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THE WIGNER EFFECT IN GRAPHITE. RELATIONSHIP BETWEEN ADVANTAGE FACTOR AND LOCATION OF SAMPLES IN AN OPERATING PILE.

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THE WIGNER EFFECT IN GRAPHITE. RELATIONSHIP BETWEEN ADVANTAGE FACTOR AND LOCATION OF SAMPLES IN AN OPERATING PILE

Problem Assignment No. 323 MLC 2301

A.Novick, T.J.Neubert, and M.Burton

October 20, 1944

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0. Abstract

The extent of the Wigner effect in graphite at any point in an operating pile is sensitive to the local structural situation. It is, for example, greater near a slug. The purpose of control experiments in the W pile is to give information in regard to the average graphite in advance of the actual date of occurrence of such changes. The ratio of the anticipated time required for a specific change in the average graphite to the time required in the experimental sample is known as the advantage factor for the position of exposure of the sample; the same term is defined in another (equivalent) way in reference to the experiments at X described in this report. The advantage factor, F, was determined for samples exposed in a variety of positions at X. For the doughnuts described F ≅ 2.3; for short interslug cans F ≅ 2.1; for long interslug cans the value drops to 1.2. The diameter of the active metal in a slug at X is 1.1". The distances between active metal in the two cases were respectively ~1" and ~2.1". The advantage factors given are relative to graphite in an average position in the pile. The factors relative to graphite in the worst position (namely, adjacent to operating tubes at W) would be lower. The need for short test cans and proper geometry of test samples for the control experiments at W is particularly stressed.

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1. Purpose

Favorable locations in an operating pile can give Wigner effects in graphite samples greater than those to be expected in the structural graphite of a pile (CC-1567). Knowledge of the methods of production of such exaggerated exposure is important for the testing program at W. Use of such favored locations for test samples will give knowledge of changes to be expected in graphite considerably in advance of occurrence of such changes in the structural material. This report gives details of a series of experiments performed in the X pile to extend our information concerning the relative advantage of such favorable locations.

The graphite in the structural material of the W pile may be classified in two categories; namely, that in immediate contact with the operating tubes and that more remote from those tubes. The former we can refer to as the intensely exposed graphite, while that located **equidistant** between the operating tubes can be referred to as the average exposed graphite. The maximum intensely exposed graphite and the maximum average exposed graphite will both be at positions near the center of the operating pile.

Exposure of test samples of graphite at positions adjacent to operating holes is not possible at X, nor will it be possible at W. On the other hand, test holes penetrating into the region of average exposure are available both at X and at W. A variety of conditions of exposure was obtained at X by location of samples within hollow tuballoy slugs ("doughnuts"), in cans of different lengths between adjacent slugs, in cans making contact with a slug on one end, and in cans remote from slugs both in the operating hole and in the average hole. Details of the location of these samples are given in 3.1. The experiments described in this report were all run simultaneously. Samples of the same kind were introduced into the X pile at the same time and were removed at the same time. No important changes were made in the pile during the period of operation.[1]

2. Advantage factor, definition

Wigner-effect changes in elastic modulus and in resistance are not linear functions of exposure (CC-2233). Consequently, simple comparison of gross changes observed after long exposures does not indicate the relative effectiveness of different positions. The curves in Figure 1 give the changes in elastic modulus and in electrical resistance as a function of exposure time at a calculated fixed intensity level in an arbitrary position[2] at ~ 35°. Any actually observed changes in properties would require a definite equivalent time for their production under the conditions set for Figure 1. Comparison of such equivalent times for production of changes in properties in two or more positions gives the proper effective relation of those positions.

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[1] There were no local changes in loading in the period Sept.4-14, 1944.

[2] See Appendix 1 for a brief description of the origin of this figure.

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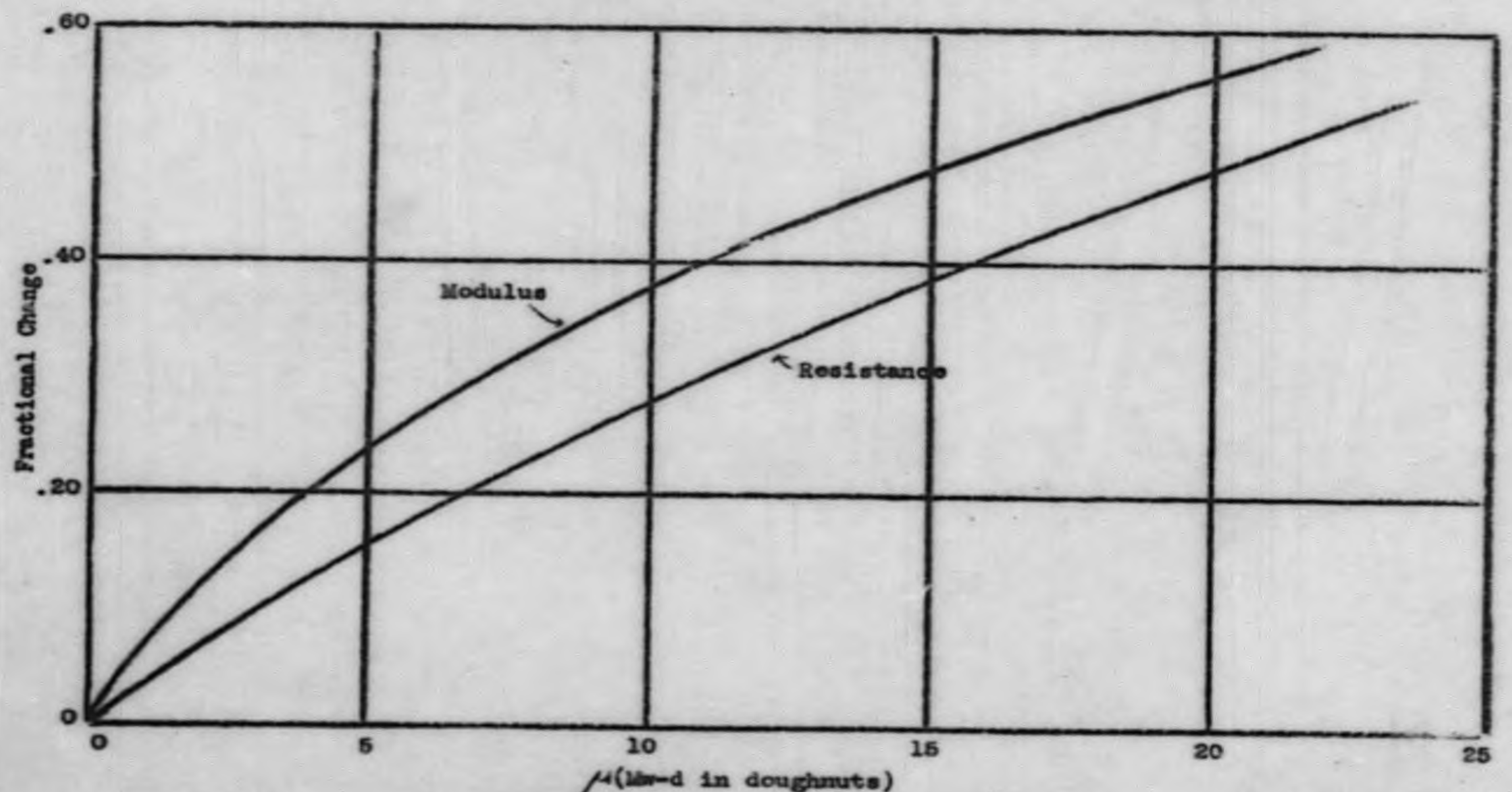

Figure 1. Changes in Electrical Resistance and Elastic Modulus in Doughnuts (T = 35°C)

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For convenience the standard position with which all other positions are compared in this report is the non-operating hole B in the center of the lattice near the center of the pile. Comparisons can be made to this position on two bases. In the first place, mere change in location of a graphite sample with reference to the center of the pile, all other factors being constant, would alter the relative rate of change of a property. In general, it is possible to calculate from a cosine law what the effect would be in a sample exposed in a particular locale at the center of the pile from the actual observation in a similar locale located more remotely from the center, but in a direction parallel to the operating holes. Calculation of the variation of the effect in the perpendicular directions is more complex. The relative thermal neutron density in these directions has been recently calculated by Nordheim (CP-2019).

Let us take as standard the equivalent time required to produce a particular effect in hole B at the center of the pile; i.e., μ_B. Let us designate by μ_1 the equivalent time required to produce a change in a sample in a special locale near the center of the pile during the identical elapsed time of exposure. Then we define the advantage factor for such a locale by the relation $F_1 = \mu_1/\mu_B$.

The value calculated for the advantage factor can depend upon the property examined. Considerable reversal of the resistance occurs on exposure at 100°, while healing of the change in the elastic modulus already is detectable at 130°. Thus, the advantage factor can be a function of temperature, and the determination will be more sensitive to temperature on the basis of resistance change than on the basis of elastic modulus change. The temperature of the reference position in hole B was thought to be near 40°C, although there is some question on that point to which reference will be made later. The other positions at which samples were exposed had temperatures which ranged from 40° to perhaps 100°C. In those cases where the temperature was suspected to be above 50°C, the advantage factor as determined from the change in elastic modulus is the only reliable value; the factor as determined from resistance change will be too low.

Advantage factors calculated from resistance changes have straightforward significance only when the samples under comparison have been exposed at the same temperature. Strictly speaking, Figure 1 should be used only for observations made on pieces exposed at ~35°.

3. Experimental

3.1. Details of the experiments

All samples were constructed of Kendall graphite. They had the form of small cylinders, .156 inch in diameter. Three different lengths were used in the experiments: 1.57 inches, 1.45 inches, and .58 inch. The last samples were needed for exposure in certain short cans, exposed in inter-slug positions. The long cans contained both short and long samples in order to eliminate any possible systematic error resultant from sample size. Initial and final measurements of elastic modulus and electrical resistance were made as described in previous reports (CC-520, CC-216).

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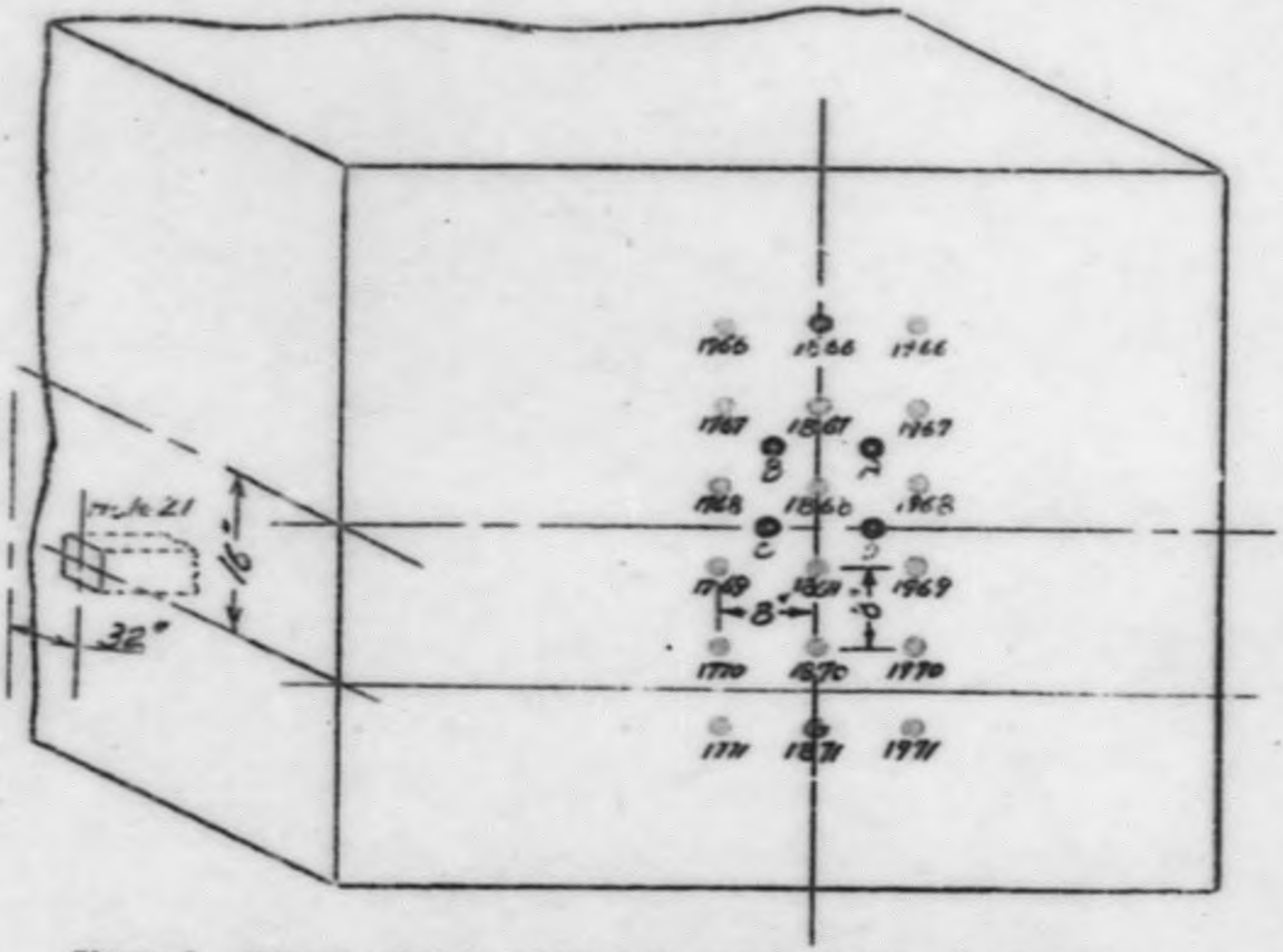

Figure 2. Part of cubical section from center of pile. Only the holes of interest to this report are indicated. Holes 1866 and 1871 are loaded with poison slugs. Green, as well as other holes not indicated, are loaded. Holes 1867 and 1868 are only partially loaded (for details see Figure 4, p. 6).

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The experiment was conducted at Site X during the ten-day period from September 4 to September 14, 1944, when the pile produced 24.15 Mw-d of energy.

Samples were exposed in the charging ducts 1867 and 1868, in the unloaded "lettered" hole B, and in the experimental hole 21. The relationship of hole B and holes 1867, 1868, and 21 is indicated in Figure 2. Holes 1767 and 1768 also shown in Figure 2 were loaded with metal in the usual fashion. Holes 1866 and 1871, also shown in Figure 2, were poisoned with cadmium extending one foot front and back of center. On September 13 an additional 6 inches of cadmium was added. Thus, during the last day of exposure the poisoned slugs extended 18 inches back of center in each tube. This change is not believed to have had a significant effect on the exposed samples.

Hole B: Samples were attached with 25 aluminum wire (see Figure 3) to a one-eighth inch aluminum rod which was in turn inserted in the hole. The specimens were spread out. Some were in a region where the four nearest holes were filled with metal, and some were along the region where only two of the nearest holes were loaded. The detailed arrangement is shown in Figure 4.* At the time of the experiment, the temperature of this hole during operation was believed to be 40°C ± 5°. Actually, the inlet air temperatures during that time ranged near 20°. On the other hand, the experimental results on the resistance effect in the graphite suggest that the temperature near the center probably exceeded 45°.

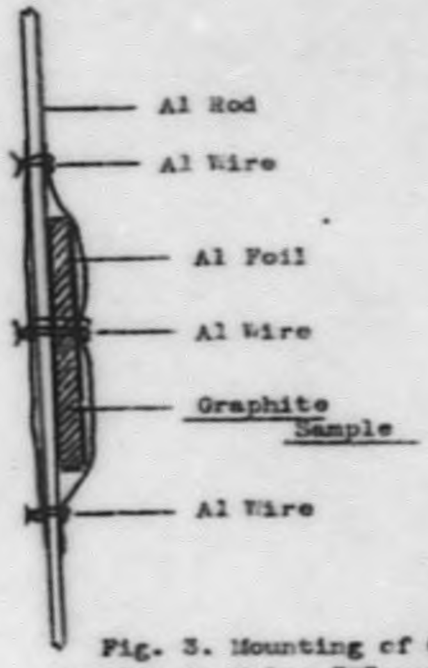

Fig. 3. Mounting of Graphite samples in Holes "B" and "1867"

Hole 1867: This is a slightly enlarged charging duct containing near the center of the pile a series of six aluminum-clad hollow tuballoy cylinders each ~4 in. long. The cylinders (referred to as doughnuts) are 1 in. I.D. and 1.75 in. O.D. A long aluminum tube runs from the charging face of the pile into and through the holes in the six cylinders. The latter were packed closely together (as shown in Fig. 4) and covered a distance estimated to be 25-26 in. Samples to be exposed were fastened by wires to the side of a 1/8 inch aluminum rod at various positions along its length, and the rod was inserted in the tube. Consequently, some of the samples were behind the doughnuts, some in it, and some in front of it. Samples on the outside of the doughnuts were thus one lattice unit, or about 8 inches from the nearest metal other than the doughnuts The actual location of the samples along the rod appears in Figure 3. The temperature in this tube at the

* See next page.

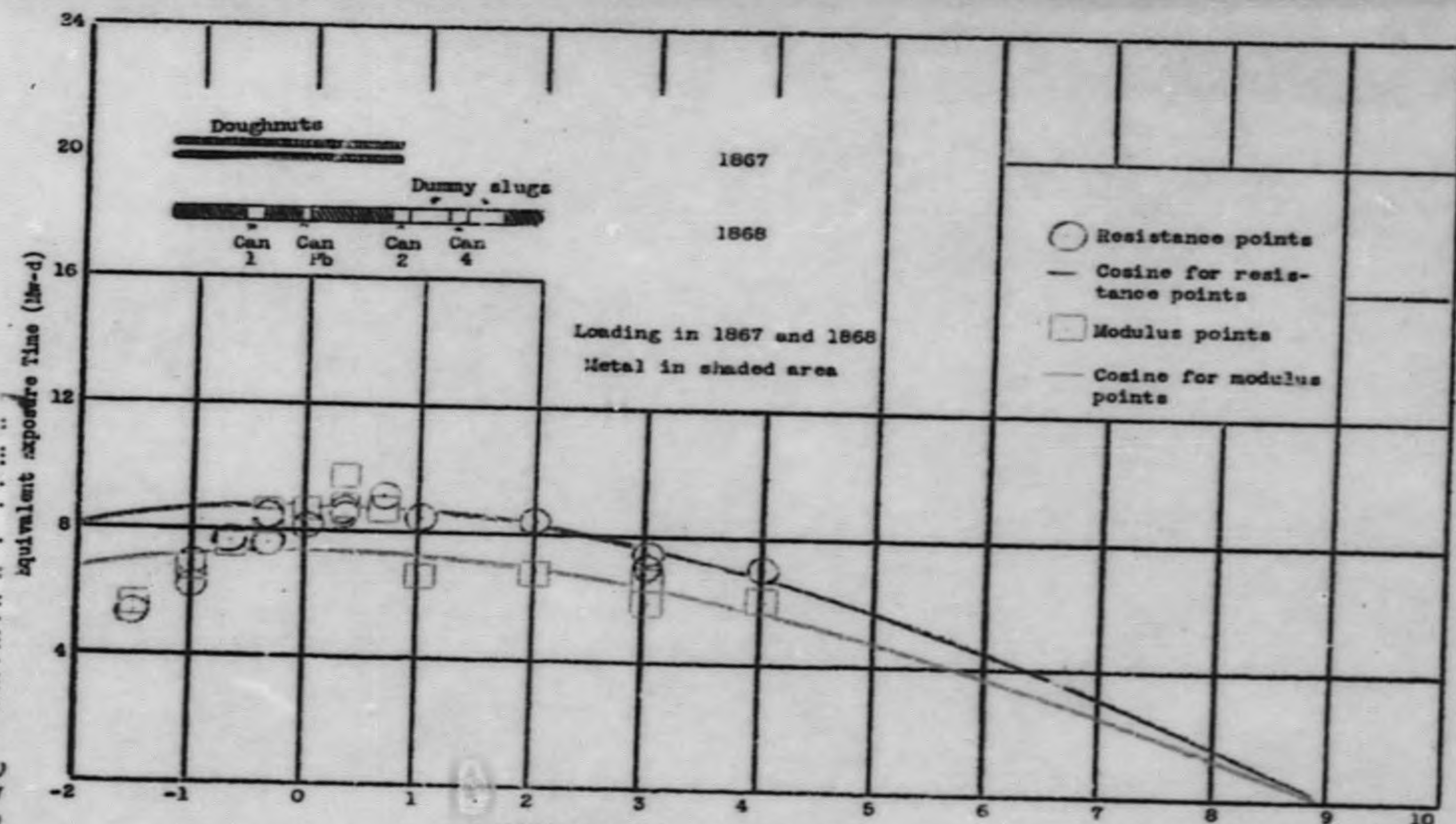

Figure 4. Relative Wigner effects obtained in Hole B of the X pile.

doughnut was 35°C ± 5°, and the temperature before the doughnut averaged about 20°C (8.9° - 30.6° depending on the time of day and the date).[3]

Hole 1868: This is an ordinary charging hole. Sample cans of the two lengths were placed between active slugs. In addition, one can was located with an active slug on only one end, and one can had dummy slugs (containing graphite) on either end. Details are indicated in Figure 4. A description of the cans follows.

Can 1 was an aluminum can 1.1 inch O.D. and 2 inches long. It had an active slug on either side. It contained 4 graphite samples 1.45 inches long and .156 inch in diameter and 2 samples .58 inch long and .156 inch in diameter. These samples were wrapped in aluminum foil and placed as nearly as possible in the center of the can and around its axis. The diameter of the bundle was slightly under 0.5 inch.

Can Pb was a lead can 1.1 inch in diameter and .84 inch long. It was between two active slugs and contained 7 samples .58 inch long and 0.156 inch in diameter. These samples were close packed in an aluminum cylinder placed inside the lead can so that the central sample was approximately on the axis of the outer can. The diameter of the group of samples was under 0.5 inch.

Can 2 was an aluminum can like #1 in dimensions and loading of samples, but it was located in the pile with an active slug on only one end and with a dummy graphite slug on the other.

Can 4 was like can 1 in dimensions and contents, but in the pile it had dummy graphite slugs on both ends (see Figure 4).

The temperature in all these cans was probably between 80°C and 100°C, with the temperature decreasing in the order Pb, 1, 2, 4.

Hole 21: This is one of the experimental holes in a horizontal position normal to the charging holes. It is 16 inches below, and 32 inches toward the charging face from, the geometrical center of the pile. Four cans of samples were placed at 3 inch intervals in a stringer underlying holes 1471 and 1571. The position of these specimens in the pile varied between approximately 4 inches and approximately 5.6 inches from the nearest metal. Since no systematic trends were discovered in the behavior of these specimens during exposure, the data on the exact positions with regard to the nearest metal are not included in this report. Temperatures in these cans were probably near 120°C.

3.2. Results

Hole B: Table 1 lists the changes found in the various positions in hole B and the equivalent exposure times (computed using Figure 1 as already described). Figure 4 gives these equivalent times, for both elastic modulus and electrical resistance observations, as a function of distance along the hole.

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[3] See Appendix 2 for inlet air temperature ranges on Sept. 4-14, 1944.

Table 1. Equivalent Exposure Times in Hole B

Number	Length of sample, in.	Distance from center, in.	$\Delta E/E_o$	μ_e*	$\Delta R/R_o$	μ_r*
1	1.56	- 18	.261	5.60	.168	5.40
2	1.56	- 12	.290	6.52	.206	6.84
	1.46		.299	6.84	.193	6.36
3	1.56	- 8	.319	7.56	.226	7.68
	0.58		.316	7.38	.182	5.92
4	1.56	- 4	.345	8.56	.243	8.44
	1.46		.340	8.32	.223	7.60
5	1.56	0	.348	8.72	.237	8.16
	0.58		.352	8.84	.202	6.72
6	1.56	+ 4	.352	8.80	.247	8.60
	1.46		.372	9.68	.249	8.72
7	1.56	+ 8	.348	8.72	.257	9.06
8	1.56	+ 12	.294	6.64	.245	8.52
9	1.56	+ 24	.295	6.68	.243	8.40
	0.58		.349	8.72	.132	4.05
10	1.56	+ 36	.272	5.92	.219	7.44
	1.46		.289	6.48	.209	7.04
11	1.56	+ 48	.276	6.04	.206	7.04

* μ_e and μ_r refer to equivalent times taken respectively from elastic modulus and from resistance data.

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Evidently elastic modulus data for samples more than 12 inches in front of center fit a cosine curve on the expected 9 foot base (Nordheim, private communication) fairly well. The points in the range one foot back and front of center lie above the curve. The explanation is that in this region the adjacent charging holes are all loaded (cf. Figure 4). This loading more than compensates for the poisoning of the pile in this region, which would otherwise cause a negative departure from the cosine curve. Hence the value of the equivalent exposure time (μ_B) to be used as a standard for calculation of advantage factors is not the extrapolated maximum of the cosine curve but rather the average of the central points. These points, 4 to 7 in Table 1, give an average value of μ_B of 8.8 Mw-d. The data clearly indicate the disadvantage of exposing samples in regions remote from metal. The advantage factor for the outlying points calculated by comparison of the extrapolated maximum with the average of points 4 to 7 is 7.34/8.8 = 0.83. Were it not for the poisoning, the extra loading at the center would make that factor smaller.

The resistance-data equivalent times plotted in Figure 4 show a different peculiarity. The cosine curve is based upon the points remote from the center. The observed values toward and in back of the center fall off markedly below the curve. Our experience with results of this kind indicates that the result is attributable to a higher temperature of the samples in this region. There is no other definite evidence of such a temperature trend. The explanation for the increased temperature of the graphite in this region probably lies in the method of inserting the samples. They were wrapped tightly in aluminum foil which was in turn surrounded by another foil and affixed to the rod by wires, as shown in Figure 3. These samples may make contact through their foils to the graphite walls of the hole so that in certain parts of the hole the temperature may be determined more by a local graphite contact than by the air streaming through the hole. It might seem reasonable to take the equivalent exposure time from values based on low-temperature points. The value adopted for the equivalent exposure time would then be that corresponding to the center point on the extrapolated cosine curve, namely, 8.8 Mw-d.

It thus appears that the equivalent time determined from resistance data agrees with that found from elastic modulus data. However, this value does not deserve too much credence. In Figure 4 the resistance-data equivalent time curve lies above the modulus-data equivalent time curve. The explanation lies in the nature of Figure 1. The resistance-equivalent time curve there is for an arbitrary temperature of 35°. On the other hand, the air stream in the front of hole B probably averaged a temperature of 20° (see Appendix 2). The ratio $\Delta E/E_o$ vs $\Delta R/R_o$ is known to vary sharply with temperature because of the sensitivity of $\Delta R/R_o$-vs-exposure to temperature even at 70° (cf. CC-1668, CC-1669). The difference between the two curves in Figure 4 is clear-cut evidence that $\Delta R/R_o$ is sensitive to temperature even in the range below 35°. Consequently, equivalent times determined from Figure 1 (established for 35°) are not properly applicable to resistance changes occurring at 20°.

On the other hand, we have seen that the elastic-modulus equivalent times near the center actually exceed the extrapolated values because of the higher radiation level in that locale. If the temperature were constant (at presumably ~ 20°) through the hole, the experimental resistance equivalent times at the center should likewise lie above the extrapolated curve. Their failure to do so is evidence that the temperature in that region is higher than in the front part of the hole. The fact that they lie so close to the elastic-modulus equivalent times is evidence that the temperature in that region is not much above 35°.

The equivalent time at the center of hole B is therefore accepted to be that found from elastic modulus data, namely, 8.8 Mw-d.

Hole 1867: Table 2* gives the positions, property changes, and equivalent exposure times found for samples exposed in 1867. Plots of the equivalent exposure times (for elastic modulus and electrical resistance) as a function of distance, in Figure 5,† indicate clearly that the "26 inch doughnut" lies with its center 3 inches to the back of the center of the pile. Table 5‡ gives the advantage factors for points in the doughnuts (about 2.2 for both modulus and resistance data) and for the extrapolated maximum of the cosine curve for the outlying points. It is apparent that these outlying points are in a region remote from metal; the nearest metal is approximately 8 inches away.

Noteworthily, the elastic-modulus and the resistance equivalent exposure times are approximately the same for the region within the doughnuts. The measured temperature in that region was ~35°. Thus, such a result was to be expected. On the other hand, the equivalent-time points as determined from resistance data for the region outside the doughnuts are higher than those determined from elastic modulus data. The explanation is the same as that already given for similar results in hole B; namely, the temperature outside the doughnuts averaged about 20° and therefore Figure 1 (established for 35°) gives high values of equivalent time based on resistance data. The value F_r = .92 compared with F_e = .73 for "extra-doughnut" points is thus explained. Only the F_e value has direct significance.

Hole 1868: The interslug cans 1, Pb, 2, and 4 were exposed in this hole. The data are given in Table 3.** In this case, evidently, the temperature is sufficiently high to invalidate the significance of the resistance results except possibly in the coolest can, #4. It is interesting that the advantage factor found for the samples exposed in can Pb is approximately the same as that found for samples exposed in doughnuts, namely, ~ 2.2. The advantage of this short, tight geometry over the long, tight geometry in can #1 is quite evident. The agreement between the values of F_e for samples remote from slugs in can #4 and for extra-doughnut samples (i.e., ~0.74) is according to reasonable expectation. The reduced value of F_r for can #2 samples (i.e., 1.05) as compared with can #1 samples (i.e., 1.19) is attributable, of course, to the presence of active metal on one end of can #2 and on both ends of can #1. The difference between values of F_e for #1 and #2 (1.19 - 1.05 = .14)

* See page 11.
† See page 13.
‡ See page 15.
** See page 12.

Table 2. Equivalent exposure times in hole 1867

Number	Length of sample, in.	Distance from center, in.	$\Delta E/E_o$	t_e	$\Delta R/R_o$	t_r
1	1.56	- 22.50		(sample lost)		
2	"	- 20.25	.249	7.24	.190	6.24
3	"	- 17.50	.328	7.88	.206	6.88
4	"	- 14.25	.560	20.00	.428	17.28
5	"	- 11.25	.565	20.32	.453	18.56
6	"	- 8.25	.533	18.16	.450	18.40
7	"	- 5.25	.572	20.80	.512	21.68
8	"	- 2.25	.519	17.28	.432	17.4
9	"	+ .75	.577	21.84	.454	18.6
10	"	+ 3.75	.520	17.36	.474	19.68
11	"	+ 6.75	.560	20.00	.503	21.28
12	"	+ 9	.517	17.20	.441	17.84
13	"	+ 12.75	.296	6.72	.229	7.84
14	"	+ 15.75	.276	6.04	.226	7.72
15	"	+ 19.75	.295	6.68	.229	7.84
16	"	+ 24.75	.259	5.56	.243	8.4
17	"	+ 30.75	.246	5.16	.203	6.80
18	"	+ 37.75	.210	4.16	.183	6.00
19	"	+ 45.75	.210	4.16	.178	5.76
20	"	+ 54.75	.204	3.96	.172	5.56
21	"	+ 64.75	.215	4.28	.175	5.68
22	"	+ 76.75	.144	2.48	.111	3.32
23	"	+ 88.75	.083	1.16	.066	1.88
24	"	+ 100.75	.014	0.12	.026	.68
25	"	+ 112.75	.000	0	.012	.28

Table 3. Equivalent Exposure Times in Hole 1868

Number	Length of sample, in.	Distance from center, in.	$\Delta E/E_o$	μ_o*	$\Delta R/R_o$	μ_r*
1	1.46	-6"	.390	10.44	.181	5.88
	1.46		.380	10.00	.177	5.68
	1.46		.431	12.40	.187	6.20
	1.46		.359	9.12	.184	6.00
	0.58		.470	14.50	.148	4.68
	0.58		.500	16.12	.165	5.28
Ave.				12.09		5.62
Pb	0.58	0	.569	20.64	.185	6.08
	0.58		.532	18.12	.198	6.64
	0.58		.574	21.00	.209	7.00
	0.58		.581	21.30	.228	7.80
	0.58		.487	15.36	.215	7.28
	0.58		.523	17.76	.227	7.76
	0.58		.592	22.20	.174	5.64
Ave.				19.48		6.59
2	1.46	49"	.368	9.52	.207	6.92
	1.46		.340	8.32	.210	7.04
	1.46		.333	8.08	.226	7.08
	1.46		.374	9.76	.219	7.44
	0.58		.337	8.22	.216	8.96
	0.58		.372	9.68	.203	6.80
Ave.				8.93		7.47
4	1.46	415"	.252	5.32	.177	5.76
	1.46		.332	8.00	.176	5.72
	1.46		.267	5.76	.172	5.56
	1.46		.294	6.64	.163	5.20
	0.58		.293	6.70	.125	3.84
	0.58		.316	6.80	.141	4.40
Ave.				6.54		5.09

* The cosine correction for μ_o and μ_r was not applied. At most it would have amounted to 2 per cent.

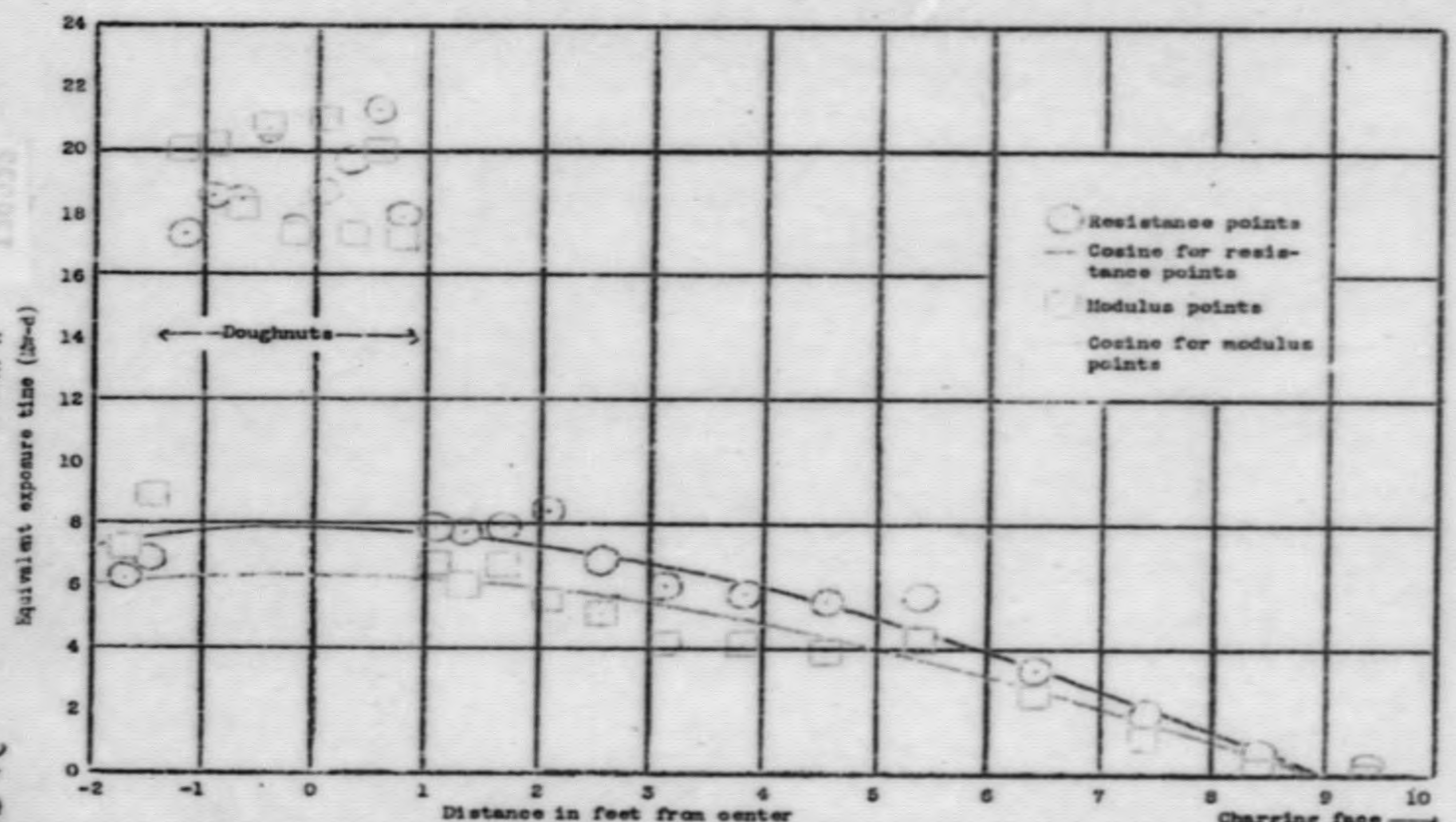

Figure 5. Relative Wigner effects obtained in Hole 1867 of the X pile.

Table 4. Equivalent Exposure Times in Hole 21

Number*	Length of sample, in.	ΔE/L₀	τ_e uncorrected	ΔR/R₀	τ_r uncorrected
5	1.56	.350	8.72	.119	3.64
	1.56	.359	9.12	.109	3.32
	1.46	.374	9.76	.110	3.32
	0.58	.409	11.36	.080	2.40
Ave.			9.74		3.18
6	1.56	.343	8.48	.098	2.92
	1.56	.339	8.32	.103	3.08
	1.46	.399	10.88	.103	3.08
	0.58	.383	10.33	.088	2.60
Ave.			9.50		2.92
7	1.56	.391	10.52	.093	2.72
	1.56	.363	9.28	.119	3.64
	1.46	.393	10.60	.106	3.16
	0.58	.384	10.20	.069	2.00
Ave.			10.15		2.84
8	1.56	.358	9.12	.120	3.64
	1.56	.377	9.84	.123	3.68
	1.46	.440	12.84	.110	3.32
	0.58	.350	8.72	.090	2.64
Ave.			10.13		3.32
Grand Average			9.88		3.06

* Cans 5-8 were arranged at 3 inch intervals in the region below holes 1470 and 1570.

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Table 5. Advantage Factors

Location	$\Delta E/E_o$	ρ_e from Tables 1-4	$F_e = \rho_e/\rho_B$	$\Delta R/R_o$	ρ_r	$F_r = \rho_r/\rho_B$	Description of Position
B	.352	8.80	1	.243	8.80	1	~5.6" from nearest metal. See 3.2.
Donuts 1867	.547	19.12	2.18	.470	19.44	2.21	
Extra donut 1867	.287	6.38	0.73	.230	7.[illegible]5	.92	Extrapolated cosine 8" from metal.
Can #1 1868	.390	10.44	1.19	.182	5.92	.67	2" can, metal on both ends.
Can Pb 1868	.556	19.7	2.24	.210	7.09	.80	0.85" can, metal on both ends.
Can #2 1868	.363	9.3	1.06	.218	7.35	.83	2" can, metal on one end.
Can #4 1868	.292	6.57	0.75	.176	5.70	.65	2" can, blanks on both ends.
Lattice 21	.366	9.88	1.12	.109	3.06	.35	4" - 5.6" from nearest metal.

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is less than that between values for #2 and #4 (1.05 - .75 = .3). The explanation probably lies in the absence of active metal from that region of hole 1867 and the resultant increase in average distance of can #4 from surrounding active metal.

Experimental hole 21: The average distance to metal for the samples in hole 21 ranges from about 4 to about 5.6 inches; i.e., the value ranges less than that for the samples in hole B in the center of the pile. However, hole 21 is two lattice units below the other holes discussed and passes through a region of the pile (under channels 1470 and 1570) which is changing rapidly in flux (cf. Nordheim, CP-2019). It is difficult to calculate a value for equivalent exposure times in hole 21 extrapolated to the center of the pile. Also, the temperature in hole 21 is sufficiently high and uncertain to interfere with interpretation of the resistance data. The data are given in Table 4 and summarized (uncorrected) in Table 5. The high value for F_e (= 1.12) is attributable to the slightly better geometry in hole 21 compared with the center of hole B and to a somewhat more important factor, namely, the generally higher neutron density in this region (cf. Nordheim, CP-2019).

4. Discussion

Estimates of advantage factor have been given previously several times. In all those cases the results have been confused by lack of control or information. Samples, for example, may not have been in the pile at the same time, or the temperature may not have been well known, or the loading of the pile may have been changed during the experiment. In the experiments for which data are given in this report, the pile was operated without important change in loading[4] for ten days, and during that time none of the samples were disturbed. It should be emphasized that the advantage factors given are intended to be for change in the environment in very closely the same region in the pile; i.e., the rate of change of a property of a sample exposed inside of a doughnut is compared with the rate of change of an average sample exposed very near that doughnut. For convenience, all values have been calculated back to the center of the pile, and the advantage factor is defined on the basis of such calculations, but the advantage factor for a particular environment compared with a sample near that position should apply equally well to positions more remote from the center. Of course, this statement has not been subjected to experimental verification, nor have we studied the effect of the pile power level on the advantage factor, but it seems reasonable to assume that for a particular operating temperature it would be independent of such variations[5]. On the other hand, changes of relative fast and slow neutron fluxes might have a serious effect on the observed advantage factors. Such conditions would obtain when lattice distance, moderator, or poisoning conditions are changed. Such considerations emphasize the necessity for studying the advantage factor itself at W.

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[4]Some of the outlying channels were unloaded and reloaded. A minor change in poisoning in holes 1866 and 1871 on Sept. 13 was without significant effect in the region of interest.

[5]Note that the kind of temperature effect noted for $\Delta R/R_0$ values at ~35° is too rapid to be likened to simple healing previously noted (CC-1668, CC-1669).

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Since the advantage factor compares a particular test sample under stipulated conditions near the center of the pile with average structural graphite near the center of the pile, it follows that the actual factor of advantage over average graphite throughout the pile is greater than the defined value obtained from comparison with the standard.

The advantage factor obtained for the short interslug can turned out agreeably high. The result is not entirely real. It emphasizes a point not heretofore discussed in this report. The presence of the poison in hole 1866 causes a sharp decrease of the thermal neutron density in that vicinity. The effect spreads over the surrounding holes. The thermal neutron density near 1867 is about 11% less than that near hole 1868 (cf. Nordheim, CP-2019). The problem is to estimate how this variation in thermal neutron density affects the relative density of Wigner-effective neutrons in holes 1867, B, and 1868. Evidently, the density of such neutrons increases in the direction 1867, B, 1868. Consequently, the observed values for F_e and F_r in the doughnuts in hole 1867 are incorrectly low; i.e., for doughnuts, $F > 2.2$. On the other hand, the conclusion regarding the effectiveness of the interslug position is incorrectly high. For interslug positions F is < 2.2.

A rough quantitative estimate of the corrections can be made by comparisons confined to hole 1868. First, we note the genuinely large advantage factor in the short interslug can, i.e., somewhat less than 2.2. We note also the difference between advantage factors in cans 1 and 2, the former between slugs, the latter with the slug on only one end. This difference is .15. If we subtract this difference from the advantage factor for can 2 we get an estimated advantage factor $F \cong .9$ for samples exposed in long cans between dummy slugs near a central position in hole 1868. This value should obviously be greater than that for can 4, where an adjacent channel is unloaded. The difference $2.2 - .9 \cong 1.3$ can be regarded roughly as the extra contribution of Wigner-effective neutrons in specially advantageous positions. The number $1.3/2.2 \cong .6$ represents the fraction of the Wigner effect produced in the neighborhood of slugs by neutrons of presumably local origin. The number of such neutrons is obviously determined by the thermal neutron density in that region. An 11% difference in thermal neutron density will consequently produce a change in the fraction of Wigner-effective neutrons in the neighborhood of a doughnut or of a slug of roughly $.6 \times .11 \cong 7\%$. Then the figure F for doughnuts should be ~ 2.3 and the figure F for short interslug positions should be ~ 2.1.

The latter figure F for short interslug positions $\cong 2.1$ is still astonishingly high. It cannot all be a contribution from the effective solid angle relationship. Part of the advantage factor may be a contribution at the ends of slugs from the Wilkins effect, for there is a slightly greater flux of primary neutrons from the end of slugs into interslug cans than there is in the center of a doughnut into an enclosed sample. It seems even that a more careful consideration of this problem will suggest another contribution which we have not yet recognized.

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Another point of interest concerns the high advantage factors both for doughnuts and for the short interslug positions. Their high value suggests that primary neutrons may have a much greater Wigner effect than is ordinarily attributed them.

Evidently the graphite within 0.85 inch of a water-tube at H will experience a much larger Wigner effect than the more remote graphite. Apparently, the Wigner effect in such graphite should not be enhanced over the average by more than half as much as the samples in short interslug cans. The slightly increased distance through the water will reduce the enhancement even further. The gain over the average in Wigner effect in any sample is the advantage factor minus 1. Thus the gain in samples completely surrounded by metal is about 1.2, and the gain in graphite in immediate contact with the water-tubes will not be over 0.6. Consequently, the advantage factor for graphite immediately adjacent to the H water-tubes will not exceed 1.6. Of course, no samples will be taken from such points. If it should turn out that the advantage factor can be measured at H in short interslug cans, and if the advantage factor (as determined by comparison with samples taken from cans between short dummy slugs) turns out to be 2.1 over the graphite in the center of the lattice, it follows that the advantage factor over the most intensely exposed structural graphite in the pile will be greater than 2.1/1.6 = 1.3.

This result emphasizes the desirability of choosing a geometry for exposure of test samples at H which will give the highest possible advantage factor. Such results are necessary for predictions in regard to the most intensely exposed graphite.

The matter of temperature of test and reference samples deserves further comment. In the first place, comparison of cold test samples and warmer reference samples by the electric resistance method gives deceptively high results; in this sense the elastic modulus data are distinctly more reliable. Furthermore, in general, comparison of data obtained at distinctly different temperatures does not yield a result having straightforward significance so far as the prediction of danger is concerned. The theory and mechanism of the Wigner effect in graphite are by no means fully elucidated. Nevertheless, it appears clear that all the disturbances are not of the same kind and that they may make different contributions to disagreeable effects which we desire to anticipate and avoid. The most troublesome disturbances will probably be the most stable; i.e., those disturbances which are not readily removed at intermediate temperatures. Thus, comparison of effects in cold test samples to tests in warmer reference samples not only would yield a high calculated advantage factor but might also create a falsely based optimism concerning the estimated time of development of undesirable properties.

5. Suggestions for W Graphite Control Program

The following suggestions derive directly from the results of this report and from the discussion.

(a) The specimen can should be as short as possible.

(b) The test specimens should be close packed. Also, they should lie as closely as possible to the axis of the can.

(c) Adequate means must be provided for cooling of test samples.

(d) All advantage factor data obtained should be checked by elastic modulus measurements as well as by electrical resistance measurements.

(e) Reference samples should be exposed in cans between short dummy slugs and with dummy slugs on only one end so that an estimate may be made of the necessary corrections for geometry.

(f) Care must be taken to make comparisons between samples exposed at the same temperature.

Appendix 1

Resistance and Modulus Change versus Exposure Curves

The electrical resistance curve (Figure 1) is based on three different experiments. First an experiment was performed at Clinton where the resistance of a sample of Kendall graphite inside the doughnuts was measured during operation for a ten day period from July 21 to July 31. In addition, data have been obtained on a set of samples exposed in 1867 outside the doughnuts from measurements obtained on samples removed after a number of increasing periods of time. The curves secured from these two sets of information were of the same shape and could be superimposed by multiplying the exposures of each point of the second set by a constant factor. These curves, however, extended only to about 55% change in resistance. In order to fix the outer end of the curve, the results obtained on long-bombarded doughnut samples were considered. It was observed that this curve was essentially congruent with the former below 25% change but lay slightly higher for the end of the curve. Consequently, an average curve was drawn through this region.

The relationship between $\Delta E/E_0$ and $\Delta R/R_0$ has been well established for $\sim 35^{\circ}$ by a number of independent experiments extending over a wide range of exposure. The $\Delta E/E_0$ vs. exposure time curve was calculated from the $\Delta R/R_0$ vs. exposure time curve by simple application of the established relationship between the two relative changes.

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Appendix 2

The data for temperature range of inlet cooling air at the X pile during the experiments herein described are given below.

Date	Temp. range, °C
Sept. 4, 1944	20.6 - 30.6
5	18.9 - 28.3
6	16.9 - 25
7	15.6 - 24.4
8	11.1 - 23.3
9	8.9 - 26.1
10	11.7 - 26.7
11	16.7 - 19.2
12	17.2 - 23.3
13	15.3 - 25.3
14	13.9 - 25.6

END