	1.4×10^{-4}	18	40	0.8	0.0	2.1×10^{-5}	"
BD23	3.2 "	137	55	7.1	2.7	1.1×10^{-3}	7.0	22	2.5	-	Spalled*	"
BD50	4.9 "	137	35	8.6	3.1	3.8×10^{-4}	7.0	40	1.5	-	"	"
GX302	2.4 "	137	65	7.7	2.8	1.3×10^{-4}	12.0	80	0.8	-	"	"
BD24	3.7 "	137	55	7.6	2.7	3.7×10^{-4}	7.0	18	2.2	-	"	"
BD8	3.4 "	137	50	8.4	2.9	5.0×10^{-4}	7.0	5	0.2	-	"	"

Fuel Tube No.	Initial Perm. † (cm²/s)	1st Impregnation Visc. (cP)	Impreg. time (h)	Resin pick-up (%)	Carbon pick-up (%)	Permeability (cm²/s) †	2nd Impregnation Visc. (cP)	Impreg. time (h)	Resin pick-up (%)	Carbon pick-up (%)	Pressure Perm. † (cm²/s)	Vac. Perm. †† (cm²/s)
1st Run - Soak (Total immersion in impregnant only)												
BD37	4.0×10^{-2}	7	16	6.1	2.0	1.1×10^{-3}	5	7	1.2	0.9	5×10^{-6}	1.6×10^{-6}
GX305	5.4 "	7	16	6.3	2.1	4.9×10^{-4}	9.5	7	1.2	0.9	1.2×10^{-5}	9.4×10^{-7}
GX286	6.0 "	7	16	7.5	2.7	7.5×10^{-4}	9.5	7	1.1	0.9	1.4×10^{-4}	1.4×10^{-6}
GX202	2.1 "	7	16	4.9	1.5	6.7×10^{-4}	9.5	7	1.4	1.0	4.9×10^{-4}	5.0×10^{-6}
GX182	2.7 "	7	16	5.9	1.7	9.3×10^{-4}*	9.5	7	1.3	1.1	5.4×10^{-5}	3.3×10^{-7}
GX153	2.2 "	7	16	6.0	2.0	7.8×10^{-4}	5	7	1.1	0.9	3.4×10^{-5}	1.1×10^{-6}
GX148	2.9 "	7	16	6.2	2.0	3.4×10^{-4}	9.5	7	1.3	0.9	4.5×10^{-6}	1.4×10^{-6}
GX142	3.2 "	7	16	6.0	1.9	1.5×10^{-3}	9.5	7	1.2	1.0	1×10^{-3}	4.0×10^{-6}
GX77	3.1 "	7	16	6.7	2.3	1.2×10^{-3}	9.5	7	1.3	1.0	1.9×10^{-4}	5.0×10^{-6}
GX58/1	4.9 "	7	16	5.8	1.9	4.3×10^{-4}	9.5	7	1.2	1.0	1.9×10^{-5}	6.4×10^{-6}
GX58	4.3 "	7	16	6.4	2.2	2.9×10^{-3}	5	7	1.2	0.9	7.6×10^{-5}	1.2×10^{-6}
GX8	4.9 "	7	16	6.6	2.3	3.4×10^{-3}	9.5	7	1.2	0.9	7.7×10^{-5}	4.3×10^{-6}
BD69(S)	4.0 "	7	16	5.7	2.8	8.5×10^{-4}	5	7	0.6	0.2	4.0×10^{-6}	-
GXA26(S)	6.0 "	7	16	7.8	Broken							
GX315(S)	2.0 "	7	16	4.9	2.1	5.0×10^{-4}	5	7	0.6	0.3 0	1.0×10^{-6}	-
2nd Run - Pressure Impregnation			(min)									
GX142	Broken											
GX297	2.7×10^{-2}	137	120	6.5	2.5	8.2×10^{-5}	7	7	-	0.2	1.1×10^{-4}	1.6×10^{-5}(a)
GX251	7.9 "	119	65	8.1	2.9	5.1×10^{-4}	7	7	-	0.5	2.0×10^{-4}	1.6×10^{-5} "
GX231	7.7 "	135	60	5.9	2.2	1.5×10^{-3}	7	7	-	0.4	3.0×10^{-4}	1.7×10^{-5} "
GX229	5.0 "	135	55	7.1	2.8	5.8×10^{-4}	7	7	-	0.2	1.3×10^{-4}	1.7×10^{-5} "
GX214	6.5 "	105	75	5.6	1.7	2.4×10^{-3}	7	7	-	2.3	Cracked	-
GX150	7.3 "	175	75	6.8	2.7	4.8×10^{-3}	7	7	3.0	1.4	2.7×10^{-4}	-
GX149	2.5 "	135	80	5.1	1.9	1.1×10^{-3}	7	7	0.4	0.1	1.4×10^{-4}	1.6×10^{-5} "
GX122	4.4 "	135	60	6.1	2.1	1.4×10^{-3}	7	7	0.5	0.1	1.2×10^{-4}	0.8×10^{-5} "
GXA27/2	3.4 "	137	65	6.7	2.3	8.3×10^{-4}	7	7	0.5	0.2	4.1×10^{-4}	-
" /1	3.5 "	135	55	5.4	2.1	6.7×10^{-4}	18	7	0.6	0.3	2.1×10^{-4}	3.1×10^{-5} "
GXA27	3.8 "	135	55	5.4	2.0	2.5×10^{-3}	7	7	-	0.4	1.5×10^{-4}	1.4×10^{-5} "
GX68(S)	4.8 "	135	-	7.0	2.7	6.6×10^{-4}	7	7	0.3	0.0	2.0×10^{-4}	5.8×10^{-5} "
BD70/1(S)	2.4 "	135	80	5.5	2.0	1.9×10^{-4}	12	7	0.2	0.1	1.5×10^{-4}	2.5×10^{-5} "
BD70(S)	3.0 "	135	75	7.4	3.0	2.7×10^{-4}	12	7	0.2	0.1	1.9×10^{-4}	1.1×10^{-5} "

NOTES: *Spalled. †Measured at mean pressure 3.6×10^{6} dyne/cm² (Nitrogen). ††Measured at mean pressure 0.5×10^{6} dyne/cm² (Air).
(a) Result in doubt due to furnace controller failure leading to excessive heating rate during baking.

Table 16

Deliveries of Fuel Tubes and End Plugs to Sigri Kohlefabrikate G.m.b.H.

Delivery No.	Date from U.K.	No. of Fuel Tubes	No. of Centre Plugs	No. of Outer Plugs	Dragon Grade No.
1	13.6.62	70	12	64	6
2	27.7.62	40	57	140	9
3	13.8.62	25	nil	nil	9
4	24.8.62	45	nil	nil	9
5	21.9.62	80	42	86	9
6	31.10.62	71	nil	112	9

second impregnation is time controlled, as in general no penetration occurs. As might be expected, there is a relationship between the original permeability and the resin uptake during the first impregnation (see Figs. 15 and 16).

After impregnation the components are cleaned prior to performing the heat treatment cycle indicated in the specification. In the case of the fuel tubes, losses due to spalling during this treatment are lower than anticipated and when spalling does occur it is generally found that inclusions or defects are present at the base of the spall as illustrated by the examples shown in Fig. 17.

Detailed results of the work carried out by Sigri Kohlefabrikate up to the end of November, 1962 are shown in Tables 17 to 24, while Figs. 18 and 19 illustrate the dependence of apparent permeability on the pumping time during the course of the vacuum permeability test following two impregnation treatments.

After impregnation the fuel tubes and end plugs will be returned to Winfrith for a final high temperature heat treatment prior to the assembly of the fuel elements (see Section 3.3).

2.5 Top Block Graphite

The overriding requirement of the material used in the Top Block, which acts as the locating feature for the fuel tubes outside the core section and to which attachment is made for charging and discharging individual fuel elements, is one of strength. After surveying high strength graphites which were available in the size required it was decided to use a material which had been developed by Société Le Carbone Lorraine for rocket applications. A summary of the properties of this material, designated Grade P2239, is given in Table 25 [9]. Because of the special interest of the Project in the strength properties, a contract was placed with Sud Aviation, Paris, France, to determine the ultimate strengths in tension compression and bending and to establish the variation of the strength with temperature. The material examined was taken from that produced for the Dragon Top Blocks and the results obtained are shown in Figs. 20 to 24.

2.6 Present Supply Position

The programme for the supply of graphite for fuel tubes and end plugs is so extended in place and time that it is necessary to maintain a careful watch on the overall supply position. Otherwise there is a strong likelihood of a shortage of material.

The original estimate of the requirement of $3\frac{1}{4}$" dia, 79" long Dragon Grade 9, given in Table 26 was based on very scanty evidence. This estimate has proved to be reasonably accurate up to December, 1962 when an appraisal of the situation indicated that, taking all the losses up to that time into account, the number of rods required is 865 compared to 842 in the original estimate.

The supply position is reviewed frequently to ensure that sufficient material is available to meet the commitment for the First Charge of the Reactor Experiment.

Table 17

Impregnation of Fuel Rods (2nd delivery)

	Original			First Impregnation								Second Impregnation						
No.	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm^2 sec^{-1} (Pressure Decay	Vacuum Decay)	Remarks
0071	5148.1	3.6×10^{-2}	-	528	178	8.04	7.10	51.5	4.14	3.7×10^{-5}	-	0.21	-	<0	-	3.2×10^{-6}	5.3×10^{-7}	R
0072	5098.2	5.5×10^{-2}	-	288	120	7.99	-	51.7	4.14	4.6×10^{-5}	-	0.20	-	<0	-	5.3×10^{-6}	2.0×10^{-6}	R
0073	5179.9	2.3×10^{-2}	-	264	89	7.65	-	50.0	3.83	1.0×10^{-5}	-	0.22	-	<0	-	3.7×10^{-6}	2.4×10^{-7}	-
0074	5148.0	3.1×10^{-2}	-	528	178	7.69	5.62	44.6	3.43	2.4×10^{-4}	-	0.80	-	62.5	0.50	1.5×10^{-5}	-	R
0075	5117.9	5.1×10^{-2}	-	528	178	8.36	-	54.1	4.52	2.3×10^{-4}	-	0.32	-	0	0	2.0×10^{-5}	-	R
0076	5096.5	5.0×10^{-2}	-	264	130	8.85	6.94	51.0	4.52	1.7×10^{-4}	-	0.31	-	7.23	0.224	8.4×10^{-6}	4.9×10^{-6}	R
0077	5119.5	5.0×10^{-2}	-	144	100	9.01	-	52.2	4.71	1.9×10^{-4}	1	0.37	-	<0	0	4.0×10^{-6}	8.2×10^{-7}	R
0078	5125.5	4.2×10^{-2}	-	264	130	8.66	6.99	51.3	4.44	1.1×10^{-4}	-	0.21	-	<0	-	1.4×10^{-5}		R
0081	5089.6	6.6×10^{-2}	-	144	100	9.22	7.85	51.2	4.72	1.4×10^{-4}	-	0.36	-	<0	0	5.3×10^{-6}	2.9×10^{-6}	R
0082	5092.1	5.4×10^{-2}	-	528	178	9.01	7.62	51.5	4.64	8.2×10^{-5}	-	0.26	-	0.73	0.001	4.4×10^{-6}	1.2×10^{-6}	R
0083	5124.6	3.5×10^{-2}	-	288	120	5.34	-	51.7	2.76	1.5×10^{-5}	-	0.19	-	<0	-	2.2×10^{-6}	4.3×10^{-7}	-
0085	5090.2	5.3×10^{-2}	-	192	100	8.97	7.65	51.9	4.66	5.5×10^{-5}	-	0.22	-	<0	0	4.6×10^{-6}	8.7×10^{-7}	Delivered
0088	5091.3	6.0×10^{-2}	-	528	178	8.45	6.75	49.7	4.20	3.8×10^{-4}	-	0.39	-	26.3	0.102	9.8×10^{-6}	3.9×10^{-6}	R
0089	5061.9	3.9×10^{-2}	-	528	178	9.75	8.41	55.3	5.39	7.0×10^{-5}	-	0.30	-	<0	0	4.0×10^{-6}	9.1×10^{-7}	R
0090	5058.7	6.6×10^{-2}	-	264	130	9.66	7.85	50.8	4.91	1.0×10^{-4}	-	0.31	-	4.2	0.013	1.2×10^{-5}	-	R
0092	5133.1	4.2×10^{-2}	-	528	178	8.36	7.04	52.0	4.35	8.3×10^{-5}	-	0.23	-	0	0	5.1×10^{-6}	4.7×10^{-6}	R
0093	5063.8	broken at 2.1 ata		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0094	5091.8	4.7×10^{-2}	-	120	215	7.91	6.21	46.6	3.68	4.1×10^{-4}	-	0.47	-	36.1	0.169	1.5×10^{-5}	-	R
0095	5135.2	3.8×10^{-2}	-	528	178	8.26	5.89	51.2	4.23	2.1×10^{-4}	-	0.36	-	<0	-	1.1×10^{-5}	-	R
0096	5125.8	3.4×10^{-2}	-	528	178	8.16	6.67	51.2	4.18	1.4×10^{-4}	-	0.19	-	<0	-	5.4×10^{-6}	2.7×10^{-6}	Delivered
0097	5085.9	7.4×10^{-2}	-	288	120	9.39	-	52.8	4.95	-	6	0.29	-	<0	-	4.0×10^{-6}	6.4×10^{-7}	R
0098	5107.5	3.5×10^{-2}	-	144	95	8.86	-	52.9	4.69	8.6×10^{-5}	-	0.25	-	<0	-	6.7×10^{-6}	2.9×10^{-6}	R
0099	5110.3	4.9×10^{-2}	-	264	130	9.04	7.44	50.9	4.6	1.4×10^{-4}	-	0.49	-	21.3	0.104	7.5×10^{-6}	2.9×10^{-6}	R
0100	5113.5	3.9×10^{-2}	-	528	178	8.85	7.26	50.6	4.48	9.4×10^{-5}	-	0.21	-	7.14	0.015	6.1×10^{-6}	3.7×10^{-6}	R
0101	5127.9	3.9×10^{-2}	-	144	95	8.20	-	52.7	4.33	6.2×10^{-5}	-	0.18	-	<0	-	1.1×10^{-5}	-	R
0102	5107.6	5.1×10^{-2}	-	528	178	8.68	6.94	50.7	4.41	3.0×10^{-4}	-	0.31	-	13.85	0.043	1.2×10^{-5}	-	R
0103	5075.5	5.4×10^{-2}	-	144	95	9.31	7.68	51.2	4.76	9.2×10^{-5}	-	0.27	-	<0	-	6.0×10^{-6}	3.1×10^{-6}	R
0104	5110.9	4.7×10^{-2}	-	264	130	8.68	7.0	51.0	4.43	5.3×10^{-5}	-	0.20	-	<0	-	3.0×10^{-5}	-	R
0105	5124.1	4.0×10^{-2}	-	264	130	8.27	7.35	56.5	4.68	8.8×10^{-5}	-	0.26	-	3.62	0.009	1.1×10^{-5}	-	R
0106	5099.4	4.2×10^{-2}	-	144	100	9.35	-	51.6	4.83	1.7×10^{-4}	-	0.30	<0	-	-	7.9×10^{-6}	2.1×10^{-6}	R
0107	5153.3	3.5×10^{-2}	-	144	95	8.31	7.24	51.6	4.29	1.5×10^{-5}	-	0.21	<0	-	-	4.1×10^{-6}	5.1×10^{-7}	R
0108	5100.0	4.9×10^{-2}	-	264	130	8.92	7.15	51.2	4.56	1.1×10^{-4}	-	0.23	-	-	-	2.2×10^{-5}	-	R
0109	5074.4	7.0×10^{-2}	-	528	178	9.24	7.34	51.1	4.56	2.8×10^{-4}	-	0.37	-	0.5	0.002	6.4×10^{-5}	-	R
0110	5119.6	4.5×10^{-2}	-	288	120	8.73	-	52.2	4.56	-	6	0.23	-	-	-	-	-	R
0111	5068.0	6.4×10^{-2}	-	144	95	9.24	7.61	51.0	4.71	1.3×10^{-4}	-	0.28	-	<0	0	1.1×10^{-5}	-	R
0112	5066.9	6.7×10^{-2}	-	120	215	8.97	7.83	54.4	4.88	2.4×10^{-4}	-	0.48	-	<0	0	1.0×10^{-5}	-	R
0113	5097.3	broken at 3.7 ata		-	-	-	-	-	-	-	-	-		-	-	-	-	-
0114	5100.2	3.9×10^{-2}	-	144	95	8.52	7.14	51.5	4.39	7.5×10^{-5}	-	0.29	-	<0	0	4.4×10^{-6}	1.6×10^{-6}	R
0115	5116.6	4.4×10^{-2}	-	144	95	8.47	7.07	51.7	4.38	3.4×10^{-5}	-	0.17	-	<0	0	7.1×10^{-6}	3.9×10^{-6}	Delivered
0116	5069.1	4.6×10^{-2}	-	144	95	9.66	7.97	551.2	4.95	6.2×10^{-5}	-	0.30	-	0	0	9.3×10^{-6}	5.5×10^{-6}	R

Notes: 1 = Slight spall. 6 = Not measured, R = Re-impregnated, a = Threads damaged on receipt.

Table 18

Impregnation of Fuel Rods (3rd delivery)

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Resin Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability $cm^2\ sec^{-1}$ (Pressure Decay	Vacuum Decay)	Remarks
0281	5076.7	broken at 2.1 ata -			-	-	-	-	-	-	-	-	-	-	-	-	-	-
0282	5092.2	5.6×10^{-2}	a	192	140	8.64	-	51.3	4.43	-	6	0.17	-	< 0	-	1.2×10^{-5}	-	-
0283	5085.9	6.0×10^{-2}	-	192	140	9.0	-	52.5	4.73	-	6	0.27	-	0	0	2.6×10^{-6}	-	-
0284	5039.5	broken at 1.1 ata -			-	-	-	-	-	-	-	-	-	-	-		-	-
0285	5035.0	6.7×10^{-2}	a	192	140	9.71	-	51.8	5.03	-	6	1.36	-	2.09	0.03	9.5×10^{-6}	-	-
0286	5080.7	5.6×10^{-2}	a	192	140	9.04	-	51.5	4.66	-	6	0.27	-	< 0	-	1.4×10^{-6}	-	-
0287	5066.9	5.2×10^{-2}	-	192	140	9.26	-	50.2	4.65	-	6	0.18	-	< 0	-	4.5×10^{-7}	-	-
0288	5105.5	6.5×10^{-2}	-	192	140	8.75	-	51.7	4.53	2.0×10^{-4}	6	0.42	-	9.42	-	1.3×10^{-6}	-	-
0289	5133.5	4.5×10^{-2}	a	192	140	9.0	-	51.9	4.67	broken at impregnation			-	-	-	-	-	-
0290	5037.4	6.1×10^{-2}	-	192	140	9.71	-	52.2	5.07	-	6	0.47	-	19.7	0.09	1.9×10^{-6}	-	-
0291	5074.4	4.4×10^{-2}	-	192	140	8.81	-	51.8	4.56	4.1×10^{-5}	-	0.18	-	<0	-	2.2×10^{-6}	-	-
0292	5034.0	6.9×10^{-2}	-	192	140	9.95	-	53.6	5.34	-	6	0.74	-	29.0	0.21	6.4×10^{-6}	-	-
0293	5079.1	5.9×10^{-2}	-	192	140	9.83	-	53.4	5.25	-	6	0.42	-	<0	-	1.3×10^{-5}	-	-
0294	5064.3	5.3×10^{-2}	-	192	140	9.27	-	51.3	4.76	-	6	0.38	-	11.3	0.04	6.4×10^{-7}	-	-
0295	5019.7	8.2×10^{-2}	-	192	140	9.43	-	51.7	4.88	-	6	0.89	-	29.3	0.26	5.2×10^{-7}	-	-
0296	5070.0	5.3×10^{-2}	a	192	140	9.92	-	55.6	5.52	-	6	0.32	-	<0	-	4.3×10^{-6}	-	-
0297	5034.8	4.4×10^{-2}	-	192	140	10.4	-	58.3	6.06	-	6	0.33	-	25.0	0.08	2.5×10^{-6}	-	-
0298	5109.4	broken at 6.4 ata -			-	-	-	-	-	-	6	-	-	-	-	-	-	-
0299	5090.2	4.3×10^{-2}	-	192	70	8.72	-	50.3	4.39	3.6×10^{-5}	-	0.27	-	14.7	0.04	6.9×10^{-6}	-	-
0300	5144.5	2.9×10^{-2}	-	192	140	8.51	-	50.9	4.33	broken at impregnation			-	-	-	-	-	-
0301	5124.8	3.8×10^{-2}	-	192	70	8.39	-	48.9	4.11	-	6	0.17	-	8.33	0.01	1.7×10^{-5}	-	-
0302	5130.5	2.9×10^{-2}	-	192	70	8.63	-	41.5	3.58	-	6	0.18	-	23.2	0.04	6.0×10^{-6}	-	-
0303	5077.8	4.8×10^{-2}	a	192	70	8.91	-	50.6	4.60	-	6	0.32	-	16.9	0.05	9.9×10^{-6}	-	-
0304	5109.7	4.6×10^{-2}	-	192	70	8.73	-	50.5	4.41	4.5×10^{-5}	-	0.27	-	4.2	0.01	8.8×10^{-6}	-	-
0305	5052.1	5.9×10^{-2}	-	192	70	9.37	-	48.8	4.57	-	6	0.35	-	30.3	0.11	1.3×10^{-5}	-	-

Table 19

Impregnation of Fuel Rods (4th delivery)

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) cm² sec⁻¹	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. press. dec. cm² sec⁻¹	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm² sec⁻¹ (Pressure Decay	Vacuum Decay)	Remarks
0117	5107.0	4.3×10^{-2}	-	288	100	8.09	-	51.3	4.15	-	6	0.27	-	27.3	0.08	2.9×10^{-6}	-	-
0118	5161.9	2.9×10^{-2}	-	288	100	6.65	-	48.3	3.21	-	6	0.30	-	43.5	0.13	2.4×10^{-6}	-	-
0119	5124.2	3.3×10^{-2}	-	288	100	7.42	-	51.0	3.79	1.1×10^{-4}	-	0.22	-	21.6	0.05	1.9×10^{-6}	-	-
0120	5122.8	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0121	5131.2	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0122	5101.0	4.9×10^{-2}	-	288	100	8.0	-	51.2	4.09	2.8×10^{-4}	-	0.53	-	20.8	0.16	$<10^{-6}$	-	-
0123	5096.1	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0124	5023.2	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0125	5106.2	4.9×10^{-2}	-	168	85	9.3	-	51.5	4.79	-	-	0.33	-	30.3	0.10	1.5×10^{-5}	-	-
0126	5020.2	9.7×10^{-2}	-	168	85	9.34	-	51.4	4.80	-	6	0.53	-	38.6	0.23	4.8×10^{-5}	-	-
0127	5075.1	5.1×10^{-2}	-	168	85	8.92	-	56.4	5.04	-	6	0.18	-	16.8	0.03	6.7×10^{-6}	-	-
0128	5115.5	5.1×10^{-2}	-	168	85	9.03	-	51.0	4.61	-	6	0.18	-	14.2	0.03	1.4×10^{-5}	-	-
0129	5134.0	3.9×10^{-2}	-	168	85	9.24	-	51.6	4.77	-	6	0.29	-	33.7	0.10	9.5×10^{-7}	-	-
0130	5146.3	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0131	5088.0	5.1×10^{-2}	-	288	100	9.09	-	50.5	4.60	-	6	0.39	-	26.8	0.11	3.5×10^{-6}	-	-
0132	5094.0	5.2×10^{-2}	-	288	100	9.17	-	51.6	4.74	-	6	0.31	-	0	-	$<10^{-6}$	-	-
0133	5123.2	4.0×10^{-2}	-	288	100	8.46	-	51.1	4.33	-	6	0.15	-	1.26	-	2.5×10^{-6}	-	-
0134	5070.0	5.6×10^{-2}	-	168	85	8.89	-	51.7	4.59	-	6	0.24	-	30.2	0.07	1.9×10^{-6}	-	-
0135	5113.8	6.8×10^{-2}	-	288	100	8.6	-	51.4	4.42	-	6	0.73	-	33.7	0.25	2.1×10^{-6}	-	-
0136	5001.0	8.2×10^{-2}	-	168	85	9.21	-	51.3	4.73	-	6	0.29	-	(90.97)	(0.27)	3.4×10^{-5}	-	-
0137	5101.8	4.5×10^{-2}	-	168	85	8.57	-	52.0	4.46	-	6	0.23	broken during impregnation			-	-	-
0138	5117.0	4.5×10^{-2}	-	168	85	8.24	-	52.6	4.34	-	6	0.35	-	29.6	0.11	1.4×10^{-6}	-	-
0139	5086.6	5.7×10^{-6}	-	168	85	9.45	-	51.8	4.88	-	6	0.42	-	36.0	0.15	1.9×10^{-5}	-	-
0140	5121.9	3.4×10^{-2}	-	168	85	9.20	-	52.0	4.26	-	6	0.22	-	31.7	0.07	1.0×10^{-5}	-	-
0141	5047.6	broken at 6.0 ata		-	-	-	-	-	-	-	-	0.15	-	-	-	-	-	-
0142	5082.1	5.1×10^{-2}	-	192	90	8.81	-	51.0	4.49	-	1,6	0.15	-	5.0	-	$<10^{-6}$	-	-
0143	5112.9	broken at 1.6 ata		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0144	5092.3	7.4×10^{-2}	-	192	90	9.12	-	50.8	4.64	1.5×10^{-4}	-	0.42	-	25.9	0.11	$<10^{-6}$	-	
0145	5026.5	8.3×10^{-2}	-	192	90	8.61	-	50.7	4.37	-	6	0.97	-	39.9	0.38	2.9×10^{-6}	-	-
0146	5033.8	7.5×10^{-2}	-	192	90	9.21	-	51.1	4.71	-	6	0.68	-	35.4	0.25	1.4×10^{-6}	-	-
0147	5030.2	8.5×10^{-2}	-	192	90	8.77	-	50.4	4.42	-	6	0.73	-	38.9	0.29	2.6×10^{-5}	-	-
0148	5101.3	3.9×10^{-2}	-	168	85	8.15	-	51.3	4.18	-	6	0.33	-	25.9	0.09	2.4×10^{-6}	-	-
0149	5064.9	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0150	5120.7	3.1×10^{-2}	-	168	85	7.60	-	60.6	4.61	-	6	0.57	-	34.5	0.20	1.1×10^{-5}	-	-
0151	5108.0	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0152	5127.9	3.7×10^{-2}	-	216	156	8.94	-	50.5	4.52	-	6	0.22	-	13.8	0.03	1.2×10^{-5}	-	-
0153	5087.8	5.1×10^{-2}	-	216	156	9.52	-	50.4	4.80	-	6	0.41	-	22.4	0.11	8.6×10^{-6}	-	-
0154	5156.1	2.4×10^{-2}	-	216	156	8.54	-	50.1	4.28	-	6	0.15	-	2.53	0.04	5.4×10^{-6}	-	-
0155	5037.4	Cracked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0156	5080.4	5.5×10^{-2}	-	216	156	9.52	-	49.1	4.68	-	6	0.18	-	21.4	0.05	2.0×10^{-5}	-	-
0157	5074.0	7.9×10^{-2}	-	168	85	9.69	-	51.4	4.98	-	6	0.29	-	32.9	0.09	6.0×10^{-6}	-	-
0158	5131.6	4.5×10^{-2}	-	168	85	8.33	-	51.8	4.32	-	6	0.18	-	20.6	0.04	2.1×10^{-6}	-	-
0159	5092.7	3.9×10^{-2}	-	192	90	8.81	-	51.1	4.50	-	6	0.23	-	0	-	1.4×10^{-6}	-	-
0160	5102.2	6.3×10^{-2}	-	192	90	9.03	-	50.3	4.54	-	1,6	0.20	-	11.9	0.02	2.1×10^{-6}	-	-
0161	5084.0	5.3×10^{-2}	-	168	85	9.38	-	52.2	4.89	1.0×10^{-4}	6	0.20	-	[illegible]	0.04	$<10^{-6}$	-	-

Table 20

Impregnation of Fuel Rods (5th delivery)

No.	Original			First Impregnation								Second Impregnation						Third Impregnation	
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm^2 sec^{-1} (Pressure Decay)	(Vacuum Decay)	Permeability cm^2 sec^{-1} Vacuum Decay	Remarks
0162	5086.1	4.4 x 10^{-2}	-			8.87													
0163	5070.2	broken at 2.4 ata																	
0164	5159.8	2.7 x 10^{-2}	-			8.2	-	49.9	4.12	-	6	0.33							
0165	5061.3	7.6 x 10^{-2}	-			9.27	-	49.8	4.62	-	6	0.90							
0166	5074.2	crack																	
0167	5114.0	4.8 x 10^{-2}				8.68													
0168	5068.6	7.9 x 10^{-2}				9.36	-	52.7	4.93	-	6	0.60							
0169	5144.1	3.0 x 10^{-2}				8.39													
0170	5099.0	5.4 x 10^{-2}				8.33													
0171	5005.0	1.1 x 10^{-1}				9.70	-	51.0	4.95	-	6	2.17							
0172	5025.6	9.4 x 10^{-2}				9.75													
0173	5072.9	4.7 x 10^{-2}				8.52													
0174	5110.6	4.4 x 10^{-2}				9.13	-	47.3	4.32	1.5 x 10^{-4}		0.39							
0175	5142.8	3.1 x 10^{-2}				8.36	-	51.8	4.33	1.4 x 10^{-4}		0.21							
0176	5079.3	5.1 x 10^{-2}				9.02	-	51.3	4.63	1.6 x 10^{-4}		0.43							
0177	5005.7	6.5 x 10^{-2}				9.78	-	51.7	5.06	-	6	0.66							
0178	5034.5	7.0 x 10^{-2}				9.94													
0179	5033.8	6.5 x 10^{-2}				9.37													
0180	5066.6	4.4 x 10^{-2}				8.61													
0181	5085.5	5.2 x 10^{-2}				9.24													
0182	5118.3	3.2 x 10^{-2}				8.06													
0183	5029.6	broken at 6.2 ata																	
0184	5106.5	5.1 x 10^{-2}				9.43	-	50.7	4.78	-	6	0.24							
0185	5110.1	5.3 x 10^{-2}				8.59	-	51.9	4.46	8.8 x 10^{-5}		0.22							
0186	5095.9	4.0 x 10^{-2}				8.65													
0187	5068.0	5.0 x 10^{-2}				8.81													
0188	5106.7	4.0 x 10^{-2}				8.33													
0189	5094.5	7.0 x 10^{-2}				9.12													
0190	5072.1	5.2 x 10^{-2}				9.65	-	51.5	4.97	1.2 x 10^{-4}		0.21							
0191	5099.6	4.7 x 10^{-2}				8.38	-	52.5	4.40	-	6	0.54							
0192	5080.5	5.5 x 10^{-2}				9.33													
0193	5163.0	3.4 x 10^{-2}				8.12													
0194	5095.0	4.8 x 10^{-2}				8.59													
0195	5132.2	2.9 x 10^{-2}				8.70													
0196	5128.1	3.0 x 10^{-2}				8.24	-	51.4	4.24	-	6	0.22							
0197	4991.0	1.2 x 10^{-2}				9.95													
0198	5069.4	5.9 x 10^{-2}				9.21													
0199	5064.5	4.7 x 10^{-2}				9.25													

Table 20 (continued)

No.	Original			First Impregnation								Second Impregnation						Third Impregnation	
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm^2 sec^{-1} (Pressure Decay)	(Vacuum Decay)	Permeability cm^2 sec^{-1} Vacuum Decay	Remarks
0200	5039.2	8.5 x 10^{-2}				8.72													
0201	5108.0	5.0 x 10^{-2}				9.06													
0202	5035.4	8.3 x 10^{-2}				9.54													
0203	5048.4	6.6 x 10^{-2}				9.64	-	50.6	4.88	-	6	1.09							
0204	4989.1	1.3 x 10^{-1}				10.49													
0205	5079.3	5.2 x 10^{-2}				9.01	-	46.5	4.19	-	6	0.47							
0206	4989.2	1.0 x 10^{-1}				10.34													
0207	5003.0	1.0 x 10^{-1}				9.33													
0208	5090.0	6.3 x 10^{-2}				9.35	-	50.8	4.75	-	6	0.46							
0209	5067.3	6.2 x 10^{-2}				9.07													
0210	5131.6	3.6 x 10^{-2}				8.10													
0211	5105.5	5.6 x 10^{-2}				8.80													
0212	5069.8	6.2 x 10^{-2}				8.31													
0213	5053.6	6.7 x 10^{-2}				8.65	-	51.3	4.44	-	6	1.32							
0214	5045.6	6.2 x 10^{-2}				9.53													
0215	5070.1	7.7 x 10^{-2}				8.48													
0216	5038.4	7.6 x 10^{-2}				9.25													
0217	5140.1	3.1 x 10^{-2}				8.10	-	51.7	4.19	-	6	0.36							
0218	5037.8	7.1 x 10^{-2}				9.31													
0219	5103.1	5.0 x 10^{-2}				8.29													
0220	5132.3	3.6 x 10^{-2}				7.82													
0221	5005.3	9.7 x 10^{-2}				10.05													
0222	5137.2	little crack, measurement impossible																	
0223	5115.1	4.4 x 10^{-2}				8.68													
0224	5078.2	5.2 x 10^{-2}				8.71	-	51.7	4.50	-	6	0.59							
0225	5095.0	5.3 x 10^{-2}				8.43													
0226	5162.4	2.5 x 10^{-2}				8.23													
0227	5036.0	8.1 x 10^{-2}				9.39	-	52.4	4.92	-	6	0.60							
0228	5058.9	6.2 x 10^{-2}				9.43													
0229	5065.6	6.3 x 10^{-2}				8.96	-	51.7	4.63	-	6	0.96							
0230	5145.5	2.5 x 10^{-2}				7.31	-	51.7	3.78	-	6	0.11							
0231	5078.4	4.8 x 10^{-2}				8.56	-	50.4	4.31	-	6	0.69							
0232	5014.5	broken at 1.8 ata																	
0233	5020.5	8.5 x 10^{-2}				9.34													
0234	5045.3	8.8 x 10^{-2}				9.49													
0235	5038.1	1.1 x 10^{-1}				9.36													
0236	5024.8	5.1 x 10^{-2}				10.05	-	55.5	5.58	-	6	0.61							
0237	5100.8	4.6 x 10^{-2}				8.85													
0238	5088.6	5.8 x 10^{-2}				9.04	-	50.4	4.56	-	6	2.43							
0239	5052.4	5.8 x 10^{-2}				9.33													
0240	5117.5	3.9 x 10^{-2}				7.64	-	51.9	3.97	4.2 x 10^{-4}		0.37							
0241	5114.9	little crack, measurement impossible																	

Table 21

Impregnation of Long End Plug (2nd delivery)

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability $cm^2\ sec^{-1}$ (Pressure Decay	Vacuum Decay)	Remarks
0077	1182.0	2.8×10^{-2}	-	240	72	6.97	-	49.6	3.46	-	6	0.14	-	0	-	$<10^{-6}$	-	-
0078	1177.0	2.9×10^{-2}	-	240	72	6.86	-	50.0	3.43	-	6	0.098	-	43.1	-	1.1×10^{-5}	-	-
0079	1171.4	3.4×10^{-2}	-	216	131	8.26	-	-	-	-	3	-	-	-	-	-	-	-
0080	1165.6	4.2×10^{-2}	-	216	131	8.63	7.41	50.5	4.36	8.3×10^{-5}	-	0.12	-	<0	-	-	-	-
0081	1177.7	3.0×10^{-2}	-	168	75	7.28	6.24	51.1	3.72	2.1×10^{-5}	-	5.09	-	0.48	0.02	$<10^{-6}$	1.8×10^{-7}	-
0082	1175.0	2.8×10^{-2}	-	288	152	8.05	-	52.2	4.21	-	6	0.20	-	0	-	6.2×10^{-6}	9.4×10^{-7}	-
0083	1163.4	4.6×10^{-2}	-	192	140	8.08	-	51.1	4.14	-	6	0.16	-	15.8	0.03	1.6×10^{-6}	7.3×10^{-7}	-
0084	1169.5	4.4×10^{-2}	-	216	156	8.68	-	49.7	4.31	-	6	0.45	-	40.0	0.18	6.0×10^{-5}	-	-
0085	1168.2	2.8×10^{-2}	-	216	131	8.93	7.72	56.4	5.04	5.0×10^{-5}	-	0.12	-	<0	0	-	-	-
0086	1179.0	2.8×10^{-2}	-	192	185	7.62	6.82	-	-	-	3	-	-	-	-	-	-	-
0087	1170.7	2.8×10^{-2}	-	216	131	8.08	6.77	51.5	4.16	5.4×10^{-5}	-	0.13	-	<0	0	0	-	-
0088	1174.0	2.8×10^{-2}	-	240	72	7.34	-	50.0	3.67	7.2×10^{-5}	-	0.08	-	50.0	0.04	1.8×10^{-5}	-	-
0089	1175.9	3.4×10^{-2}	-	216	156	6.85	-	50.0	3.42	-	6	-	-	4.75	0.08	8.0×10^{-6}	4.0×10^{-6}	-
0090	1178.2	2.8×10^{-2}	-	192	185	7.62	6.76	50.1	3.82	1.8×10^{-5}	-	0.15	-	16.7	0.03	-	-	-
0091	1173.5	4.3×10^{-2}	-	216	156	8.22	-	50.7	4.17	2.9×10^{-4}	-	0.21	-	23.1	0.05	6.0×10^{-6}	1.4×10^{-6}	-
0092	1163.5	4.2×10^{-2}	-	240	72	8.65	-	50.0	4.33	-	6	0.45	-	30.9	0.14	2.7×10^{-6}	1.8×10^{-7}	-
0094	1178.6	3.1×10^{-2}	-	216	156	7.47	-	43.8	3.27	-	6	0.14	-	23.5	0.03	1.5×10^{-5}	-	-
0095	1179.5	2.6×10^{-2}	-	192	185	7.79	7.13	50.2	3.91	1.9×10^{-5}	-	0.10	-	<0	0	-	-	-
0096	1155.9	6.6×10^{-2}	-	216	156	8.49	-	49.6	4.21	-	6	0.51	-	44.3	0.23	3.1×10^{-6}	2.7×10^{-7}	-
0097	1172.5	3.2×10^{-2}	-	240	72	8.23	-	57.0	4.69	-	6	0.41	-	<0	-	6.2×10^{-6}	2.5×10^{-6}	-
0098	1162.6	5.1×10^{-2}	-	216	156	8.81	-	49.3	4.35	-	6	0.98	-	48.3	0.48	7.8×10^{-6}	1.7×10^{-6}	-
0099	1179.0	2.8×10^{-2}	-	192	185	8.44	6.61	45.6	3.85	4.3×10^{-5}	-	0.13	-	<0	-	-	-	-
0100	1160.8	4.9×10^{-2}	-	240	72	8.67	-	55.3	4.80	-	6	0	-	<0	-	1.5×10^{-5}	-	-
0101	1170.7	2.9×10^{-2}	-	216	131	7.29	7.05	57.3	4.18	4.4×10^{-5}	-	0.11	-	<0	-	-	-	-
0102	1166.3	**Damaged material**		-	-	**impregnation impossible!**			-	-	-	-	-	-	-	-	-	-
0103	1161.4	5.8×10^{-2}	-	192	185	8.97	8.46	50.0	4.48	1.8×10^{-4}	-	0.16	-	5.0	0.008	-	-	-
0104	1169.9	3.3×10^{-2}	-	216	156	8.0	-	51.8	4.14	-	6	0.18	-	9.1	0.02	1.9×10^{-5}	-	-
0105	1181.7	2.3×10^{-2}	-	240	72	7.93	-	61.7	4.89	-	6	0.19	-	<0	-	7.8×10^{-6}	2.9×10^{-6}	-
0106	1180.5	2.9×10^{-2}	-	240	72	7.98	-	49.3	3.83	-	6	0.20	-	<0	-	9.2×10^{-6}	1.7×10^{-6}	-
0107	1172.3	4.0×10^{-2}	-	192	185	9.01	8.49	49.7	4.48	9.1×10^{-5}	-	0.02	-	<0	0	-	-	-
0108	1165.4	5.2×10^{-2}	-	240	72	8.36	-	61.8	5.17	-	6	0.66	-	<0	-	1.3×10^{-5}	-	-
0109	1162.1	4.6×10^{-2}	-	168	75	8.74	8.21	-	-	-	3,6	-	-	-	-	-	-	-
0110	1164.7	3.8×10^{-2}	-	72	92	8.74	-	49.8	4.35	-	6	0.18	-	<0	-	2.7×10^{-6}	4.1×10^{-7}	-
0111	1177.1	2.8×10^{-2}	-	240	72	8.21	-	50.0	4.00	-	6	0.29	-	27.8	0.08	$<10^{-6}$	1.1×10^{-7}	-
0112	1172.3	2.4×10^{-2}	-	72	86	7.67	-	50.3	3.86	-	6	0.12	-	0	-	7.3×10^{-6}	5.8×10^{-6}	-
0113	1177.1	2.8×10^{-2}	-	72	92	9.25	-	48.1	4.45	-	6	0.29	-	34.4	0.09	2.5×10^{-6}	2.2×10^{-7}	-
0114	1170.6	4.0×10^{-2}	-	72	92	9.16	-	47.2	4.33	-	6	0.30	-	18.8	0.06	4.2×10^{-5}	-	-
0115	1152.0	7.3×10^{-2}	-	288	152	9.24	-	49.8	4.60	-	1,6	0.84	-	37.6	0.32	1.6×10^{-6}	6.0×10^{-7}	-
0116	1175.6	2.8×10^{-2}	-	192	185	7.83	7.08	51.2	4.01	2.3×10^{-5}	-	0.08	-	<0	0	-	-	-

No.	Original			First Impregnation							Second Impregnation						
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin Uptake %	Polym. Content %	Carbon Yield %	[illegible]	Permeab. (press. dec.) cm^{-2} sec^{-1}		[illegible] %	Polym. Content %	Carbon Yield %	Sec. Carbon [illegible] %	Permeability cm^2 sec^{-1} Pressure Decay	Vacuum Decay	[illegible]
0117	1166.0	4.2×10^{-2}	-	240	72	8.70	-	47.8	[illegible]	-	-	[illegible]	-	32.8	0.13	2.7×10^{-6}	4.0×10^{-7}	-
0118	1180.3	2.8×10^{-2}	-	288	152	8.20	-	49.8	3.99	2.7×10^{-4}	-	0.22	-	32.0	0.12	3.1×10^{-6}	-	
0119	1172.0	4.0×10^{-2}	-	72	92	8.56	-	46.9	4.02	-	6	0.16	-	26.3	0.04	2.1×10^{-5}	-	-
0120	1169.5	3.4×10^{-2}	-	192	140	7.88	-	50.8	4.00	-	6	0.17	-	23.8	0.04	5.3×10^{-6}	9.5×10^{-8}	-
0121	1174.7	2.8×10^{-2}	-	72	92	8.73	-	45.1	3.94	-	6	0.53	-	24.6	0.13	7.8×10^{-6}	5.6×10^{-7}	2
0122	1177.0	3.8×10^{-2}	-	288	152	8.40	-	50.1	4.21	-	6	0.34	-	35.7	0.12	7.8×1^{-6}	1.7×10^{-7}	-
0123	1164.5	4.0×10^{-2}	-	240	72	8.52	-	59.4	5.07	-	6	0.45	-	< 0	-	2.5×10^{-6}	-	-
0124	1179.5	2.8×10^{-2}	-	240	72	8.21	-	48.8	4.01	3.3×10^{-4}	-	0.26	-	25.0	0.07	3.1×10^{-6}	1.2×10^{-7}	-
0125	1165.5	4.2×10^{-2}	-	168	75	8.56	8.00	49.6	4.25	-	3	-	-	-	-	-	-	-
0126	1169.5	4.2×10^{-2}	-	240	72	8.74	-	59.4	5.19	-	6	0.29	-	28.6	0.15	7.0×10^{-5}	-	-
0127	1170.6	3.3×10^{-2}	-	72	92	9.03	-	46.4	4.19	-	6	0.35	-	30.6	0.11	3.9×10^{-6}	8.9×10^{-7}	-
0128	1174.0	2.8×10^{-2}	-	240	72	7.61	-	50.5	3.84	-	6	0.15	-	<0	-	9.2×10^{-6}	3.9×10^{-7}	-
0129	1176.6	2.5×10^{-2}	-	192	185	7.55	6.49	50.0	3.78	3.4×10^{-5}	-	0.15	-	<0	0	-	-	-
0130	1172.5	2.7×10^{-2}	-	216	156	7.62	-	50.3	3.84	-	6	0.14	-	<0	-	1.3×10^{-5}	-	3
0131	1146.7	6.3×10^{-2}	-	72	92	9.37	-	48.1	4.50	-	6	0.46	-	38.6	0.19	7.5×10^{-5}	-	-
0132	1172.3	2.8×10^{-2}	-	72	86	7.04	-	51.0	3.59	-	6	0.032	-	<0	-	5.4×10^{-6}	1.3×10^{-6}	-
0133	1151.8	6.5×10^{-2}	-	528	178	9.07	7.95	52.0	4.72	4.2×10^{-4}	-	0.25	-	<0	0	-	-	-
0134	1168.2	3.8×10^{-2}	-	216	156	8.17	-	49.7	4.06	-	6	0.20	-	41.6	0.08	1.1×10^{-5}	-	-
0135	1173.5	3.9×10^{-2}	-	216	156	8.10	-	49.8	4.03	3.5×10^{-4}	-	0.26	-	31.8	0.06	6.2×10^{-6}	1.8×10^{-6}	-
0136	1162.7	5.5×10^{-2}	-	72	92	8.42	-	50.8	4.28	-	1,6	0.28	-	18.2	0.05	2.6×10^{-5}	-	-
0137	1177.5	2.9×10^{-2}	-	288	152	8.31	-	50.0	4.06	-	6	0.18	-	27.3	0.05	3.1×10^{-6}	-	-
0138	1161.4	4.6×10^{-2}	-	72	86	8.90	-	48.9	4.35	-	6	0.37	-	51.1	0.69	2.7×10^{-6}	1.3×10^{-7}	-
0139	1170.6	4.0×10^{-2}	-	168	75	8.57	7.96	50.2	4.3	3.7×10^{-5}	-	0.08	-	0	0	-	-	-
0140	1177.6	2.8×10^{-2}	-	528	178	7.80	6.53	50.3	3.92	3.9×10^{-5}	-	0.36	-	0	0	-	-	-
0141	1158.6	7.4×10^{-2}	-	216	156	8.83	-	49.4	4.36	-	6	0.89	-	49.1	0.44	3.1×10^{-6}	-	-
0142	1174.4	2.9×10^{-2}	-	72	92	7.66	-	48.2	3.69	-	6	0.17	-	28.6	0.05	1.5×10^{-5}	-	-
0143	1163.5	4.2×10^{-2}	-	288	152	9.16	-	59.4	5.44	-	6	0.42	-	0	-	9.1×10^{-6}	1.9×10^{-6}	-
0144	1165.0	4.7×10^{-2}	-	216	156	7.42	-	49.5	3.68	-	6	0.18	-	50.0	0.09	3.1×10^{-6}	3.6×10^{-7}	-
0145	1170.8	3.3×10^{-2}	-	240	72	8.06	-	49.8	4.02	-	6	0.14	-	41.2	0.06	5.2×10^{-6}	9.5×10^{-7}	-
0146	1175.1	3.5×10^{-2}	-	72	86	7.68	-	51.2	3.93	7.9×10^{-5}	-	0.12	-	<0	-	4.9×10^{-6}	8.2×10^{-7}	-
0147	1173.9	2.8×10^{-2}	-	240	72	7.70	-	41.6	3.20	-	6	0.54	-	35.4	0.19	2.4×10^{-4}	-	-
0148	1176.8	3.4×10^{-2}	-	168	75	7.79	7.02	50.8	3.96	2.0×10^{-5}	6	0.12	-	0	0	-	-	-
0149	1162.8	4.4×10^{-2}	-	288	152	8.66	-	50.6	4.38	-	1,6	0.24	-	12.8	0.03	6.2×10^{-6}	8.7×10^{-7}	-
0150	1167.8	3.7×10^{-2}	-	240	72	8.37	-	50.1	4.20	-	6	0.21	-	12.0	0.03	10^{-6}	1.0×10^{-7}	-
0151	1171.5	3.2×10^{-2}	-	72	92	8.02	-	48.7	3.91	-	6	0.07	-	16.7	0.02	4.7×10^{-6}	4.9×10^{-7}	-
0152	1172.0	2.6×10^{-2}	-	192	140	7.23	-	50.7	3.66	-	6	0.23	-	21.4	0.05	2.3×10^{-6}	1.4×10^{-7}	-
0153	1145.7	7.3×10^{-2}	-	168	78	9.19	8.57	-	-	-	3	-	-	-	-	-	-	-
0154	1165.0	4.6×10^{-2}	-	192	140	8.19	-	51.3	4.20	-	6	0.13	-	12.5	0.02	4.7×10^{-6}	4.4×10^{-7}	-
0155	1173.0	4.0×10^{-2}	-	528	178	8.24	6.97	53.3	4.39	7.6×10^{-5}	-	0.12	-	<0	0	-	-	-

Table 21 (continued).

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability (Pressure Decay	cm^2 sec^{-1} Vacuum Decay)	Remarks
0156	1162.5	5.0×10^{-2}	-	216	156	8.45	-	49.7	4.20	-	6	0.43	-	<0	-	4.3×10^{-6}	9.8×10^{-7}	1
0157	1167.0	3.6×10^{-2}	-	528	178	8.07	6.54	51.6	4.16	1.4×10^{-4}	-	0.28	-	<0	0	-	-	-
0158	1166.4	5.5×10^{-2}	-	72	86	8.52	-	49.6	4.22	-	6	0.22	-	44.4	0.10	3.7×10^{-5}	-	-
0159	1177.5	2.8×10^{-2}	-	240	72	8.35	-	60.1	5.02	-	6	0.44	-	0	-	4.5×10^{-6}	1.3×10^{-6}	-
0161	1151.1	6.3×10^{-2}	-	240	72	9.31	-	49.8	4.64	-	6	0.58	-	38.6	0.22	4.3×10^{-6}	1.6×10^{-6}	-
0162	1165.1	4.4×10^{-2}	-	216	156	7.78	-	51.0	3.97	-	6	0.18	-	0	-	2.0×10^{-5}	-	-
0163	1155.1	5.4×10^{-2}	-	528	178	8.90	7.70	53.6	4.77	1.3×10^{-4}	-	0.066	-	<0	0	-	-	-
0165	1177.7	2.8×10^{-2}	-	528	178	8.33	7.29	52.1	4.34	4.8×10^{-5}	-	0.15	-	0	0	-	-	-
0166	1159.4	5.6×10^{-2}	-	528	178	8.94	7.49	51.8	4.63	3.6×10^{-4}	-	0.28	-	0	0	-	-	-
0167	1169.4	2.5×10^{-2}	-	192	185	7.45	6.46	51.2	3.82	3.6×10^{-5}	-	0.14	-	0	0	-	-	-
0168	1172.0	2.9×10^{-2}	-	192	74	7.89	-	50.3	3.97	-	6	0.16	-	25.0	0.04	6.2×10^{-6}	6.2×10^{-7}	-
0169	1173.0	3.7×10^{-2}	-	240	72	7.86	-	41.1	3.23	4.6×10^{-4}	-	0.10	-	16.7	0.02	7.8×10^{-6}	4.9×10^{-7}	-
0170	1173.5	3.0×10^{-2}	-	216	156	7.57	-	50.1	3.79	-	6	0.18	-	18.2	0.03	7.7×10^{-6}	1.9×10^{-6}	
0171	1181.5	2.4×10^{-2}	-	216	156	6.47	-	50.3	3.25	-	6	0.12	-	20.0	0.02	4.7×10^{-6}	2.5×10^{-7}	-
0173	1154.0	5.9×10^{-2}	-	192	140	8.53	-	50.9	4.34	-	6	0.28	-	26.5	0.07	7.2×10^{-6}	-	-
0174	1158.4	5.9×10^{-2}	-	240	72	9.03	-	49.8	4.49	-	6	0.55	-	45.5	0.25	1.3×10^{-5}	-	-
0175	1172.8	3.7×10^{-2}	-	216	131	8.53	7.55	51.6	4.41	4.4×10^{-5}	-	0.10	-	<0	0	-	-	-
0176	1158.2	6.3×10^{-2}	-	240	72	8.93	-	49.6	4.43	-	6	0.80	-	46.4	0.37	1.0×10^{-5}	-	-
0178	1170.6	3.3×10^{-2}	-	192	74	8.12	-	48.8	3.96	-	2,6	-	-	-	-	-	-	-
0179	1167.1	4.4×10^{-2}	-	72	86	8.34	-	50.8	4.24	-	6	0.20	-	28.0	0.06	2.7×10^{-6}	-	-
0180	1173.6	3.7×10^{-2}	-	288	152	8.67	-	48.7	4.22	-	6	0.31	-	23.7	0.07	2.1×10^{-6}	1.1×10^{-6}	-
0181	1169.0	4.0×10^{-2}	-	192	74	8.09	-	49.9	4.04	-	6	0.17	-	<0	-	4.9×10^{-6}	2.3×10^{-7}	-
0182	1171.8	4.6×10^{-2}	-	192	74	8.49	-	49.9	4.24	-	1,6	0.31	-	<0	-	2.9×10^{-5}	-	-
0183	1170.7	4.4×10^{-2}	-	168	75	8.53	7.96	-	-	-	3	-	-	-	-	-	-	-
0184	1165.5	5.4×10^{-2}	-	528	178	8.08	7.64	48.3	3.90	2.5×10^{-4}	-	0.14	-	<0	0	-	-	-
0185	1171.6	3.6×10^{-2}	-	216	156	7.71	-	49.2	3.79	6.0×10^{-5}	-	0.20	-	<0	-	1.4×10^{-5}	-	-
0186	1163.5	4.4×10^{-2}	-	240	72	8.87	-	73.0	6.47	-	6	0.19	-	<0	-	1.6×10^{-6}	1.6×10^{-6}	-
0187	1183.9	2.3×10^{-2}	-	192	140	6.97	-	49.9	3.48	-	6	0.24	-	20.7	0.05	1.9×10^{-6}	1.9×10^{-7}	-
0188	1175.8	3.2×10^{-2}	-	192	74	7.87	-	49.8	3.92	-	6	0.09	-	9.1	0.01	$<10^{-6}$	2.4×10^{-7}	-
0189	1175.6	2.4×10^{-2}	-	192	74	7.72	-	50.2	3.88	4.6×10^{-5}	-	0.07	-	22.2	0.02	1.1×10^{-5}	-	-
0190	1163.0	5.9×10^{-2}	-	72	86	8.92	-	50.1	4.46	-	6	0.36	-	31.8	0.11	9.4×10^{-6}	4.9×10^{-7}	-
0191	1168.7	4.1×10^{-2}	-	528	178	8.83	-	-	-	-	3	-	-	-	-	-	-	-
0192	1174.0	3.7×10^{-2}	-	288	152	8.57	-	50.1	4.29	-	6	0.20	-	12.0	0.02	5.4×10^{-7}	8.8×10^{-8}	-
0193	1172.0	3.8×10^{-2}	-	240	72	7.80	-	52.3	4.08	-	6	0.16	-	10.5	0.02	7.8×10^{-6}	-	-
0194	1173.2	2.3×10^{-2}	-	192	140	7.50	-	51.0	3.82	-	6	0.14	-	<0	-	$<10^{-6}$	4.9×10^{-8}	-
0195	1162.3	5.2×10^{-2}	-	192	74	7.78	-	48.4	3.77	-	5	-	-	48.0	0.66	8.7×10^{-5}	-	-
0196	1179.0	2.5×10^{-2}	-	240	72	8.39	-	49.6	4.16	-	6	0.13	-	<0	-	3.1×10^{-6}	4.9×10^{-7}	-
0197	1192.9	2.9×10^{-2}	-	192	140	6.81	-	52.0	3.54	-	6	0.32	-	0	-	4.7×10^{-6}	4.3×10^{-8}	-
0198	1167.8	3.3×10^{-2}	-	192	140	8.19	-	51.8	4.24	1.3×10^{-4}	-	0.14	-	<0	-	1.0×10^{-6}	1.1×10^{-7}	-
0199	1177.9	2.4×10^{-2}	-	240	72	7.95	-	49.7	3.96	-	6	0.13	-	43.8	0.06	10^{-6}	7.5×10^{-8}	-

Table 21. (continued).

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability $cm^2\ sec^{-1}$ (Pressure Decay	Vacuum Decay)	Remarks
0200	1166.4	5.5×10^{-2}	-	192	185	8.70	8.21	-	-	-	3	-	-	-	-	-	-	-
0201	1160.5	3.5×10^{-2}	-	240	72	8.65	-	49.6	4.29	-	6	0.28	-	-	-	5.9×10^{-6}	5.9×10^{-7}	-
0202	1174.5	3.4×10^{-2}	-	240	72	8.18	-	49.9	4.08	-	6	0.28	-	14.7	0.04	1.0×10^{-6}	1.9×10^{-7}	-
0203	1156.5	5.9×10^{-2}	-	168	75	8.97	8.33	-	-	-	3	-	-	-	-	-	-	-
0204	1179.9	2.5×10^{-2}	-	192	140	7.13	-	51.0	3.64	-	6	0.12	-	<0	-	$<18^{-6}$	9.6×10^{-8}	-
0206	1160.0	5.7×10^{-2}	-	216	156	8.68	-	49.6	4.31	-	6	0.41	-	50.0	0.21	7.8×10^{-6}	6.5×10^{-7}	-
0207	1183.0	2.8×10^{-2}	-	72	86	6.91	-	50.0	3.46	-	6	0.098	-	0	-	$<19^{-6}$	1.3×10^{-7}	1
0208	1158.4	5.9×10^{-2}	-	72	86	9.12	-	49.8	4.54	-	1,6	0.21	-	19.2	0.04	$<10^{-6}$	6.7×10^{-7}	-
0209	1147.4	8.0×10^{-2}	-	216	156	8.93	-	50.3	4.49	-	6	0.43	-	-	-	1.6×10^{-5}	-	-
0210	1169.6	4.0×10^{-2}	-	216	131	8.82	3.34	51.3	4.52	1.1×10^{-4}		0.13	-	<0	0	-	-	-
0211	1180.4	2.4×10^{-2}	-	192	74	7.29	-	50.0	3.64	-	6	0.082	-	10.0	0.01	3.9×10^{-6}	7.1×10^{-7}	-
0212	1182.7	2.5×10^{-2}	-	240	72	7.90	-	49.2	3.88	-	6	0.18	-	18.2	0.03	7.8×10^{-6}	2.1×10^{-7}	-
0213	1160.2	4.9×10^{-2}	-	168	75	9.00	8.39	50.2	4.52	3.9×10^{-5}	-	0.04	-	<0	0	-	-	-
0214	1175.8	2.8×10^{-2}	-	288	152	8.01	-	50.2	4.03	-	6	0.12	-	<0	-	4.7×10^{-6}	1.9×10^{-7}	-
0215	1177.5	2.8×10^{-2}	-	216	131	7.94	6.65	51.0	4.05	5.3×10^{-5}	-	0.04	-	<0	0	-	-	-
0216	1174.8	3.5×10^{-2}	-	192	74	8.06	-	49.7	4.01	8.0×10^{-5}	-	0.082	-	30.0	0.02	2.6×10^{-6}	7.8×10^{-7}	-
0217	1178.2	3.1×10^{-2}	-	216	131	7.99	6.74	51.3	4.10	5.9×10^{-5}	-	0.15	-	<0	0	-	-	-
0218	1155.7	4.4×10^{-2}	-	216	131	8.94	7.93	48.7	4.36	-	3	-	-	-	-	-	-	-
0219	1154.4	4.2×10^{-2}	-	168	75	9.17	8.54	-	-	-	3	-	-	-	-	-	-	-
0220	1169.3	3.4×10^{-2}	-	192	74	8.55	-	50.2	4.29	-	1,6	0.28	-	38.2	0.12	3.1×10^{-6}	6.8×10^{-7}	-
0221	1162.6	4.2×10^{-2}	-	528	178	8.73	7.10	53.4	4.66	2.4×10^{-4}	-	0.22	-	<0	0	-	-	-
0222	1178.9	2.8×10^{-2}	-	72	86	7.96	-	50.2	4.00	-	6	0.08	-	40.0	0.03	6.2×10^{-6}	4.0×10^{-7}	-

NOTES:

1 = Slightly spalled
3 = Heavily spalled
6 = Not measured.

Table 22

Impregnation of Long End Plug (5th delivery)

	Original			First Impregnation								Second Impregnation						Third Impregnation	
No.	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm^2 sec^{-1} (Pressure Decay)	Permeability cm^2 sec^{-1} (Vacuum Decay)	Permeability cm^2 sec^{-1} Vacuum Decay	Remarks
0093	1162.5	4.5 x 10^{-2}				8.55	-	50.4	4.31	-	6	0.46							
0281	1163.3	3.9 x 10^{-2}				9.06	-	44.8	4.06	-	6	0.44							
0282	1151.9	5.4 x 10^{-2}				9.42	-	50.2	4.73	-	6	0.19							
0283	1168.0	2.0 x 10^{-2}				7.64	-	49.9	3.81	-	6	0.28							
0284	1170.7	3.7 x 10^{-2}				8.57	-	49.5	4.24	-	6	0.11							
0285	1157.8	broken at 6.7 ata																	
0286	1177.4	2.3 x 10^{-2}				7.72	-	49.8	3.84	-	6	0.33							
0287	1169.1	3.3 x 10^{-2}				8.54	-	50.0	4.27	-	6	0.18							
0288	1155.0	5.0 x 10^{-2}				9.52	-	49.1	4.67	-	6	0.59							
0289	1165.0	broken at 4.1 ata																	
0290	1166.8	3.5 x 10^{-2}				8.11	-	49.9	4.05	3.2 x 10^{-4}		0.25							
0291	1175.5	2.2 x 10^{-2}				6.34	-	49.5	3.14	-	6	0.26							
0292	1162.9	3.8 x 10^{-2}				9.23	-	48.6	4.49	-	6	0.54							
0293	1166.0	4.8 x 10^{-2}				8.98	-	50.3	4.52	-	6	0.68							
0294	1151.0	5.5 x 10^{-2}				9.44	-	48.1	4.54	-	6	0.28							
0295	1162.0	4.4 x 10^{-2}				8.93	-	50.4	4.50	-	6	0.30							
0296	1158.5	4.7 x 10^{-2}				8.87	-	51.1	4.53	-	6	0.41							
0297	1166.9	broken at 6.8 ata																	
0298	1176.7	little crack measurement impossible																	
0299	1173.8	2.6 x 10^{-2}				7.93	-	50.0	3.96	-	6	0.23							
0300	1165.5	3.4 x 10^{-2}				8.58	-	50.9	4.37	-	6	0.08							
0301	1158.3	5.2 x 10^{-2}				8.89	-	49.4	4.39	-	6	0.36							
0302	1185.9	1.7 x 10^{-2}				6.94	-	50.7	3.52	6.7 x 10^{-5}		0.23							
0303	1168.0	3.1 x 10^{-2}				8.38	-	45.9	3.85	-	6	0.08							
0304	1161.8	4.8 x 10^{-2}				8.75	-	50.2	4.39	-	6	0.21							
0305	1168.1	3.9 x 10^{-2}				8.65	-	51.0	4.41	-	6	0.16							
0306	1170.6	2.7 x 10^{-2}				7.31	-	50.9	3.72	-	6	0.31							
0307	1156.0	4.9 x 10^{-2}				8.75	-	54.9	4.80	-	6	0.28							
0308	1175.6	2.5 x 10^{-2}				8.43	-	50.9	4.29	-	6	0.22							
0309	1176.1	2.4 x 10^{-2}				7.27	-	49.2	3.58	-	6	0.32							
0310	1179.2	2.1 x 10^{-2}				8.29	-	32.7	2.71	2.3 x 10^{-5}	1	1.38							
0311	1159.0	5.0 x 10^{-2}				7.96	-	50.4	4.01	-	5	0.38							
0312	1171.5	3.5 x 10^{-2}				8.25	-	49.8	4.11	-	6	0.39							
0313	1164.6	broken at 5.2 ata																	
0314	1155.0	5.0 x 10^{-2}				9.45	-	50.4	4.76	-	6	0.45							
0315	1156.0	4.7 x 10^{-2}				8.43	-	50.1	4.22	-	6	0.42							

Table 22 (continued).

	Original			First Impregnation								Second Impregnation						Third Impregnation	
No.	Weight g	Permeab. (press.dec.) cm² sec⁻¹	Remarks	Pre-polym Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm² sec⁻¹	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm² sec⁻¹ (Pressure Decay)	Permeability cm² sec⁻¹ (Vacuum Decay)	Permeability cm² sec⁻¹ Vacuum Decay	Remarks
0316	1169.5	3.8×10^{-2}				7.89	-	50.9	4.02	-	6	0.23							
0317	1169.4	3.8×10^{-2}				6.37	-	49.3	4.13	-	1,6	0.19							
0318	1156.8	4.3×10^{-2}				9.14	-	50.1	4.58	-	1,6	0.16							
0319	1166.8	4.4×10^{-2}				8.71	-	49.3	4.29	4.0×10^{-4}		0.15							
0320	1167.8	3.6×10^{-2}				8.57	-	50.6	4.34	2.7×10^{-4}		0.14							
0321	1164.4	5.2×10^{-2}				8.42	-	50.5	4.25	-	6	0.33							
0322	1166.5	3.6×10^{-2}				8.87	-	49.4	4.38	-	6	0.25							
0323	1156.7	5.0×10^{-2}				9.54	-	50.1	4.78	4.8×10^{-4}		0.36							
0324	1177.6	2.5×10^{-2}				7.89	-	50.6	3.99	-	6	0.47							
0325	1186.3	1.7×10^{-2}				5.62	-	49.9	2.80	-	6	0.16							
0326	1166.7	4.3×10^{-2}				8.42	-	49.8	4.19	-	6	0.12							
0327	1156.5	5.1×10^{-2}				8.87	-	49.5	4.39	-	6	0.23							
0328	1157.1	5.1×10^{-2}				9.16	-	50.5	4.63	-	6	0.17							
0329	1171.7	3.0×10^{-2}				8.22	-	51.5	4.23	-	6	0.16							
0330	1168.4	3.6×10^{-2}				8.25	-	50.1	4.13	-	6	0.27							
0331	1156.0	broken at 5.5 ata																	
0332	1164.5	4.9×10^{-2}				8.84	-	50.6	4.47	-	6	0.16							
0333	1166.5	3.7×10^{-2}				8.57	-	48.2	4.13	-	6	0.40							
0334	1170.1	2.6×10^{-2}				7.49	-	50.5	3.78	-	6	0.49							
0335	1183.5	1.7×10^{-2}				7.34	-	50.4	3.70	-	6	0.11							
0336	1157.5	4.7×10^{-2}				8.82	-	49.4	4.36	-	6	0.41							
0337	1184.9	1.6×10^{-2}				6.92	-	50.9	3.52	-	6	0.38							
0381	1171.8	3.3×10^{-2}				8.33	-	50.6	4.21	-	6	0.15							
0382	1165.5	3.8×10^{-2}				8.46	-	51.1	4.32	-	6	0.27							
0383	1170.4	3.3×10^{-2}				8.73	-	49.3	4.30	3.8×10^{-4}		0.20							
0384	1165.9	5.3×10^{-2}				8.80	-	39.1	3.44	-	6	1.41							
0385	1167.5	3.5×10^{-2}				8.65	-	49.6	4.29	-	6	0.39							
0386	1169.4	3.3×10^{-2}				8.27	-	51.7	4.28	-	6	0.11							
0387	1164.4	5.8×10^{-2}				8.39	-	51.3	4.30	-	6	0.22							
0388	1173.3	3.2×10^{-2}				8.46	-	46.1	3.90	-	6	0.30							
0389	1167.8	5.6×10^{-2}				8.15	-	50.3	4.10	-	6	0.42							
0390	1160.2	4.8×10^{-2}				8.82	-	50.4	4.45	2.2×10^{-4}		0.15							
0391	1166.5	5.6×10^{-2}				8.84	-	50.4	4.46	-	6	0.16							
0392	1157.8	4.2×10^{-2}				8.37	-	50.7	4.24	-	6	0.09							
0393	1168.4	5.2×10^{-2}				8.33	-	50.8	4.23	-	6	0.37							
0394	1161.4	4.6×10^{-2}				9.09	-	50.1	4.55	2.2×10^{-4}		0.07							
0395	1162.1	3.7×10^{-2}				8.85	-	50.3	4.45	-	1,6	0.14							
0396	1161.4	4.4×10^{-2}				8.68	-	50.2	4.36	-	6	0.36							
0397	1166.3	5.8×10^{-2}				9.10	-	48.9	4.45	-	6	0.51							
0398	1171.8	3.2×10^{-2}				8.50	-	50.7	4.31	-	6	0.38							

Table 22 (continued).

No.	Original			First Impregnation								Second Impregnation						Third Impregnation	
	Weight g	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) $cm^2\ sec^{-1}$	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability $cm^2\ sec^{-1}$ (Pressure Decay)	(Vacuum Decay)	Permeability $cm^2\ sec^{-1}$ Vacuum Decay	Remarks
0399	1166.9	3.7×10^{-2}				8.58	-	49.6	4.26	-	6	0.13							
0400	1164.4	5.3×10^{-2}				9.33	-	48.7	4.54	-	6	0.44							
0401	1154.0	4.4×10^{-2}				8.81	-	49.8	4.39	6.6×10^{-4}		0.21							
0402	1163.4	3.8×10^{-2}				8.16	-	50.6	4.13	-	1,6	0.24							
0403	1171.0	3.5×10^{-2}				7.67	-	49.2	3.77	-	6	0.46							
0404	1166.2	3.3×10^{-2}				8.61	-	49.3	4.24	-	6	0.21							
0405	1168.7	3.7×10^{-2}				7.99	-	50.8	4.06	-	6	0.21							
0406	1173.0	3.5×10^{-2}				8.47	-	44.4	3.76	-	6	0.63							
0407	1161.4	3.8×10^{-2}				8.26	-	49.1	4.06	-	6	0.44							
0408	1168.4	3.4×10^{-2}				8.53	-	49.9	4.26	-	6	0.15							

Table 23

Impregnation of Short End Plug (2nd delivery)

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym.-Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin Uptake %	Polym.-Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability (Pressure Decay	cm^2 sec^{-1} Vacuum Decay)	Remarks
0224	877.4	4.2×10^{-2}	-	216	131	8.59	broken at curing		-	-	-	-	-	-	-	-	-	-
0225	878.4	4.2×10^{-2}	-	216	131	8.90	7.59	50.8	4.53	9.4×10^{-5}	-	0.27	-	0	0	$<10^{-6}$	1.2×10^{-7}	-
0226	882.5	2.6×10^{-2}	-	216	252	8.55	7.88	50.5	4.32	5.7×10^{-5}	-	0.26	-	0	0	$<10^{-6}$	4.6×10^{-7}	-
0227	879.8	3.1×10^{-2}	-	216	252	8.90	8.23	50.6	4.51	1.4×10^{-4}	-	0.30	-	0	0	$<10^{-6}$	4.1×10^{-7}	-
0228	869.0	3.7×10^{-2}	-	216	252	8.91	8.37	50.4	4.49	1.7×10^{-4}	-	0.20	-	13.8	0.03	$<10^{-6}$	1.7×10^{-7}	-
0229	877.5	3.8×10^{-2}	-	216	131	8.56	7.22	51.5	4.36	6.3×10^{-5}	-	0.15	-	0	0	3.2×10^{-6}	9.1×10^{-7}	-
0230	873.2	3.8×10^{-2}	-	216	131	8.74	7.71	51.1	4.46	6.2×10^{-5}	-	0.08	-	0	0	1.7×10^{-5}	-	-
0231	894.5	1.3×10^{-2}	-	168	75	7.43	6.45	-	-	-	3	-	-	-	-	-	-	-
0232	890.0	1.4×10^{-2}	-	528	178	7.21	6.34	50.1	3.62	2.8×10^{-5}	-	0.30	-	0	0	8.8×10^{-6}	2.4×10^{-7}	-
0233	878.0	4.3×10^{-2}	-	192	185	8.60	8.06	-	-	-	3	-	-	-	-	-	-	-
0234	879.9	3.2×10^{-2}	-	192	185	8.10	7.68	-	-	-	3	-	-	-	-	-	-	-
0235	885.3	2.7×10^{-2}	-	528	178	8.29	7.42	51.4	4.26	4.4×10^{-5}	-	0.21	-	0	0	$<10^{-6}$	1.3×10^{-7}	-
0236	894.8	1.4×10^{-2}	-	216	131	6.90	5.58	51.4	3.55	2.9×10^{-5}	-	0.17	-	0	0	1.8×10^{-6}	5.0×10^{-7}	-
0237	876.6	4.3×10^{-2}	-	168	75	8.60	8.00	55.0	4.82	3.9×10^{-5}	-	0.07	-	0	0	1.5×10^{-5}	-	-
0238	873.5	4.2×10^{-2}	-	216	252	8.89	8.31	50.5	4.94	1.1×10^{-4}	-	0.16	-	0	0	$<10^{-6}$	3.6×10^{-7}	-
0239	866.2	3.2×10^{-2}	-	192	185	9.10	8.54	53.0	4.82	-	3	-	-	-	-	-	-	-
0240	878.4	2.5×10^{-2}	-	216	252	8.56	7.99	50.6	4.34	6.1×10^{-5}	-	0.03	-	0	0	$<10^{-6}$	8.6×10^{-8}	-
0241	877.7	3.1×10^{-2}	-	216	252	8.50	7.96	-	-	-	3	-	-	-	-	-	-	-
0242	881.4	3.1×10^{-2}	-	168	75	8.24	7.70	-	-	-	3	-	-	-	-	-	-	-
0243	875.8	3.2×10^{-2}	-	192	185	9.03	8.47	-	-	-	3	-	-	-	-	-	-	-
0244	873.4	3.6×10^{-2}	-	240	72	0.71	-	49.3	4.29	-	6	0.16	-	-	-	2.2×10^{-6}	8.9×10^{-7}	-
0245	892.8	1.3×10^{-2}	-	168	75	7.44	4.65	48.2	3.58	2.0×10^{-5}	-	0.11	-	-	-	$<10^{-6}$	1.2×10^{-7}	-
0246	867.7	4.0×10^{-2}	-	216	131	8.77	broken at curing		-	-	-	-	-	-	-	-	-	-
0247	896.4	2.2×10^{-2}	-	528	178	7.09	6.11	49.7	3.53	2.1×10^{-5}	-	0.34	-	0	0	$<10^{-6}$	9.3×10^{-8}	-
0248	895.7	1.3×10^{-2}	-	528	178	7.10	6.24	49.2	3.49	2.0×10^{-5}	-	0.33	-	0	0	$<10^{-6}$	1.4×10^{-7}	-
0249	880.9	2.9×10^{-2}	-	192	185	7.89	6.98	50.4	3.98	3.8×10^{-5}	-	0.07	-	0	0	1.3×10^{-5}	-	-
0250	882.5	3.0×10^{-2}	-	540	72	8.21	-	49.8	4.09	-	6	0.16	-	-	-	3.7×10^{-5}	-	-
0251	875.5	4.1×10^{-2}	-	240	72	8.85	-	50.1	4.44	-	6	0.22	-	-	-	6.4×10^{-6}	6.3×10^{-7}	-
0252	896.6	1.3×10^{-2}	-	192	185	6.39	5.49	50.1	3.20	2.7×10^{-5}	-	0.62	-	5.3	0.03	1.9×10^{-6}	3.2×10^{-7}	-
0253	882.8	3.5×10^{-2}	-	528	178	8.56	7.46	51.7	4.43	4.1×10^{-5}	1	0.16	-	-	-	-	-	3
0254	882.5	3.2×10^{-2}	-	528	178	8.16	7.14	50.4	3.60	5.3×10^{-5}	-	0.24	-	0	0	7.7×10^{-6}	4.5×10^{-7}	-
0255	894.0	1.4×10^{-2}	-	528	178	7.34	6.30	49.2	3.54	2.4×10^{-5}	-	0.31	-	0	0	$<10^{-6}$	1.7×10^{-7}	-
0256	871.6	4.5×10^{-2}	-	216	252	8.93	8.27	51.3	4.58	2.1×10^{-4}	3	0.19	-	-	-	-	-	3
0257	881.0	3.9×10^{-2}	-	168	75	8.41	7.87	-	-	-	2	-	-	-	-	-	-	-
0258	879.2	4.7×10^{-2}	-	216	131	8.82	7.74	49.5	4.36	6.4×10^{-5}	-	0.20	-	0	0	2.0×10^{-5}	-	-
0259	878.6	4.1×10^{-2}	-	216	131	8.55	8.00	51.1	4.37	7.5×10^{-5}	-	0.22	-	0	0	$<10^{-6}$	6.2×10^{-7}	-
0260	877.7	4.1×10^{-2}	-	168	75	8.85	8.29	-	-	-	2	-	-	-	-	-	-	-

Table 23 (continued).

No.	Original			First Impregnation								Second Impregnation						
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym.-Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym.-Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm^2 sec^{-1} (Pressure Decay	Vacuum Decay)	Remarks
0261	878.9	3.5 x 10^{-2}	-	240	72	8.39	-	49.9	4.18	-	6	0.15	-	-	-	1.4 x 10^{-6}	1.4 x 10^{-6}	-
0262	883.4	2.4 x 10^{-2}	-	216	252	8.57	7.99	50.6	4.34	5.1 x 10^{-5}	-	0.14	-	0	0	$<10^{-6}$	7.4 x 10^{-8}	-
0263	883.0	2.9 x 10^{-2}	-	240	72	8.07	-	49.7	4.01	4.0 x 10^{-4}	-	0.14	-	-	-	$<10^{-6}$	5.2 x 10^{-7}	-
0264	875.6	3.7 x 10^{-2}	-	528	178	8.83	8.09	51.6	4.56	-	2	-	-	-	-	-	-	-
0265	874.1	4.3 x 10^{-2}	-	168	75	8.82	8.22	-	-	-	2	-	-	-	-	-	-	-
0266	880.2	4.1 x 10^{-2}	-	192	185	8.41	7.85	-	-	-	2	-	-	-	-	-	-	-
0257	882.3	3.3 x 10^{-2}	-	192	185	7.88	6.97	50.7	4.00	4.4 x 10^{-5}	-	0.13	-	0	0	5.3 x 10^{-4}	3.0 x 10^{-6}	-
0258	800.1	3.8 x 10^{-2}	-	528	178	8.68	7.68	51.6	4.48	1.3 x 10^{-4}	-	0.18	-	0	0	$<10^{-}$	4.8 x 10^{-7}	-
0269	863.2	3.8 x 10^{-2}	-	216	131	9.14	7.71	51.1	4.67	1.8 x 10^{-4}	3	0.22	-	-	-	-	-	3
0270	884.1	3.2 x 10^{-2}	-	528	178	8.08	7.41	51.6	4.17	2.4 x 10^{-5}	-	0.02	-	0	0	$<10^{-6}$	3.2 x 10^{-7}	-
0271	897.8	1.3 x 10^{-2}	-	240	72	7.91	-	43.1	3.41	-	6	0.08	-	-	-	$<10^{-6}$	9.3 x 10^{-8}	-
0272	891.6	1.4 x 10^{-2}	-	168	75	7.97	7.51	-	-	-	3	-	-	-	-	-	-	-
0273	870.9	3.3 x 10^{-2}	-	216	252	8.74	8.13	51.3	4.49	1.2 x 10^{-4}	-	0.03	-	0	0	$<10^{-6}$	7.0 x 10^{-7}	-
0274	880.8	3.8 x 10^{-2}	-	168	75	8.54	8.03	50.0	4.27	5.7 x 10^{-5}	-	0.07	-	0	0	8.9 x 10^{-6}	9.8 x 10^{-6}	-
0275	881.5	2.6 x 10^{-2}	-	240	72	7.76	-	46.5	-	-	6	0.14	-	-	-	$<10^{-6}$	8.1 x 10^{-7}	-
0276	884.3	2.4 x 10^{-2}	-	192	185	7.81	7.29	-	-	-	3	-	-	-	-	-	-	-
0277	884.3	3.3 x 10^{-2}	-	216	131	8.14	7.09	50.7	4.13	6.5 x 10^{-5}	-	0.18	-	0	0	2.5 x 10^{-5}	-	-
0278	857.5	3.9 x 10^{-2}	-	168	75	7.44	8.83	-	-	-	2	-	-	-	-	-	-	-
0279	881.9	3.5 x 10^{-2}	-	192	185	8.22	7.68	50.2	4.13	4.0 x 10^{-5}	-	0.11	-	0	0	$<10^{-6}$	3.0 x 10^{-7}	-
0280	879.2	2.8 x 10^{-2}	-	216	252	8.47	7.88	50.7	4.29	1.0 x 10^{-4}	-	0.26	-	0	0	2.0 x 10^{-5}	-	-

Table 24

Impregnation of Short End Plug (5th delivery)

No.	Original			First Impregnation								Second Impregnation						Third Impregnation	
	Weight g	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Pre-polym. Time hr.	Visc. of Impr. cP	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeab. (press.dec.) cm^2 sec^{-1}	Remarks	Resin-Uptake %	Polym. Content %	Carbon Yield %	Sec. Carbon Cont. %	Permeability cm^2 sec^{-1} (Pressure Decay)	(Vacuum Decay)	Permeability cm^2 sec^{-1} Vacuum Decay	Remarks
0338	870.0	4.1×10^{-2}				8.40	-	51.3	4.31	-	6	0.22							
0339	873.9	4.0×10^{-2}				8.96	-	50.9	4.56	-	6	0.31							
0340	871.5	3.3×10^{-2}				9.12	-	47.7	4.35	-	6	0.22							
0341	860.5	7.6×10^{-2}				9.89	-	50.9	5.03	-	6	0.27							
0342	872.1	4.4×10^{-2}				8.01	-	50.1	4.01	-	6	0.19							
0343	871.0	4.9×10^{-2}				9.51	-	51.6	4.91	-	6								
0344	862.8	7.3×10^{-2}				8.03	-	49.8	4.00	-	6	0.30							
0345	858.9	7.3×10^{-2}				10.44	-	51.9	5.42	-	6	0.15							
0346	869.4	4.6×10^{-2}				7.95	-	50.5	4.01	-	6	0.17							
0347	869.7	3.6×10^{-2}				9.31	-	52.6	4.90	-	6	0.26							
0348	869.9	4.2×10^{-2}				8.92	-	50.5	4.50	-	6	0.29							
0349	862.0	3.8×10^{-2}				9.84	-	50.7	4.99	-	6	0.31							
0350	870.1	4.7×10^{-2}				9.33	-	51.6	4.81	-	6	0.22							
0351	868.6	3.8×10^{-2}				7.77	-	52.0	4.04	-	6	0.51							
0352	866.5	4.5×10^{-2}				7.97	-	50.2	4.00	-	6	0.26							
0353	872.2	4.4×10^{-2}				8.21	-	50.2	4.12	-	6	0.21							
0354	867.5	4.2×10^{-2}				9.86	-	49.7	4.90	-	6	0.26							
0355	868.8	3.7×10^{-2}				6.19	-	65.8	4.07	-	6	0.49							
0356	871.2	5.5×10^{-2}				8.67	-	49.4	4.28	-	6	0.40							
0357	864.6	4.3×10^{-2}				9.93	-	51.7	5.13	-	6	0.30							
0358	863.4	6.2×10^{-2}				8.96	-	50.0	4.48	4.6×10^{-4}		0.34							
0359	879.6	5.1×10^{-2}				7.11	-	41.9	2.98	2.9×10^{-4}									
0360	868.1	4.7×10^{-2}				8.05	-	51.4	4.14	-	6	0.30							
0361	866.7	4.1×10^{-2}				8.61	-	50.0	4.30	-	1,6	0.22							
0362	868.4	2.9×10^{-2}				7.81	-	50.0	3.90	-	6	0.22							
0363	868.4	4.6×10^{-2}				8.54	-	51.8	4.42	2.4×10^{-4}		0.19							
0364	873.5	4.2×10^{-2}				8.94	-	51.1	4.57	-	6	0.24							
0365	376.0	4.4×10^{-2}				8.97	-	51.8	4.65	-	6	0.25							
0366	873.9	4.5×10^{-2}				8.10	-	51.9	4.20	-	6	0.53							
0368	873.9	3.9×10^{-2}				8.01	-	50.0	4.00	-	6	0.15							
0369	878.0	3.6×10^{-2}				7.71	-	50.5	3.89	1.2×10^{-4}		0.24							
0370	874.4	3.5×10^{-2}				7.65	-	49.7	3.79	8.3×10^{-5}		0.15							
0371	862.0	6.0×10^{-2}				10.08	-	51.5	5.19	-	6	0.39							
0372	871.5	3.1×10^{-2}				7.81	-	50.5	3.94	-	6	0.11							
0373	872.1	5.0×10^{-2}				9.48	-	51.1	4.84	-	6	0.22							
0374	864.5	3.8×10^{-2}				9.86	-	50.8	5.01	-	6	0.34							
0375	869.6	5.1×10^{-2}				9.55	-	52.3	4.99	-	6	0.22							
0376	870.9	4.4×10^{-2}				8.90	-	48.5	4.32	-	6	0.25							
0377	872.7	3.8×10^{-2}				7.89	-	50.6	3.99	-	6	0.28							
0378	874.1	4.3×10^{-2}				9.15	-	51.1	4.68	-	6	0.27							
0379	868.5	4.4×10^{-2}				9.41	-	51.4	4.84	-	6	0.19							
0380	868.7	little crack measurement impossible																	

Table 25

Summary of Properties of Le Carbone-Lorraine Graphite Grade P2239 (Formed by Compression)

(1) Mechanical and Structural Properties (Room Temperature)

Transverse rupture strength	7,000 psi
Compressive strength	approx double flexural
Tensile strength	approx half flexural
Young's modulus	1.3×10^{-6} psi
Density	1.8 g/cc
Open Porosity	.8%
Shore hardness	55/65

The tensile strength increases with temperature up to approximately 2500°C and then falls off rapidly. At this temperature the strength is approximately double that at 20°C. The modulus increases by more than 50% over the same range.

(2) Thermal and Electrical Properties

Thermal expansion at 100°C	$4.0 \times 10^{-6}/°C$
at 1000°C	$5.3 \times 10^{-6}/°C$
at 2000°C	$6.1 \times 10^{-6}/°C$
Thermal conductivity (20°C)	
Perpendicular to compression axis	0.3/0.35 cals/cm °C sec
Parallel to compression direction	0.2/0.25 cals/cm °C sec

At 1500°C the conductivity is about 30% of the 20°C value.

Specific heat at 100°C	0.18 cals/g°C
at 300°C	0.35 cals/g°C
at 1000°C	0.48 cals/g°C
Electrical resistivity (20°C)	1.5×10^{-3} ohm-cm

Table 26

Estimated Requirements of 3¼" Diameter Graphite Rods in Order to Provide the First Charge for the Reactor Experiment

Losses Subsequent to Purification and Graphitisation

	No. of Components		
	Fuel tube	Outer end plug	Inner end plug
Material to be supplied to machining contractor	606	564	113
Machining and handling loss (7%)	43	40	8
No. left after machining and handling	563	524	105
Material faults found in machining (15%)	85	79	16
No. finished machined	478	445	89
Loss on pressure test (10%)	48	45	9
No. to be impregnated	430	400	80
Loss on impregnation (20%)	86	80	16
No. finished impregnation	344	320	64
Samples	24	12	12
No. to be supplied for degassing	320	308	52
Degassing, assembly and handling loss	40	68	12
No. of finished components for reactor loading	280	240	40

NOTE:

All the above components are assumed to be machined from 79" lengths of 3¼" diameter bar. Each bar could yield one fuel tube or 2 inner and 3 outer end plugs or 4 outer end plugs. On this basis the required input to the machining stage is 762 rods.

Taking into account losses occurring during purification arising from cracked bars and the taking of samples, the number of bars required for purification is 842.

3. WORK IN SUPPORT OF THE FIRST CHARGE

3.1 Fission Product Diffusion

3.1.1 Noble Gases

One of the most important features in the evaluation of the properties of the type of material destined for the initial charge of the Reactor Experiment is the determination of fission product diffusion behaviour through the graphite components [10,11,12]. In the Dragon Project Materials Branch interest has centred on the determination of the diffusion coefficient for Kr-85, krypton being one of the noble gas fission products and a contract was placed with Brown Boveri/Krupp, G.m.b.H. to carry out this work.

All the measurements have been made on tubular specimens of the same outside and inside diameters as in the Reactor Experiment and approximately 6" in length. The tube wall separates two circulating gas systems one containing helium only while the other contains helium with a trace of Kr-85 [13]. Pressures in each circuit can be adjusted independently to allow measurements of the diffusion coefficient to be made with equal total pressures in each circuit or alternatively to study the influence of helium back-sweeping on the diffusion coefficient of Kr-85.

Since it would be impracticable to perform a diffusion test on each component before loading into the Reactor an important objective in this work is to obtain a correlation between the diffusion coefficient for Kr-85 and the permeability to gases since the latter is relatively easy to measure and can be used to characterise each component during the test programme prior to final assembly.

The gas permeability coefficients for a series of impregnated specimens on which diffusion measurements have been made are shown in Table 27. Except for specimen H6/80, all these specimens had been doubly impregnated with furfuryl alcohol. The results of experiments in which the influence of total pressure on the diffusion coefficient for Kr-85 was studied, are shown in Table 28 and Fig. 25. These results suggest that for fuel tube material exhibiting a permeability coefficient to air at room temperature (determined by a simple vacuum decay test) of the order of 10^{-5} cm^2/sec, the diffusion coefficient for Kr-85 at 20 atmospheres and room temperature is less than 10^{-7} cm^2/sec. Further experiments are now proceeding in which the temperature coefficient for Kr-85 diffusion will be studied to allow prediction of the diffusion coefficient under the operating conditions of the Reactor Experiment.

Additional work has been carried out to determine the extent of the back-sweeping of Kr-85 produced by an opposing pressure gradient of helium, the pressure gradients used spanning the range expected in the Reactor Experiment. Although these results, which are reported in Tables 29 and 30 have not yet been fully evaluated, it would appear that even in this fine pored material some back-sweeping occurs which

Table 27

Gas Permeability Coefficients for Specimens used in Krypton Diffusion Studies*

Specimen Number	Test Gas	K Δp = 1.0 atm p_m = 0.5 atm (cm^2/s)	B_o (cm^2)	K_o (cm)
C5/82	He	8.8 x 10^{-6}	57 x 10^{-17}	44 x 10^{-12}
	N_2	4.4 "	37 "	53 "
C5/83	He	19 "	180 "	86 "
	N_2	10 "	66 "	121 "
H6/80	He	32 "	580 "	95 "
H6/82/II	He	51 "	-	-
	Air	31 "	-	-
H6/82/III	He	28 "	-	-
	Air	14 "	-	-
B6/63	He	1.4 "	3.4 x 10^{-17}	7.4 x 10^{-12}
	N_2	0.6 "	4.8 "	8.0 "
B6/64	He	3.0 "	14 "	16 "
	N_2	1.6 "	8.8 "	21 "
B6/66	He	3.5 "	306 "	176 "

*Determined at Winfrith by H. Beutler and P. D. Good

Table 28

Effect of Total Pressure on the Diffusion Constant for Kr-85 in He Through Dragon Fuel Element Graphite

(Brown Boveri-Krupp, F.R. of Germany)

Specimen Number	$D\ (cm^2/s) \times 10^7$		
	0.5 atm	1 atm	5 atm
C5/82	12.8	7.1	1.73
C5/83	27.0	14.5	3.30
H6/80	15.4	8.7	2.52
H6/82/II	3.3	2.0	0.88
H6/82/III	2.0	1.5	0.63
B6/63	1.8	1.5	0.35
B6/64	4.0	2.4	0.72
B6/66	7.5	4.5	1.00

Table 29

Back-Diffusion of Kr-85 Against a Pressure Gradient of He Through Dragon Fuel Element Graphite

(Brown Boveri-Krupp, F.R. of Germany)

	Back-diffusion constant $(cm^2/s) \times 10^7$		
$P_{HeKr-85}:P_{He}$ (atm)	1.0:1.0	1.0:1.1	1.0:1.5
Specimen Number			
H6/80	8.7	1.7 2.3	0.56 0.90
H6/82/II	2.0	0.36 0.17	0.072 0.096
H6/82/III	1.5	0.14 0.12	0.14 0.072

Table 30

Diffusion and Back-Diffusion of Kr-85 in Helium through Single-Impregnated Fuel Tube Material at Room Temperature

(Brown Boveri-Krupp, F.R. of Germany)

$P_{HeKr-85}$: P_{He} (atm)		Diffusion Constant $cm^2/sec \times 10^5$			
		Individual Measurements			Mean
Specimen No. H/6/79/III					
1.0	1.0	6.15	5.63	6.06	5.95
1.0	1.1	3.93	4.06		4.00
1.0	1.2	2.09	2.23		2.16
1.0	1.4	0.73	0.73		0.73
2.0	2.0	3.39	3.68		3.53
2.0	2.1	1.88	2.07		1.98
2.0	2.2	1.40	1.43		1.41
2.0	2.4	0.55	0.62	0.57	0.58
5.0	5.0	2.03	1.88		1.95
5.0	5.1	0.98	1.11	1.01	1.03
5.0	5.2	0.52	0.53		0.52
5.0	5.4	0.22	0.26		0.24
Specimen H/6/79/I					
1.0	1.0	4.91	5.00	5.11	5.01
1.0	1.1	2.79	3.53	3.31	3.28
1.0	1.2	1.73	1.84	1.79	1.78
1.0	1.4	0.42	0.38		0.40
2.0	2.0	3.02	2.87		2.94
2.0	2.1	2.08	2.03		2.05
2.0	2.2	0.65	0.64		0.64
2.0	2.4	0.15	0.15		0.15
5.0	5.0	1.04	1.03		1.03
5.0	5.1	0.61	0.64	0.63	0.63
5.0	5.2	0.30	0.34		0.32
5.0	5.4	0.081	0.076		0.078

will assist in a further minimisation in the escape of the noble gas fission products into the primary circuit.

3.1.2 Non-gaseous Fission Products

Although the design philosophy of the Reactor Experiment has been based on the control of fission product activity through the gaseous purge system it has become evident that not all the fission products behave as the noble gases but are transported through graphite bodies by mechanisms other than gaseous diffusion. Thus, recently reported work [14] has shown, for example, that caesium, strontium and barium move with approximately equal rapidity through graphites in which the gaseous permeability varies by nearly three orders of magnitude. This, coupled with the fact that the diffusion constants are associated with activation energies between 7 and 20 Kcals has lead to the conclusion that the transmission process is one of activated surface diffusion on the pore walls of the graphite. This view is also held by workers at General Atomic [15] who have also shown that the diffusion coefficients cannot be correlated with material or helium permeability. Diffusion coefficients for barium and caesium are stated to be of the order of 10^{-6} cm^2/sec or less but there is also evidence that these fission products are very strongly adsorbed leading to very high mass flows. Because of the very high adsorption coefficient for these fission products on the graphite it is questionable whether the purge flow will be effective in carrying them into the fission product trapping system. Under these circumstances it is expected that the fuel element graphite will adsorb the fission products. The loss of these fission products into the primary circuit is then likely to depend on the rate of evaporation from the surface of the fuel elements after the delay in passing through the fuel tube and the main problems may then be associated with deposition in the heat exchangers.

The situation is, however, complicated by other factors such as the possibility of reaction with the impurities in the coolant and the graphite, surface migration along the fuel tube and the degree of retention within the fuel compacts themselves. It is evident that a true picture of the migration behaviour of fission products which move by surface diffusion will only come with the operation of the Reactor itself but it is hoped that irradiation experiments in which the conditions of operation of the Reactor are simulated, particularly the Pluto loop, will indicate the type of behaviour which can be expected during operation of the Reactor Experiment.

3.2 Mechanical and Physical Properties

Initial work on the characterisation of the fuel element graphite from the viewpoint of its physical and mechanical properties was carried out under contract to Dragon by the Hawker Siddeley Nuclear Power Co. Ltd. This study was not exhaustive but the main objective at this time was to obtain sufficient information to provide design data. Measurement of the ultimate strength in flexion and modulus of elasticity were made at temperatures up to 1000°C in addition to a determination of the coefficient of thermal expansion. The thermal conductivity in the parallel direction only was measured on unimpregnated material up to 745°C. These results are summarised in Tables 31 and 32 [16].

Table 31

Thermal Properties of Fuel Element Graphite (Grade 1)

TEMPERATURES °C	330	370	485	545	745
Thermal Conductivity cal/cm/°C/sec (Parallel) (Untreated)	0.147	0.122	0.105	0.093	0.087

TEMPERATURE RANGES	20-400°C	20-600°C	20-800°C	20-1000°C
Thermal Expansion Coefficient (x 10^{-6}/°C)				
Parallel (Untreated)	1.89	2.13	2.34	2.49
Perpendicular (Untreated)	3.8	4.5	4.8	5.5
Parallel (2 Impregnations)	1.81	2.05	2.20	2.31

Table 32

Summary of Mechanical Properties of Fuel Element Graphite (Grade 1)

	PARALLEL			PERPEN-DICULAR
	20°C	600°C	1,000°C	20°C
1. Transverse Rupture Test (4 point loading)				
Elastic Modulus - Untreated (psi x 10^6)	1.76 + 12% - 8%	1.79 + 14% - 9%	1.83 + 12% - 4%	0.71
2 Impregnations	2.65 + 8% - 9%	2.57 + 7% - 12%	2.44 + 10% - 8%	-
Flexural Strength - Untreated (psi)	3,600 + 8% - 14%	4,000 + 20% - 13%	4,400 + 11% - 39%	3,000
2 Impregnations	5,800 + 5% - 9%	6,600 + 8% - 11%	7,200 + 11% - 20%	-
% Strain at Fracture - Untreated	0.18 + 11% - 28%	0.20 + 20% - 20%	0.22 + 18% - 41%	0.13
2 Impregnations	0.20 + 15% - 15%	0.24 + 8% - 13%	0.28 + 7% - 14%	-
2. Compression Test				
Elastic Modulus - Untreated	0.81	-	-	0.42
(psi x 10^6) 2 Impregnations	1.32	-	-	0.64
Ultimate Compressive - Untreated	11,000	-	-	9,100
Strength (psi) 2 Impregnations	17,400	-	-	12,300

In the case of thermal conductivity it was possible to indicate proposed standard values for EY 9 type graphites from the limited low temperature data at that time available and from a knowledge of the temperature dependence of the thermal conductivity in graphites generally. Since this time more data has accumulated which has, in general, justified the originally estimated values. All the data are plotted in Fig. 26, together with the original proposed standard values. In addition some values are shown on this curve showing measurements made on a section of fuel tube which had previously been irradiated in a Risø capsule experiment [17]. (Conditions of irradiation: temperature c.a. 900°C integrated neutron dose approximately 2×10^{20} nvt at $E > 0.1$ MeV.)

Work is still proceeding on the determination of physical mechanical properties. Measurements of the mechanical properties up to temperatures in excess of 2000°C are being carried out by Sud Aviation, France, and as mentioned in Section 3.5 it is hoped that during 1963 the graphite irradiation programme at the Reactor Centrum Nederland will yield information concerning the effects of irradiation on important physical and mechanical properties.

3.3 Degassing, Regassing and Oxidation

An important feature arising from the use of furfuryl alcohol impregnation in the production of the fuel elements is the nature of the furfuryl alcohol carbon blocking the pore system. After baking to 1000°C the carbon contains appreciable quantities of gas and also leads to a very high reactivity in oxidising environments [8]. During the early work on impregnation it was found that the gas content could be reduced to acceptable levels and the overall oxidation rate significantly reduced by high temperature heat treatment following impregnation [8]. A regraphitisation treatment is probably most desirable but in practice could not be considered because of the difficulty in regraphitising fully machined components and because such a treatment is likely to lead to distortion. Furthermore, it was found that the rate of heating during the degassing operation was critical particularly in the range 1000°C to 1500°C where heating rates in excess of about 100°C/hour led to the components being damaged by spalling, similar in form to that which can occur during the initial baking following impregnation.

Following this exploratory work a contract was placed with the Central Institute of Industrial Research, Oslo, Norway to study, in more detail, problems related to the degassing and regassing of the graphites which would be used in the Reactor Experiment. These studies include measurements of the gas content after various heat treatments coupled with the influence of environment during storage. In this latter context the water vapour content of the storage atmosphere is particularly important since it is generally believed that the main source of gas release during the heating of graphite is that arising from the presence of adsorbed water vapour.

Because of the considerably greater mass of the reflectors in the Reactor and the consequent impracticability of performing a degassing and dry storage operation prior to stacking in position, it is likely that the reflectors will be initially responsible for the major proportion of oxidising impurities during the commissioning of the Reactor. Work is also proceeding on this topic but will not be covered in this paper. Once the Reactor is commissioned however, the insertion of fresh fuel elements is likely to lead to surges in oxidising impurity levels in the primary circuit.

Accordingly the work on the fuel element graphite at the Central Institute of Industrial Research has been aimed at deciding upon an appropriate heat treatment operation to be carried out on the fuel element graphite after impregnation and prior to final assembly and to measure the gas release on subsequent heating after storage in different environments. Some results obtained on carrying out two different treatments are shown in Tables 33 and 34.

In the first treatment, specimens were heated under controlled conditions under vacuum to 1500°C while an alternative process was to heat to 1900°C in argon. Immediately after cooling some of the specimens were reheated and the gas evolution measured at temperature intervals in the range 350°C to 2000°C. Other specimens were stored for known times in nitrogen, containing 100 vpm water vapour and in air containing 13,800 vpm water vapour, prior to the measurements of the gas evolution.

Comparing the results shown in Tables 33 and 34 it will be noted that immediately after degassing the vacuum treated specimens exhibit a lower gas content than those treated to a higher temperature in argon. During storage, however, it is evident that the adsorption is much more pronounced with the vacuum treated specimens, the gas contents being an order of magnitude greater than in the 1900°C treated samples even though the latter were stored for double the time before analysis. Summarised results of other similar experiments are shown in Table 35 and these tend to confirm the above conclusions.

This work is continuing and final decisions on the nature of the degassing operation and storage condition have not yet been made. It is likely however, that the heat treatment will be essentially similar to the treatment in argon described above and that no specially dry storage conditions will be imposed.

As mentioned previously in this section, the degassing operation plays an important role in minimising the overall oxidation of the graphite. The Project has investigated the oxidation problems associated with the fuel element and it has been found that although the overall level of oxidation is of a tolerable magnitude and severe attack at the area which is expected to suffer the worst damage (at the top of the purge channel) can be avoided by good design, difficulties may arise as a result of pitting corrosion. This problem together with a more detailed account of the work on oxidation is covered separately in this Symposium [4].

3.4 Radiation Effects

In considering the irradiation damage which is likely to occur during the operation of the Reactor Experiment it is first necessary to take into account the neutron flux levels and energies which are expected. Table 36 shows the maximum and average anticipated values for the integrated fast neutron doses which would be achieved during one year's operation at full power. Since the damage to the graphite is primarily caused by fast neutron bombardment only neutron energy values above 0.1 MeV have been considered.

In the Dragon irradiation programme [18], which has been mainly concerned with fuel irradiation, the fuel element graphite specimens have generally been of a tubular shape in order to contain the fuel so as to simulate conditions in the Reactor Experiment. This has precluded a systematic investigation of the effects of the irradiation on the properties of the graphite, not only

Table 33

Fuel Element Graphite 8/6

Heat Treatment A: 1500°C

$20^{\circ}C \xrightarrow{4\ hr} 1000^{\circ}C \xrightarrow{5\ hr} 1500^{\circ}C$ (4 hr)

Rotary pump giving ~10^{-1} mm Hg. After cooling to 200°C, admittance of N_2 (pure, with 5 vpm H_2O). Table below showing vacuum fusion gas analyses of parallels.

Analysis No.	Sample Weight in g	Exposure Conditions	Gas Analysis N cm³/100 g				Total
			Temp. °C	H_2	N_2	CO	
0286	0.3966	immediately analysed	350	0.311	1.047	-	
			750	0.518	-	-	
			1000	0.744	-	0.61	
			1200	0.941	-	-	
			1500	0.226	-	-	
			2000	0.433	-	-	
				3.173	1.047	0.61	4.830
0287	0.3574	immediately analysed	350	1.107	-	-	
			750	1.128	-	-	
			1000	0.815	-	-	
			1200	0.611	-	-	
			1500	0	-	-	
			2000	0.313	-	-	
				3.974	-	-	3.974
0318	0.3490	stored in N_2 (100 vpm water vapour) for 36 days	350	28.031	3.017	3.997	
			750	11.190	0.794	0.740	
			1000	2.865	-	1.036	
			1200	3.209	-	1.332	
			1500	4.981	-	-	
			2000	7.306	-	1.332	
				57.582	3.811	8.437	69.830
0319	0.38445	stored in N_2 (100 vpm water vapour) for 36 days	350	22.451	2.523	2.822	
			750	7.249	0.649	1.881	
			1000	2.953	-	-	
			1200	2.826	-	1.478	
			1500	4.731	-	1.075	
			2000	6.300	-	0.806	
				46.510	3.172	8.062	57.744
0320	0.3840	stored in air containing ~13,800 vpm water vapour for 36 days	350	63.735	2.526	15.740	
			750	10.126	0.289	3.498	
			1000	4.083	-	4.440	
			1200	3.122	-	0.807	
			1500	4.119	-	0.538	
			2000	4.820	-	0.807	
				90.005	2.815	25.830	118.650
0321	0.4308	stored in air containing ~13,800 vpm water vapour for 36 days	350	65.453	2.701	16.908	
			750	5.641	-	3.358	
			1000	2.081	-	2.758	
			1200	2.698	-	0.959	
			1500	3.287	-	0.360	
			2000	3.457	-	0.600	
				82.616	2.701	24.943	110.260

Table 34

Graphite Sample 8/6

Heat Treatment B: 1900°C

$20^\circ\mathrm{C} \xrightarrow{4\ \mathrm{hr}} 1000^\circ\mathrm{C} \xrightarrow{5\ \mathrm{hr}} 1900^\circ\mathrm{C}$ (4 hr)

Heating in inert gas, i.e. 1 atm Argon, flow 7 l/min. After cooling to 200°C, the samples placed in a desiccator filled with Argon. Table below showing vacuum fusion gas analysis of parallels.

Analysis No.	Sample Weight in g	Exposure Conditions	Gas Analysis N cm^3/100 g				Total
			Temp. °C	H_2	N_2	CO	
0307	0.34361	immediately analysed	350 750 1000 1200 1500 2000	13.245 1.525 1.752 0.685 0.841 1.351	- - - - - -	2.085 0.379 - - - -	
				19.139	-	2.464	21.603
0311	0.2641	immediately analysed	350 750 1000 1200 1500 2000	5.797 1.277 1.356 1.153 1.978 2.031	- - - - 0.429 -	2.791 - 0.507 1.522 1.269 3.044	
				13.592	0.429	9.133	23.154
0347	0.2901	stored in N_2 (100 vpm water vapour) for 71 days	350 750 1000 1200 1500 2000	0 0.202 0.434 0.764 1.760 2.478	0.337 - - - - -	0.294 0.441 - 0.882 0.882 -	
				5.638	0.337	2.499	8.474
0348	0.3234	stored in N_2 (100 vpm water vapour) for 71 days	350 750 1000 1200 1500 2000	0 0.170 0.641 0.626 2.271 2.445	0.076 - - - - -	- 0.396 0.132 0.396 - -	
				6.153	0.076	0.924	7.153
0359	0.32300	stored in air containing 13,800 vpm water vapour for 76 days	350 750 1000 1200 1500 2000	1.361 0.855 0.420 0 2.891 2.231	1.334 - - - - -	0.516 0.516 0.258 0.516 0 0	
				7.758	1.334	1.806	10.898
0360	0.28	stored in air containing 13,800 vpm water vapour for 76 days	350 750 1000 1200 1500 2000	3.099 1.760 0.385 0 2.725 1.394	- - - - - -	0.572 0.429 0 0 0 0	
				9.363	-	1.001	10.364

Table 35

Gas Release from Impregnated Dragon Grade-3 Graphite Stored in Atmospheres Containing 100 vpm and 13,800 vpm Water Vapour

Specimen	Heat treatment conditions	Gas content (μl/g)					
		Immediately analysed		Stored in N_2 +100 vpm H_2O		Stored in Air 13,800 vpm H_2O	
		H_2	CO	H_2	CO	H_2	CO
Fuel element graphite 8/6 Furfuryl alcohol char content 4.4% by wt ($K > 10^{-5}$ cm^2/s)	1500°C (10^{-1} mm Hg)	32 40	6 0	576 465	84 81	900 826	258 249
				36 days		36 days	
	1900°C (1 atm Ar)	191 136	25 91	56 62	25 9	78 94	18 10
				71 days		76 days	
Fuel element graphite 8/10 Furfuryl alcohol char content 4.7% by wt ($K = 1.8 \times 10^{-6}$ cm^2/s)	1500°C (10^{-1} mm Hg)	68	54	257 334	95 236	469 459	258 253
				85 days		88 days	
	1900°C (1 atm Ar)	134 128	30 117	118 109	22 16	140 241	34 43
				72 days		77 days	
Fuel element graphite 8/11 Furfuryl alcohol char content 5.0% by wt ($K = 7.1 \times 10^{-6}$ cm^2/s)	1500°C (10^{-1} mm Hg)	93 63	106 40	450 -	189 -	603 528	227 143
				30 days		79 days	
	1900°C (1 atm Ar)	106 50	52 91	75 93	21 30	196 214	41 41
				72 days		77 days	

because of the [illegible] arising from the shape of the specimens but also because in most cases the irradiated graphite is highly active due to contamination with fission products. In the post-irradiation examination of the graphite attention has therefore been mainly devoted to examining the effect of the irradiation on the principal dimensions though some measurements of permeability and thermal conductivity changes have also been made. A further limitation is associated with the level of fast neutron dose achieved during the irradiation. Although the fission rate in the fuel specimens is equivalent to, or in excess of that expected in the Reactor Experiment the fast neutron dose is only a fraction of the values given in Table 36. Thus, for example, in the early Dido irradiations, the damage flux, set at a lower limit of neutron energy of 0.1 MeV, is only of the order of one hundredth of that in the Reactor Experiment [19]. Even-so, with integrated fast neutron doses of only from 1 to 6 x 10^{19} n cm^{-2} at temperatures of about 800°C measurements of the dimensions of the graphite fuel cans indicated shrinkage of between 0.1 and 0.2%.

Similar results were deduced from the first charge of the Pluto Loop experiment though these results were complicated by the influences arising from dimensional changes in the fuel. Additional measurements showed that the irradiation did not affect the gas permeability significantly but caused the thermal conductivity to fall by about 12% [20]. Dimensional changes observed in a fuel sleeve irradiated at Risø (estimated neutron dose 2 x 10^{20} n cm^{-2} $E > 0.1$ MeV) are shown in Table 37. These indicate shrinkages of about 0.25% in the direction perpendicular to the extrusion direction and 0.06% in the parallel direction. The effect of the irradiation on the thermal conductivity could not be accurately measured as it was not possible to perform a measurement on the unirradiated tube because of size limitations. Comparing the value measured on a section cut from the irradiated tube with typical unirradiated values from Fig. 26 suggests that the thermal conductivity had been reduced by about 40%. This has already been referred to in Section 3.2.

If the total doses received in the above experiments are compared with those expected in the Reactor shown in Table 37 it can be seen that considerable changes are likely to occur in the properties of the graphite during operation. If, for example, the contraction is a linear function of dose then considerable dimensional changes are to be expected. Data obtained from General Atomic and Hanford referred to in Section 4.2 (Table 40 and Fig. 30) do in fact show that the shrinkage of EYX 60 graphite continues to increase with dose and values of the order of 1.6% in both parallel and perpendicular direction can be expected at levels of exposure comparable with those in the Reactor Experiment. This would result in the fuel tubes in the reactor shrinking during one year's operation at full power to the extent of 1" of more. Although this degree of shrinkage is not disturbing in itself differential effects arising from the influence of temperature and flux variations may lead to stress build-up and perhaps cracking [21].

In order to elucidate the effects of irradiation on graphite a series of irradiation experiments concerned entirely with graphite are planned in the H.F.R. at Reactor Centrum, Petten Holland. In these experiments it is hoped to measure the major properties (dimensions, thermal expansion, thermal conductivity, Young's Modulus and strength) both before and after irradiation.

Table 36

Anticipated Fast Neutron Doses for 1 Year Operation of Dragon at Full Power

	Neutron Energy Levels	
	$E > 0.1$ MeV	$E > 1$ MeV
Integrated flux in Core Centre	2.20×10^{21}	0.85×10^{21}
Integrated flux in Core Average	1.69×10^{21}	0.63×10^{21}

Table 37

Dimensional changes resulting from irradiation of fuel element sleeve in Risø Cone Replacement Rig. No. 1.

(Estimated neutron dose 2×10^{20} n cm^{-2} $E > 0.1$ MeV)

1. Diameter (inches) (perpendicular to direction of extrusion)

Two measurements made at right angles at each station

Station	Before Irradiation		After Irradiation		Change	
1	2.511	2.511	2.505	2.504	- 0.006	- 0.007
2	2.511	2.511	2.505	2.505	- 0.006	- 0.006
3	2.511	2.511	2.506	2.505	- 0.005	- 0.006
M	2.511	2.511	2.504	2.505	- 0.007	- 0.006
4	2.511	2.511	2.506	2.505	- 0.005	- 0.006
5	2.511	2.511	2.506	2.505	- 0.005	- 0.006
6	2.511	2.511	2.506.	2.508	- 0.005	- 0.003

2. Length (inches) (parallel to direction of extrusion)

Before Irradiation	After Irradiation	Mean Change
20.748 20.749	20.733 20.735 20.740 20.737	- 0.012

Work of a more basic nature is being carried out.

(a) under direct contract by the Battelle Institute, Geneva, Switzerland

(b) under an arrangement with Hanford Laboratories.

At the Battelle Institute, optical and electron microscopic techniques are being used to study the effects of radiation damage on the microstructure of graphite. Currently specimens of irradiated graphite supplied by Hanford Laboratories are being examined.

Under the above arrangement with Hanford, a series of model graphites of known composition was made by Compagnie Pechiney and at AERE, Harwell. The first series, which is currently being irradiated by Hanford had, as primary variable, the proportion of carbon black in the mix. Initial results are given in Table 3d.

4. GRAPHITE DEVELOPMENT

4.1 Development of Alternatives to Morgan EYX 60 Graphite

The position reached by November, 1959 was summarised at the Dragon Graphite Symposium [1]. At that stage the only manufacturing development was being carried out by AERE, Harwell. Up to that time, the main requirements for fuel element graphite had been high density and low permeability and two different types of material, coded HX 10 and HX 12 respectively had accordingly been developed [7,22].

It was found, however, that HX 10 was unsuitable for treatment by the particular furfuryl alochol impregnation process developed for the impregnation of the EY 9 family of materials. The impregnated material frequently spalled during the curing and baking process and the resultant permeability was not better than 10^{-5} cm^2/sec. These defects were attributed to the coarser pore spectrum of HX 10. HX 12 was not taken further because of doubts concerning the irradiation behaviour of its furfuryl alcohol resin binder.

After the inception of the Project, work was continued at AERE, Harwell so as to reap the benefit of the manufacturing experience there.

The work was directed towards producing an HX 10 type of material which, by variation of the raw materials, would have pore properties suitable for impregnation with furfuryl alcohol. To this end an extensive permutation experiment was carried out in which the proportions of four filler components were systematically varied. The four filler components used were:-

(i) British Reactor Grade A graphite ground to -60 mesh B.S.S.

(ii) British Reactor Grade A graphite ground in a vibrating ball mill to give a 5-20 micron product (so-called Vibro-Energy mill fines).

(iii) Dixitherm M, a medium thermal carbon black, particle size 0.4 micron, supplied by the Anchor Chemical Company, Manchester, England.

(iv) Dixi-R-Paris, an ultrafine carbon black, particle size 0.02 micron, supplied by the Anchor Chemical Company, Manchester, England.

Table 38

Preliminary Irradiation Results on Dragon Graphites Manufactured with Varying Carbon Black Contents

(Graphites Prepared by Compagnie Pechiney, Chedde, France and Irradiated by Courtesy of Dr. R. E. Nightingale, Hanford Atomic Products Operation, U.S.A.).

Hanford Identification Number	Sample No.	Pechiney Grade	Mix Composition			Irradiation Results	
			Graphite Powder (% of the grist)	Thermax Medium Thermal Carbon Black (% of the grist)	Pitch Binder (% of the grist)	Length change (%)	
						Transverse	Parallel
61-79	2828-2 2828-4	PZ 43	50	50	31.0	- 0.068 ± 0.008	- 0.061 ± 0.004
61-78	2822-1 2822-2 2822-3 2822-4	PZ 42	67	33	26.5	- 0.043 ± 0.005	- 0.060 ± 0.004
61-77	2837-2 2837-4	PZ 44	75	25	28.5	- 0.047 ± 0.005	- 0.046 ± 0.000
61-76	2847-2 2847-4	PZ 45	80	20	28.5	- 0.044 ± 0.008	- 0.039 ± 0.005
61-75	3599-2 3599-3	PZ 46	100	0	44.0	- 0.014 ± 0.008	- 0.035 ± 0.015

CSF (for comparison)	
0.000	- 0.015

NOTES

1. All the above specimens were baked at atmospheric pressure and were not impregnated. They were graphitised in several different runs to 2700°C (using the same heating schedule) and then reheated all together to 3000°C, the final temperature being held for ½ hour. The maximum particle size of the graphite was 122 microns.

2. Samples were irradiated in a Hanford Reactor at approximately 650°C to an exposure of 2640 Mwd/At (equivalent to approximately 6.2×10^{20} nvt, E > 0.18 MeV)

Examination of the test results on the 24 different mixes when grouped according to composition led to the following general conclusions [23]:-

(i) increasing the ratio of total graphite to total carbon black caused an increase in the number of pores of all sizes;

(ii) increasing the ratio of Vibro-energy Mill graphite fines to -60 B.S.S. graphite caused a decrease in the number of large pores but increased the overall open porosity;

(iii) the effect of introducing fine carbon black into the mix was not very marked.

Extrapolation of these trends led to the formulation of a mixture to give a steep pore size distribution commencing at about 1 micron. This graphite which had the following composition (exclusive of binder):-

Graphite powder -60 mesh	42% by weight
Vibro-energy Mill graphite fines	18%
Medium thermal carbon black	40%

was manufactured under standard conditions and the pore size distribution was found to be satisfactory. Tubes of this material, designated HX 20, impregnated twice with furfuryl alcohol using a standard Dragon procedure gave a permeability of 10^{-7} cm^2/sec measured using a Kr-85 radioactive tracer method, after heat treatment to 2000°C in an argon atmosphere.

Some effort was then devoted to examining the influence of the separate manufacturing steps in order to improve the product quality.

The mixing and extrusion stages were examined in some detail. It was eventually concluded that the method of constraining the samples during baking is all-important. This was confirmed by the condition of samples which came out well. In all such samples the ends had internal flaws, the frequency of which lessened towards the centre of the rod.

Although at least six different packing experiments were carried out, good samples were not made systematically and the tantalising situation remains that good samples have been apparently fortuitous. This leads to the supposition that there is a particular combination of packing and baking methods which is successful, or else some unknown factor has still to be discovered.

This work at Harwell is essentially of a research nature: parallel work aimed primarily at pilot plant production has been carried by Compagnie Pechiney, Chedde, Haute Savoie, France.

The initial departure point for the work by Compagnie Pechiney was a requirement for a high density reflector (apparent density 1.90-1.95 g/cm^3). Since no suitable production grade was available, a development contract was placed in April, 1960 with Compagnie Pechiney. A survey of possible methods showed that the best approach was to use an extruded graphite - carbon black pitch composition and to use pressure baking i.e. an HX 10 type of graphite [7]. The results of this work have been reported [24] and are summarised in Table 39.

TABLE 3[illegible]

(A) INFLUENCE OF THE PROPORTION OF BLACK ON THE APPARENT DENSITY

Formulation (Graphite Size grading CO_2 throughout)	Treatment				Apparent Density (g/cm^3)				
	Baked to 900°C (atmos. press.)		Pressure Baked to 550°C then rebaked to 900°C (atmos. press.)		Baked				
	Graph	Imp Graph	Graph	Extruded	900°C atmos. press.	550°C under press.	550°C under press. then 900°C atmos. press.	After impregnation	**Graphitised**
½ Graph ½ Black	X			1.78	1.75				1.85
		X						1.78	1.92
			X			1.74	1.81		1.95
⅔ Graph ⅓ Black	X			1.82	1.75				1.81
		X						1.82	1.89
			X			1.7[illegible]	1.81		1.89
¾ Graph ¼ Black	X			1.82	1.74				1.79
		X						1.81	1.86
			X			1.72	1.7[illegible]		1.84
$\frac{4}{5}$ Graph $\frac{1}{5}$ Black	X			1.81	1.72				1.75
		X						1.79	1.81
			X			1.6[illegible]	1.7[illegible]		1.79

(B) INFLUENCE OF THE SIZE GRADING OF THE GRAPHITE FRACTION ON THE APPARENT DENSITY

Formulation	Treatment					Apparent Density (g/cm^3)				
	Baked to 900°C (Atmos. Press.)		Pressure Baked to 550°C then rebaked to 900°C (atmos. press.)			Baked				
	Graph	Imp Graph	Graph	Graph	Extruded	900°C atmos. press.	550°C under press.	550°C under press. then 900°C atmos. press.	After impregnation	Graphitised
Size Grading F01		X			1.82	1.77			1.85	1.92
			X				1.73	1.83		1.90
⅔ Graph ⅓ Black				X					1.87	1.93
Size Grading CO_2	X				1.82	1.75				1.81
		X							1.82	1.89
⅔ Graph ⅓ Black			X				1.75	1.81		1.89
				X					1.85	1.92
Size Grading A01	X				1.79	1.71				1.79
⅔ Graph ⅓ Black			X				1.68	1.75		1.85

At the end of the development work (September, 1960) it was intended to transfer to production scale and preliminary successful experiments with 200 mm diameter extrusions had already reached a density of 1.90 g/cm^3. However, reactivity results from Zenith became available and as a result the density requirement was eased to 1.80-1.85 g/cm^3. This completely transformed the problem and so work on high density graphite by Compagnie Pechiney was curtailed.

The Project decided in October, 1960 to sponsor its own development of fuel element graphite. An extensive survey of the European graphite industry had been carried out in February, 1960. The industry can be roughly divided into two types of manufacturer:-

(a) large-scale manufacturers (capacity up to 40,000 tons/annum) specialising in large electrodes;

(b) smaller scale manufacturers specialising in higher priced fine grain components such as electric brushes.

As a result of the survey it had been recommended that development work should be carried out with one of each of the above types of manufacturer. In the event, however, agreement was only reached with a representative of the large-scale type of manufacturer, Compagnie Pechiney.

Two main types of composition were chosen for study, of which one was effectively a continuation of the high density development:-

graphite - carbon black - pitch
coke - carbon black - pitch.

It should be pointed out that the high density development indirectly assisted the development of low permeability graphite because many of the processing problems are common to both types of development.

Of the two main compositions studied, in an attempt to simulate the pore size distribution of EY 9 type materials, that based on coke-carbon black pitch gave consistently poor results. Much better results were obtained, on the laboratory scale, with the other type of composition based on graphite carbon black pitch.

This work (which confirmed the Harwell work mentioned earlier), showed that a steep pore size distribution can only be achieved with a very fine mix containing a high proportion of carbon black.

Two mixes were chosen for transfer to pilot plant production (i.e. specimen size 85 mm diameter, 2200 mm long). These were coded G1 and G2 and their respective compositions are given below:-

	Composition (parts by weight) G1	 G2
Graphite powder (-60 mesh)	2/3	2/9
Micronised graphite powder	nil	4/9
Thermal carbon black (Thermax)	1/3	1/3
Coal tar pitch	To suit the extrusion conditions.	

The pore spectra of G1 and G2 are given in Fig. 27. The G1 composition with its larger "tail" of coarse pores (as measured by a mercury porosimeter) was retained in order to confirm whether the furfuryl alcohol impregnation process is so specific as had been deduced earlier [1].

Subsequent work led to the abandonment of the G1 type of composition. Its larger "tail" of coarse pores was apparently the cause of ressuage and spalling problems. The G2 formulation then had to be modified in order to accommodate an inevitable change in the particle size of the micronised graphite component. The revised G2 formulation, termed G4, had the following composition:-

	G4
Graphite powder (-60 mesh)	1/3
Micronised graphite powder	1/3
Thermal carbon black	1/3
Coal tar pitch	To suit the extrusion conditions.

The pore spectrum of G4 given in Fig. 27 shows that it is a close substitute for G2. It illustrates the fact that a change of particle size of one of the ingredients is less serious as knowledge is gained of the factors governing the pore spectrum. This knowledge has been crystallised in a patent application which relates the problem to the size distribution of the components (D.P.P.S.42).

Although most of the laboratory work was concentrated on the G2 and G4 compositions given above, various alternatives have been examined. Thus several types of carbon black have been investigated, but only the coarser blacks, such as medium thermal and fine thermal blacks, gave material of good texture. A substitution of a medium thermal black by a fine thermal black resulted, as expected, in a slight shift towards a finer pore spectrum. An interesting point to note is that although replacement of the graphite powder by coke powder results in material of poor texture, the pore spectra of graphites made from similar coke/black/pitch and graphite/black/pitch mixes are vitually indistinguishable. Additionally various extrusion lubricants were investigated but since they impaired the cohesion of the mix, subsequent processing was rendered more difficult.

A considerable effort was put into experiments on baking of full-scale G1, G2 and G4 extrusions. It was clearly demonstrated that there is a considerable interaction between the material being baked and its surrounding packing. Measurements of the pseudo-compressibility and elasticity of coke, coke/sand and graphite packing powders suggested that coke/sand was the best compromise as a packing material.

During baking the material initially expands both radially and longitudinally. If the radial expansion is not restrained then longitudinal fissures develop. However, later on during the baking process the material begins to contract. If too great an initial constraint is applied then the subsequent longitudinal contraction is hindered and transverse cracks develop.

Originally a solution to the problem of baking was sought in one of two ways:-

(a) By formulating a method of packing which would allow material to be baked to 800 or 900°C in a single operation.

(b) By baking in a constrained packing until a specific temperature and then rebaking in a relatively loose packing medium.

Detailed examination of the irreversible dimensional changes occurring during the baking of G4 (see Fig. 28) suggested that a single-stage baking operation was unlikely to succeed and exploratory work on the lines of method (a) above confirmed this belief.

As work on the two-stage operation continued it became evident that a further factor was interfering, namely the modification of the packing due to distillation and decomposition products from the binder (note the evolution of the weight loss in Fig. 30). This new factor led to the development of a packing material composed of sand and plaster of Paris which exhibited the radial constraint of sand and which had considerable ability to "soak up" material from the binder.

In the meantime, the work on the two-stage baking operation was aimed at defining the specific final temperature of the first baking operation. Sound products (85 mm diameter, 2 m long) were eventually obtained using the sand-plaster packing by stopping the baking process at 350°C. Baking under the same conditions to 450°C or higher led invariably to products having transverse fissures.

At this stage a re-examination of the technical position indicated that it would be more profitable to move away from mixes containing carbon black. This is elaborated in the next section.

4.2 Disadvantages of the Current Fuel Element Graphite*

The disadvantages of the present type of Dragon Grade 9 Fuel Element graphite can be listed as follows:-

(a) High cost.
(b) Poor dimensional stability under irradiation.
(c) Low thermal conductivity.
(d) Somewhat unpredictable strength characteristics.

As indicated earlier, the base material is difficult to manufacture and the average yield is not better than 33%. In addition to this, since the

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*Although this section deals with the shortcomings of the present fuel element graphite, it should be remembered that without the rapid development of such graphite the evolution of high temperature gas cooled reactors would have been delayed.

base material is not pure (or, more correctly, not reliably impure) the Project has to shoulder all the problems inherent in

(i) Purchasing the raw material from Morganite Carbon Limited, England.

(ii) Despatching it by road to Compagnie Pechiney, France for graphitisation and purification.

(iii) Returning it by road to the United Kingdom for machining by Graviner Mfg. Co. Ltd.

(iv) Flying the machined tubes and end plugs to West Germany for impregnation by Sigri Kohlefabrikate.

(v) Returning the impregnated tubes and end plugs to Winfrith for degassing.

It is obviously a far too extended production line and it results in the Project having to purchase approximately 3 rods for every rod actually placed in the Reactor (see Section 2.6). Adding the Project's losses to those estimated for Morganite Carbon Ltd., about nine rods have to be extruded and baked for every rod placed in the Reactor. The cost of all this is extremely high.

However, attempts by Compagnie Péchiney and by AERE, Harwell to make a base material with a similar pore spectrum were also generally unsuccessful. They tend to confirm the belief that this family of materials is, at the present time, an excessively difficult departure point for the fabrication of low permeability graphite fuel elements.

Furthermore, the resulting material is likely to shrink at a considerable rate under service conditions. Within the Project, the maximum graphite irradiation dose achieved is about 2×10^{20} nvt $E > 0.1$ MeV (see Section 3.4). For greater doses, the Project has to rely on data obtained by General Atomic [25] as well as information on the behaviour of samples of Morgan EYX 60 given by the Project to Hanford Laboratories in April, 1960 [26]. The General Atomic data is summarised in Table 40 whilst Fig. 30 gives the Hanford results.

Thus under the conditions of the Reactor Experiment a shrinkage of about 1.6% per year is to be expected. Although this shrinkage rate is disturbing per se, it turns out that the differential effects across a tube wall due to temperature and flux gradients are likely to be even more serious. Present calculations [21] indicate that these differential effects will be the limiting factor determining the life of the fuel element graphite in the Reactor.

A survey of all the existing high temperature graphite irradiation data indicates that high shrinkage rates are found with incompletley graphitised or poorly graphitising materials. Much greater dimensional stability is found with highly graphitic materials.

The filler must graphitise well; at the same time the graphitisation of the binder must not be inhibited. Hanford data in support of this dual condition may be summarised as follows:-

(a) A high final heat treatment temperature is necessary (3000°C is better than the usual 2700°C, but 3200°C is better still).

Table 40

Irradiation Data on EYX 60 or Related Graphite (General Atomic Reports GA 2493 and 2304)

Sample	Irradiation Temp. °C	Exposure (E > 0.1 MeV)	$\frac{\Delta L}{L}$ (%)*
Hawker Siddeley impregnated	328-420	$0.6-0.7 \times 10^{21}$	-0.72 +0.04 -0.60
Hawker Siddeley impregnated	607-660	$0.6-0.7 \times 10^{21}$	-0.72 -0.56 -0.76
Hawker Siddeley impregnated	780-960	$0.6-0.7 \times 10^{21}$	-1.36 -1.66 -1.68
Hawker Siddeley impregnated	1080-1425	$\sim 2 \times 10^{21}$	-1.2 -1.6 -1.6
Hawker Siddeley impregnated	1450	$\sim 0.6-0.7 \times 10^{21}$	-1.68 -1.08
EYX 60 impregnated by G.A.	1080-1425	$\sim 2 \times 10^{21}$	-0.80 † -0.80

* Dimensional changes are similar for both directions relative to direction of extrusion.

† Reported as -0.6 to -0.8 and -2.04 to -2.44 in G.A. 2304.

(b) Relatively stable graphite results from the use of a highly anisotropic filler such as calcined needle coke. It is postulated that the highly anisotropic needle coke assists the better crystallisation of the binder coke. Carbon black is bad as a filler for [illegible] two reasons. It graphitises poorly and [illegible] of the binder.

(c) As an alternative to (b) above, a raw coke filler may be used. It is postulated that this also leads to good recrystallisation of the binder coke because of the hydrocarbon nature of [illegible].

(d) Stability under irradiation is improved if graphite is [illegible] at high temperatures. This has the effect of [illegible] and improving the recrystallisation in the binder phase.

(e) The binder should graphitise well. A graphitising binder such as coal tar pitch is preferred to a non-graphitising binder such as furfuryl alcohol resin carbon.

(f) Any impregnant should graphitise well. This point is not well established but a joint General Atomic - Hanford experiment should provide more precise evidence of the effects of a non-graphitising impregnant. Such effects will obviously depend upon the nature of the graphite being impregnated. Thus furfuryl alcohol resin coke is expected to have a greater effect with relatively [illegible] materials.

In Dragon Grade 9 fuel element graphite there are two non-graphitising components which may be expected to be the cause of the poor dimensional stability under irradiation. First, it has been deduced in Section [illegible], that it contains an appreciable amount of carbon black. Secondly the amount of non-graphitising material is further augmented by furfuryl alcohol resin carbon, incorporated by impregnation.

It will be remembered that the specific steep pore spectrum of Dragon Grade 9 was required in order to facilitate its impregnation with furfuryl alcohol resin. Research work by Compagnie Pechiney and by A.E.R.E. Harwell suggests that such a specific pore spectrum can only be achieved by incorporating a considerable amount (~30%) of carbon black into the mix.

The paradoxical situation therefore arises that good dimensional stability under irradiation is incompatible with the realisation of ultra-low permeability graphite. This paradox can only be resolved by a reappraisal of the fission product retention characteristics required of the fuel tube.

4.3 Development of Improved Types of Fuel Element Graphite

To avoid the difficulties surveyed in the previous section, it is necessary to develop a graphite with good stability under service conditions and which at the same time gives adequate control of fission product leakage into the main coolant circuit.

In the existing type of fuel element, the low transmission coefficient for fission products is obtained by dint of reducing the overall permeability to an infinitesimal value. A re-examination of the problem of fission product control suggested that a similar transmission coefficient could be achieved with a much coarser and more permeable graphite, in the pores of which the helium purge flow through the fuel tube wall would "back-sweep" the gaseous fission products. Since such a graphite could be made entirely from graphitic or graphitisable components, it could also be designed to have better irradiation behaviour.

It was evident that diffusion theory and general statistical considerations would not permit a precise statement of the pore spectrum required in this coarser grained graphite. Nevertheless an upper limit for the permeability coefficient can be deduced bearing in mind that the total purge flow for the whole core is 28.2 Kg/h or about 20 cc/sec/fuel tube (measured at 20 atmospheres and 350°C).

A decision was therefore made to proceed with development of a wholly graphitic material which would:-

(a) have a narrow pore spectrum, in the range 2-5 microns (as measured by a high pressure mercury porosimeter),

(b) have a permeability coefficient to helium of less than 5×10^{-2} cm^2/sec (at 1000°C, 20 atmosphere total pressure and 2 psi pressure drop),

(c) have an apparent back-diffusion coefficient for Kr-85 in helium (at 1000°C, 20 atmospheres total pressure and 2 psi pressure drop), not exceeding 10^{-6} cm^2/sec.

It was recognised that such a material would have to be developed by preparing a series of samples with the aid of which a more precise relationship between permeability, pore size and back-diffusion coefficient might be established.

At AERE, Harwell, the work for the Project was commenced with the manufacture of a series of mixes made from fine petroleum coke. The results obtained up to December, 1962 have been reported [27]. The pore spectra obtained are nearly uni-pored, as desired, and of the right order ($2-5\,\mu$). The permeability coefficients are not far different from the desired value.

These samples will be used:-

(a) To further pore studies and for the examination of back-diffusion behaviour.

(b) To provide a base stock for gaseous and liquid impregnation experiments.

In parallel attempts are being made to scale-up the processing of this type of material to give $3\frac{1}{4}$" diameter rod, 6 feet long.

In the case of Compagnie Pechiney, it was decided to exploit a composition for which the initial research work had already been completed outside the terms of the Dragon contract. This new composition, termed G5, was therefore immediately transferred to pilot scale production. Initial results were disappointing in that rods of the correct size (85 mm dia, 2200 mm long) had either external or internal fissures on baking. Modifications to the binder content, the extrusion conditions and the method of baking, have gradually improved the position until rods of the required dimensions can now be made with only slight external fissures. Completely crack-free rods have recently been achieved on 1 metre lengths using a slightly more constrained packing method during the baking process.

A typical pore size distribution for G5 made in laboratory equipment and relating to 52 mm stock is given in Fig. 31.

When the pilot scale production of G5 was causing some concern, two alternative compositions (G3 and G7) were initiated. All the various formulations used on the Pechiney pilot plant are given in Table 41.

Pilot plant samples of G3 and G5 are being used in impregnation experiments using coal tar pitch, furfuryl alcohol and hydrocarbon gases as impregnants. Typical results of a pitch impregnation series with G5 are given in Table 42.

4.4 Recent Developments in Back-Diffusion Theory and Experiment

The work described in the previous section was initiated on the basis of rather crude estimates of the type of graphite required in order to exploit back-diffusion. It was also necessary to aim to bridge the gap between diffusion theory and back-diffusion experiments so as eventually to be able to specify the graphite required more precisely.

Due to the kindness of Dr. G. F. Hewitt, Chemical Engineering Division, AERE, Harwell, four back-diffusion experiments were carried out on graphites ranging from British Reactor Grade A to HX 12. The apparatus used in these experiments has already been described [28]. Briefly the sample is first encapsulated in Araldite resin and the graphite becomes a septum separating oxygen and nitrogen which can be maintained at any desired pressure. The transmission of oxygen through the graphite (either against or with the pressure gradient) is measured using a Hersch meter. With this apparatus back-diffusion coefficients as low as 10^{-7} cm^2/sec can be measured. The results obtained [29], which are given in Fig. 32, confirmed the belief that back-sweeping could be exploited.

Within the Project the question of back-diffusion has been studied theoretically by Dr. Schlösser. By assuming a uni-pore model for graphite and setting-up relationships between the permeability constants and back-diffusion coefficients he has been able to deduce a "target area" within which the B_o and K_o values of a candidate graphite should lie.

The target area is increased if a pressure dropping device is placed at the top of the fuel tube, and Fig. 33 gives the theoretical target area for

Table 41

Pechiney Graphite Compositions

Graphite Type	G1	G2	G3	G4	G5	G7
Graphite powder (- 60 mesh)	2/3	2/9	3/3	1/3	2/3	nil
Micronised graphite powder	nil	4/9	nil	1/3	1/3	nil
Thermal Carbon Black	1/3	1/3	nil	1/3	nil	nil
Coke Powder (- 60 mesh)	nil	nil	nil	nil	nil	3/3
Coal Tar Pitch	To suit extrusion conditions					

Table 42

Effect of Pitch Impregnation on Pechiney Pilot Plant G5

Sample No.	No. of pitch Impregnations	Viscous Flow Coefficient (B_o)	Non-viscous Flow Coefficient (K_o)
195 - 3E	0	71×10^{-12} cm^2	88×10^{-7} cm
195 - 3C	1	38×10^{-12} cm^2	44×10^{-7} cm
195 - 3B	2	5.9×10^{-12} cm^2	7.3×10^{-7} cm

that condition. It can be inferred from Table 42 and [27] that no candidate graphite to date has reached this target area. If this is true it will obviously be necessary to steer the impregnation processes so that the small rather than the larger through pores are blocked. One the other hand it should be pointed out that, since the theory makes considerable assumptions, it is possible that existing Harwell and Pechiney graphites may already be acceptable. Only experimental work can clarify this. Such work is already under way at AERE, Harwell.

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6. ACKNOWLEDGMENTS

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APPENDIX 1

SPECIFICATIONS FOR THE FURFURYL ALCOHOL IMPREGNATION OF GRAPHITE FUEL TUBES AND END PLUGS FOR THE FIRST CHARGE OF THE REACTOR EXPERIMENT

1.1 Specification for the Impregnation of Fuel Tubes Machined to Drawing CD.33990

Fuel tubes shall be impregnated in accordance with the following procedure:-

1.2 Preparation of Impregnant for First Impregnation

The impregnant used for the first impregnation shall have a viscosity of 120 centipoises measured at ambient temperature. It shall have been made from a mixture of 2 per cent. by volume orthophosphoric acid. (Analar quality, specific gravity 1.75) in technical grade furfuryl alcohol originating from the Quaker Oats Company (U.K. Suppliers - Imperial Chemical Industries Ltd.).

The impregnant shall be made by adding the required volume of phosphoric acid (itself at room temperature) drop-wise into the vortex created by a high-speed stirrer, after previously cooling the furfuryl alcohol to -10°C. The cooling of the alcohol shall be effected by the use of internal or external cooling coils. Under the above conditions there should be no colour change during mixing and no globules of resin should be formed.

The required viscosity shall be obtained by allowing the continuously stirred furfuryl alcohol/catalyst mixture to partially polymerise in air. This should take about two weeks at 15°C.

Dilution with a freshly prepared furfuryl alcohol/catalyst mixture is not permitted. When the required viscosity has been reached, refrigeration may be used to maintain the viscosity of a batch of impregnant approximately constant.

In the absence of clear evidence regarding "bulk effects" in the impregnant the volume of a batch of impregnant should be less than 10 litres.

1.3 Operations

1.3.1 Weigh (to nearest gram). The weight of a machined fuel tube is approximately 4900g.

1.3.2 Measure permeability coefficient (K) at 3.6×10^6 dynes cm^{-2} mean pressure decaying from, say, 95 to 85 psi absolute. There should be a ballast volume in the circuit to ensure that the time to decay from 95 to 85 psia is at least 10 seconds.

During pressurising, some tubes have exploded and suitable safety precautions should therefore be taken. The expected value of K is in the range $1.5 - 7.0 \times 10^{-2}$ cm^2 sec^{-1}.

1.3.3 Impregnate from inside wall using 100 psig pressure until the core section is just penetrated (not saturated) on the flats. Record the time taken to penetrate. This is expected to be between 30 and 165 minutes.

1.3.4 Wash bore with furfuryl alcohol removing traces of resin, particularly on the threads.

1.3.5 Reweigh. The resin uptake is likely to be between 8 and 10% by weight.

1.3.6 Air cure for a minimum of 24 hours with the components sealed in polythene bags or similar airtight containers to prevent excessive evaporation of resin. The time of air curing shall be recorded.

1.3.7 Cure and bake in accordance with the following schedule:-

Hold at 60°C for 2 hours
" " 80°C " 2 "
" " 100°C " 2 "
" " 120°C " 16 "
" " 150°C " $1\frac{1}{2}$ "
" " 200°C " $1\frac{1}{2}$ "

200-650°C at less than 5°C/hour
650-1000°C " " " 50°C/hour
Hold at 1000°C for 1 hour

In the above schedule temperatures apply to the ware itself and not to the furnace.

1.3.8 Reweigh. The expected value of the carbon gain is about 4.5% by weight.

1.3.9 Remeasure permeability using the pressure decay method of operation (2.3.2). At this stage tubes are expected to have a permeability of about 1 x 10^{-3} cm^2/sec.

1.3.10 Impregnate from the inside wall using 100 psig **pressure,** maintaining the pressure for 7 hours. The impregnant shall be a freshly prepared mixture of 2 per cent. by volume orthophosphoric acid (Analar quality, specific gravity 1.75) in technical grade furfuryl alcohol originating from the Quaker Oats Company. Alternatively it may comprise a previously made mixture of the same composition which has been refrigerated (at less than 5°C) to prevent **polymerisation.**

The viscosity of the impregnant shall be measured immediately before use. It must not exceed 10 centipoises at ambient temperature.

Wipe the bore of each tube after impregnation, with a furfuryl alcohol impregnated paper tissue to remove traces of resin.

1.3.11 Then repeat operations 1.3.5 to 1.3.9 inclusive.

The resin uptake after the second impregnation may be quite variable ranging from 0.4 to 4.0% by weight.

Specimens that have a permeability coefficient (K) less than 10^{-5} cm^2 sec^{-1} after the second impregnation and carbonisation will then be remeasured by a vacuum decay method because of the insensitivity of the pressure decay method at this level of permeability.

1.3.12 Then repeat operation 1.3.10 **on tubes which have $K > 10^{-6}$ cm^2/sec.**

1.3.13 Then repeat operations 1.3.5 to 1.3.8 inclusive.

1.3.14 Remeasure permeability coefficient using a vacuum decay method. Material will be graded at this stage according to the permeability coefficient, i.e.

Grade 1. K less than 10^{-8} cm^2 sec^{-1}
" 2. K between 10^{-7} and 10^{-8} cm^2 sec^{-1}
" 3. K between 10^{-6} and 10^{-7} cm^2 sec^{-1}
" 4. K between 10^{-5} and 10^{-6} cm^2 sec^{-1}
" 5. K greater than 10^{-5} cm^2 sec^{-1}

1.3.15 On completion of the permeability measurement material will be packed and sealed in polythene bags.

2. SPECIFICATION FOR THE IMPREGNATION OF END PLUGS MACHINED TO DRAWINGS CD.33989 (Outer) and CD.34042 (Inner)

As for fuel tubes machined to Drawing 33990 (Section 1) modified as follows:-

(a) In Section 1.3.3, the impregnation shall be terminated when the threaded portion is just penetrated by the impregnant.

(b) Care must be taken to keep the threads and the brazing recess free from impregnant prior to and after each stage of impregnation, curing and carbonisation.

3. HANDLING

All the components covered by these impregnation specifications are extremely fragile. The utmost care must be taken not to chip corners, edges and threads during processing.

4. CLEAN CONDITIONS

The process must be operated in areas where "Clean Conditions" apply.

Clean conditions are defined as the measures taken to minimise the contamination of components by materials which could be detrimental to the safe and efficient operation of the reactor. The contaminants which may have such effects fall into the following groups:-

(a) Materials with sufficiently high cross-section for neutron capture as to have a marked effect on the economy of operation of the reactor e.g. Boron, Cadmium, Rare Earths, Hafnium, Silver, Gold, certain of the Platinum metal group, and alloys or other substances containing appreciable percentages of those elements.

(b) Materials which show irradiation induced activity with a sufficiently low rate of decay and/or at a sufficiently high level to increase significantly the general background levels or to interfere with access for maintenance, e.g. Cobalt, Zinc, etc.

(c) Materials which may promote mass transfer by reaction with graphite at elevated temperatures with the formation of CO or by catalysis of the decomposition of CO to CO_2 and C at lower temperatures e.g. water, hygroscopic materials, oxides such as silica, iron oxides and including corrosion products in the form of scale or rust etc., and all compounds in which these may be contained.

(d) Materials which under appropriate conditions of stress and/or temperature could lead to failure of metallic materials by embrittlement or inter-crystalline penetration. Such materials include metals of low melting point and/or high vapour pressure and elements or compounds which are known to embrittle certain of the constructional materials present, e.g. Antimony, Bismuth, Cadmium, Lead, Mercury, Tin, Zinc, Sulphur, Alloys based on these elements or compounds containing them including white metal bearings, low melting point fusible alloys, soft solders etc.

Additionally all components shall be only handled with gloved hands.

The furfuryl alcohol and the impregnant shall be periodically checked for water and boron contents and stored under an atmosphere of dry nitrogen.

5. INSPECTION

The inspection and testing are likely to be delegated to the Inspection Department of the firm carrying out the impregnation. However, the Project reserves the right to check any such testing and inspection on site.

Rejects may arise due to:-

(a) spalling
(b) chipping
(c) cracking

In order to minimise the cost of processing, components shall be visually inspected for defects after each baking stage. Spalled and cracked components will be rejected as soon as they are observed and stored pending a decision from the Dragon Project. Processing of chipped components may continue.

6. ACCESS TO PREMISES

The Project will require access by its duly authorised representatives to allow inspection of any or all stages of the process covered by these specifications

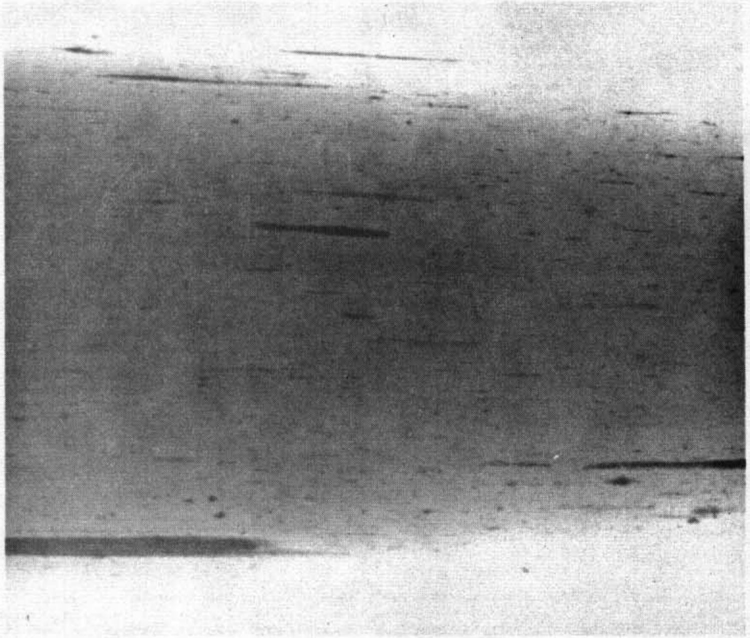


FIG.1. CRACKS IN CY119 CARBON ROD (FULL SCALE)

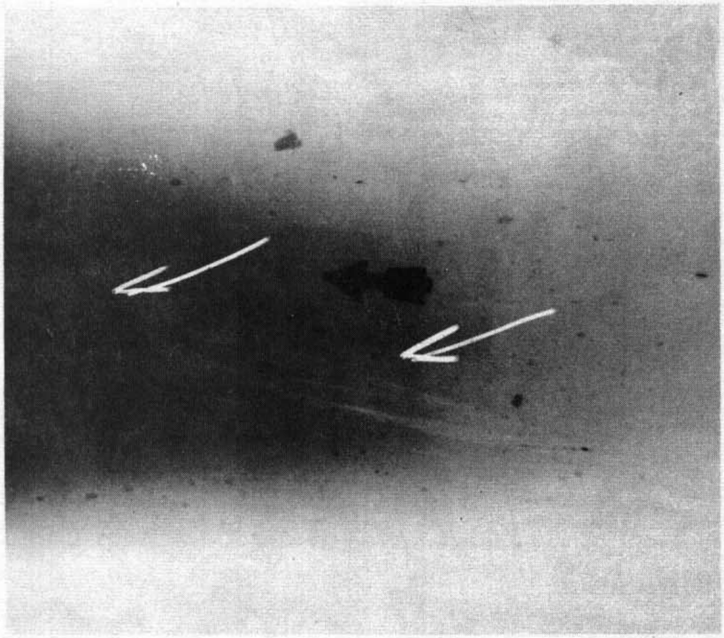


FIG.2. CRACKS IN CY119 CARDON ROD (FULL SCALE)

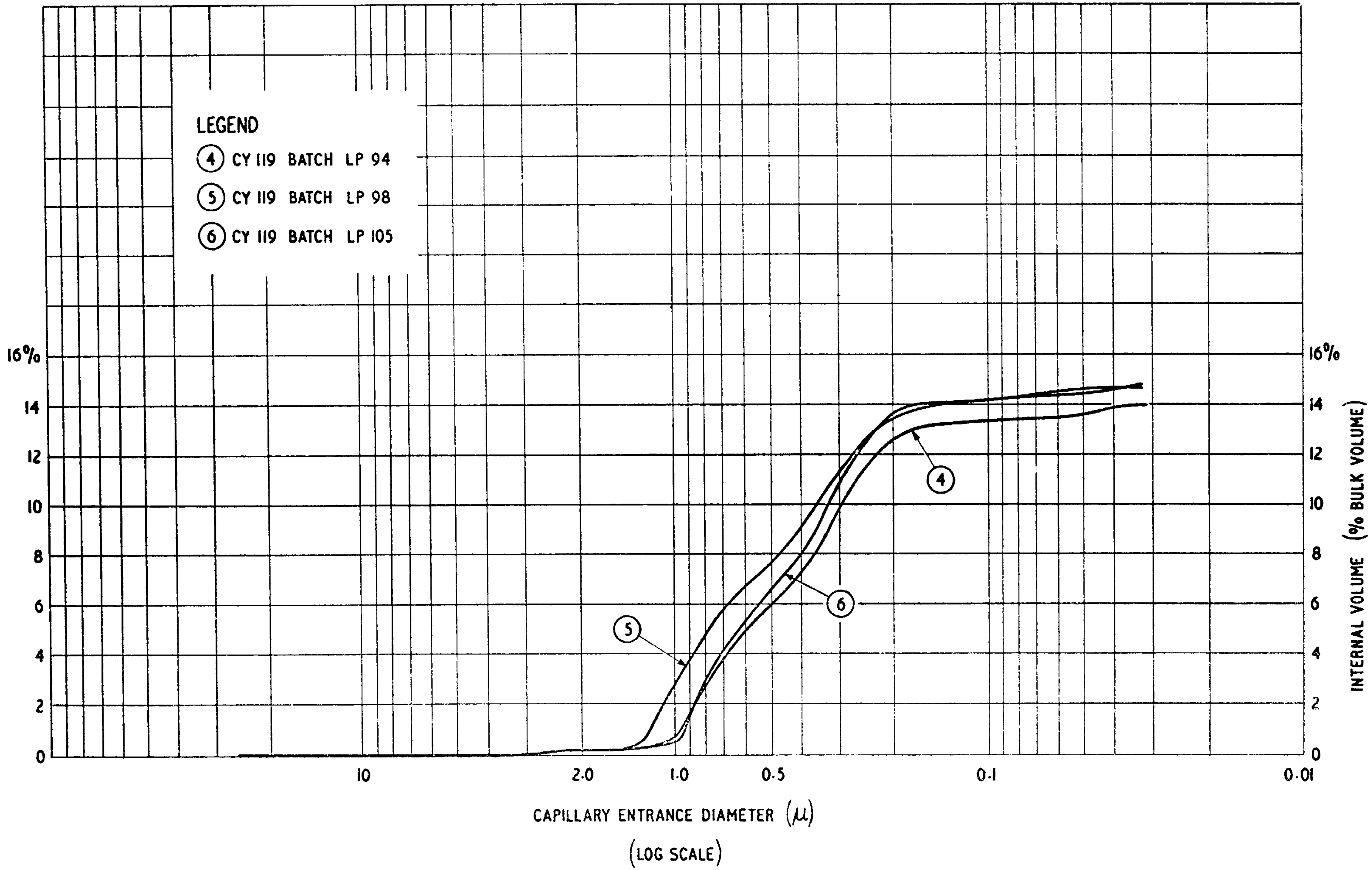
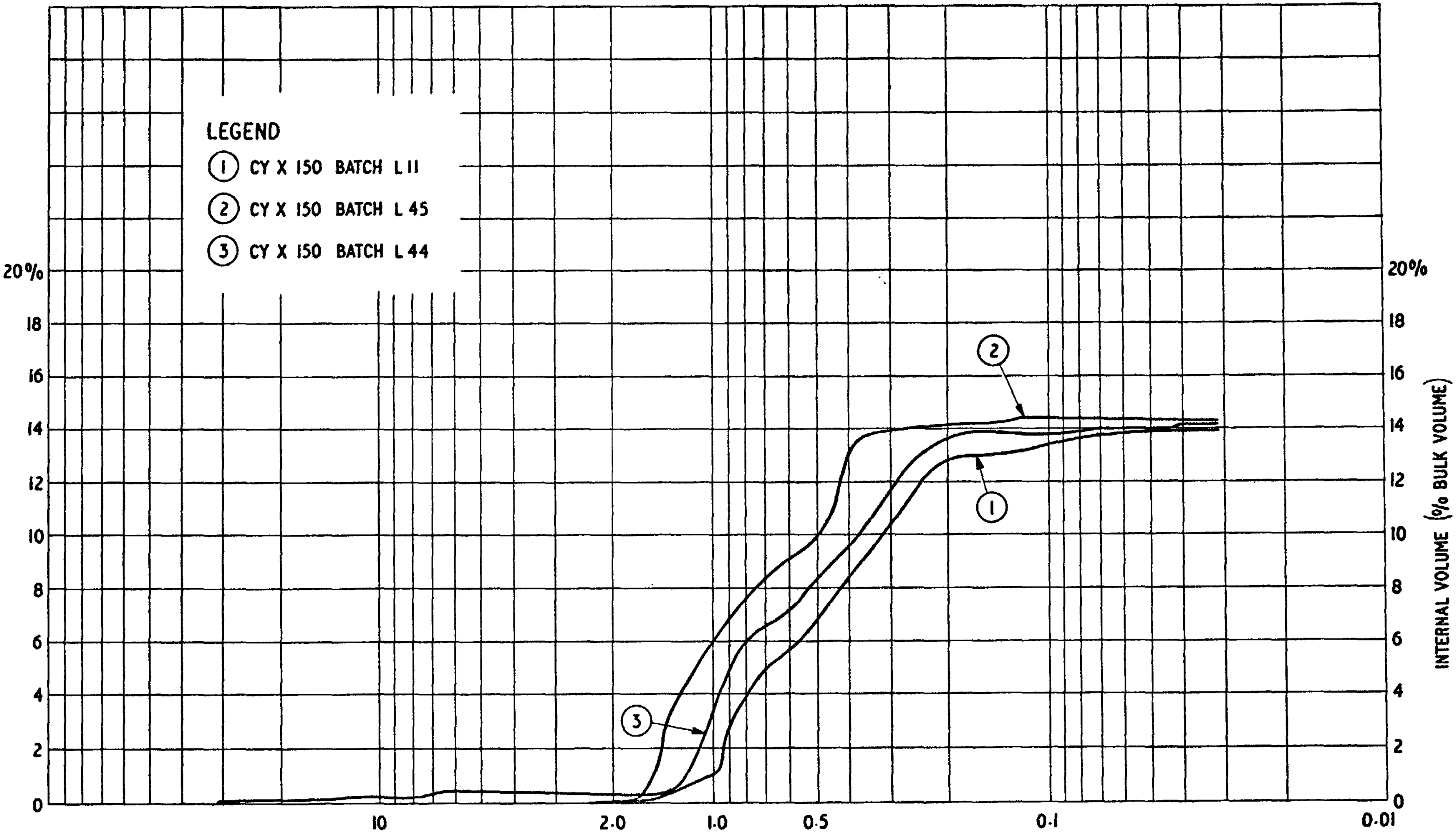


FIG. 3. PORE SPECTRA CY 119 (BAKED STAGE)
(MORGANITE CARBON LTD., ENGLAND.)



CAPILLARY ENTRANCE DIAMETER (μ)

LOG SCALE

FIG. 4 PORE SPECTRA-CY X 150 BAKED STAGE
(MORGANITE CARBON LTD., ENGLAND.)

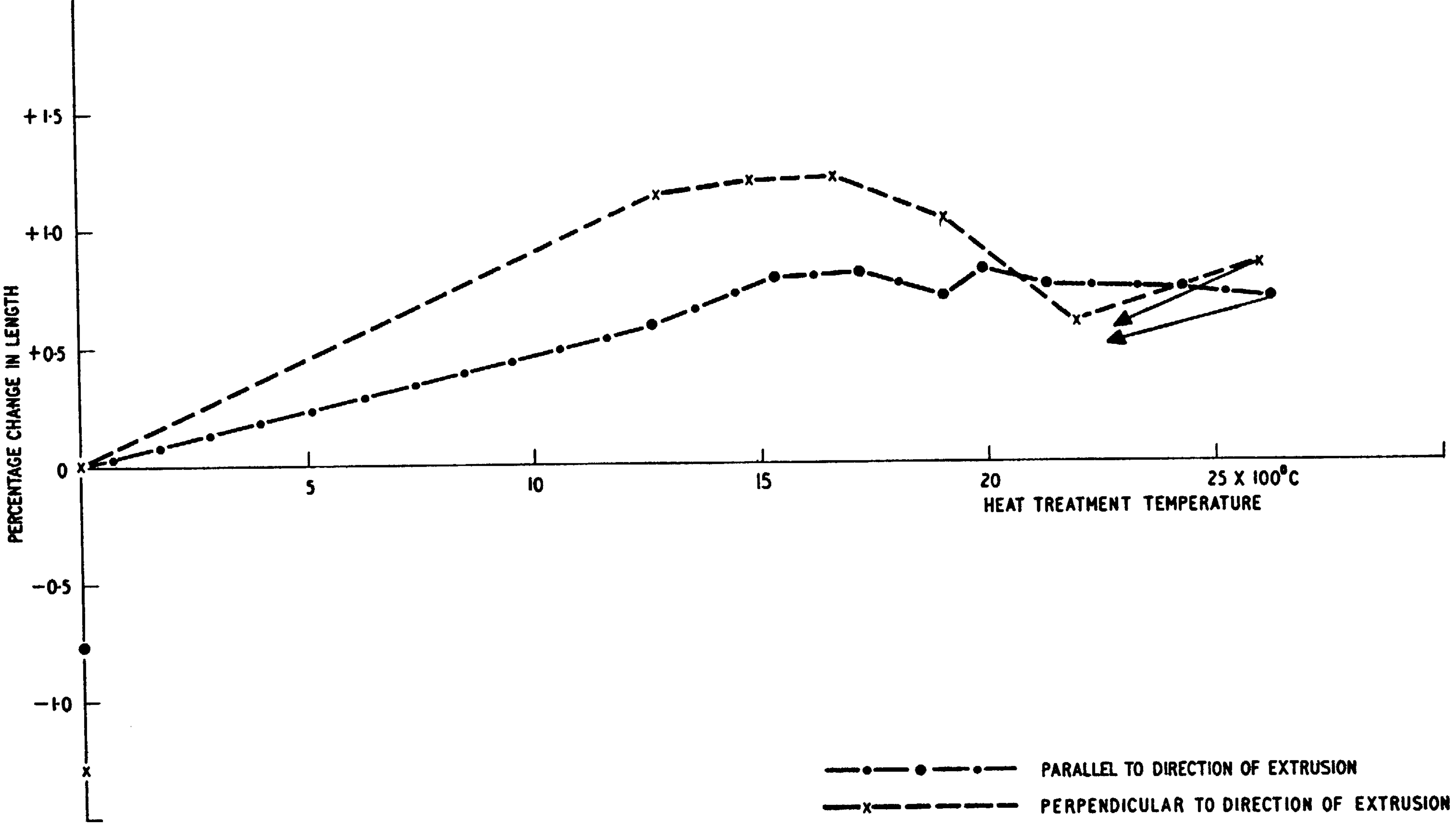


FIG. 5 SHRINKAGE CURVES FOR CY 119 CARBON
(T. BEIRNE A.E.R.E. HARWELL.)

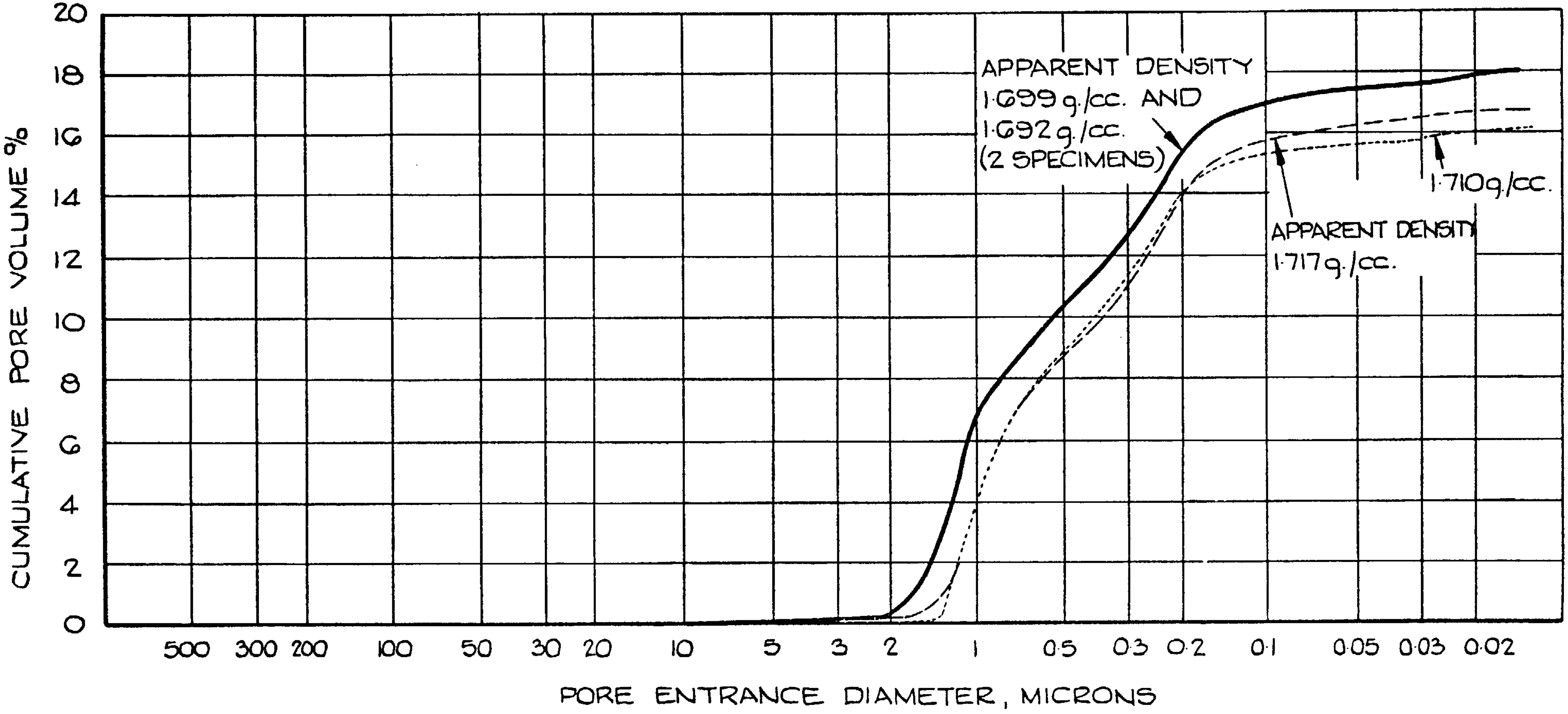


FIG.6 TYPICAL PORE SPECTRA OF DRAGON GRADE 9 AFTER PURIFICATION.
(COMPAGNIE PECHINEY, FRANCE.)

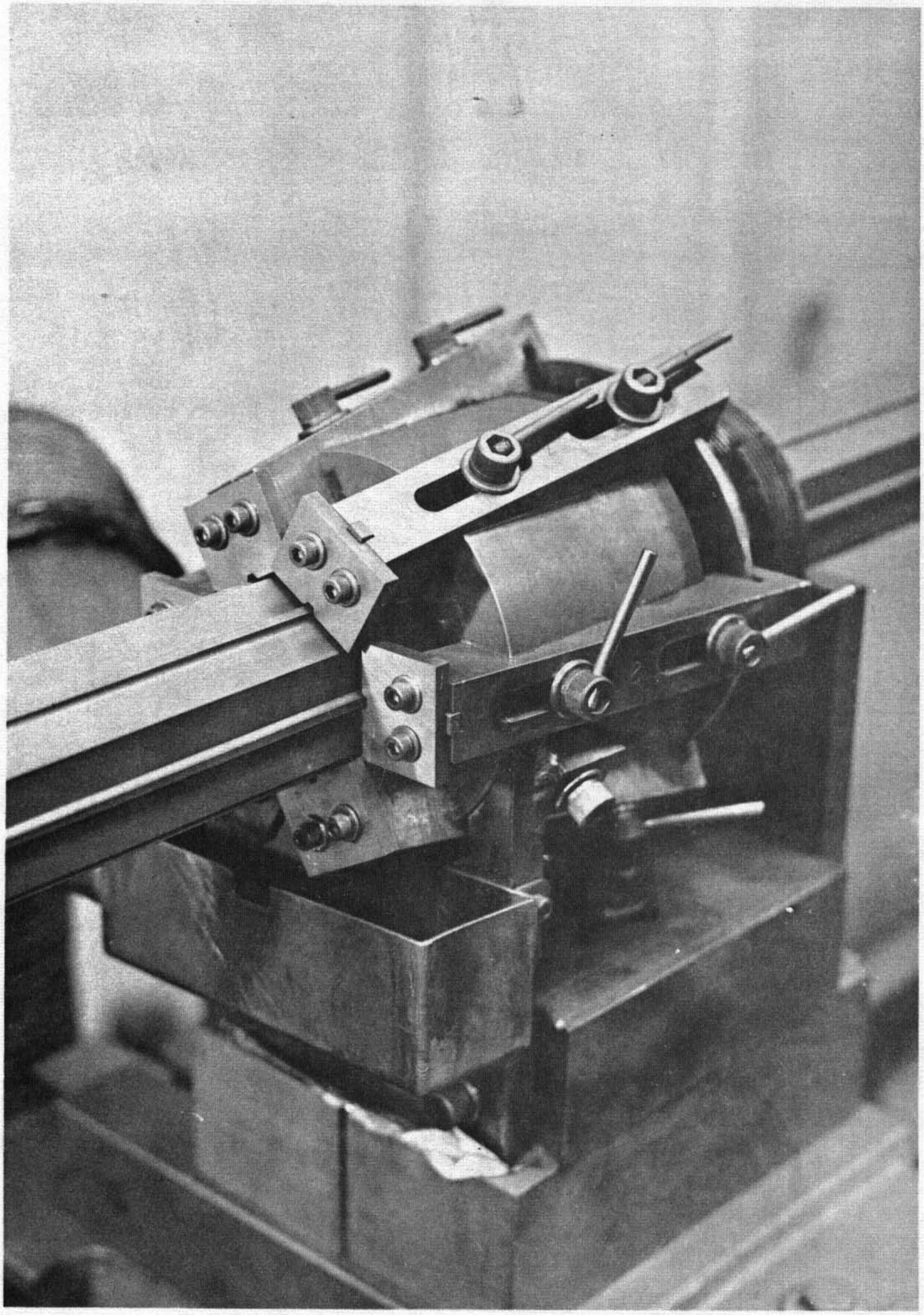


FIG. 7. MULTIPLE BROACHING TOOL USED FOR FORMING THE OUTER PROFILE OF THE FUEL TUBE. (PATENT APPLIED FOR - GRAVINER MFG. CO. LTD.)

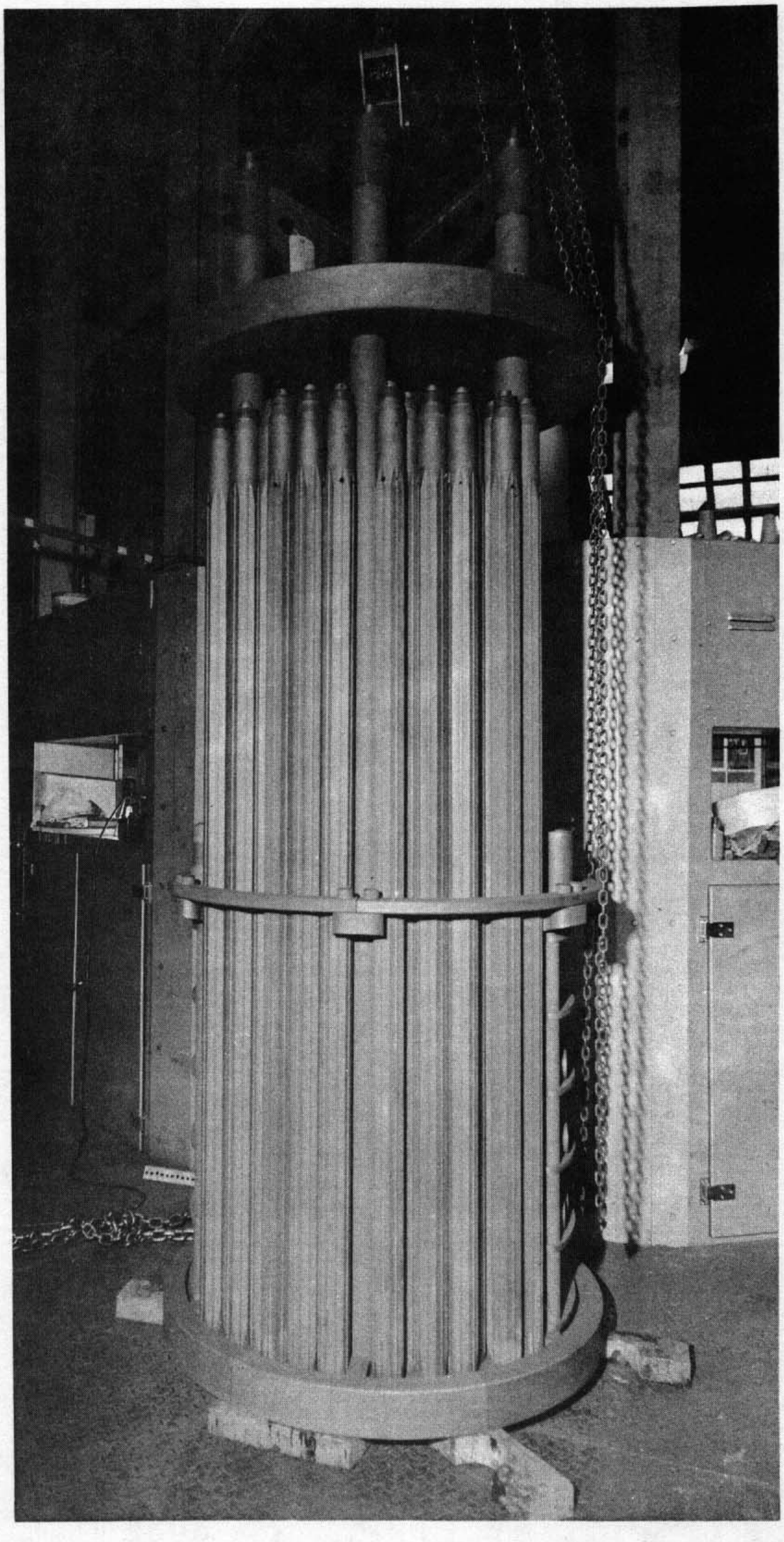


FIG. 8. FUEL TUBES FOR SEVEN ELEMENT TEST RIG ASSEMBLED PRIOR TO DEGASSING OPERATION

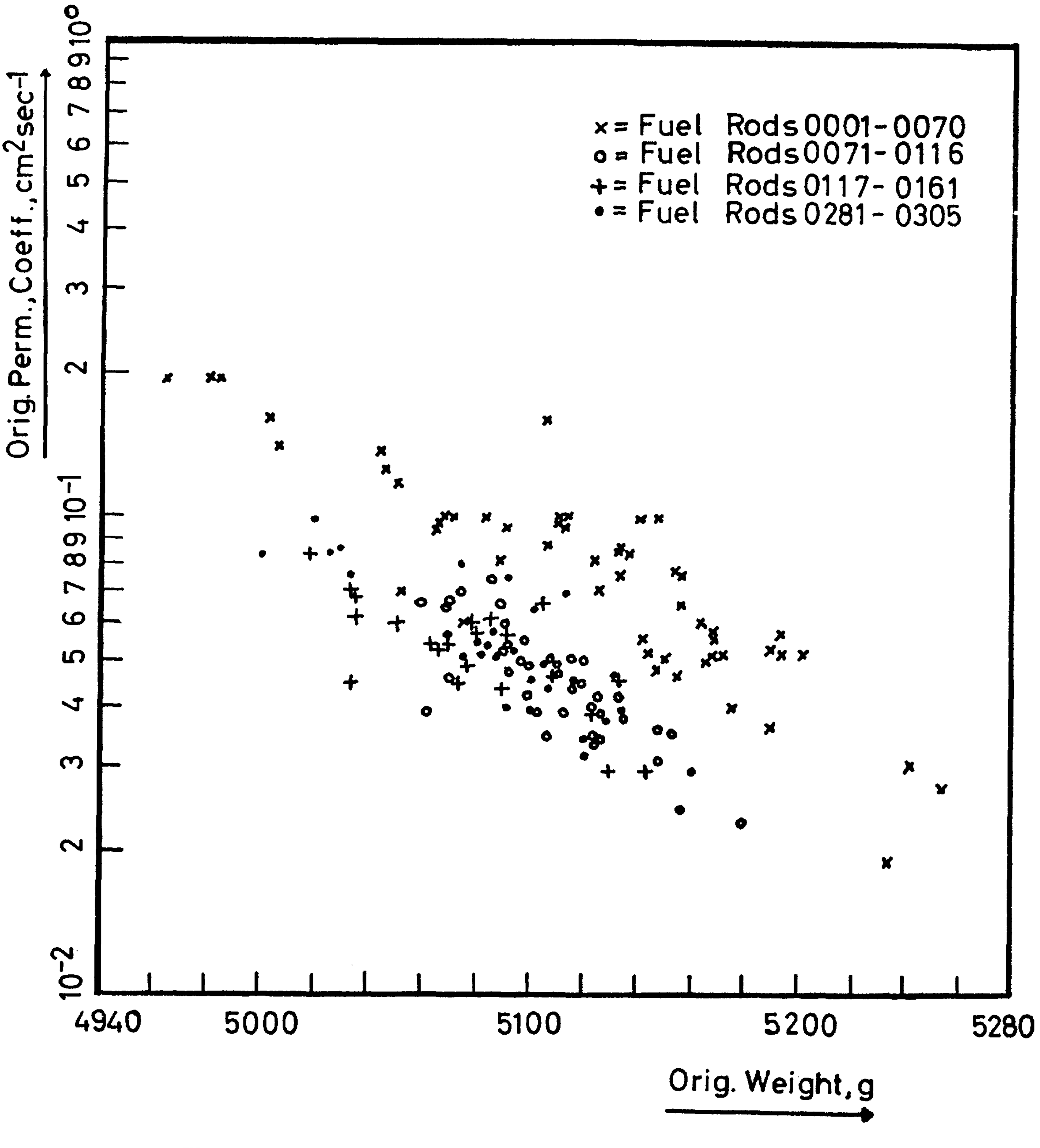


FIG. 9. RELATION BETWEEN ORIGINAL PERMEABILITY AND ORIGINAL WEIGHT.

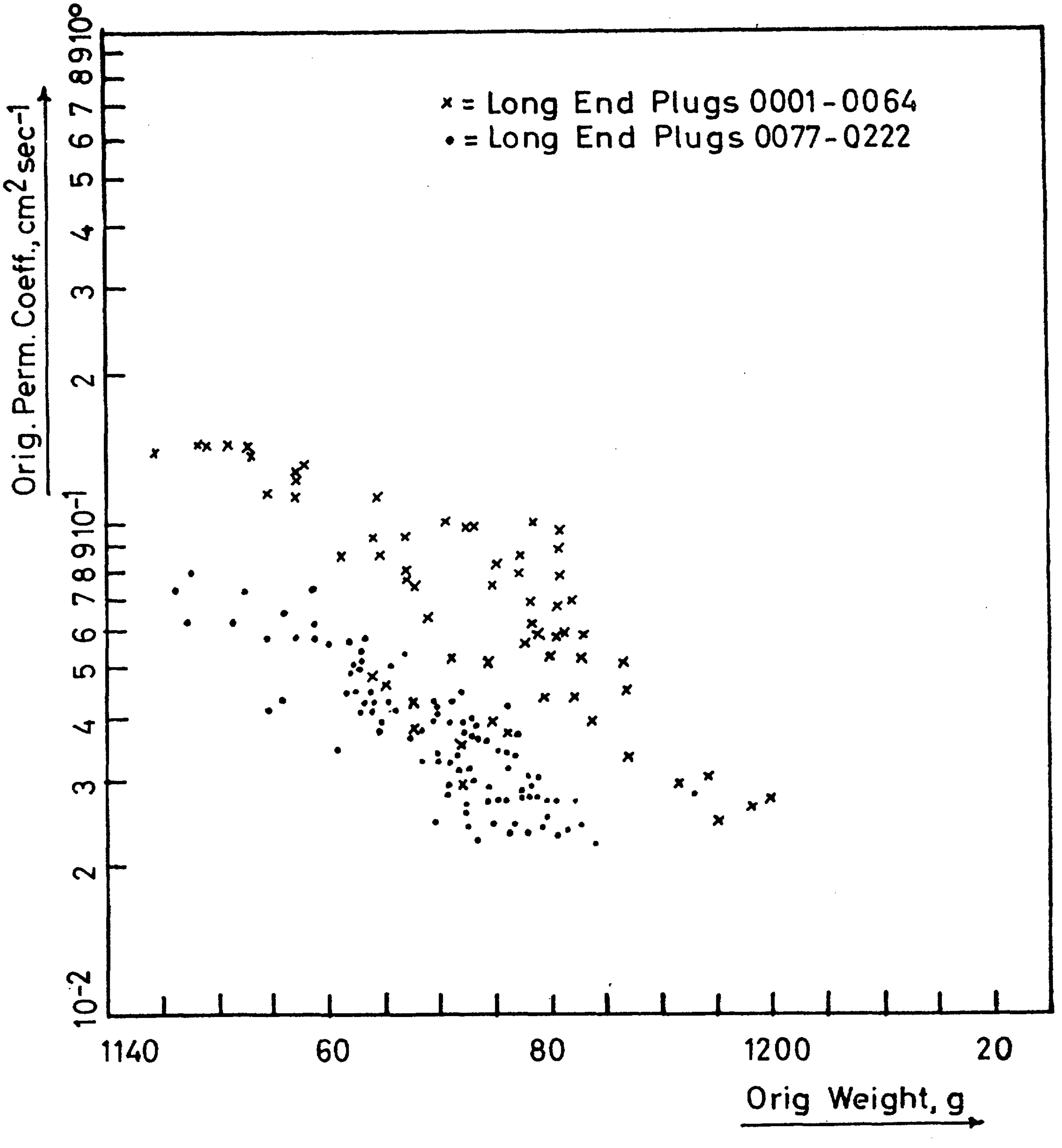


FIG. 10. RELATION BETWEEN ORIGINAL PERMEABILITY AND ORIGINAL WEIGHT.

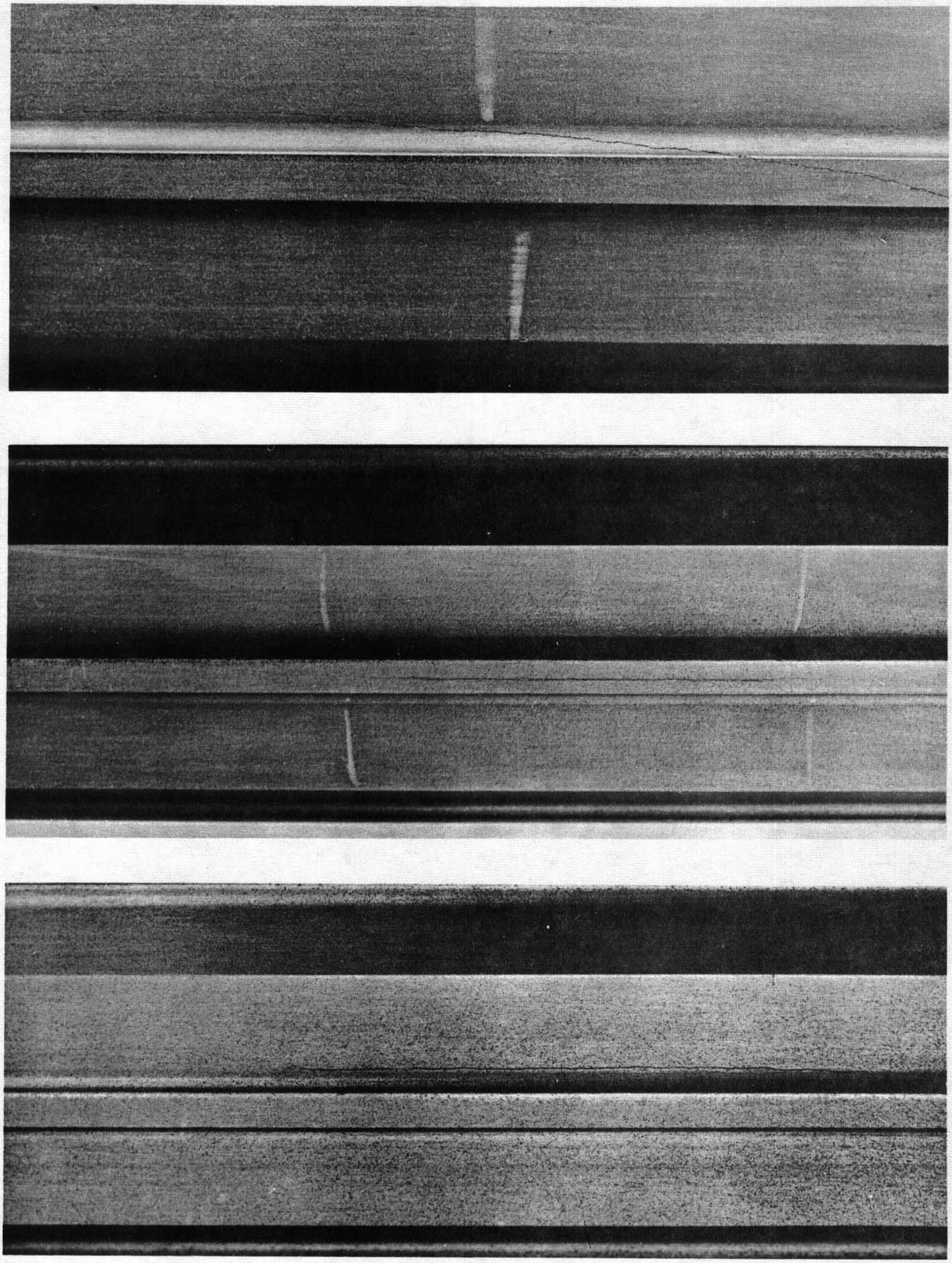


FIG. 11. FUEL RODS WITH CRACKS (4th DELIVERY).

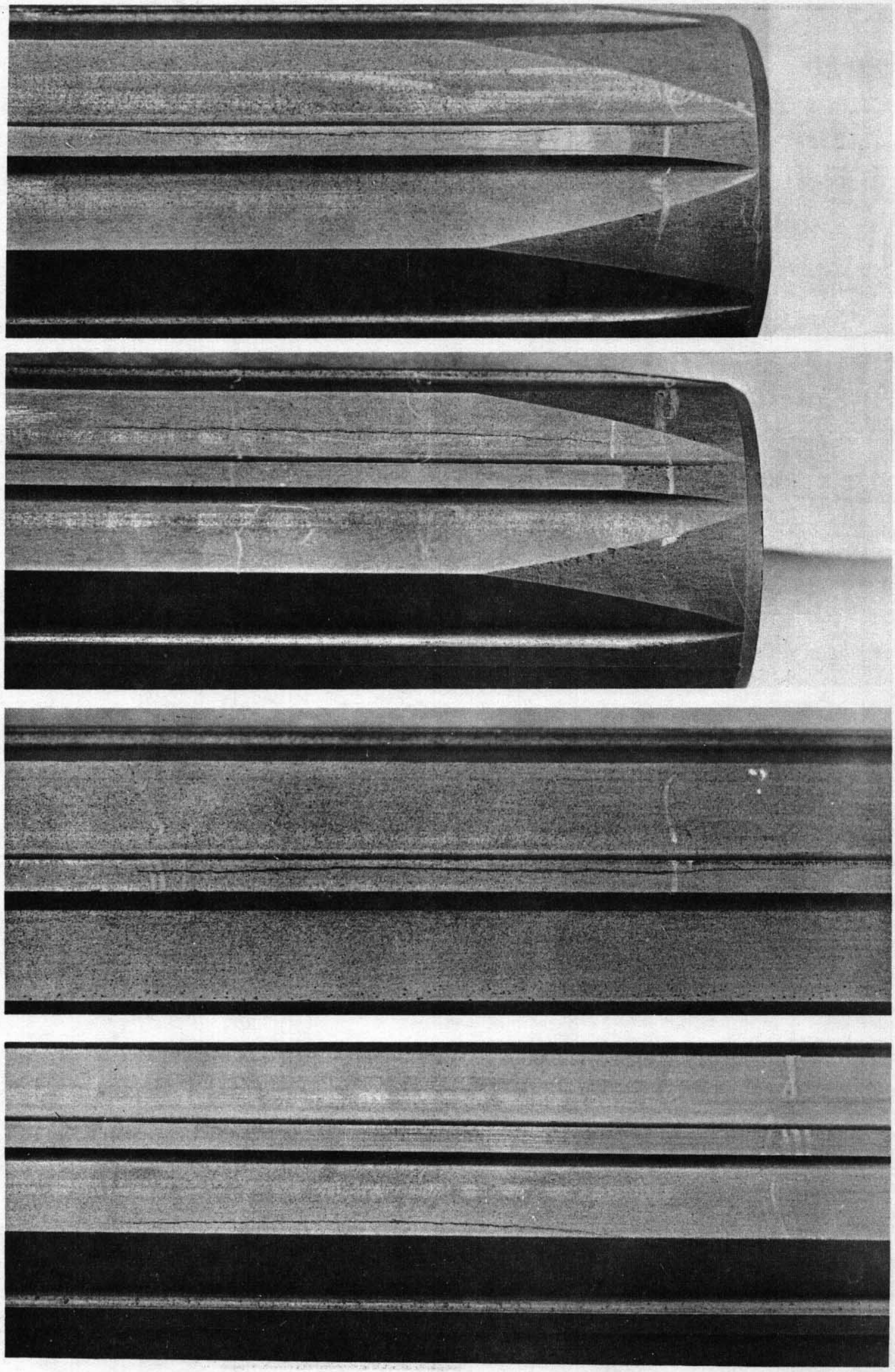


FIG. 12. FUEL RODS WITH CRACKS.

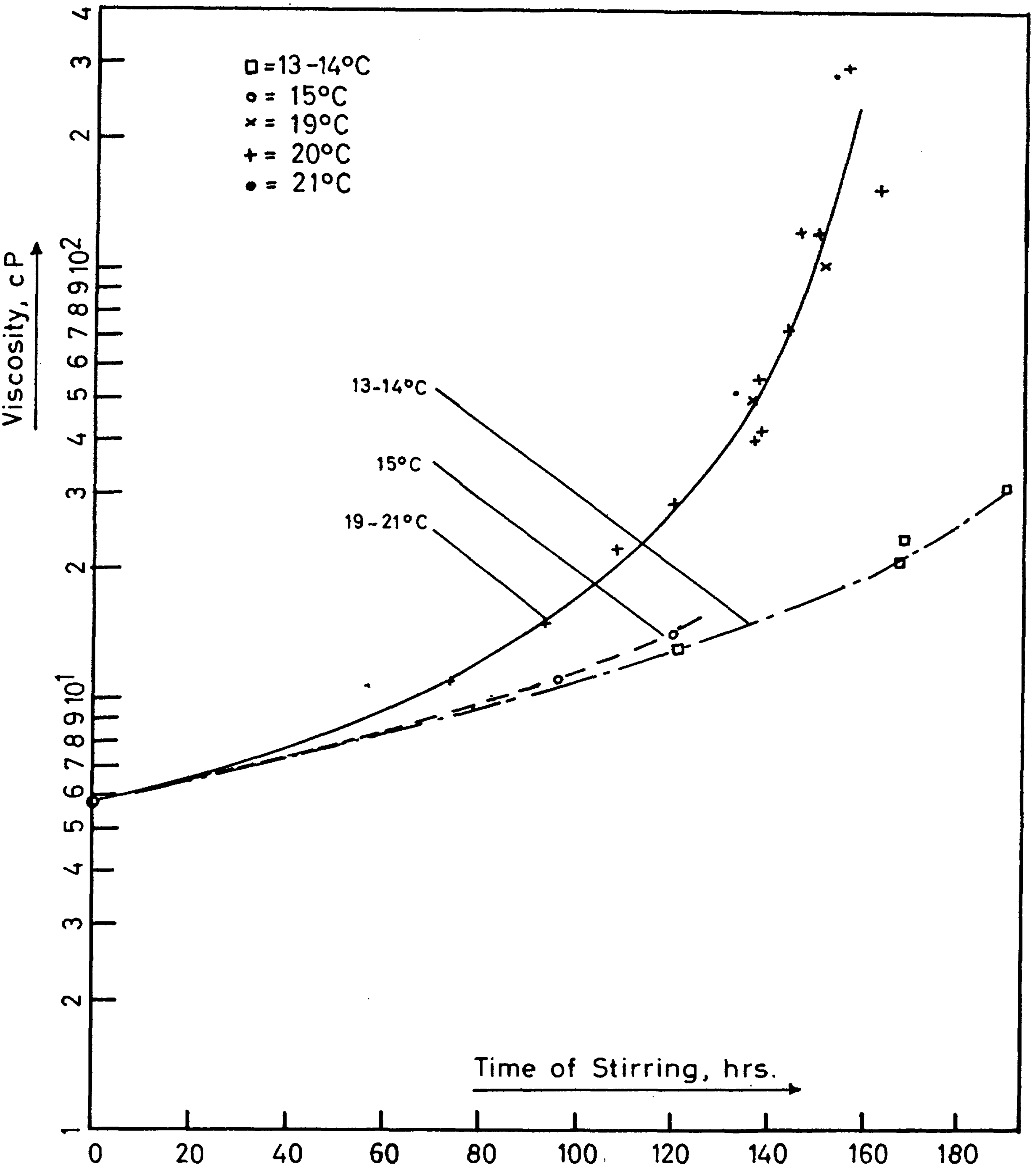


FIG. 13. INCREASE OF VISCOSITY OF FURFURYL ALCOHOL IMPREGNANT DURING PREPOLYMERISATION AT DIFFERENT TEMPERATURES.

(SIGRI KOHLEFABRIKATE, F.R. OF GERMANY)

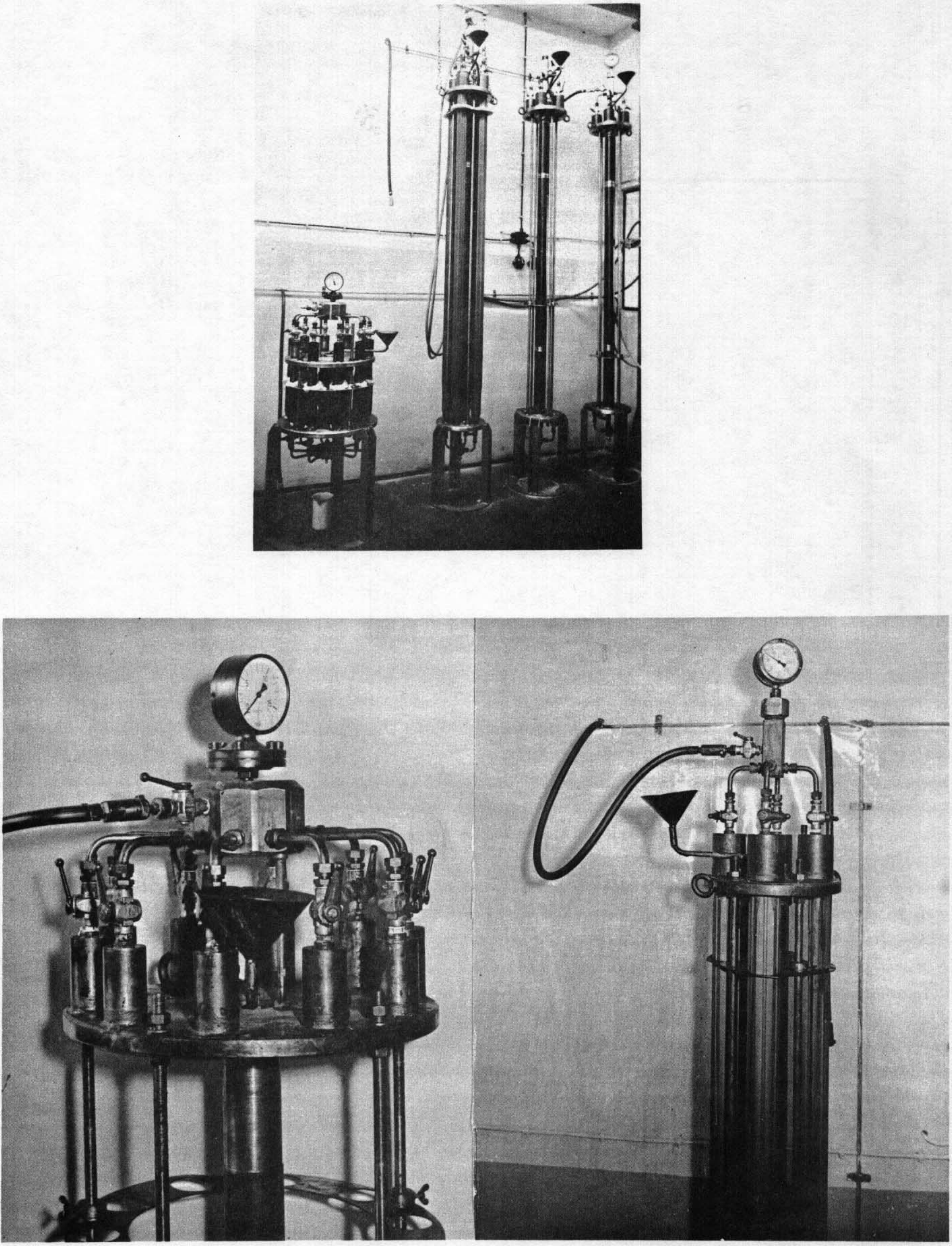


FIG. 14. IMPREGNATION EQUIPMENT (SIGRI KOHLEFABRIKATE, F.R. OF GERMANY)

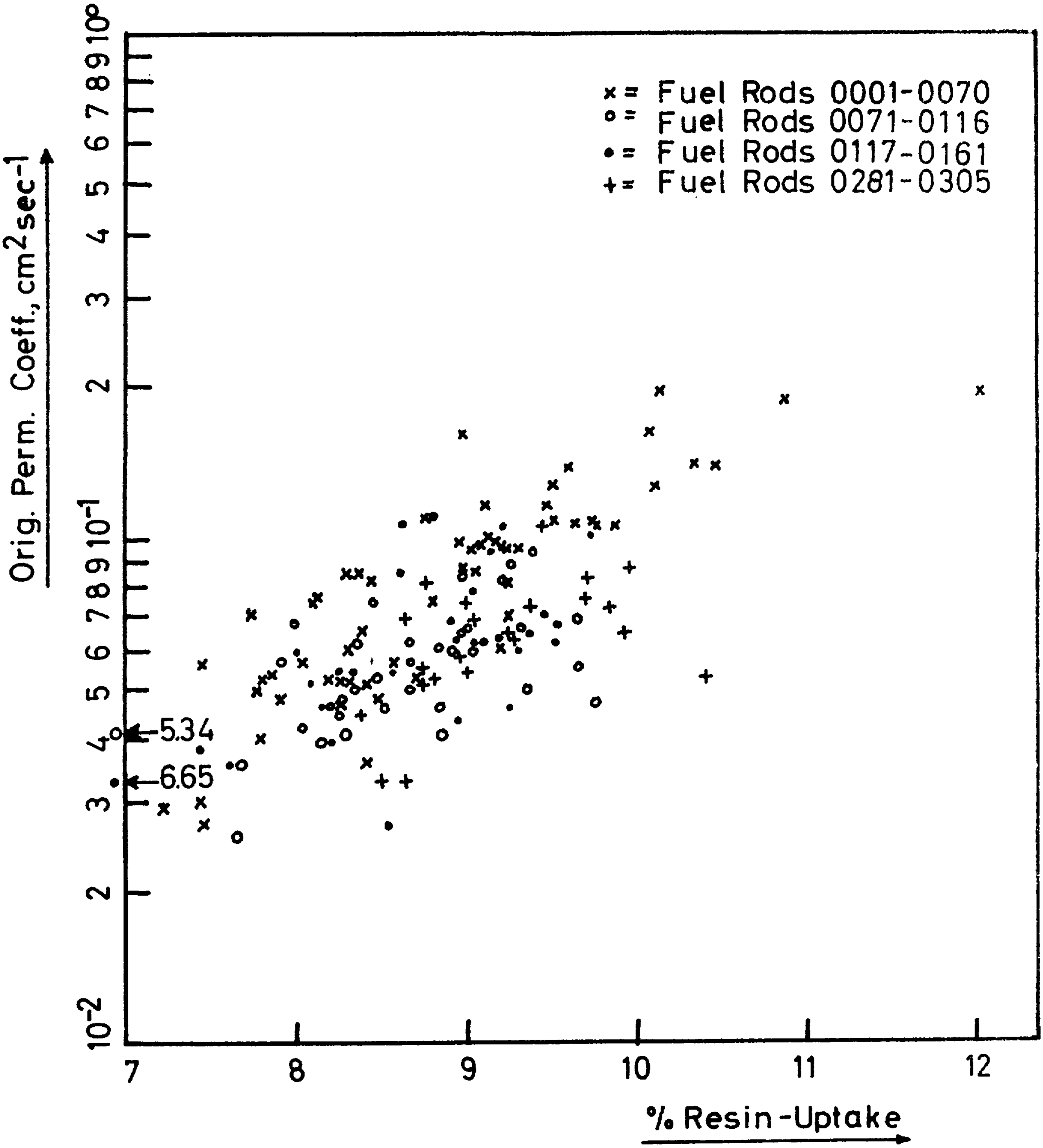


FIG. 15. RELATION BETWEEN RESIN UPTAKE (1st IMPR.) AND ORIGINAL PERMEABILITY FOR FUEL TUBES

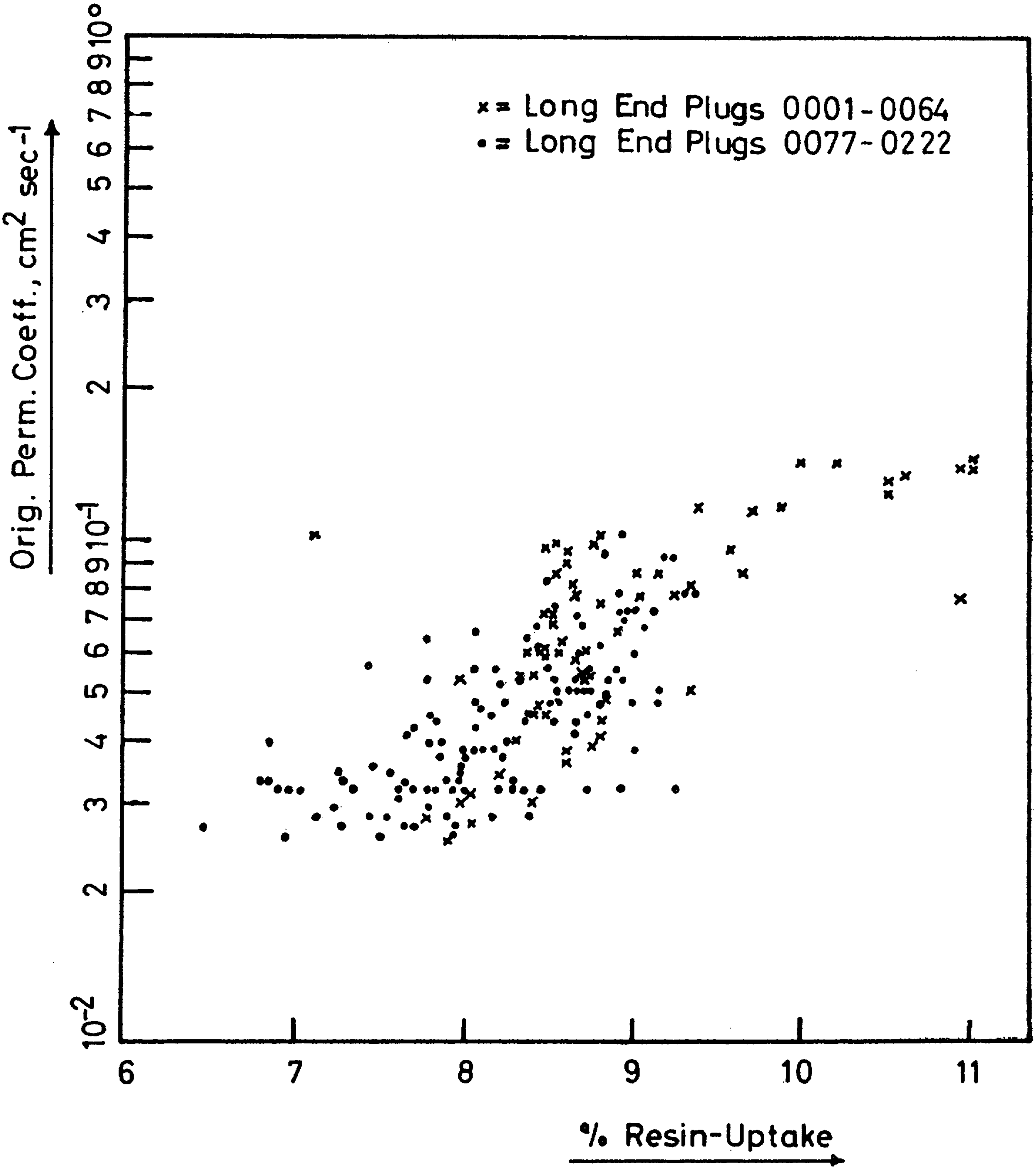


FIG. 16. RELATION BETWEEN RESIN UPTAKE (1st IMPR.) AND ORIGINAL PERMEABILITY FOR LONG END PLUGS.

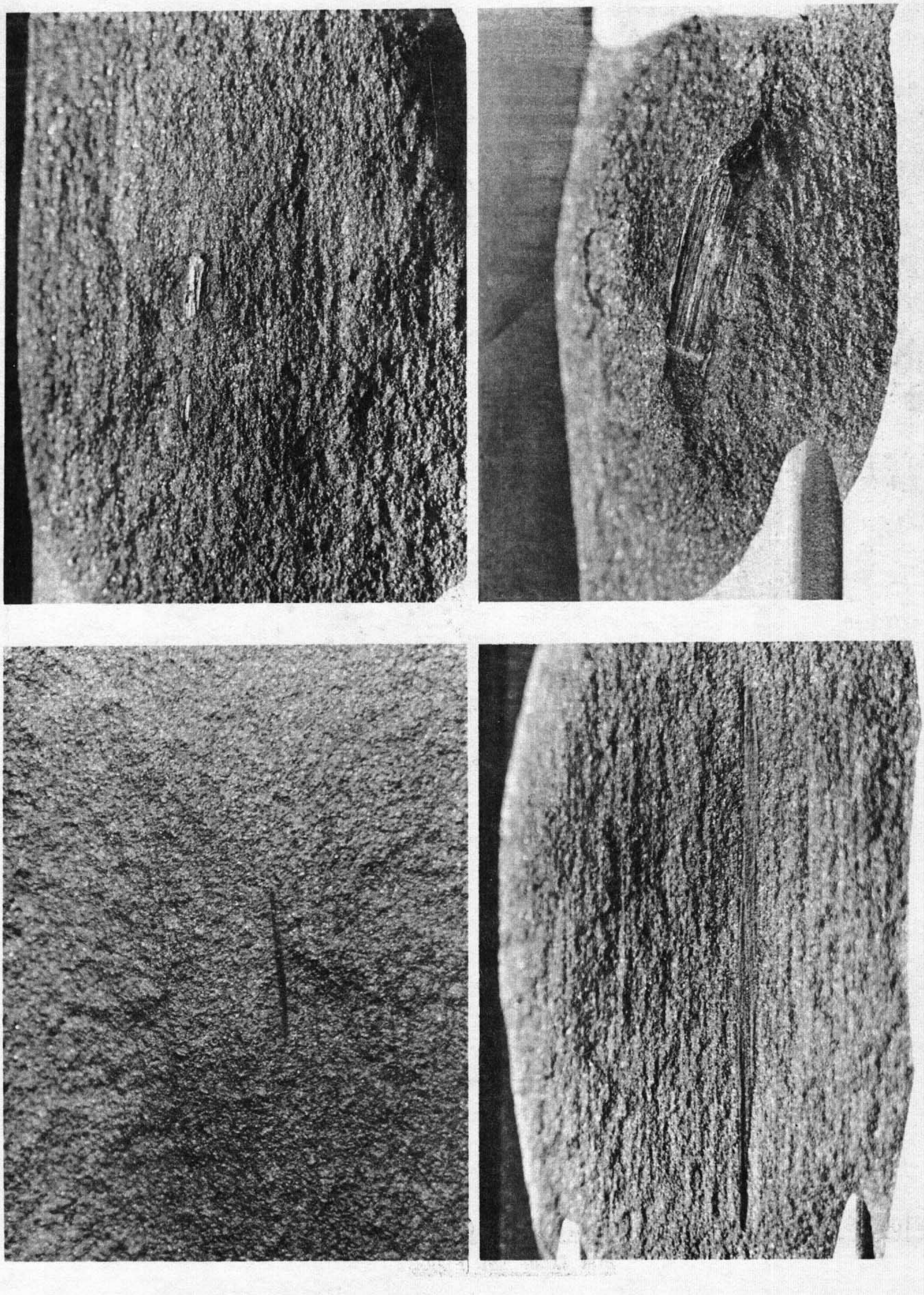


FIG. 17. EXAMPLES OF INCLUSIONS IN SPALLED RODS.

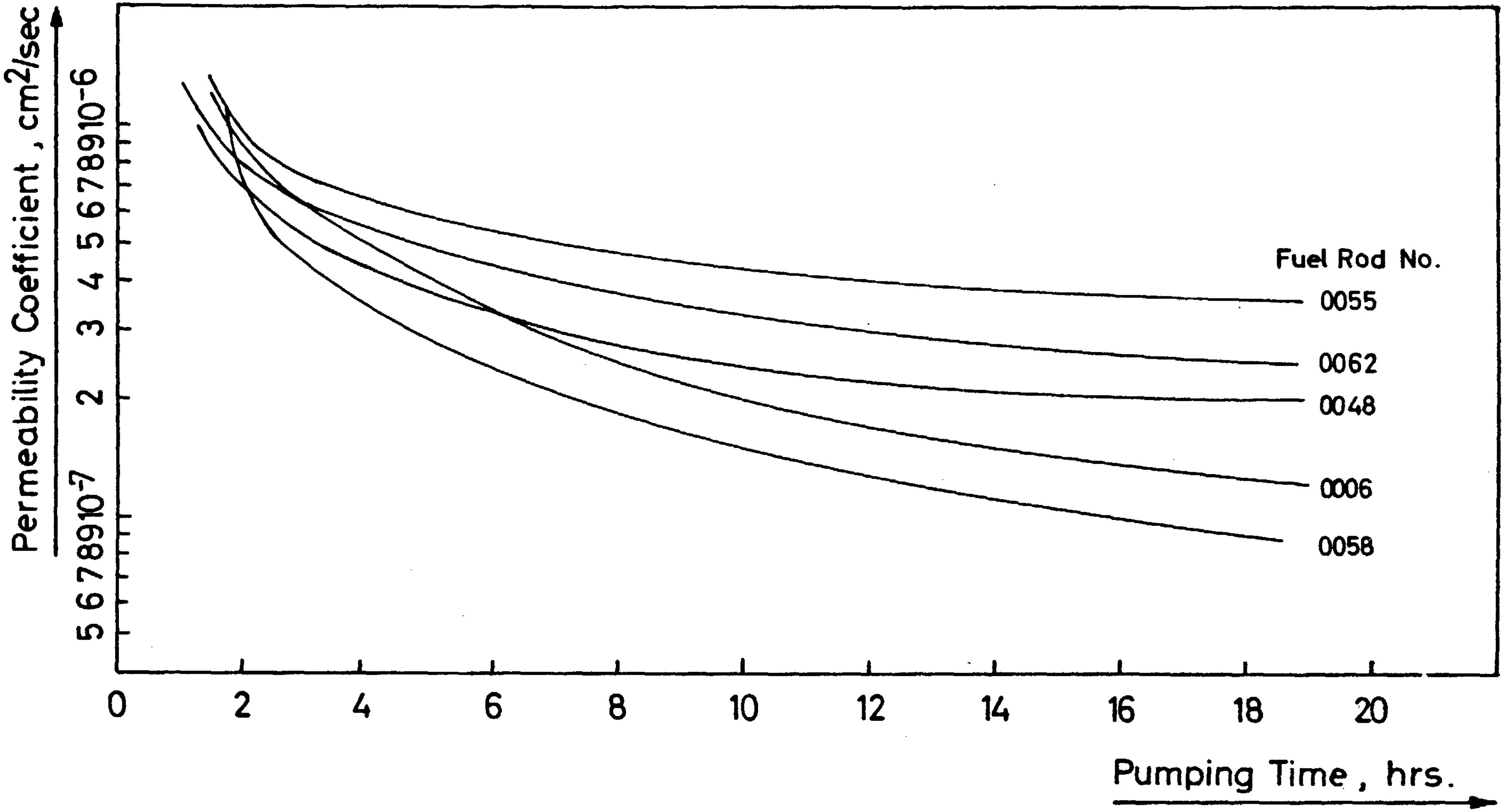


FIG.18. DEPENDENCE OF PERMEABILITY COEFFICIENT ON PUMPING TIME (GRADE 6)

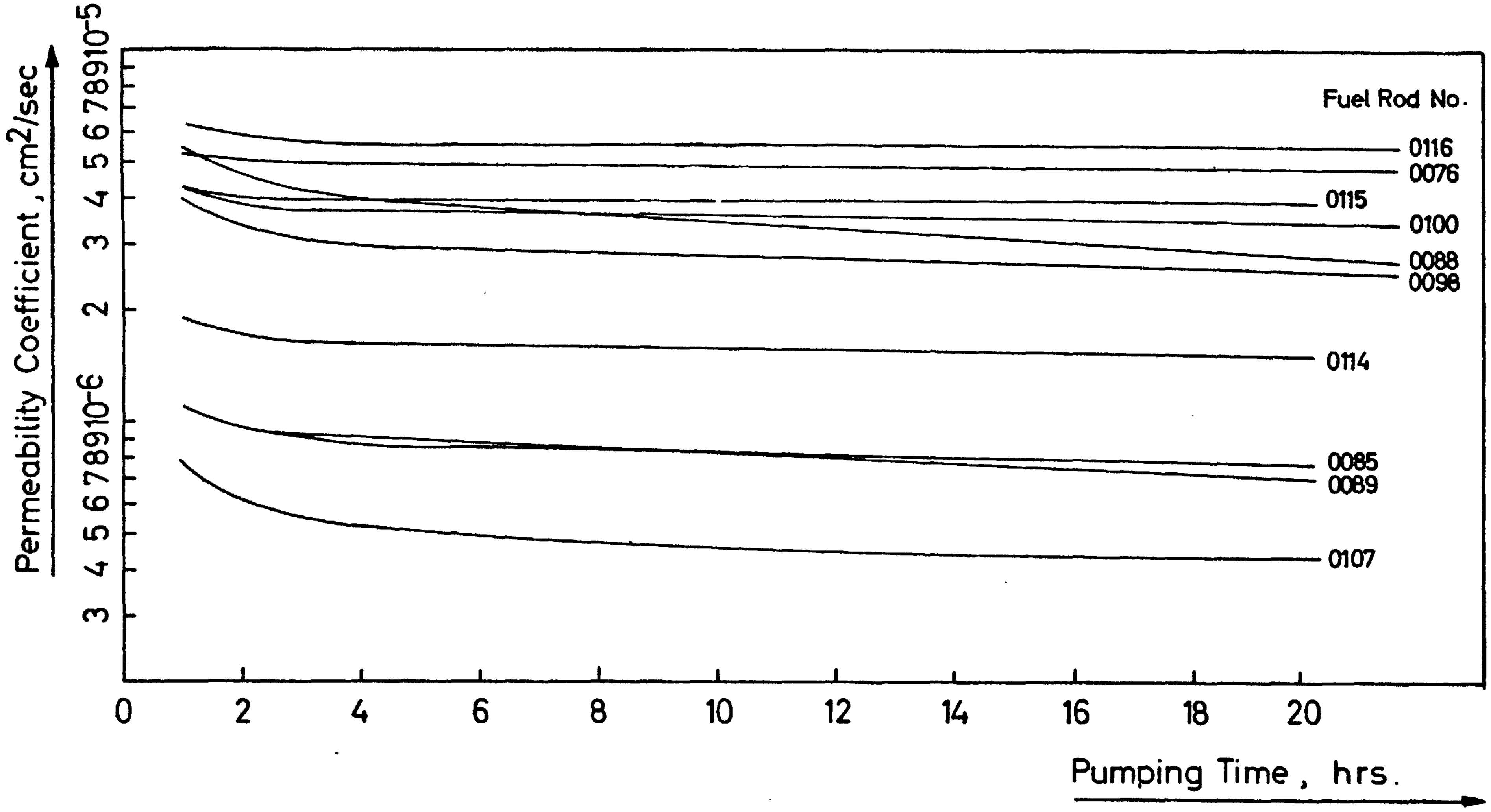


FIG 19. DEPENDENCE OF PERMEABILITY COEFFICIENT ON PUMPING TIME (GRADE 9)

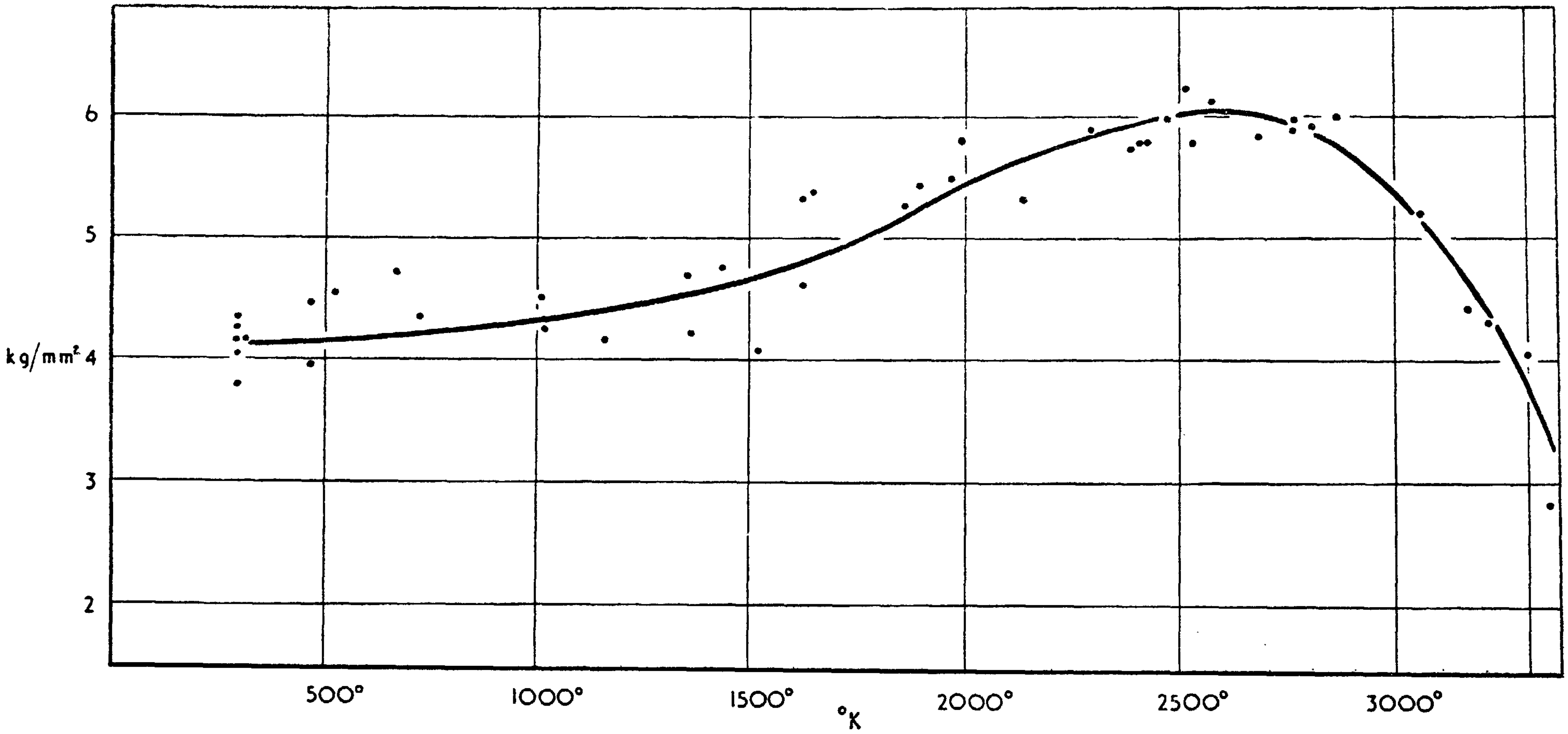


FIG. 20 MECHANICAL PROPERTIES OF TOP BLOCK GRAPHITE

ULTIMATE TENSILE STRENGTH IN THE DIRECTION PARALLEL TO EXTRUSION

(MEASURED BY SUD AVIATION, FRANCE)

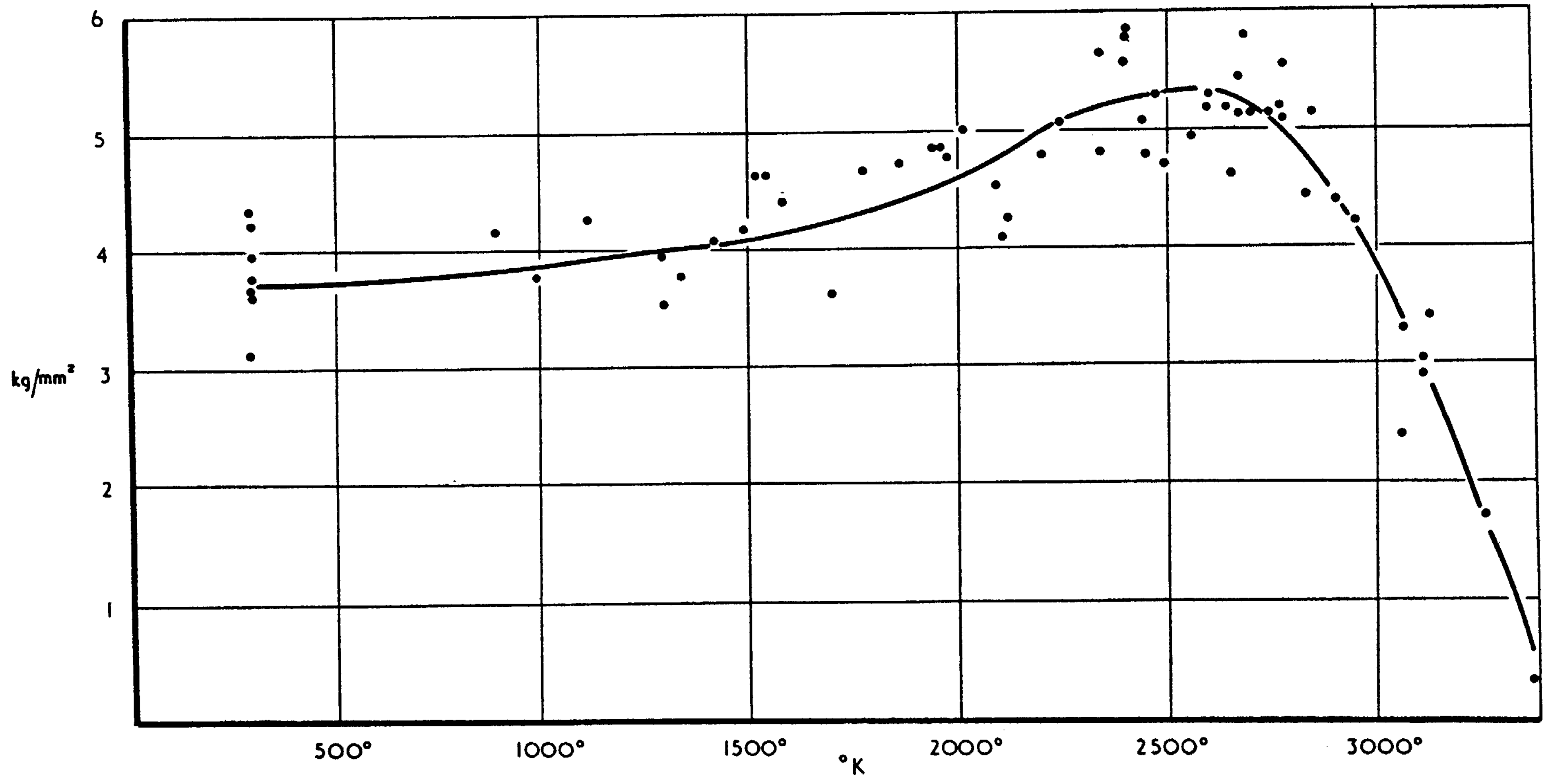


FIG. 21 MECHANICAL PROPERTIES OF TOP BLOCK GRAPHITE

ULTIMATE TENSILE STRENGTH IN THE DIRECTION PERPENDICULAR TO EXTRUSION

(MEASURED BY SUD AVIATION, FRANCE)

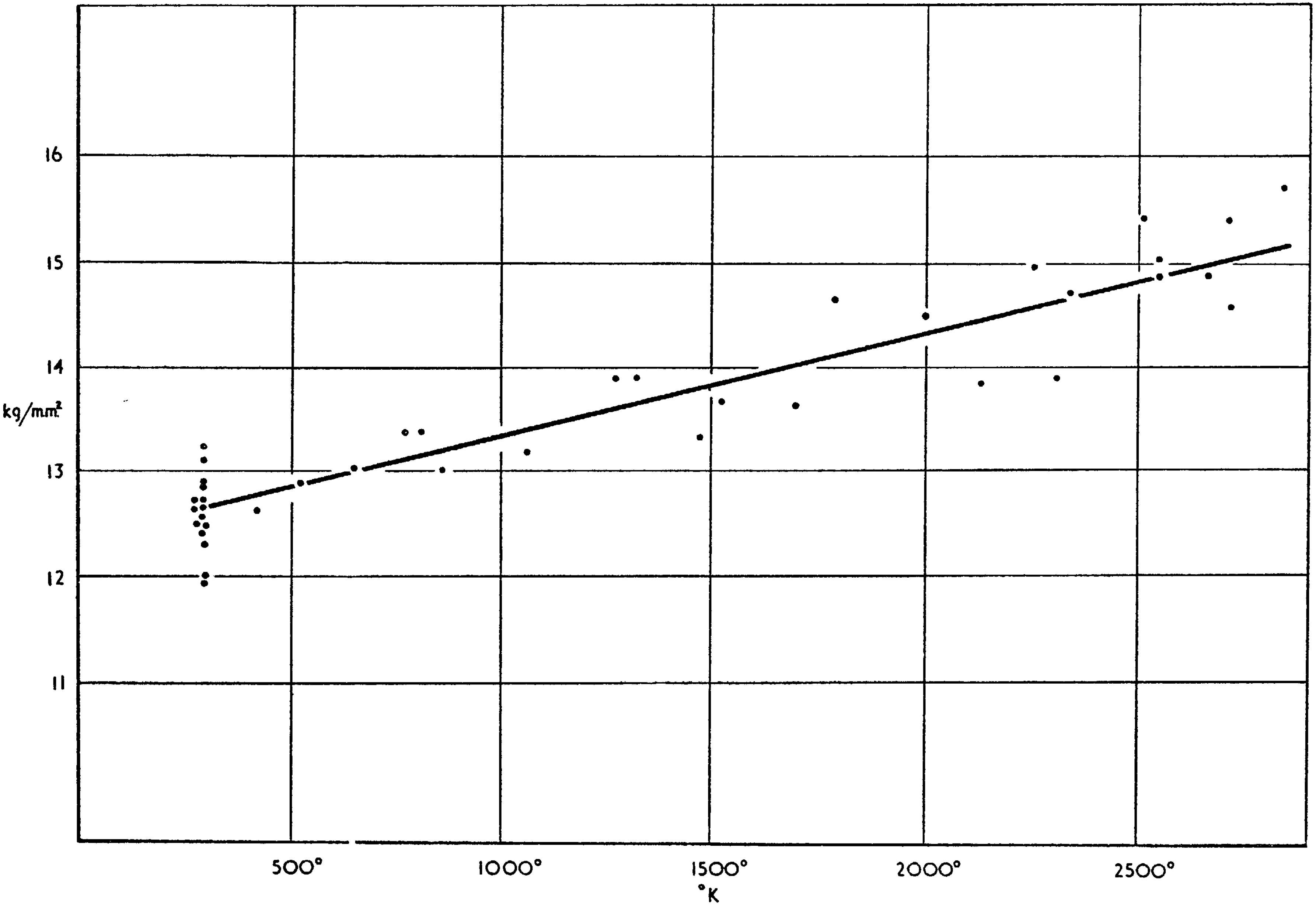


FIG. 22 MECHANICAL PROPERTIES OF TOP BLOCK GRAPHITE.

ULTIMATE COMPRESSIVE STRENGTH IN THE DIRECTION PARALLEL TO EXTRUSION
(MEASURED BY SUD AVIATION, FRANCE)

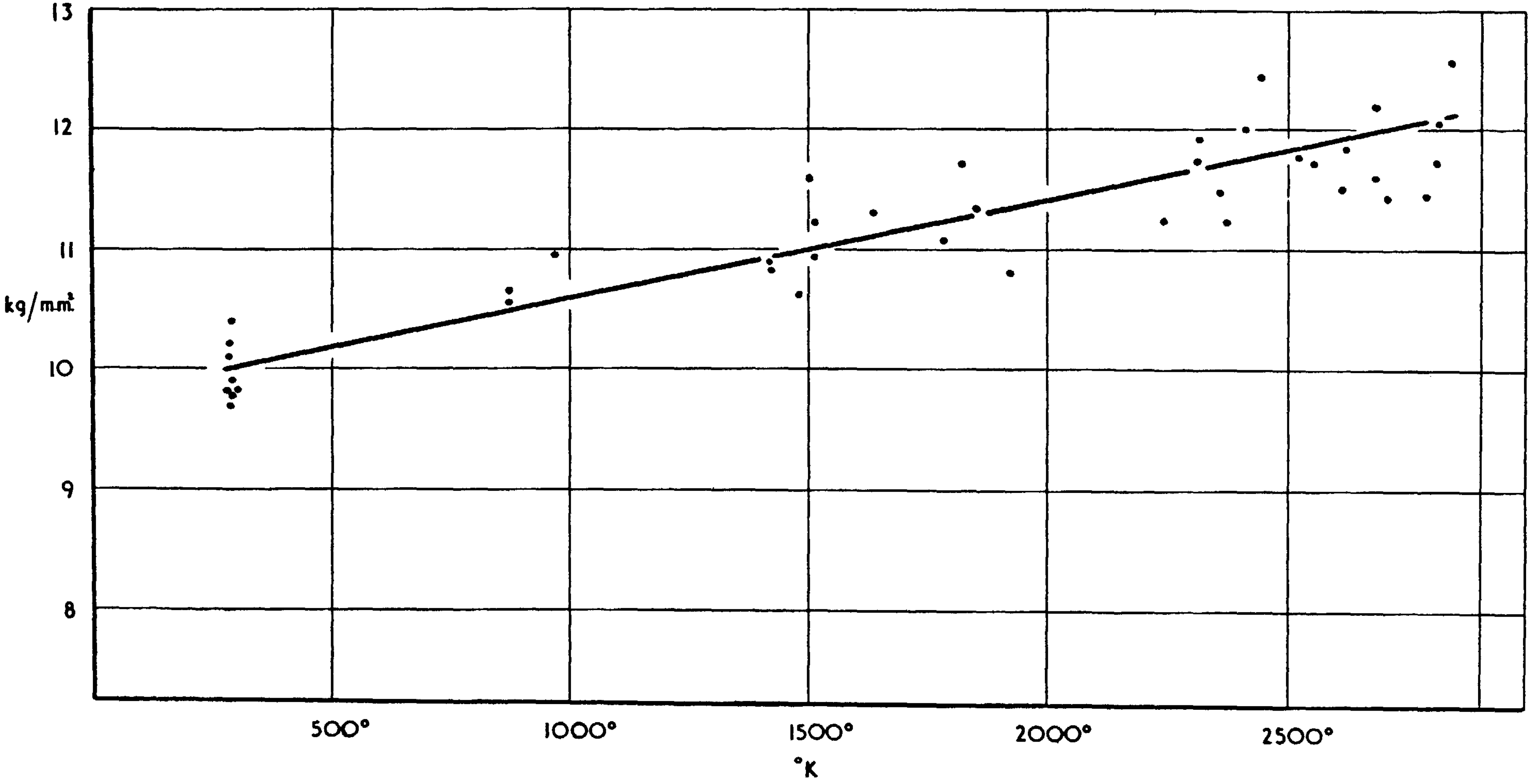


FIG.23. MECHANICAL PROPERTIES OF TOP BLOCK GRAPHITE.

ULTIMATE COMPRESSIVE STRENGTH IN THE DIRECTION PERPENDICULAR TO EXTRUSION
(MEASURED BY SUD AVIATION, FRANCE)

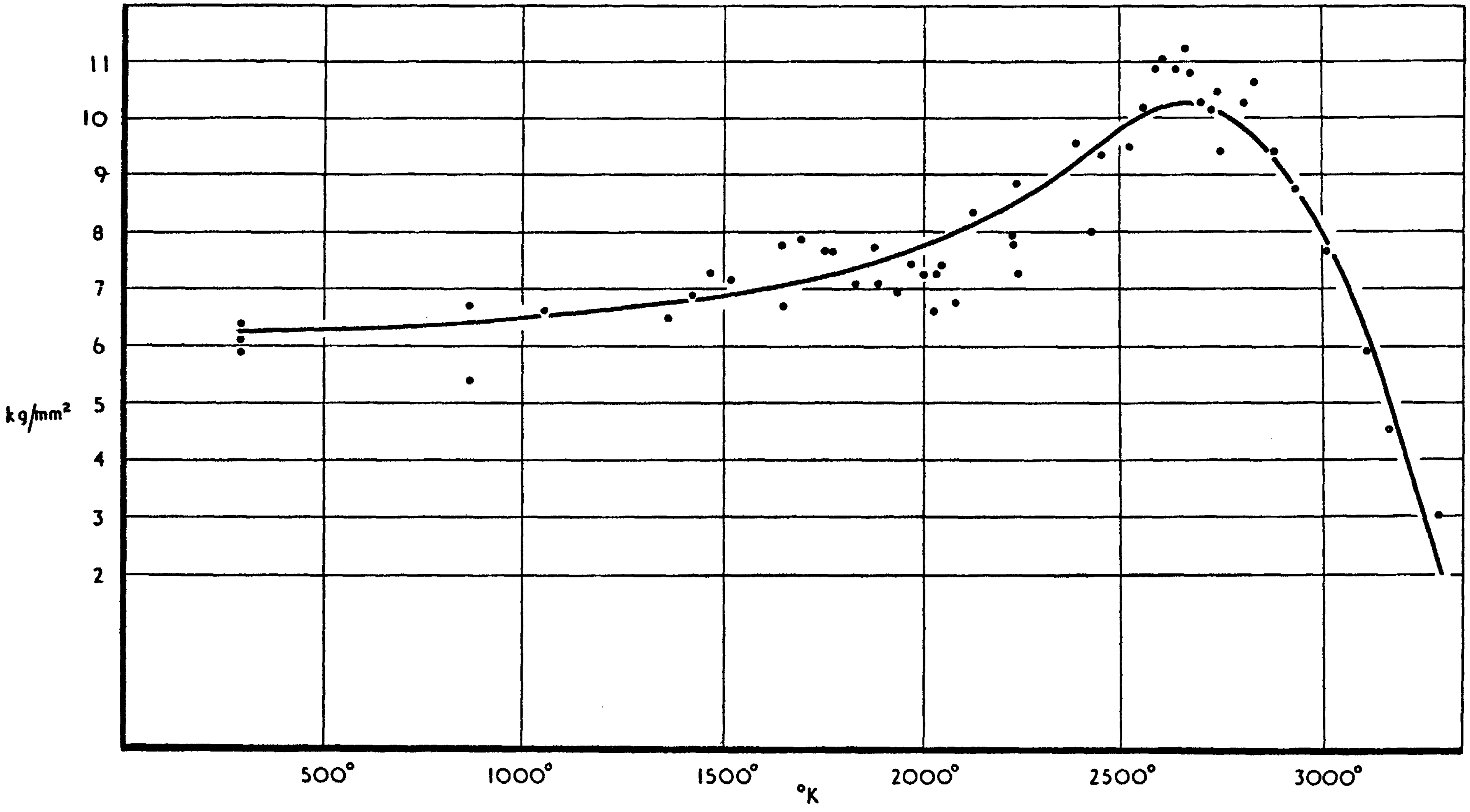


FIG. 24. MECHANICAL PROPERTIES OF TOP BLOCK GRAPHITE

ULTIMATE FLEXURAL STRENGTH IN THE DIRECTION PARALLEL TO EXTRUSION
(MEASURED BY SUD AVIATION, FRANCE)

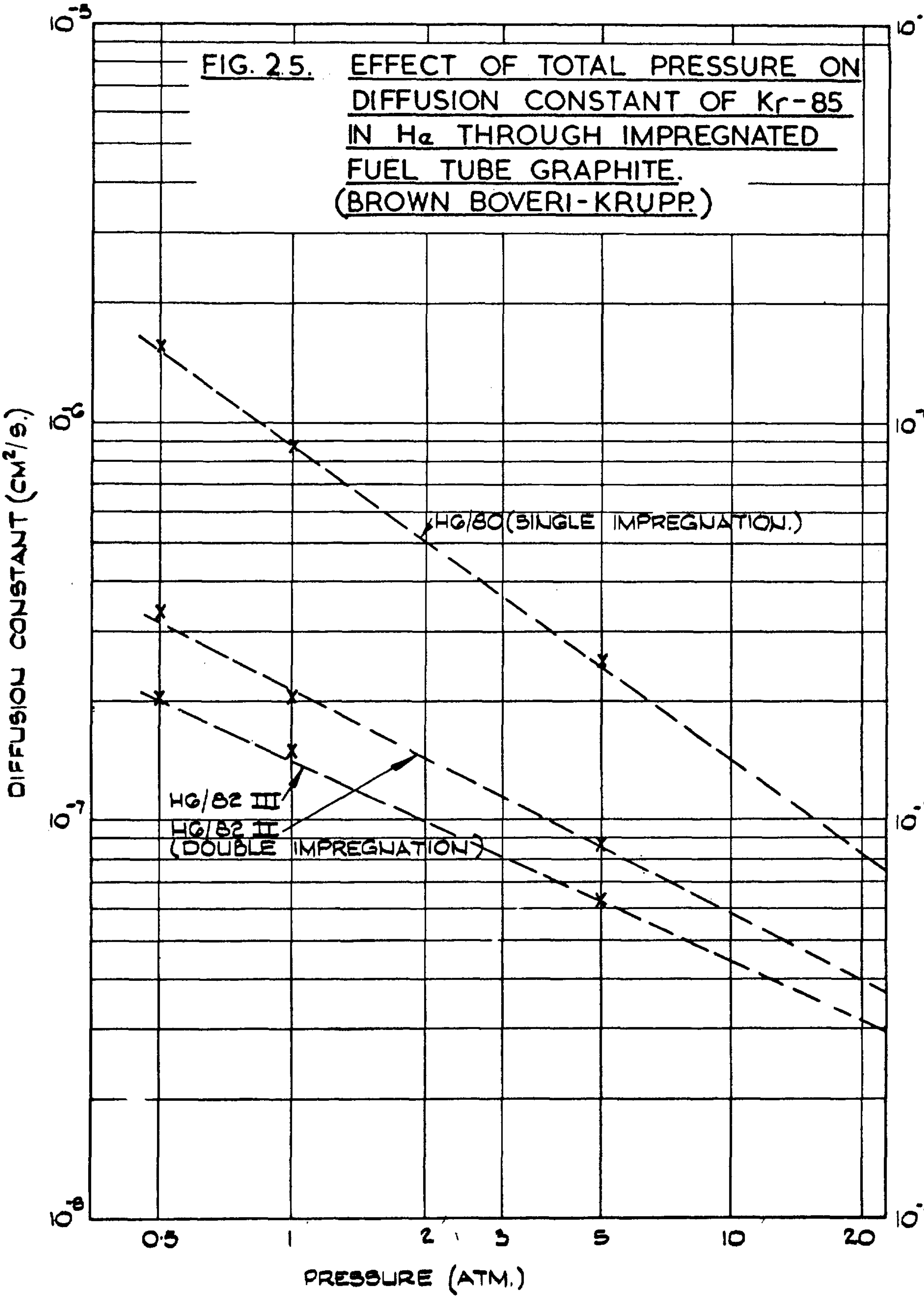


FIG. 2.5. EFFECT OF TOTAL PRESSURE ON DIFFUSION CONSTANT OF Kr-85 IN He THROUGH IMPREGNATED FUEL TUBE GRAPHITE. (BROWN BOVERI-KRUPP)

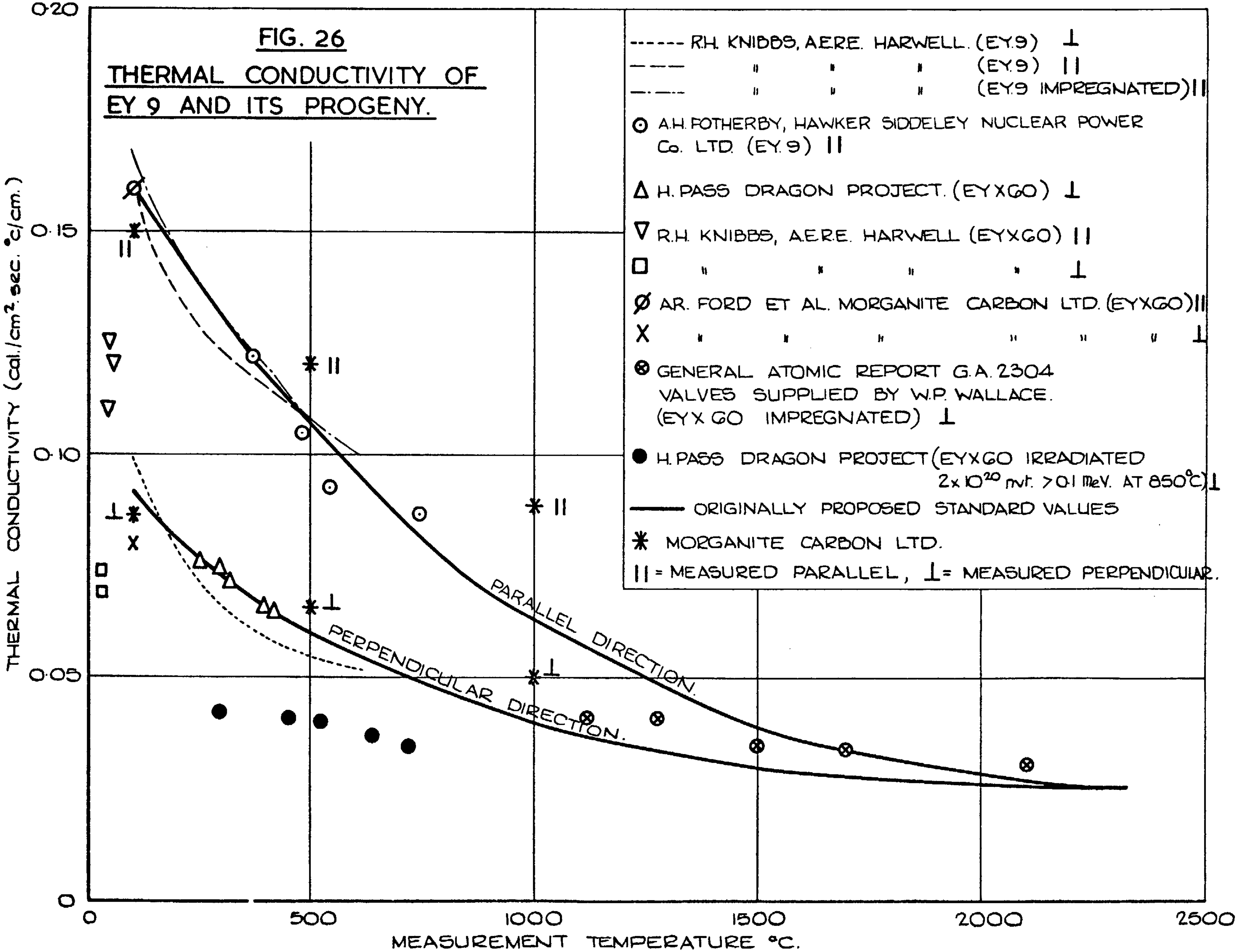


FIG. 26

THERMAL CONDUCTIVITY OF EY 9 AND ITS PROGENY.

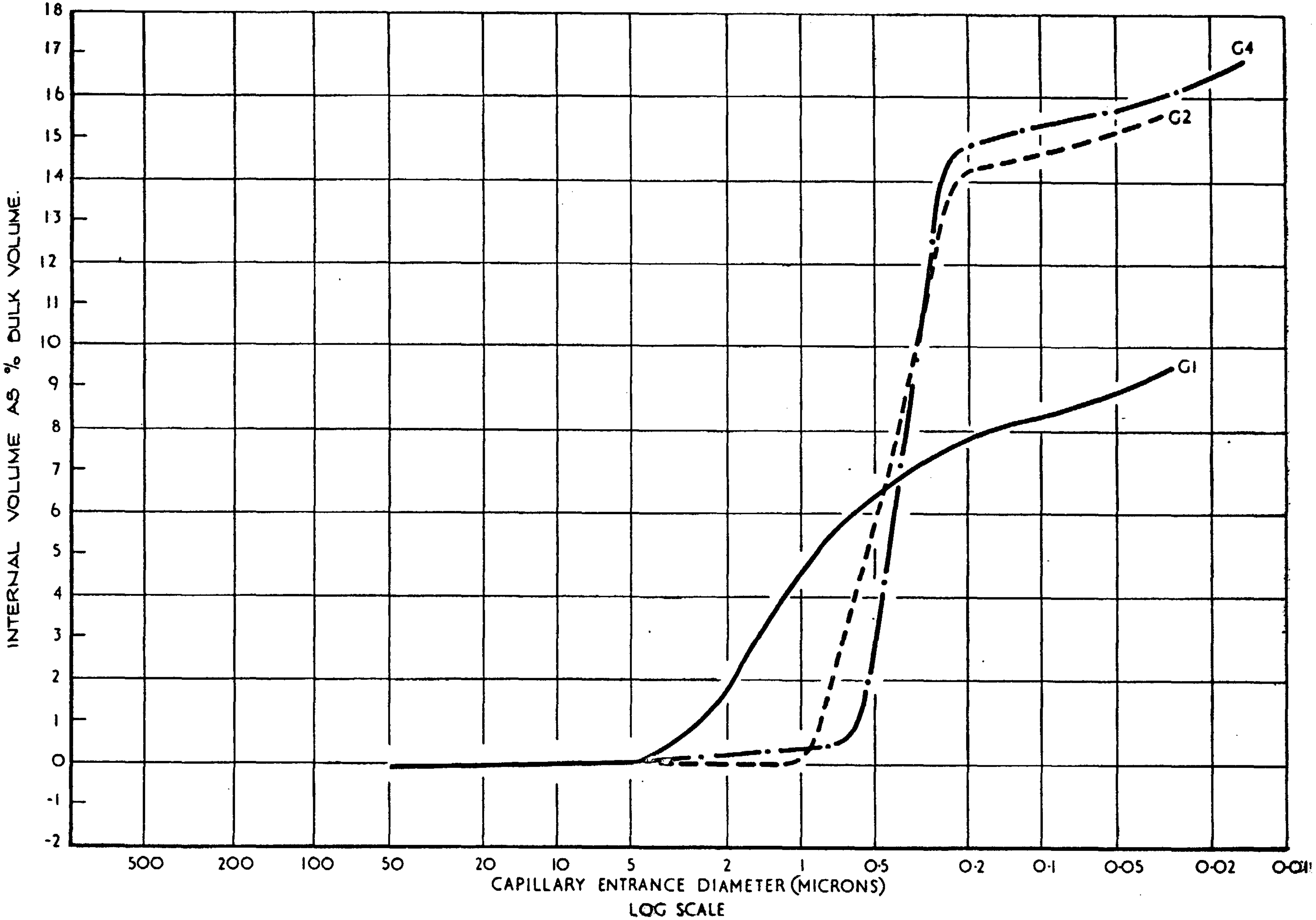


FIG. 27 PORE SIZE DISTRIBUTION CURVES. G1, G2 AND G4 GRAPHITES
(COMPAGNIE PÉCHINEY, CHEDDE, FRANCE)

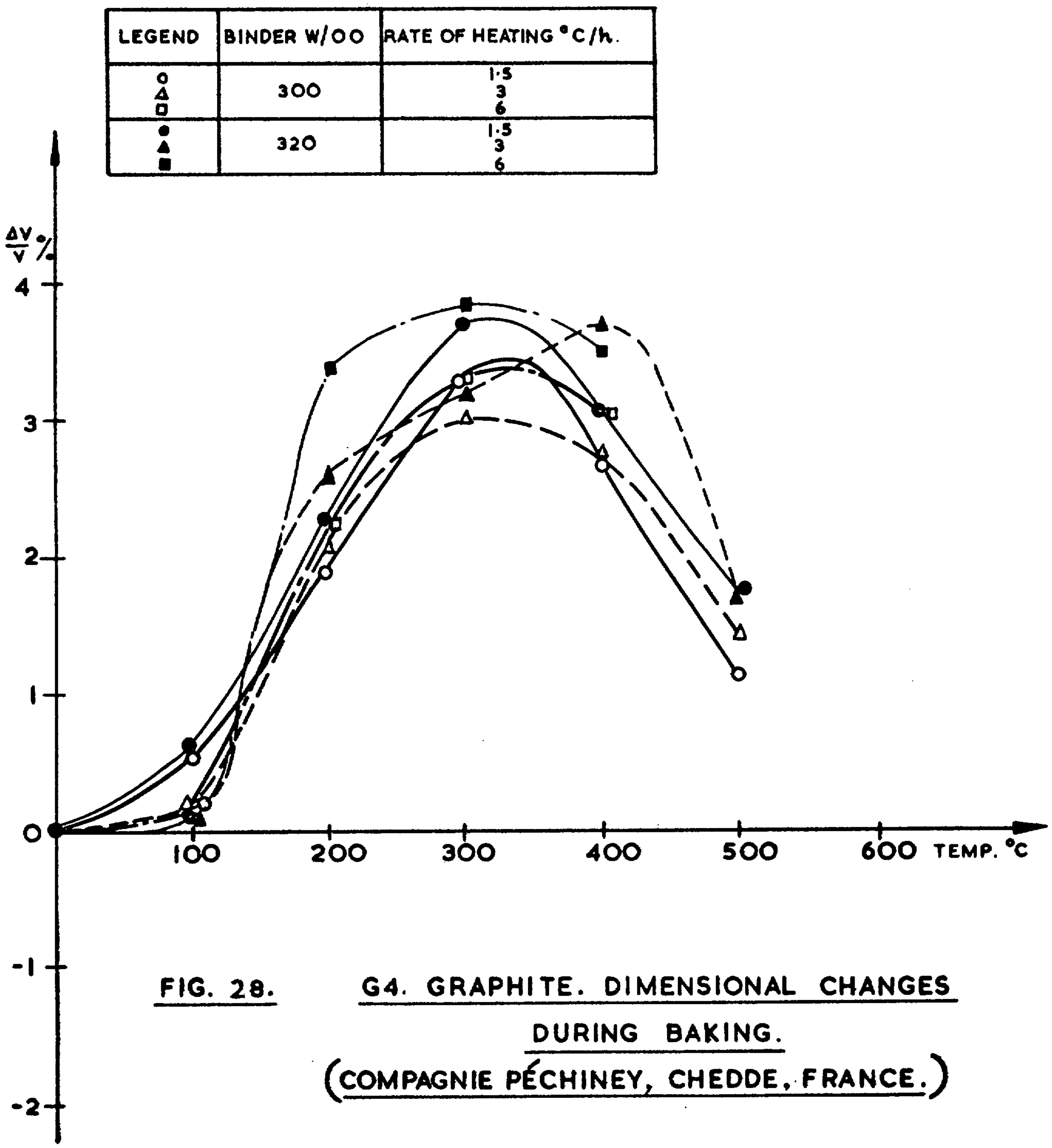


FIG. 28. G4. GRAPHITE. DIMENSIONAL CHANGES DURING BAKING.

(COMPAGNIE PÉCHINEY, CHEDDE, FRANCE.)

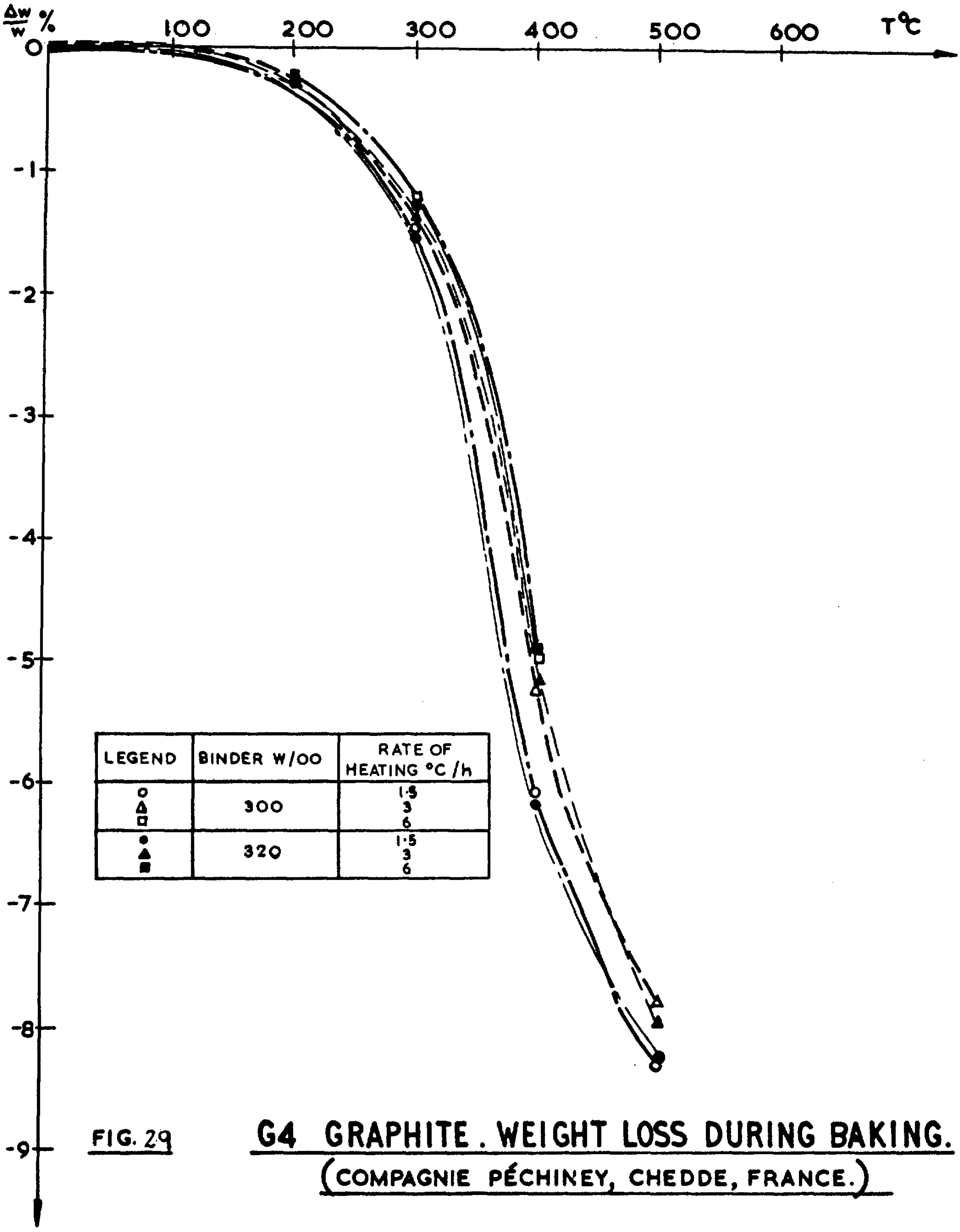


FIG. 29

G4 GRAPHITE. WEIGHT LOSS DURING BAKING.

(COMPAGNIE PÉCHINEY, CHEDDE, FRANCE.)

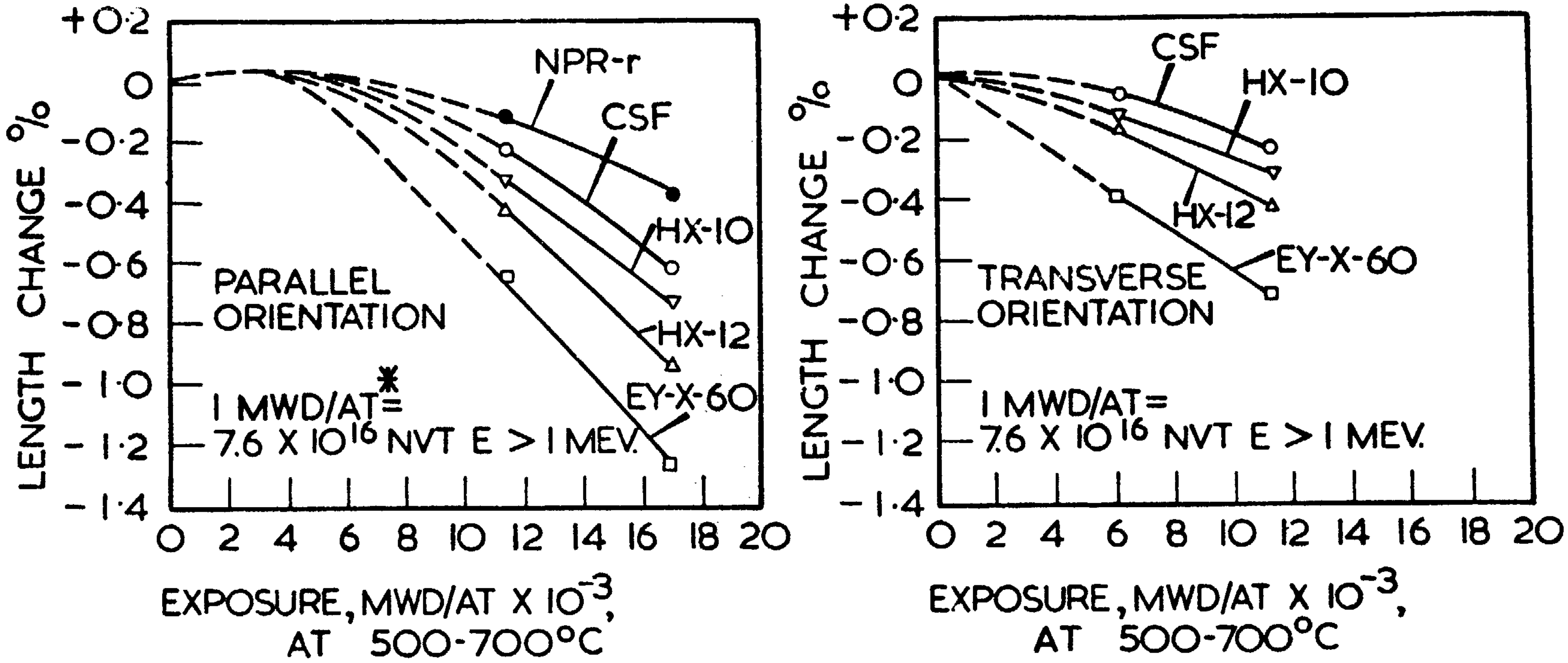
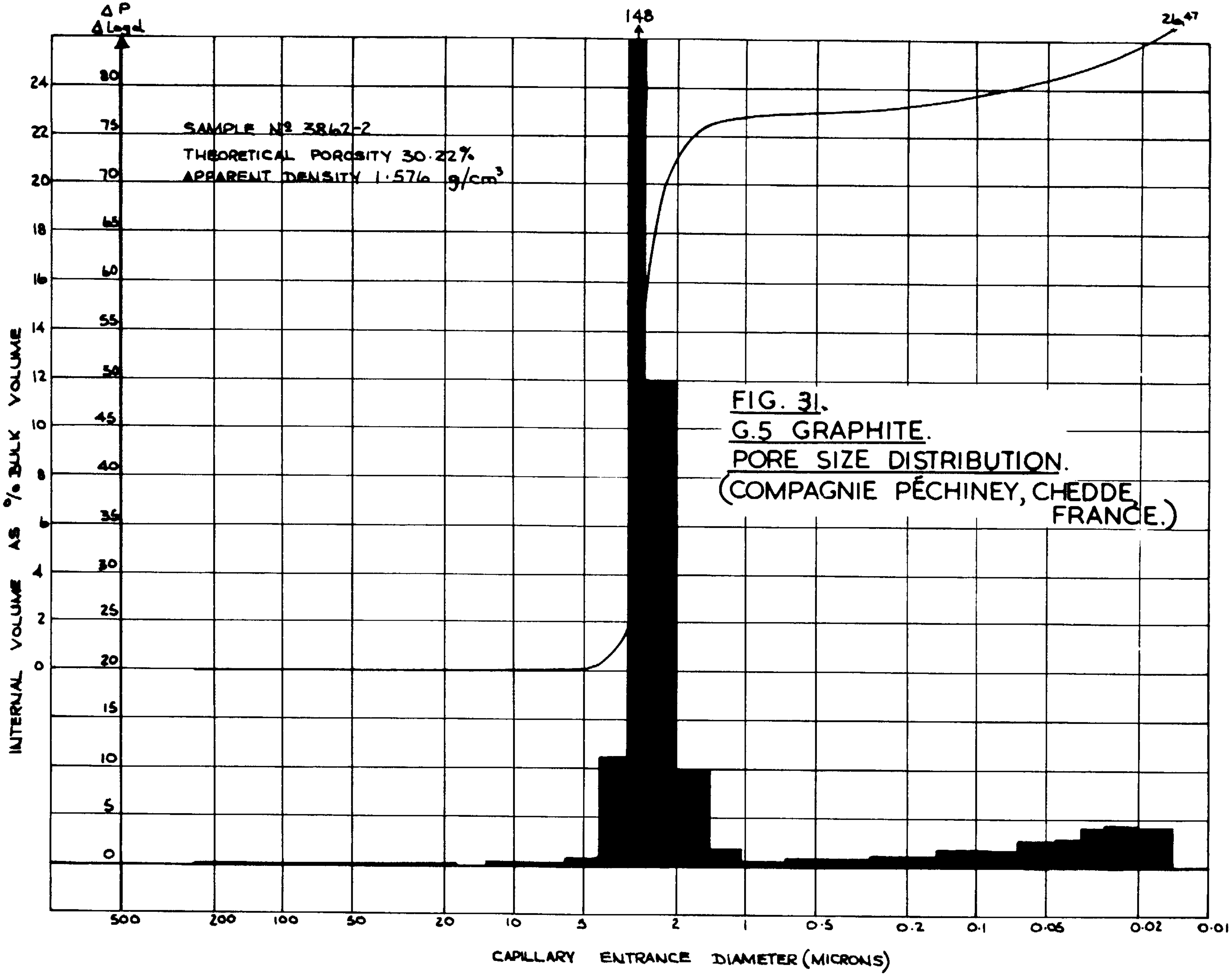


FIG. 30. IRRADIATION SHRINKAGE OF SOME LOWER PERMEABILITY GRAPHITE COMPARED WITH CSF AND NPR GRAPHITES.

(AFTER R.E. NIGHTINGALE HW-SA-2467)

* MWD/AT REFERS TO INTEGRATED POWER IN ADJACENT FUEL.



SAMPLE Nº 3862-2
THEORETICAL POROSITY 30·22%
APPARENT DENSITY 1·576 g/cm³

FIG. 31.
G.5 GRAPHITE.
PORE SIZE DISTRIBUTION.
(COMPAGNIE PÉCHINEY, CHEDDE, FRANCE.)

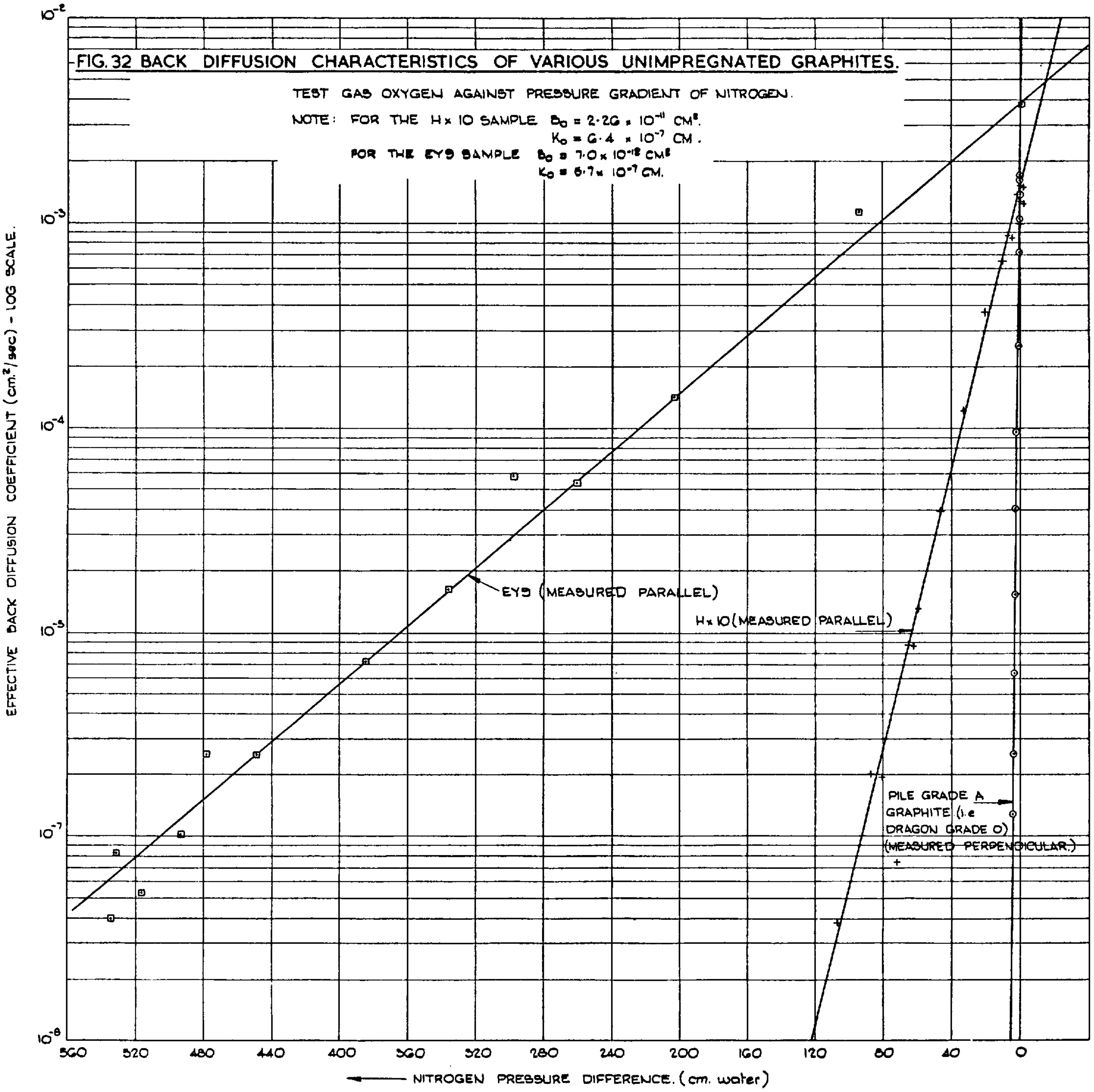


FIG. 32 BACK DIFFUSION CHARACTERISTICS OF VARIOUS UNIMPREGNATED GRAPHITES.

TEST GAS OXYGEN AGAINST PRESSURE GRADIENT OF NITROGEN.

NOTE: FOR THE H × 10 SAMPLE $B_0 = 2 \cdot 26 \times 10^{-11}$ CM^2.
$K_0 = 6 \cdot 4 \times 10^{-7}$ CM.
FOR THE EY9 SAMPLE $B_0 = 7 \cdot 0 \times 10^{-12}$ CM^2
$K_0 = 6 \cdot 7 \times 10^{-7}$ CM.

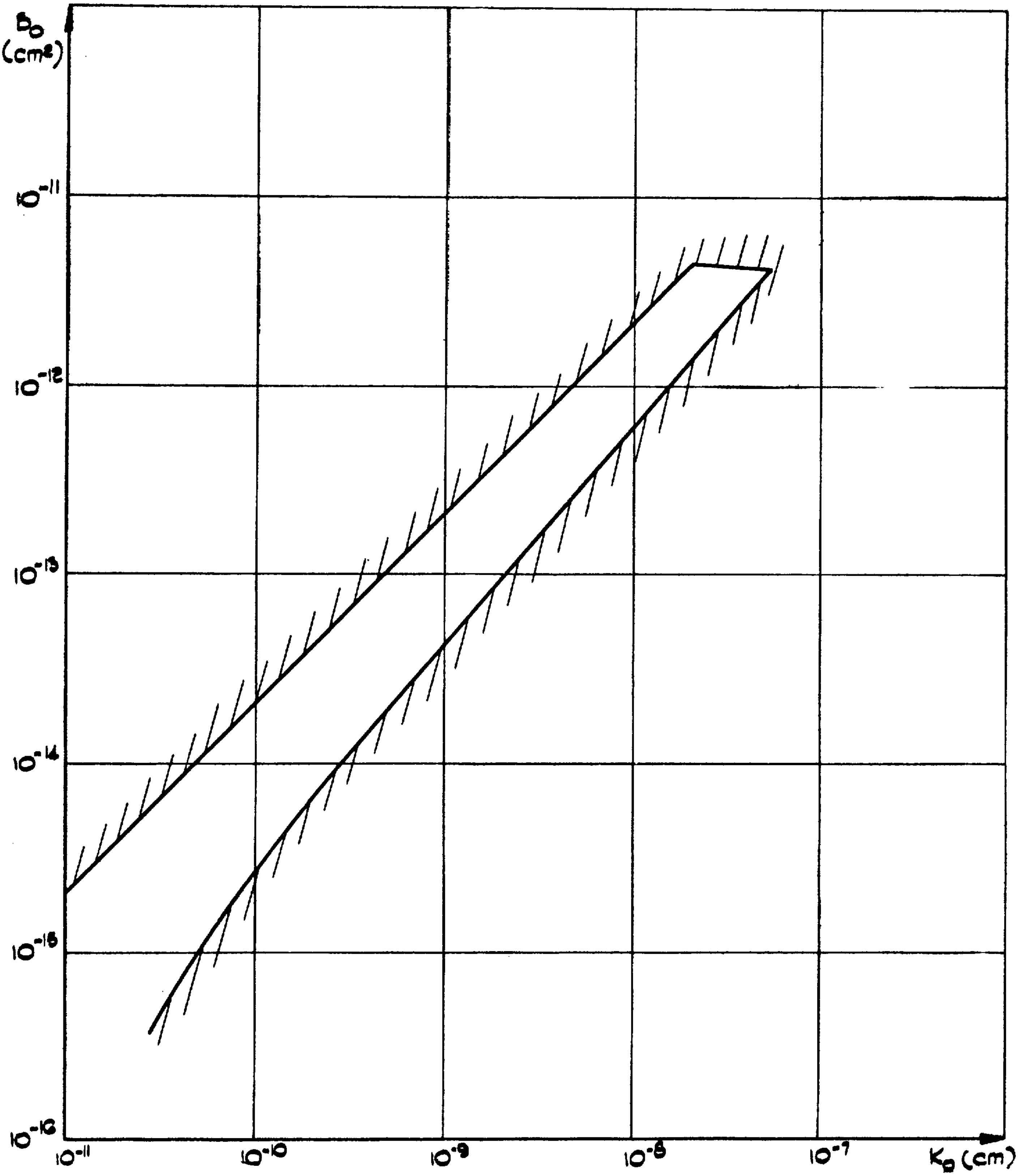


FIG. 33 "TARGET AREA" FOR DRAGON GRAPHITES AS TYPIFIED BY K_o AND B_o PERMEABILITY COEFFICIENTS.

GRAPHITES REPRESENTED BY POINTS INSIDE THE HATCHED AREA ARE SUITABLE FOR DRAGON.
CASE II : PRESSURE DROP ACROSS THE SLEEVE VARIES FROM 0·10 TO 0·37 ATM.