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DISTRIBUTION IN THE EBWR RADIAL SHIELD AT
100 MW OPERATION**

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Publicação IEA N.º 74
November — 1964

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* Work done in 1961 under the direction of Prof.M.Grotenhuis
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SUMÁRIO

Este estudo se refere ao cálculo da distribuição radial dos neutrons na blindagem do reator EBWR operando a uma potência de 100 Mw.

O caroço do reator foi considerado como uma esfera de igual volume, pois esta aproximação mostrou ser a melhor. Todos os cálculos foram feitos na direção radial, para uma blindagem constituída de água, boro, ferro, chumbo, concreto pesado e concreto comum.

Os fluxos rápido e termico foram calculados por teoria de dois grupos, com um computador IBM-704.

A determinação dos fluxos de raios gama e de gamas de captura também está apresentada neste trabalho.

O método de cálculo utilizado é explicado e os resultados obtidos são mostrados sob forma de tabelas e gráficos.

RÉSUMÉ

Cette étude se réfère au calcul de la distribution radiale des neutrons et des rayons gamma dans le blindage biologique du réacteur EBWR à la puissance de 100 Mw.

Le coeur du réacteur est assimilé à la sphère de même volume, de 146 cm de diamètre et on démontre que ceci est la meilleure approximation de la géométrie réelle. Tous les calculs ont été faits pour la direction radiale et pour un blindage constitué d'eau, de bore, de fer, de plomb, de béton lourd et de béton ordinaire.

Les flux neutroniques rapide et thermique ont été calculés en prenant une théorie à deux groupes: tous les calculs ont été faits avec un ordinateur IBM 704.

Les déterminations de flux de rayonnement gamma du coeur même et de rayonnement gamma de capture sont aussi présentées dans ce travail.

La méthode de calcul utilisée est expliquée et les résultats obtenus sont fournis sous forme de tableaux et de graphiques.

SUMMARY

The present study refers to the radial shield of the EBWR on an assumed operational level of 100 Mw.

The equal-volume sphere core, with a radius of 73 cm, was chosen for the study as indicated by calculations for the best core geometry. Shielding in the radial direction, as made up of water, boron, steel, lead, heavy concrete and light concrete, was analysed.

The fast and thermal neutron flux calculations were done by two-group analysis, with the aid of computer for the latter. Determination of the gamma flux from the core, as well as the capture gammas, comprise the rest of the calculations.

The procedures followed and the calculations made in connection with the study are explained, and the results are tabulated and plotted.

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INTRODUCTION

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2.

REMOVAL CROSS-SECTIONS

The fuel assemblies are made up of 147 elements, 3.75 by 3.75 inches in cross-section and with an active height of 4 ft. Approximately 20 % of the assemblies are spiked (ANL 5781 Addendum). The calculations for the removal cross-sections for the various components of the fuel elements, made in accordance with

AERE-R3216 - "Methods of Calculation for Use in the Design of Shields for Power Reactors"

MAA-SR-2380 - "Application of Fast Neutron Removal Theory to the Calculation of Thermal Neutron Flux Distributions in Reactor Shields"

Price, R. G., G. C. Norton and K. T. Spitzer, "Radiation Shielding", International Series of Monographs in Nuclear Energy, Pergamon Press

gave the following values:

$$\sigma_r(\text{H}_2\text{O}) = 2.99 \text{ barns}$$

$$\sigma_r(\text{U}) = 3.6$$

$$\sigma_r(\text{Zr}) = 1.9634$$

$$\sigma_r(\text{Nb}) = 2.0063$$

$$\sigma_r(\text{Ca}) = 1.9719$$

$$\sigma_r(\text{Fe}) = 1.8614$$

Removal cross-sections for the fuel elements were then determined, using the data indicated in Table 1, which yielded values as follows:

Fuel Elements

Enriched

$$\Sigma_r = 0.111 \text{ cm}^{-1}$$

Natural

$$\Sigma_r = 0.111$$

TABLE-1

VOLUME FRACTIONS AND ATOMIC DENSITIES IN 12.75" x 12.75" (32.385 cm x 32.385 cm) CELL AT ROOM TEMPERATURE

FUEL ELEMENT TYPE MATERIAL	THIN ELEMENTS				THICK ELEMENTS				SPIKES	
	ENRICHED		NATURAL		ENRICHED		NATURAL		VOLUME FRACTION	ATOMIC DENSITY ($\times 10^{24}$)
	VOLUME FRACTION	ATOMIC DENSITY ($\times 10^{24}$)	VOLUME FRACTION	ATOMIC DENSITY ($\times 10^{24}$)	VOLUME FRACTION	ATOMIC DENSITY ($\times 10^{24}$)	VOLUME FRACTION	ATOMIC DENSITY ($\times 10^{24}$)		
U^{235}	.00244	.0001156	.001276	.0000604	.00336	.0001592	.001739	.0000823	.0036	.0001702
U^{238}	.1598	.00756	.1610	.007615	.2230	.01055	.22474	.01063	.000262	.0000124
U	.1623	.007675	.1623	.007675	.2264	.01071	.2264	.01071	.003862	.0001826
H_2O	.668	.02239	.668	.02239	.588	.01970	.588	.01970	.582	.01950
Zr	.134	.005650	.134	.005650	.148	.006245	.148	.006245	.250	.01057
Nb	.00578	.0003151	.00578	.0003151	.00813	.0004431	.00813	.0004431		
Ca									.0365	.0008511
O in Spike Meat										.00757
Fe	.0302	.00256	.0302	.00256	.0302	.00256	.0302	.00256	.0302	.00256

NOTES: The rod follower has a volume fraction of .0302; in the follower $N(U^{235}) = .0001737 \times 10^{24}$, $N(Fe) = .0848 \times 10^{24}$
 The control rod has the same volume fraction as the follower: in the rod $N(Fe) = .07605 \times 10^{24}$, $N(O) = .00875 \times 10^{24}$
 U^{235} in the rod follower is included with U^{238} in the cell.

4.

Thick Elements	
Enriched	$\bar{\Sigma}_r = 0.115$
Natural	$\bar{\Sigma}_r = 0.115$
Spikes	
	$\bar{\Sigma}_r = 0.094$

The core was taken as divided into four regions, each a spherical shell with a thickness of

Region 1 - 34.46 cm (radius of inner sphere)
Region 2 - 13.20
Region 3 - 8.90
Region 4 - 16.44

Fig. 3 shows the core loading arrangement with the fuel elements distributed as follows:

Region	No. of Elements
1	36 thin elements, enriched
2	28 spikes
3	16 thick elements, enriched 20 thin elements, enriched
4	40 thick elements, enriched 4 spikes 4 thick elements, natural

The results of the calculations for the macroscopic removal cross-sections for each core region are listed below.

TABLE 2
MACROSCOPIC REMOVAL CROSS-SECTIONS

Region	Σ_r (cm ⁻¹)
1	0.111
2	0.094
3	0.113
4	0.113

FAST NEUTRON FLUX AT THE EDGE OF THE CORE

The fast neutron flux at the edge of the core was found by comparing the results derived from three methods:

METHOD 1

1. The flux at the first interface was determined, using a cross-section Σ_{s1} and the formula

$$\phi(r) = \frac{Q_1}{2\Sigma_{s1}} \left[1 - \frac{1}{2\Sigma_{s1}R_{s1}} \left(1 - e^{-2\Sigma_{s1}R_{s1}} \right) \right] \text{ n/cm}^2 \cdot \text{sec}$$

2. Using the same formula and a cross-section Σ_{s2} for the entire region from the core center to the second interface, a corresponding value of flux at the latter point was calculated.
3. Similarly, a flux calculation was made again for the first interface, this time using a cross-section Σ_{s2}
4. The effect of the inner sphere, when treated as having a cross-section of Σ_{s2} on the flux at the second interface was calculated.
5. The value found from Step 4 was subtracted from the value

6.

obtained in Step 2 to give the correct value of flux at the second interface.

6. For the other succeeding interfaces, a similar procedure was followed, whereby the effect on the flux at the outer face of a shell by the sphere within the shell is taken into account.

7. The flux at the edge of the core was finally determined by summing up all the contributions of partial fluxes at the interfaces, considering the corresponding attenuations.

METHOD 2

1. The flux at the first interface was determined using the formula

$$\phi_1(r) = \frac{Q_1}{2\Sigma_{s1}} \left[1 - \frac{1}{2\Sigma_{s2}R_{s1}} \left(1 - e^{-2\Sigma_{s1}R_{s1}} \right) \right] \text{ n / cm}^2 \times \Delta t$$

2. The contribution of the flux found from Step 1 to the flux at the edge of the core, considering attenuation, was calculated using the formula

$$\phi(R_{s4}) = \phi_1(r) \frac{R_{s1}}{R_{s4}} E_2 \left[\Sigma_{s2}(R_{s2}-R_{s1}) + \Sigma_{s3}(R_{s3}-R_{s2}) + \Sigma_{s4}(R_{s4}-R_{s3}) \right] \text{ n / cm}^2 \times \Delta t$$

3. The second region (spherical shell) was taken as a finite slab source and the flux at the second interface calculated from formula

$$\phi_2(r) = \frac{Q_2}{2\Sigma_{s2}} \left\{ 1 - E_2 \left[\Sigma_{s2}(R_{s2}-R_{s1}) \right] \right\} \text{ n / cm}^2 \times \Delta t$$

4. The contribution from this region (second) to the flux at the edge of the core was determined using the formula

$$\phi(R_{s4}) = \phi_2(r) \frac{R_{s2}}{R_{s4}} E_2 \left[\Sigma_{s3}(R_{s3}-R_{s2}) + \Sigma_{s4}(R_{s4}-R_{s3}) \right] \text{ n / cm}^2 \times \Delta t$$

5. A similar procedure was followed for the other regions, and the flux at the edge of the core was determined by adding all the contributions of the partial fluxes from each region.

METHOD 3

1. The core was treated as a homogenous sphere with an average removal cross-section $\bar{\Sigma}_r = 0.110 \text{ cm}^{-1}$ and an average source strength $\bar{Q} = 7.5 \times 10^{12} \text{ n/cm}^2 \times \text{sec}$.

2. Then the flux at the edge of the core was determined from the formula

$$\phi(R_{s4}) = \frac{\bar{Q}}{2\bar{\Sigma}_r} \left[1 - \frac{1}{2\bar{\Sigma}_r R_s} (1 - e^{-2\bar{\Sigma}_r R_s}) \right] \text{ n/cm}^2 \times \text{sec}$$

Power and source strengths for the various core regions were calculated from the curves of Figs. 1 and 2, which give values as follows:

TABLE 3

POWER AND SOURCE STRENGTHS FOR THE VARIOUS CORE REGIONS

Region	Power P_i (watts)	Source Strength Q_i ($\text{n/cm}^3 \times \text{sec}$)
1	0.281×10^8	1.27×10^{13}
2	0.403	1.11
3	0.205	0.52
4	0.111	0.10

The results of the calculations based on the three methods are tabulated below.

8.

TABLE 4

FAST NEUTRON FLUX AT THE EDGE OF THE CORE FROM EACH CORE REGION

Region	Method 1 (ϕ in $n/cm^2 \times sec$)	Method 2	Method 3 (Homogenous Core)
1	7.76×10^{10}	7.76×10^{10}	
2	4.74×10^{11}	5.35×10^{11}	
3	8.32×10^{11}	9.42×10^{11}	
4	<u>3.90×10^{12}</u>	<u>4.20×10^{12}</u>	
Total	5.28×10^{12}	5.75×10^{12}	3.20×10^{13}

FAST NEUTRON FLUX DISTRIBUTION IN THE RADIAL SHIELD

The flux based on a homogenous core was chosen for these calculations, with the flux distribution throughout the shield being determined from the formula

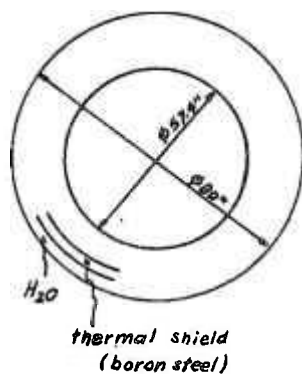
$$\phi(r) = \frac{Q}{4\pi R_s^2} \frac{R_s}{r} \left\{ A_1 E_1 [\sigma_2 a_1 + \sigma_3] + A_2 E_1 [\sigma_2 a_1 + \sigma_3] \right\} \text{ n/cm}^2 \times \text{sec}$$

and the following data:

$$\begin{aligned} Q &= 7.5 \times 10^{12} \text{ fast neutrons/cm}^3 \times \text{sec} \\ \bar{\Sigma}_s &= 0.110 \text{ cm}^{-1} \\ R_s &= 73 \text{ cm} \\ A_1 &= 1 \\ A_2 &= 0.121 \\ \sigma_1 &= 0.129 \\ \sigma_2 &= 0.091 \end{aligned} \quad \left. \vphantom{\begin{aligned} Q \\ \bar{\Sigma}_s \\ R_s \\ A_1 \\ A_2 \\ \sigma_1 \\ \sigma_2 \end{aligned}} \right\} \text{ NAA-SR-2380}$$

The resulting flux at the boundary of each shield is given in Table 5, and the distribution is plotted in Fig. 4.

CALCULATION OF THE FAST NEUTRON DISTRIBUTION IN THE RADIAL SHIELD

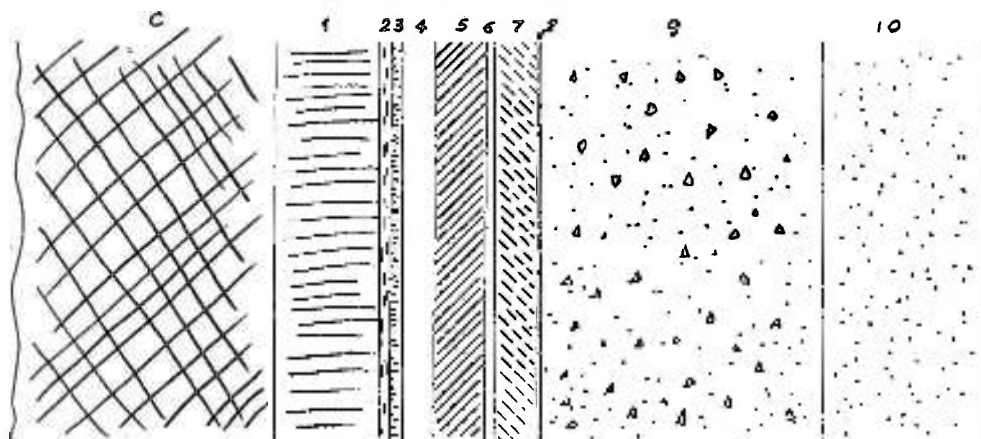


Dimensions

- 1 - Diameter of pressure Vessel 81" or 213.4 cm
- 2 - Inner diameter of reflector 80" or 203.2 cm ANL-5607
- 3 - Outer diameter of core 57.4" or 146.0 cm calculated
- 4 - Thermal Shield (boron steel) 1" or 2.54 cm ANL-5607
- 5 - Water 1" or 2.54 cm ANL-5607

thickness of reflector (H_2O)

$$\begin{array}{r} 203.2 \\ - 146.0 \\ \hline \end{array} \rightarrow \text{diameter} \rightarrow 57.2 \rightarrow \text{radius} = 28.6 \text{ cm } (H_2O)$$



Region	Material	X_i (cm)	
C	core	73	} calculated (assembly for P=100Mw)
1	H_2O	28.60	
2	Boron Steel	2.54	} Calculation of the neutron and gamma-ray distribution in EBWR Radial Shield by: F.C. Hardtke T. A. Lauritzen D. P. Moon April, 20, 1959
3	H_2O	2.54	
4	Steel	6.35	
5	Insulation	15.20	
6	Steel	1.91	
7	Lead	7.62	
8	Boron	---	
9	Heavy Concrete, M-a	156	
10	Light concrete, 03-a	86.4	

TABLE 5

FAST FLUX AT THE BOUNDARY OF EACH SHIELD

Material	Thickness (cm)	Removal Cross-section (cm^{-1})	ϕ Flux ($\text{n}/\text{cm}^2 \times \text{sec}$)
Core	73	0.110	3.20×10^{13}
H ₂ O	28.60		1.98×10^{11}
Boron steel	2.54	0.168	1.15×10^{11}
H ₂ O	2.54		7.90×10^{11}
Steel	6.35	0.168	2.03×10^{10}
Insulation & He	15.20	0	1.79×10^{10}
Steel	1.91	0.168	1.24×10^{10}
Lead	7.62	0.116	4.19×10^9
Boron	--	---	----
Heavy concrete	156	0.112	1.53×10^1
Light concrete	86.4	0.0866	1.40×10^{-2}

THERMAL NEUTRON FLUX AT THE EDGE OF THE CORE

By use of the formula

$$\phi_s^0 = \phi_s^1(0) = \frac{\bar{\phi}_s}{\Sigma_s} \quad \text{n/cm}^2 \times \text{sec}$$

and an average thermal flux value of $\bar{\phi}_s = 3.0 \times 10^{13} \text{ n/cm}^2 \times \text{sec}$

and likewise values of $\phi_s^1 \approx 9.5$ (arbitrary units)

$$\bar{\phi}_s^1 \approx 10.655 \text{ (arbitrary units)}$$

from the reactor core calculations (refer to Figs. 1 and 2), the thermal neutron flux at the edge of the core was calculated to be

$$\phi_s^0 = 4.54 \times 10^{13} \text{ n/cm}^2 \times \text{sec}$$

THERMAL NEUTRON FLUX DISTRIBUTION IN THE RADIAL SHIELD

Table 6 lists the constants used in the calculation of the thermal neutron flux distribution.

TABLE 6

TABLE OF CONSTANTS FOR THERMAL NEUTRON CALCULATION

Material	D	K	K^2	$\Sigma = DK^2$	$\lambda_{tr} = 3D$	0.71
Water	0.246	0.22	4.8×10^{-2}	1.1808×10^{-2}	0.738	0.5240
Boron steel	0.345	1.36	1.87	6.4515×10^{-1}	1.035	0.7349
Water	0.246	0.22	4.8×10^{-2}	1.1808×10^{-2}	0.738	0.5240
Steel	0.345	0.64	4.1×10^{-1}	1.4145×10^{-1}	1.035	0.7349
Insulation	0.661	4×10^{-4}	1.6×10^{-7}	1.0576×10^{-7}	1.983	1.4080
Steel	0.345	0.64	4.1×10^{-1}	1.4145×10^{-1}	1.035	0.7349
Lead	0.918	0.071	5.1×10^{-3}	4.6818×10^{-3}	2.754	1.9553
Heavy conc.	0.418	0.379	1.44×10^{-1}	6.0192×10^{-2}	1.254	0.8903
Light conc.	1.00	0.0744	5.5×10^{-3}	5.5×10^{-3}	3.0	2.13

Above values were taken from "Calculation of the Neutron and Gamma-ray Distribution in EBWR Radial Shield", F. C. Hardtke, T. A. Lauritzen and D. P. Moon, April 20, 1959.

$$\phi_p \text{ at the edge of the core} = 1.54 \times 10^{13} \text{ c/cm}^2 \times \text{sec.}$$

The calculations for thermal neutron flux were done by computer using Code RE-34. Because of the two black boundaries, the problem was divided into three parts, as shown by the programs for the sphere and slab geometry.

12.

To check if the results for attenuation were reasonable, calculation was made for a case in which Region 4 of the shield is water of infinite thickness. (See attached calculation sheets.)

Results are also plotted in Fig. 4.

GAMMA FLUX ORIGINATING FROM THE CORE

By using a treatment similar to that employed in the fast neutron flux calculations, the gamma flux at four energy groups (1, 2, 4 and 6 Mev) were determined, taking into consideration the prompt gammas from fission and delayed gammas from the decay products. The calculations were made first on the basis of a four-region core, then of a homogenous sphere with build-up disregarded, and finally of a homogenous sphere with build-up taken into account.

The subsequent tables show the various data used for and the value resulting from the different steps of the calculations. These include linear absorption coefficients, gamma source strengths, power and volume of each core region, and the total gamma fluxes at the edge of the core.

In the calculations, the values used for the total gammas per fission originating from the core (prompt and delayed) were as follows, in accordance with ANL-6000 and AERE-R-3216:

Energy (Mev)	Total Gamma per Fission
1	10.3
2	3.85
4	0.465
6	0.053

The gamma source strength Q was calculated using the data obtained and shown in Table 11 and the formula

$$Q (\text{r/cm}^2 \cdot \text{sec}) = 3.1 \times 10^{10} \frac{P}{V} (\text{fusion/cm}^2 \cdot \text{sec}) \cdot N_g (\text{r/fusion})$$

In the four-region treatment of the core, a similar procedure to that taken in the fast neutron flux calculations was followed, using the formulas indicated therein and referred to previously as METHOD 2. For the treatment of the core as a homogeneous sphere with build-up, use was made of the formula

$$\phi(R_{s4}) = \frac{Q}{2\bar{\mu}_s} \left\{ 2 - \frac{1}{2\bar{\mu}_s R_s} \left[1 - e^{-2\bar{\mu}_s R_s} + 2\bar{\mu}_s R_s e^{-2\bar{\mu}_s R_s} \right] \right\} \delta / \text{cm}^2 \cdot \text{sec}$$

with build up $B = 1 + \bar{\mu}_s R$

TABLE 7

LINEAR ABSORPTION COEFFICIENT

Energy U(18.7) (Mev)	H ₂ O(0.8)	Zr(6.44)	Fe(7.85)	Nb(8.4)	Ca(1.55)
1	0.9013	0.2488	0.3722	0.2051	0.0432
2	0.6059	0.2112	0.2640	0.1816	0.0378
4	0.6582	0.0170	0.2196	0.1761	0.0349
6	0.7368	0.0150	0.2170	0.1816	0.0346
8	0.8284	0.1384	0.2241	0.1879	0.0349

The above figures were taken from ANL-6000 and the Handbook of Chemistry and Physics, 37th Edition.

14.

TABLE 8

LINEAR ABSORPTION COEFFICIENT FOR EACH FUEL ELEMENT

Energy (Mev)	Thin Elements Enriched	Thick Elements Enriched	Spikes
	Thin Elements Natural	Thick Elements Natural	
	μ (cm ⁻¹)	μ (cm ⁻¹)	μ (cm ⁻¹)
1	0.3714	0.4156	0.2492
2	0.2823	0.3088	0.1981
4	0.1546	0.1992	0.0739
6	0.1659	0.2155	0.0726

TABLE 9

LINEAR ABSORPTION COEFFICIENT FOR EACH REGION OF THE CORE

Energy (Mev)	Region 1	Region 2	Region 3	Region 4
	μ_1 (cm ⁻¹)	μ_2 (cm ⁻¹)	μ_3 (cm ⁻¹)	μ_4 (cm ⁻¹)
1	0.3714	0.2492	0.391	0.402
2	0.2823	0.1981	0.294	0.300
4	0.1546	0.0739	0.175	0.189
6	0.1659	0.0726	0.188	0.204

TABLE 10

AVERAGE LINEAR ABSORPTION COEFFICIENT FOR EACH GAMMA ENERGY GROUP
FOR THE HOMOGENEOUS CORE

Energy (Mev)	$\bar{\mu}$ (cm ⁻¹)
1	0.371
2	0.280
4	0.163
6	0.174

TABLE 11

POWER AND VOLUME OF EACH CORE REGION

Region	Power (watts)	Volume (cm ³)
1	2.81×10^7	1.714×10^5
2	4.03×10^7	2.812×10^5
3	2.05×10^7	3.059×10^5
4	1.11×10^7	8.715×10^5

TABLE 12

GAMMA SOURCE STRENGTH FOR EACH ENERGY GROUP IN THE FOUR CORE REGIONS

Energy (Mev)	Region 1	Region 2 $Q (\gamma/cm^3 \times sec)$	Region 3	Region 4
1	5.23×10^{13}	4.56×10^{13}	2.14×10^{13}	4.06×10^{12}
2	1.96×10^{13}	1.71×10^{13}	8.01×10^{12}	1.52×10^{12}
4	2.36×10^{12}	2.06×10^{12}	9.67×10^{11}	1.83×10^{11}
6	2.69×10^{11}	2.48×10^{11}	1.10×10^{11}	2.09×10^{10}

TABLE 13

GAMMA FLUXES AT THE EDGE OF THE CORE

Energy (Mev)	From Region 1	From Region 2 $\phi (\gamma/cm^2 \times sec)$	From Region 3	From Region 4
1	3.51×10^6	2.20×10^8	3.80×10^9	5.04×10^{12}
2	5.43×10^7	1.72×10^9	1.30×10^{10}	2.53×10^{12}
4	1.76×10^9	1.30×10^{10}	2.20×10^{10}	4.80×10^{11}
6	1.29×10^8	1.03×10^9	1.80×10^9	5.08×10^{10}

TABLE 13 (Continued)

TOTAL FLUX

Energy (Mev)	Φ (γ /cm ² x sec)
1	5.04×10^{12}
2	2.83×10^{12}
4	5.17×10^{11}
6	5.49×10^{10}

TABLE 14

GAMMA FLUX AT THE EDGE OF THE HOMOGENEOUS SPHERICAL CORE, NO BUILD-UP

Energy (Mev)	Φ_s (γ /cm ² x sec)
1	4.09×10^{13}
2	2.02×10^{13}
4	4.08×10^{12}
6	4.48×10^{11}

TABLE 15

GAMMA FLUX AT THE EDGE OF THE HOMOGENEOUS SPHERICAL CORE, WITH BUILD-UP

Energy (Mev)	Φ_s (γ /cm ² x sec)
1	8.25×10^{13}
2	4.09×10^{13}
4	8.34×10^{12}
6	9.14×10^{11}

TABLE 16

GAMMA FLUX AT THE EDGE OF THE CORE AS CALCULATED BY THREE METHODS

Energy (Mev)	Core Divided Into Four Regions	Homogeneous Spherical Core No Build-up ϕ ($\gamma/cm^2 \times sec$)	Homogeneous Spherical Core With Build-up
1	5.04×10^{12}	4.09×10^{13}	8.25×10^{13}
2	2.83×10^{12}	2.02×10^{13}	4.09×10^{13}
4	5.17×10^{11}	4.08×10^{12}	8.34×10^{12}
6	5.49×10^{10}	4.48×10^{11}	9.14×10^{11}

PROMPT GAMMA FLUX ATTENUATION IN THE RADIAL SHIELD

Taking the four gamma energy groups into account, calculations were made for the gamma flux distribution by the formula

$$\phi = \frac{Q_3}{2\mu_s} \left(\frac{R_s}{R_s + a} \right) e^{-\mu a} \quad \gamma/cm^2 \times sec$$

using values from Table 16 for Q_3 , values from Table 10 for μ_s and taking $\mu = \sum_i \mu_i$ with values for μ_i from ANL-6000.

The resulting prompt and fission product gamma flux attenuation is shown in Fig. 5.

GAMMA FLUX DUE TO CAPTURE IN THE RADIAL SHIELD MATERIAL

Each shielding material was treated separately as a gamma ray source, with thermal flux distributed in a manner previously determined furnishing the neutrons for the (n, γ) reactions.

18.

In calculating the gamma flux due to capture at the outer boundary of each shield material, the thermal neutron flux was approximated by exponential and constant sources, using the following formulas:

For exponential Source

(1)

$$\phi(x) = \frac{Q_3(0)}{2k} \left\{ e^{kx} E_1(\mu_3 t) - \ln(\nu-1) + \frac{k}{k+\mu_3} \left[e^{(k-\mu_3)t} - 1 \right] + E_1[\mu_3 t (\nu-1)] \right\} \quad \gamma/\text{cm}^2 \text{ sec}$$

$$\frac{1}{2} \nu > 1 \quad \text{where} \quad \nu = \frac{k}{\mu_3}$$

k = slope of the exponential source
 μ = linear absorption coefficient

(2)

$$\phi(x) = \frac{Q_3(0)}{2k} \left\{ e^{kx} E_1(\mu_3 t) - \ln(\nu-1) + \frac{k}{k-\mu_3} \left[e^{(k-\mu_3)t} - 1 \right] - E_1[\mu_3 t (1-\nu)] \right\} \quad \gamma/\text{cm}^2 \text{ sec}, \quad \frac{1}{2} \nu < 1$$

In the two preceding formulas

$$Q_3(0) = \Sigma_2 N_\gamma \phi(0) \quad \gamma/\text{cm}^2 \text{ sec}$$

Where $\phi(0)$ is the thermal flux at the outer boundary of the shield material under consideration

N_γ is the number of gammas/fission
 Σ_2 is the absorption cross-section

For constant Source

$$\phi(a) = \frac{Q_3}{2\mu_3} \left\{ 2E_2(\mu a) + \mu a E_1(\mu a) - 2E_2(\mu a + \mu_3 t) - (\mu a + \mu_3 t) E_1(\mu a + \mu_3 t) \right\} \quad \gamma/\text{cm}^2 \text{ sec}$$

where $Q_3 = \Sigma_2 N_\gamma \phi(0) \quad \gamma/\text{cm}^2 \text{ sec}$

Σ_a = absorption cross-section
 N_γ = number of gammas/fission
 $\phi(0)$ = the constant thermal flux

Where several energies were involved, those below 4 Mev were taken as 4 Mev, while those between 4 and 8 Mev were considered as 8 Mev. Water generates only one gamma ray at 2.23 Mev, and this was taken into account.

Calling the gamma flux at the outer boundary of each shield material due to neutron capture ϕ_0 , its values were computed from data given in Table 17. Results are tabulated in Table 18.

TABLE 17

DATA USED FOR ϕ_0 CALCULATIONS

Material	k (cm ⁻¹)	E_γ (Mev)	N_γ	μ_s (cm ⁻¹)	μ_a (cm ⁻¹)
H ₂ O	0.1736	2.23	1	0.038	0.022
Fe		4	0.34	0.259	0.19
		8	0.72	0.231	
Pb	0.1956	-	-	-	-
		8	1	0.520	0.005
Heavy concrete	0.126	4	0.636	0.101	0.06
		8	0.723	0.078	
Light concrete	0.062	4	1.20	0.076	0.009
		8	0.53	0.058	

TABLE 18

GAMMA FLUX AT THE BOUNDARY OF EACH SHIELD MATERIAL DUE TO NEUTRON CAPTURE

Material	Energy (Mev)	ϕ ($\gamma/\text{cm}^2 \times \text{sec}$)
H ₂ O	2.23	7.51×10^{12}
Fe	4	9.55×10^{10}
	8	2.18×10^{11}
Pb	8	2.13×10^7
	4	1.16×10^3
Heavy concrete	8	2.42×10^4
	4	9.93×10^{-1}
Light concrete	8	2.44×10^{-1}

CAPTURE GAMMA RAYS ATTENUATION IN THE RADIAL SHIELD

For these, calculations were performed using the formula

$$\phi = \phi_0 \left(\frac{r_s}{r_s + d} \right) \left[e^{-\mu d} + \frac{1}{2} (\mu d) \right] \quad \gamma / \text{cm}^2 \times \text{sec}$$

and data given in Table 19. Fig. 6 is a plot of the capture gamma ray attenuation in the radial shielding.

TABLE 19

DATA FOR COMPUTATION OF GAMMA RAY ATTENUATION

Material	E_γ (Mev)	ϕ_0 ($\gamma/\text{cm}^2 \times \text{sec}$)	μ_s (cm^{-1})
H ₂ O	2.23	7.51×10^{12}	0.038
	4.0	-	-
	8.0	-	-

TABLE 19 (continued)

Fe	2.23	-	0.315
	4.0	9.55×10^{10}	0.259
	8.0	2.18×10^{11}	0.231
Pb	2.23	-	0.488
	4.0	-	0.475
	8.0	2.13×10^7	0.520
Heavy concrete	2.23	-	0.18
	4.0	1.16×10^3	0.101
	8.0	2.42×10^4	0.078
Light concrete	2.23	-	0.10
	4.0	9.93×10^{-1}	0.076
	8.0	2.44×10^{-1}	0.058

DOSE RATE EVALUATION AND CONCLUSIONS

1. Fast and Thermal Neutron Fluxes

Both the fast and thermal fluxes calculated outside the radial shield of the reactor (light concrete) were found to be at safe biological levels.

2. Gamma Rays

a. Prompt and Fission Product Gammas

Tabulated below are the dose rates calculated for the various gamma ray energy groups.

TABLE 20

PROMPT AND FISSION PRODUCT GAMMA RAYS DOSE RATES

Energy (Mev)	Flux ($\gamma/cm^2 \times sec$)	Dose Rate (r/hr)
1.0	6.68×10^{-13}	1.28×10^{-18}
2.0	3.03×10^{-4}	9.70×10^{-10}
4.0	2.52×10^{-1}	1.34×10^{-6}
6.0	5.08×10^{-1}	3.66×10^{-6}

b. Thermal Neutron Capture Gammas

Tabulated below are the dose rates calculated for the thermal neutron capture gammas.

TABLE 21

THERMAL NEUTRON CAPTURE GAMMA RAYS DOSE RATES

Source	Energy (Mev)	Flux ($\gamma/cm^2 \times sec$)	Dose Rate (r/hr)
H ₂ O	2.23	1.62×10^{-7}	5.75×10^{-13}
Steel	4	9.72×10^{-2}	5.15×10^{-7}
	8	2.84×10^{-1}	2.56×10^{-4}
Lead	8	2.85×10^{-2}	2.57×10^{-7}
	4	1.46×10^0	7.74×10^{-6}
Heavy concrete	8	1.44×10^2	1.30×10^{-3}
	4	9.93×10^{-1}	5.26×10^{-6}
Light concrete	8	2.44×10^{-1}	2.20×10^{-6}

The dose rate calculated at the outer boundary of the EBWR radial shield is less than 2 mr/hr, and so will not exceed the maximum permissible levels established in the last report of the ICRP: (International Commission on Radiological Protection).

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ACKNOWLEDGEMENTS

The study and corresponding calculations were made during the 1961 Spring Term of the International Institute of Nuclear Science and Engineering of the Argonne National Laboratory, in connection with my appointment as Participant in that Term.

I wish to thank Prof. R.G. Taecker, Director of the IINSE for the arrangements made to me to allow the furtherance of my training in the field of reactor shielding. Allow me to thank Professor M. Grotenhuis, Professor of Reactor Shielding, in particular for his most understanding help and guidance, and the IINSE for making available the necessary facilities and also the assistance by many members of the Staff of the Argonne National Laboratory.

SHARE SYMBOLIC CODING FORM

Problem		RE-34 H ₂ O - Fe - insulation - Fe-Pb - sphere - G _r pf(N) source		70100 - 01 - 139	
Coder		HEHL - GROTENHUIS		Date	4/25/1961
				Page	1
				Of	1
				IDENTIFICATION	
				34-39707	
Location	Op	Address, Tag	Decrement	Comments	TS
1, 0, 0, 0	D, E, C	39, 70007			
	D, E, C	1, 7, 3, 1, 3765E2, 26			
	D, E, C	6, 35E-1, 2, 7E-1, 1, 0E0, 7, 60E0, 9, 5E-1, 8, 1E-1, 1, 0E0			
1, 1, 0, 6	D, E, C	4, 5, 5, 2, 2, 2, 6			
1, 2, 0, 6	D, E, C	9, 44E9, 8, 64E9, 7, 6E9, 5, 88E9, 6, 24E9, 1, 31E10, 1, 35E10			
	D, E, C	1, 10E10, 1, 13E10, 8, 08E10, 1, 02E10, 1, 02E10, 8, 4E9, 6, 72E9			
	D, E, C	5, 54E9, 4, 37E9, 3, 53E9, 0E0, 0E0, 0E0, 3, 02E9, 3, 08E9, 2, 1E9			
	D, E, C	1, 95E9, 1, 79E9, 1, 19E9, 1, 10E9, 9, 92E9, 8, 26E9, 7, 66E9, 6, 5E9			
	D, E, C	5, 67E8, 4, 91E8			
	T, R, A	3, 4			
	D, E, C	1, 18E11, -1E0, 2, 46E-1, 1, 1808E-2, 1, 0E0, 0			
2, 9, 9, 9	D, E, C	-1, 0E0, 3, 45E-1, 1, 9145E-1, 1, 0E0, -1E0			
3, 0, 0, 5	D, E, C	-1, 0E0, 3, 45E-1, 1, 9145E-1, 1, 0E0, -1E0			
3, 0, 1, 0	D, E, C	-1, 0E0, 3, 45E-1, 1, 9145E-1, 1, 0E0, -1E0			
3, 0, 1, 5	D, E, C	-1, 0E0, 3, 45E-1, 1, 9145E-1, 1, 0E0, -1E0			
3, 0, 2, 0	D, E, C	-1, 0E0, 3, 45E-1, 1, 9145E-1, 1, 0E0, -1E0			
3, 0, 2, 8	D, E, C	-1, 0E0, 3, 45E-1, 1, 9145E-1, 1, 0E0, -1E0			
3, 0, 3, 0	D, E, C	1, 9553E0, 9, 12E-1, 4, 6812E-3, 1, 0E0, -1E0			
	T, R, A	3, 4			

SHARE SYMBOLIC CODING FORM

Problem RE-34 Heavy concrete-Light concrete-Sphere-(G_{eff}) source 70100-01-139

Coder HENL - GROTHUIS Date 4/25/1961 Page 1 of 1

LOCATION	OP	Address, Top Determinant	Comments	IDENTIFICATION
1000	DEC	39.70008		34-39708
	DEC	1.4.3, 3.8005E2, 37		
	DEC	1.0E0, 1.0E1, 8.0E-1, 1.0E1		
	DEC	8.15, 8.2		
	DEC	4.65E0, 4.03E0, 3.36E0, 2.9E0, 2.52E0, 2.18E0, 1.96E0, 1.96E0		
	DEC	8.37E07, 1.47E07, 4.14E05, 1.17E00, 3.24E05, 9.40E04, 9.69E4		
	DEC	8.176E3, 2.40E0, 6.944E2, 2.016E2, 6.04E1, 1.792E1, 5.49E0		
	DEC	1.736E0, 1.3423E0, 1.1931E0, 4.0824E0, 1.022E0, 9.62E-1		
	DEC	8.4322E-1, 8.8186E-1, 7.750E-1, 7.1012E-1, 7.1012E-1		
	DEC	2.7279E-1, 1.1268E-1, 4.5032E-2, 1.812E-2, 7.9672E-3		
	DEC	2.8978E-3, 1.2124E-3, 5.19E-4		
	TRA	3.4		
	DEC	4.16E9, -1E0, 4.18E-1, 6.0192E-2, 1.9E0, 0		
	DEC	-1.0E0, 4.18E-1, 6.0192E-2, 1.0E0, -1E0		
	DEC	-1.0E0, 1.0E0, 5.5E3, 1.0E0, -1E0		
	DEC	2.13E10, 1.0E0, 5.5E-3, 1.0E0, -1E0		
	TRA	3.4		

30.

Calculation for thermal flux, in the case of region 4 be infinite thickness water.

Constants for H₂O

K	K ²	D	σ	σ ²	K ² -σ ²
0.22	0.0480	0.246	0.1785	0.0319	0.0161

$$G = \frac{1}{2.54} \log \frac{1.18 \times 10^{11}}{7.5 \times 10^{10}} \times \frac{1}{0.434} = \frac{1}{1.102} \log 1.5733$$

$$G = \frac{1}{1.102} \times 0.1967 \quad \sigma = 0.1785$$

$\phi_f(0)$	$\sigma \phi_f(0)$	$D(K^2 - \sigma^2)$	$C = \frac{\sigma \phi_f(0)}{D(K^2 - \sigma^2)}$
1.18×10^{11}	0.2106×10^{11}	0.0040	5.265×10^{12}

$$\phi_i^s(x_i) = A_i e^{K_i x_i} + B_i e^{-K_i x_i} + C_i e^{-\sigma_i x_i}$$

If the region is infinite, then

$$\phi_{s1}(0) = A_1 + B_1 + C_1$$

$$\phi_{s1}(\infty) = 0 \rightarrow A_1 = 0$$

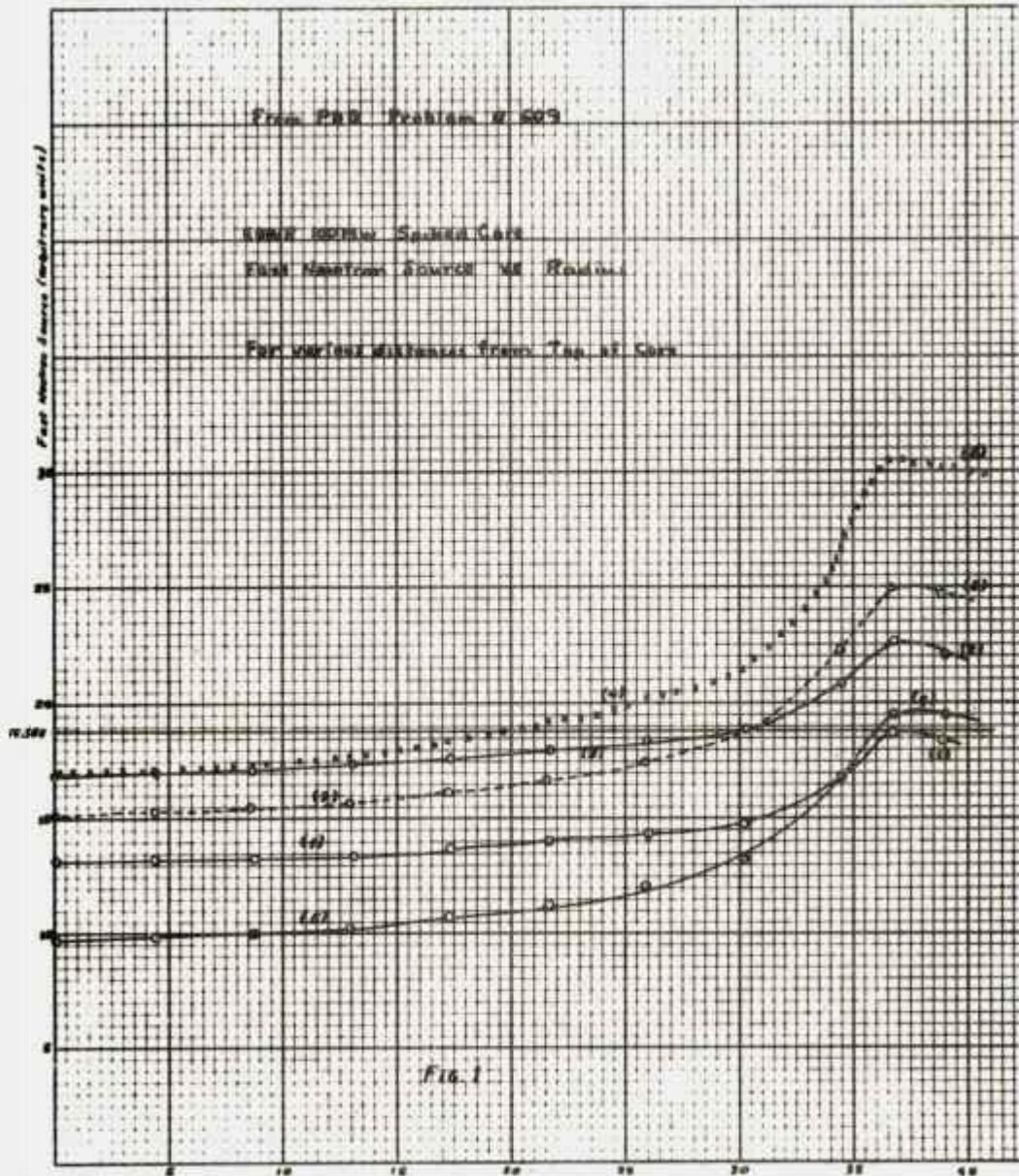
$$\therefore B_1 = \phi_{s1}(0) - C_1 \quad \phi_{s1}(0) = 0 \text{ (after black boundary)}$$

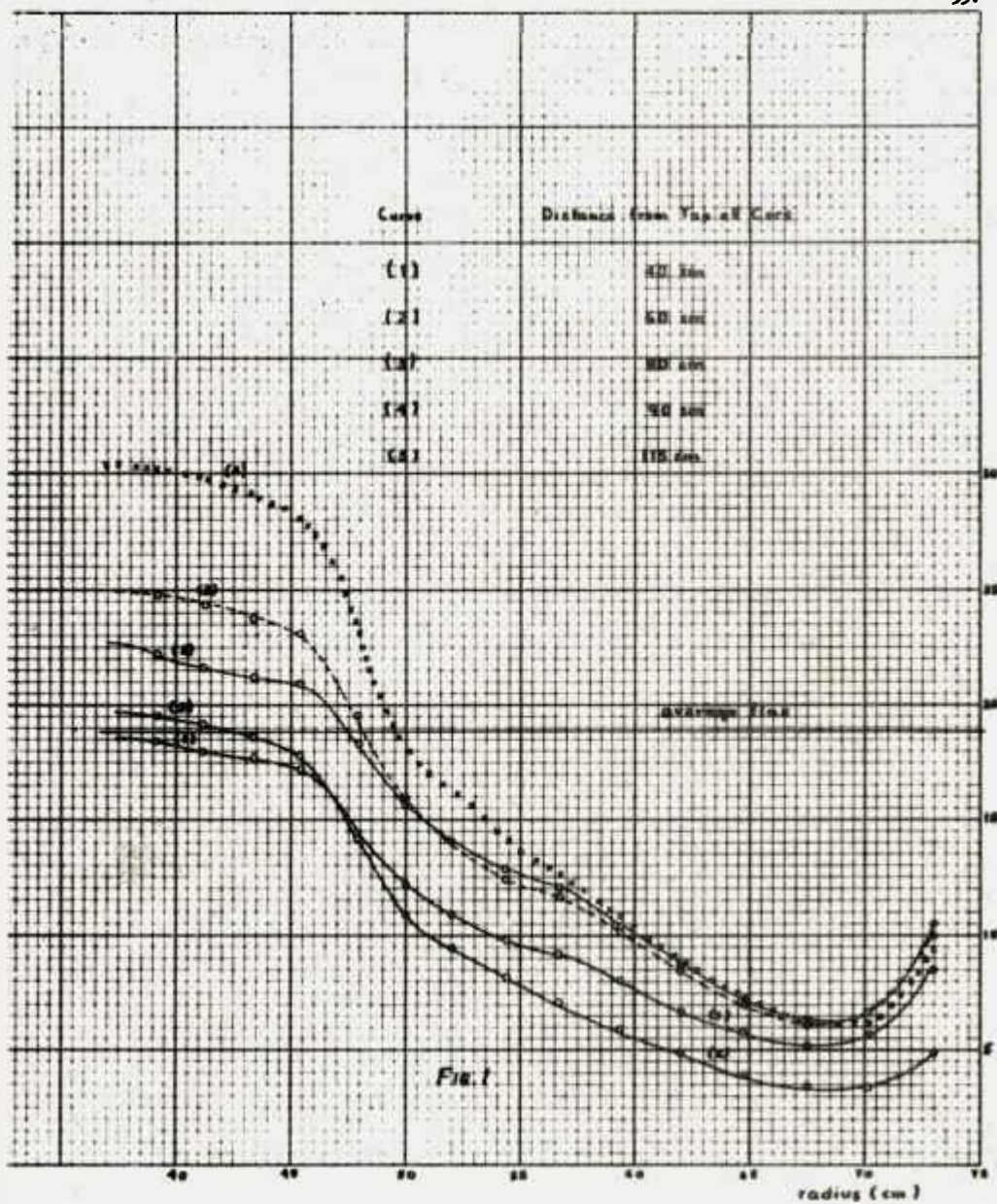
$$B_1 = 0 - 5.265 \times 10^{12}$$

$$B_1 = -5.265 \times 10^{12}$$

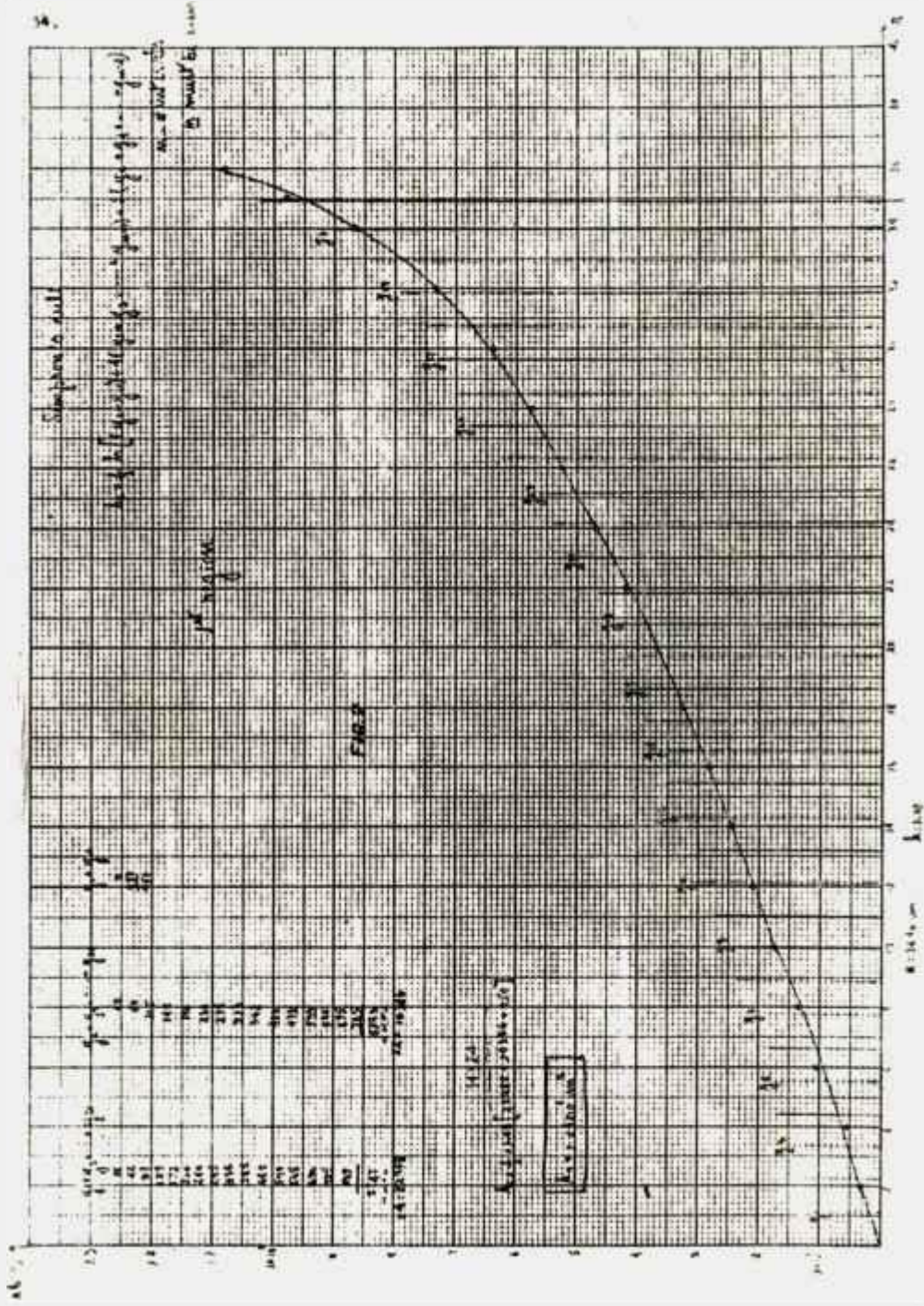
$$\phi_3(x) = Be^{-kx} + Ce^{-\sigma x} \quad B = -5.265 \times 10^{12}$$

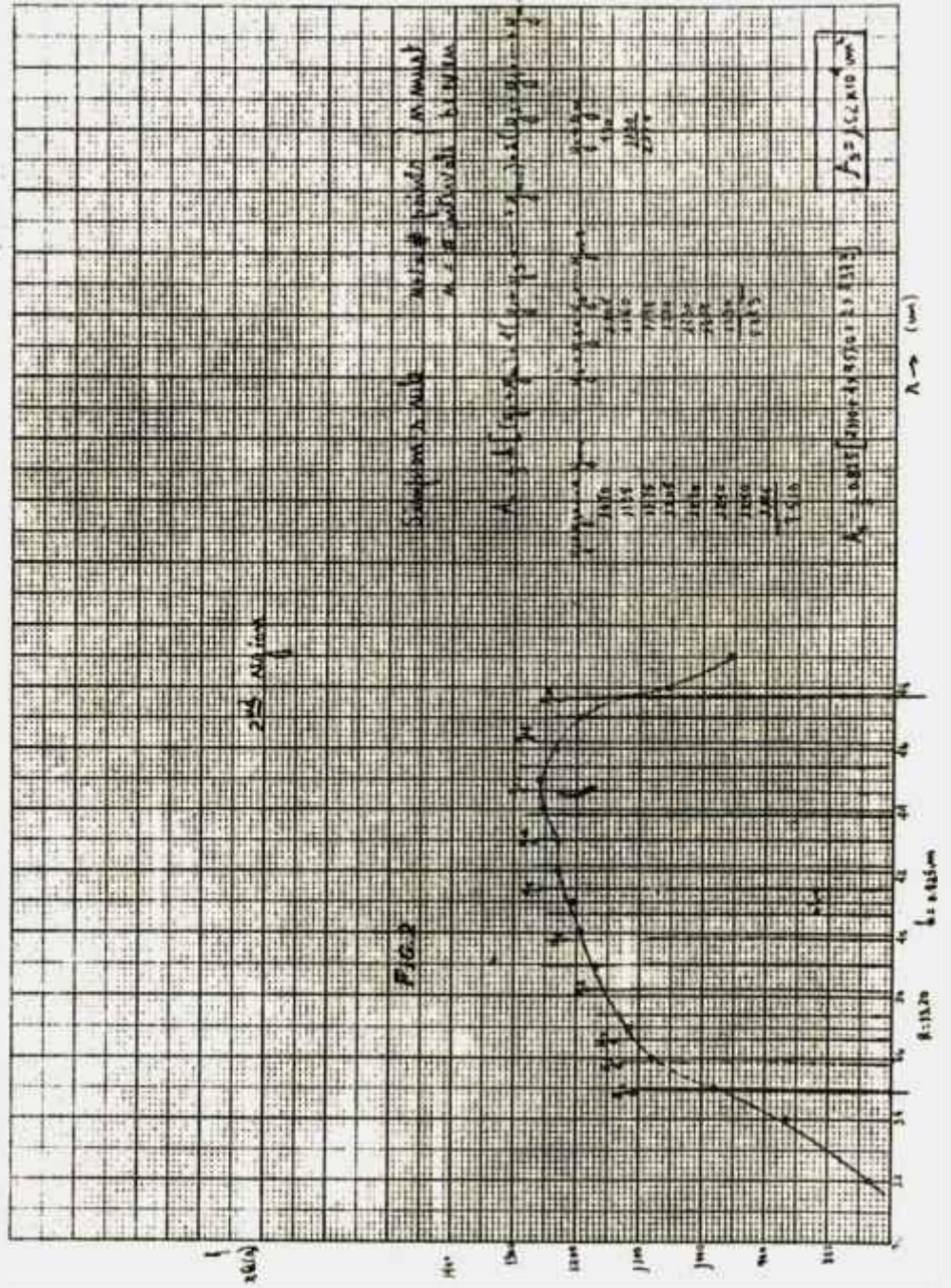
x	Kx	e^{-Kx}	Be^{-Kx}	σx	$e^{-\sigma x}$	$Ce^{-\sigma x}$	$\phi(x)$
0	0	1	-5.265×10^{12}	0	1	5.265×10^{12}	0
0.5	0.11	8.90×10^{-1}	-4.686×10^{12}	0.0890	9.10×10^{-1}	4.791×10^{12}	1.05×10^{11}
1.0	0.22	8.00×10^{-1}	-4.212×10^{12}	0.1785	8.30×10^{-1}	4.370×10^{12}	1.58×10^{11}
1.5	0.33	7.15×10^{-1}	-3.764×10^{12}	0.2678	7.60×10^{-1}	4.000×10^{12}	2.36×10^{11}
2.0	0.44	6.40×10^{-1}	-3.370×10^{12}	0.3570	6.90×10^{-1}	3.633×10^{12}	2.63×10^{11}
3.0	0.66	5.20×10^{-1}	-2.738×10^{12}	0.5355	5.80×10^{-1}	3.054×10^{12}	3.16×10^{11}
4.0	0.88	4.20×10^{-1}	-2.211×10^{12}	0.7140	5.00×10^{-1}	2.633×10^{12}	4.22×10^{11}
5.0	1.10	3.37×10^{-1}	-1.774×10^{12}	0.8925	4.20×10^{-1}	2.211×10^{12}	4.37×10^{11}
6.0	1.32	2.70×10^{-1}	-1.422×10^{12}	1.0710	3.50×10^{-1}	1.843×10^{12}	4.21×10^{11}
7.0	1.54	2.15×10^{-1}	-1.132×10^{12}	1.2495	2.90×10^{-1}	1.527×10^{12}	3.95×10^{11}
8.0	1.76	1.75×10^{-1}	-0.921×10^{12}	1.4280	2.40×10^{-1}	1.264×10^{12}	3.43×10^{11}
9.0	1.98	1.40×10^{-1}	-0.737×10^{12}	1.6065	1.95×10^{-1}	1.027×10^{12}	2.90×10^{11}
10.0	2.20	1.10×10^{-1}	-0.579×10^{12}	1.7850	1.70×10^{-1}	0.895×10^{12}	3.16×10^{11}





KSE 10 x 10 1st. 2nd. 3rd. 4th. 5th. 6th. 7th. 8th. 9th. 10th. 11th. 12th. 13th. 14th. 15th. 16th. 17th. 18th. 19th. 20th. 21st. 22nd. 23rd. 24th. 25th. 26th. 27th. 28th. 29th. 30th. 31st. 32nd. 33rd. 34th. 35th. 36th. 37th. 38th. 39th. 40th. 41st. 42nd. 43rd. 44th. 45th. 46th. 47th. 48th. 49th. 50th. 51st. 52nd. 53rd. 54th. 55th. 56th. 57th. 58th. 59th. 60th. 61st. 62nd. 63rd. 64th. 65th. 66th. 67th. 68th. 69th. 70th. 71st. 72nd. 73rd. 74th. 75th. 76th. 77th. 78th. 79th. 80th. 81st. 82nd. 83rd. 84th. 85th. 86th. 87th. 88th. 89th. 90th. 91st. 92nd. 93rd. 94th. 95th. 96th. 97th. 98th. 99th. 100th.





S = Spike
m = Thin enriched
k = Thick enriched
h = Thick natural

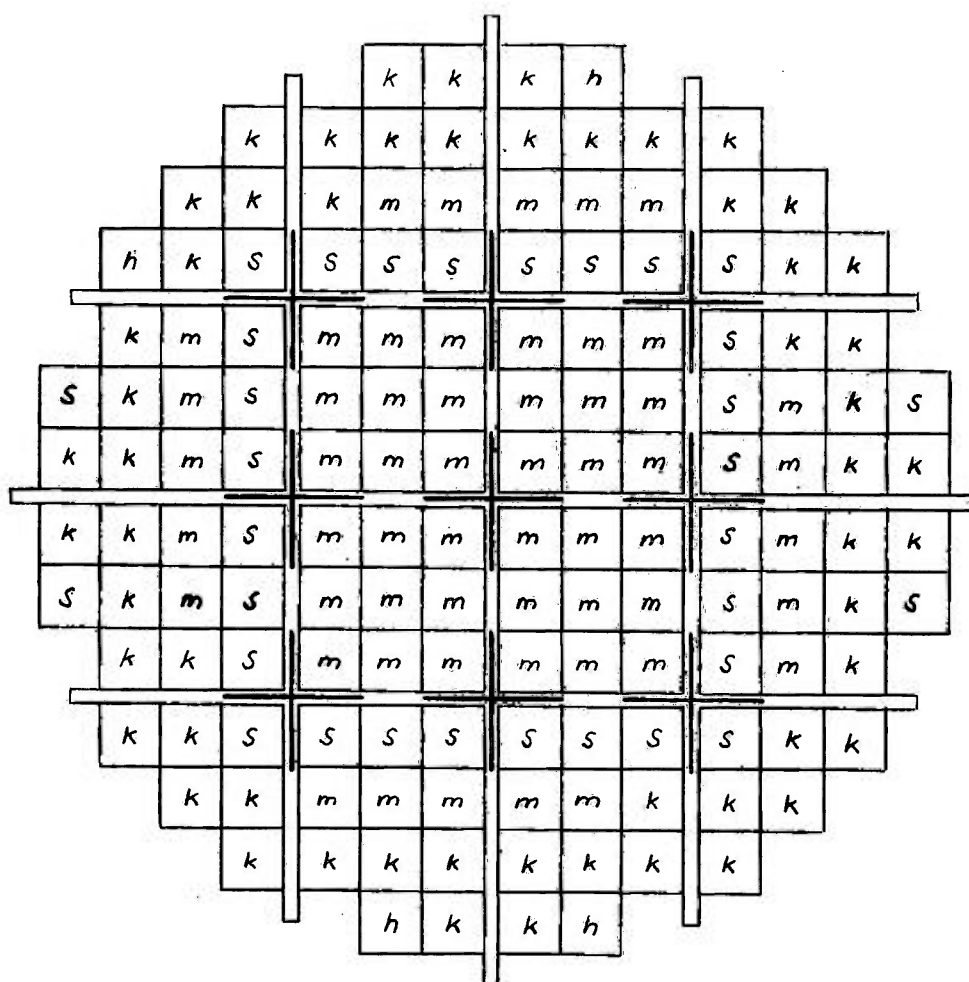
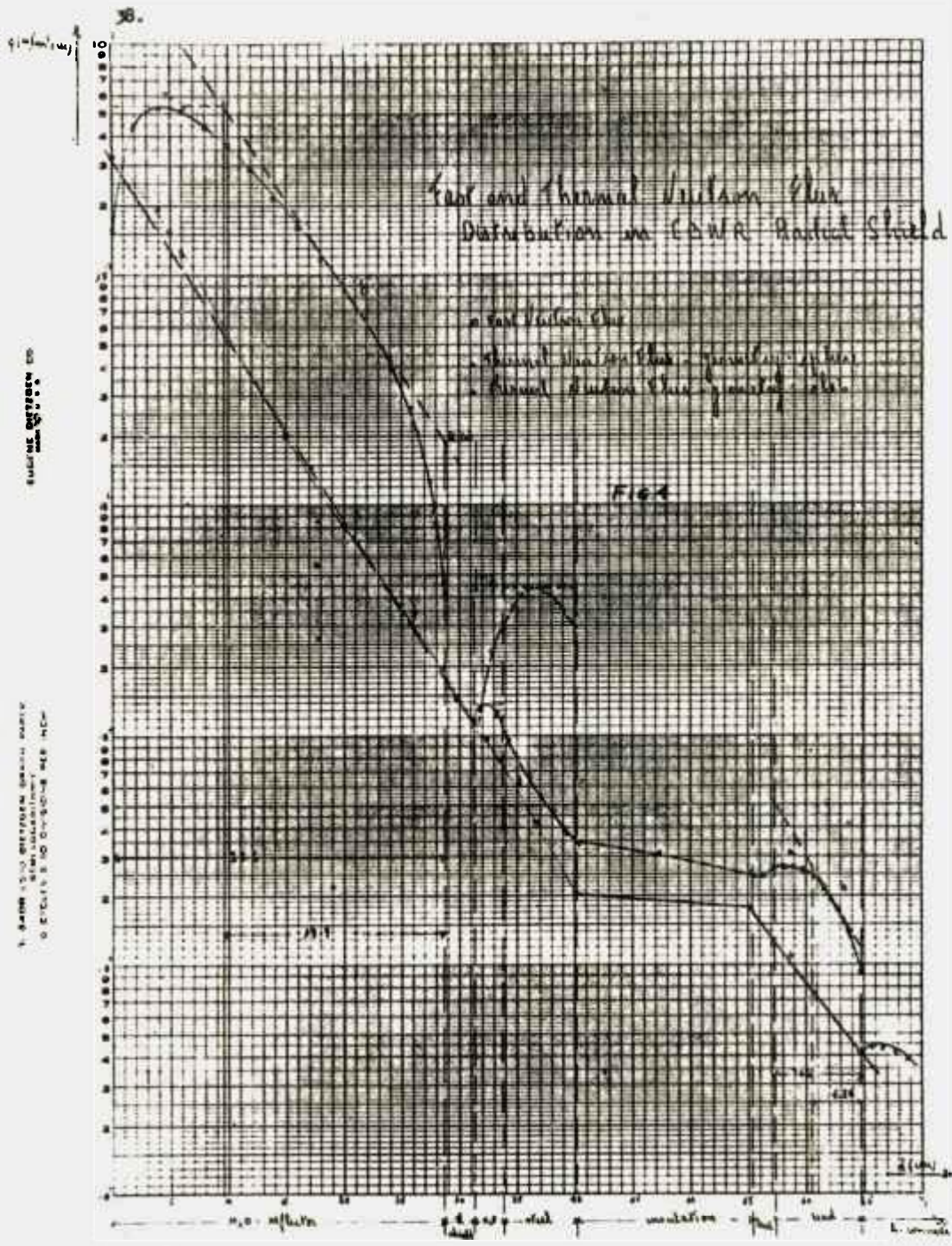


Fig. 3 CORE LOADING



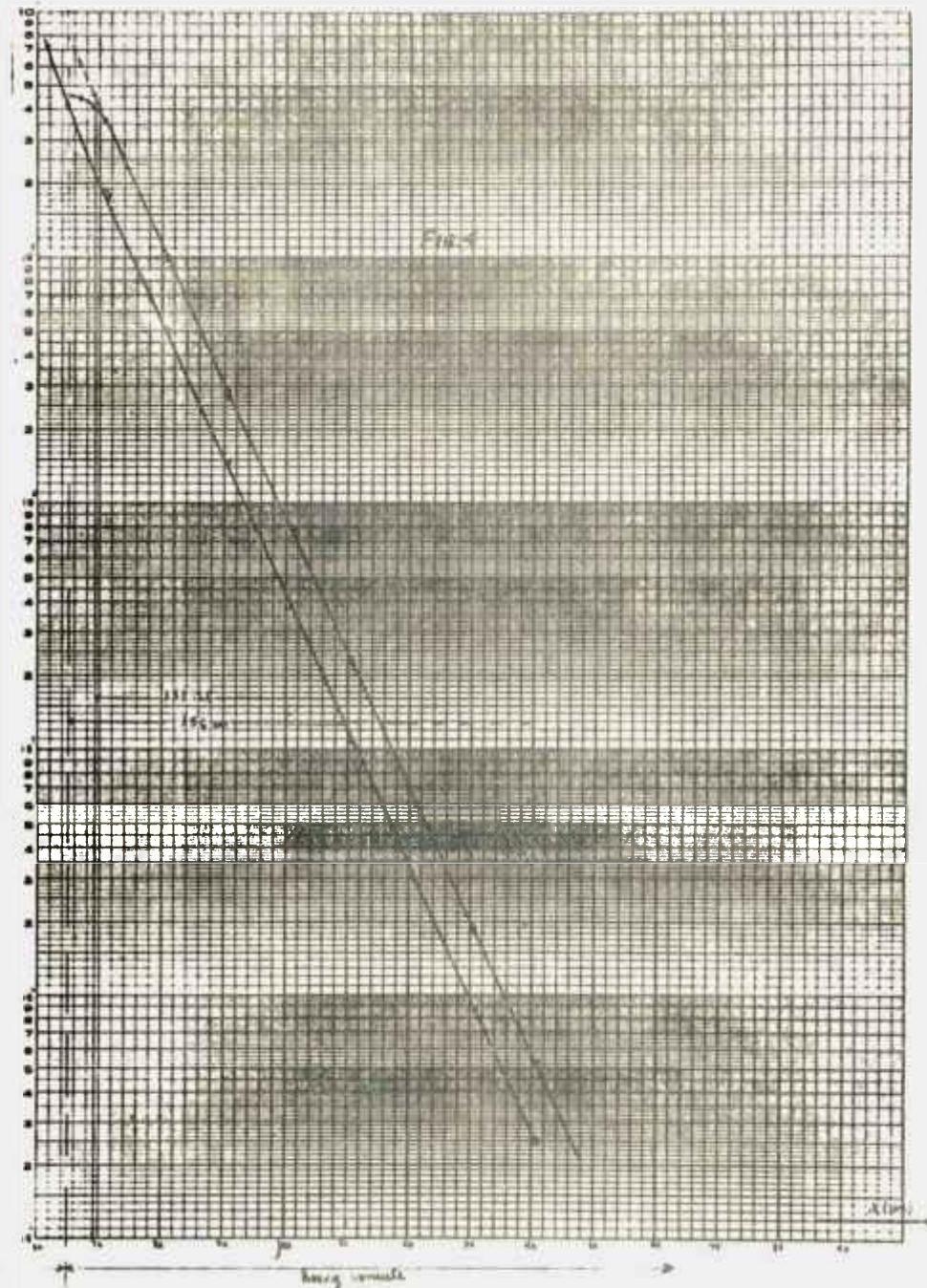
7. BATHYMETRIC SURVEY OF THE
 SEA BED
 IN THE GULF OF GUINEA

Surface Temperature $^{\circ}\text{C}$

0.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0

Distance cm

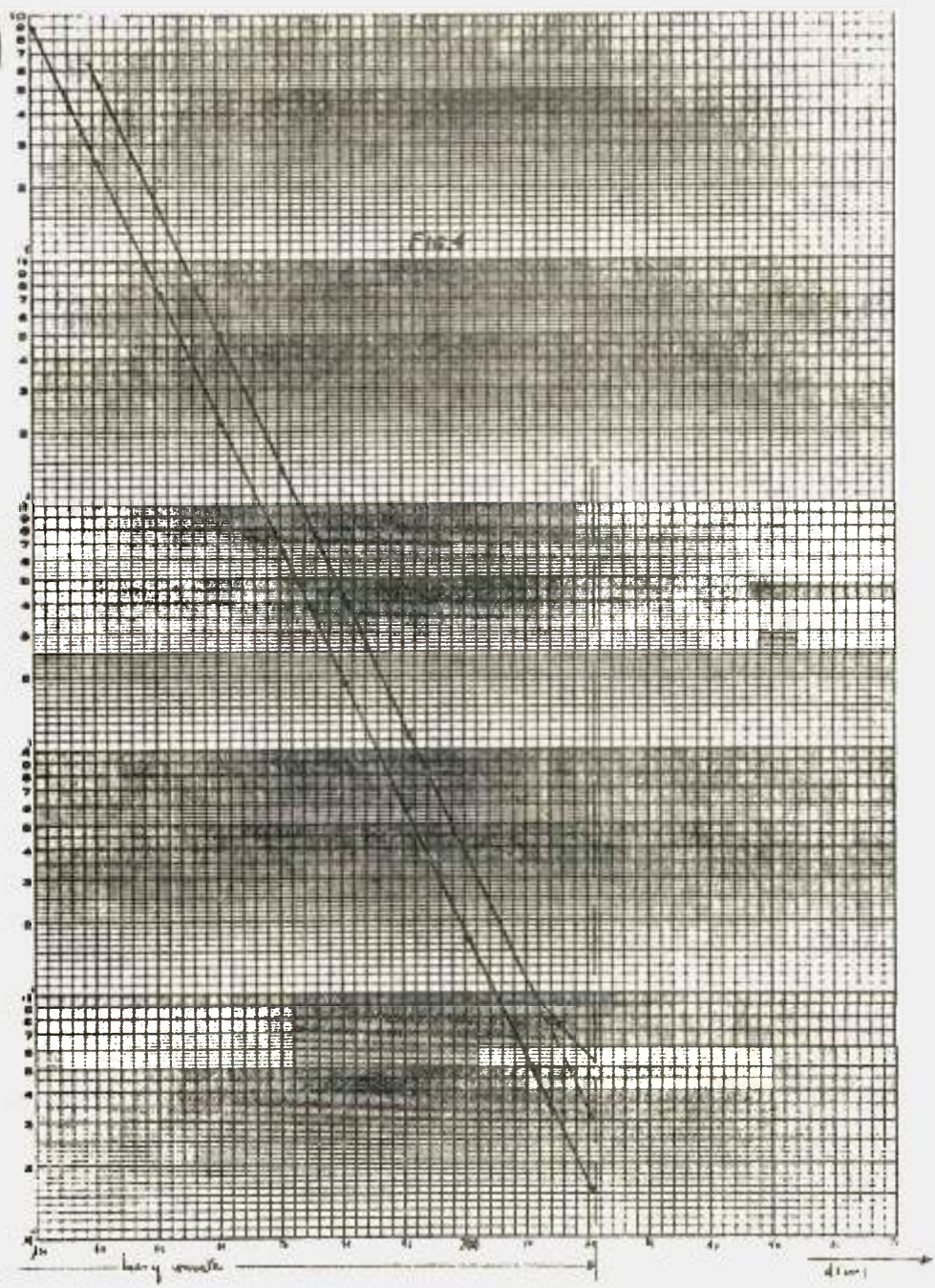
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SOLID LINE
1) CYCLES TO DIVISIONS PER INCH



40.

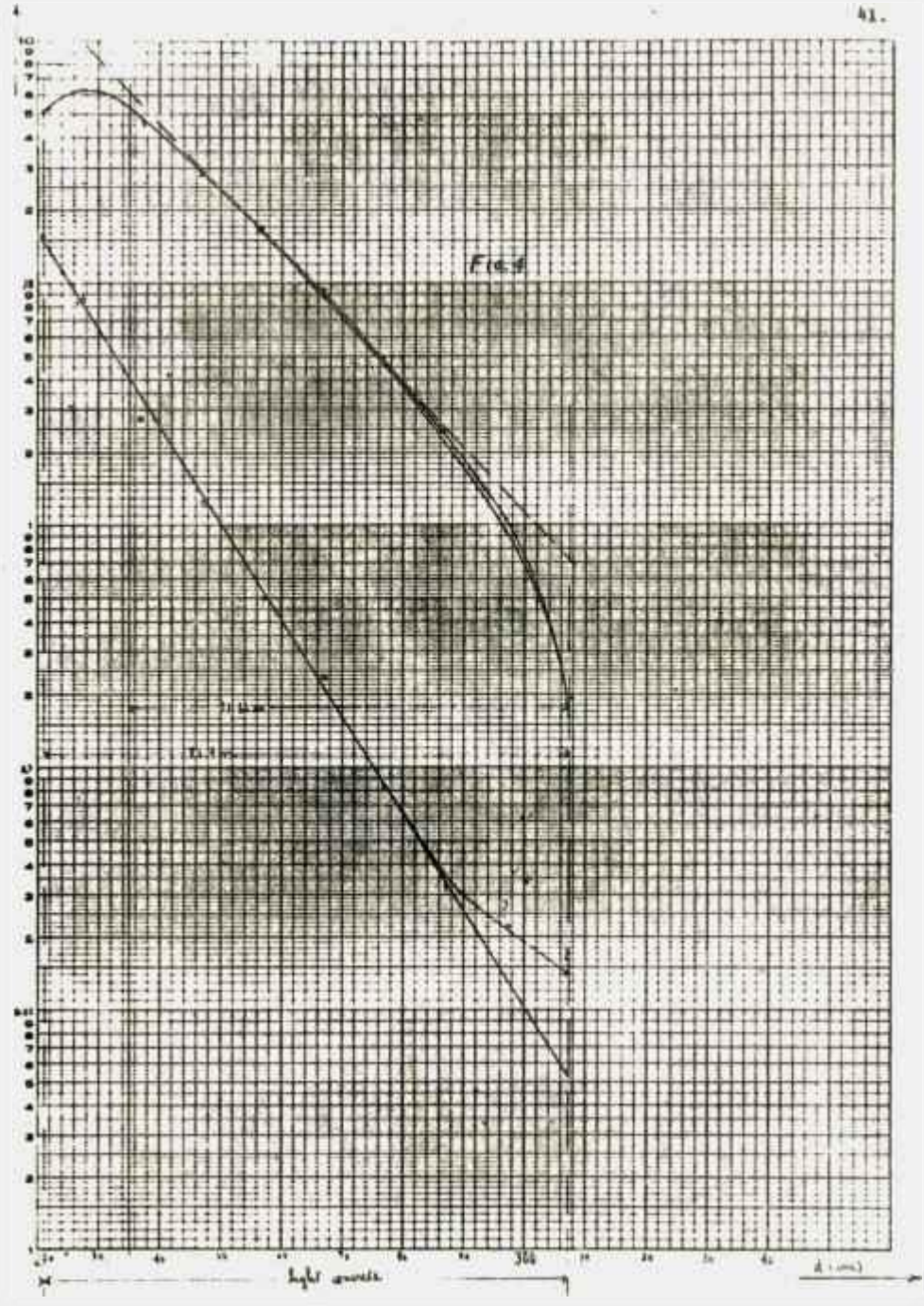
ENGINE DESIGN CO
 1925-1926

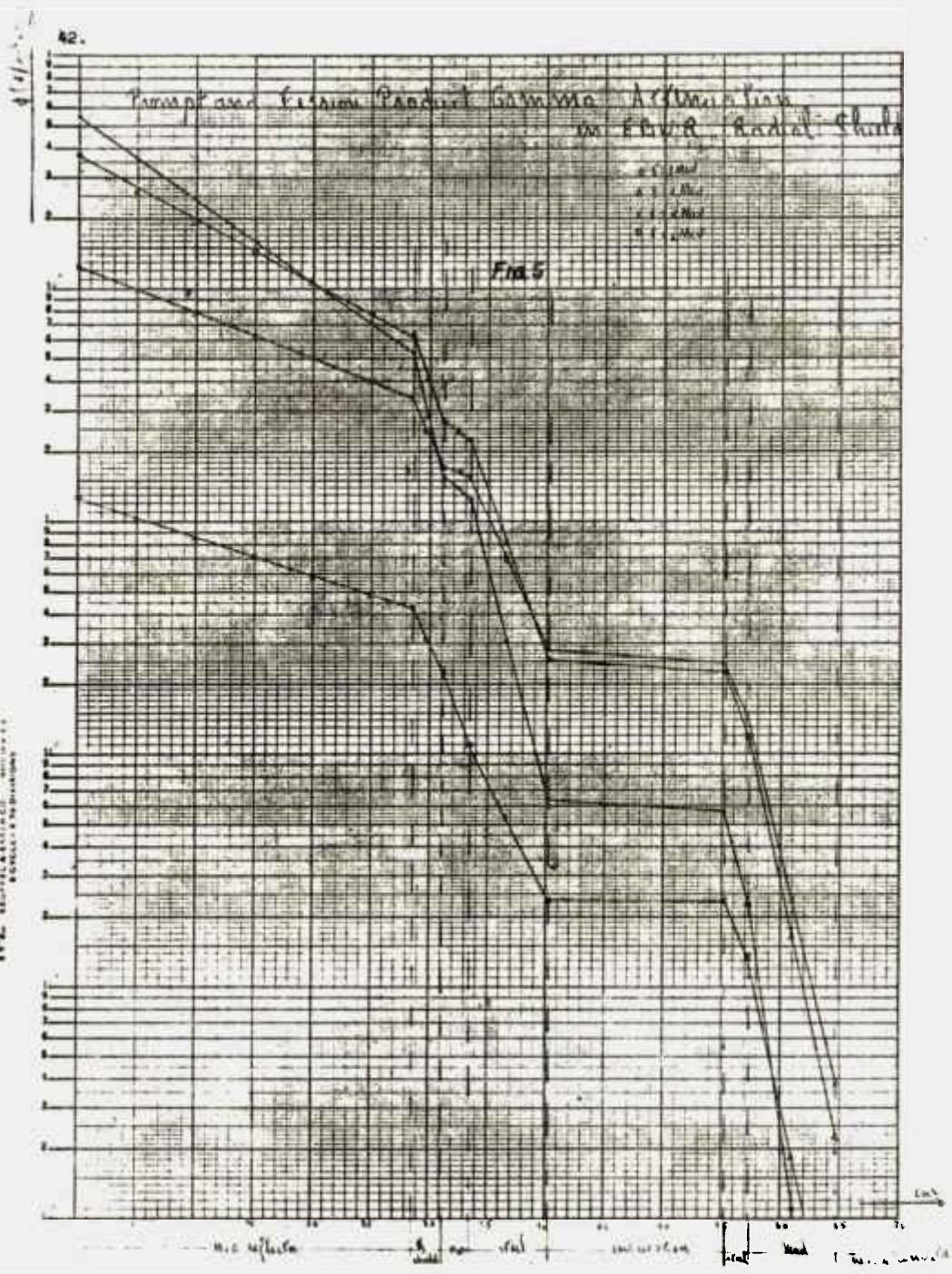
1. SCALE AND DESIGN GRAPH PAPERS
 2. SCALE AND DESIGN GRAPH PAPERS
 3. CYCLES 10 DIVISIONS PER INCH



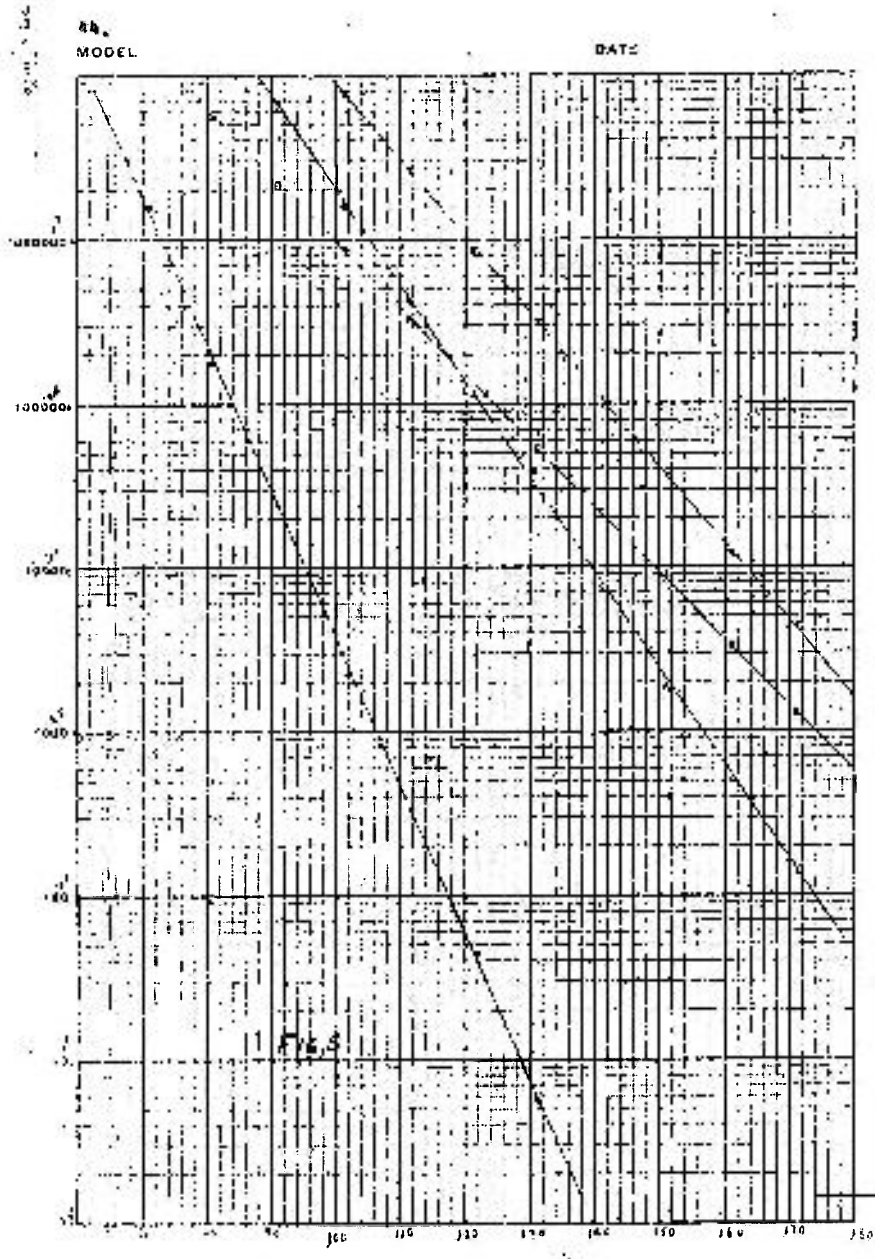
EUGENE DIEBOLD CO.

3. RADON 1510 OUTSIDE DEPTH CAP IN SEMI-CENTRAL
5. EXILES 5 TO DIVISIONS AT 1/2 CM





K-E
 359 (9)
 RESEARCH & DEVELOPMENT
 DIVISION



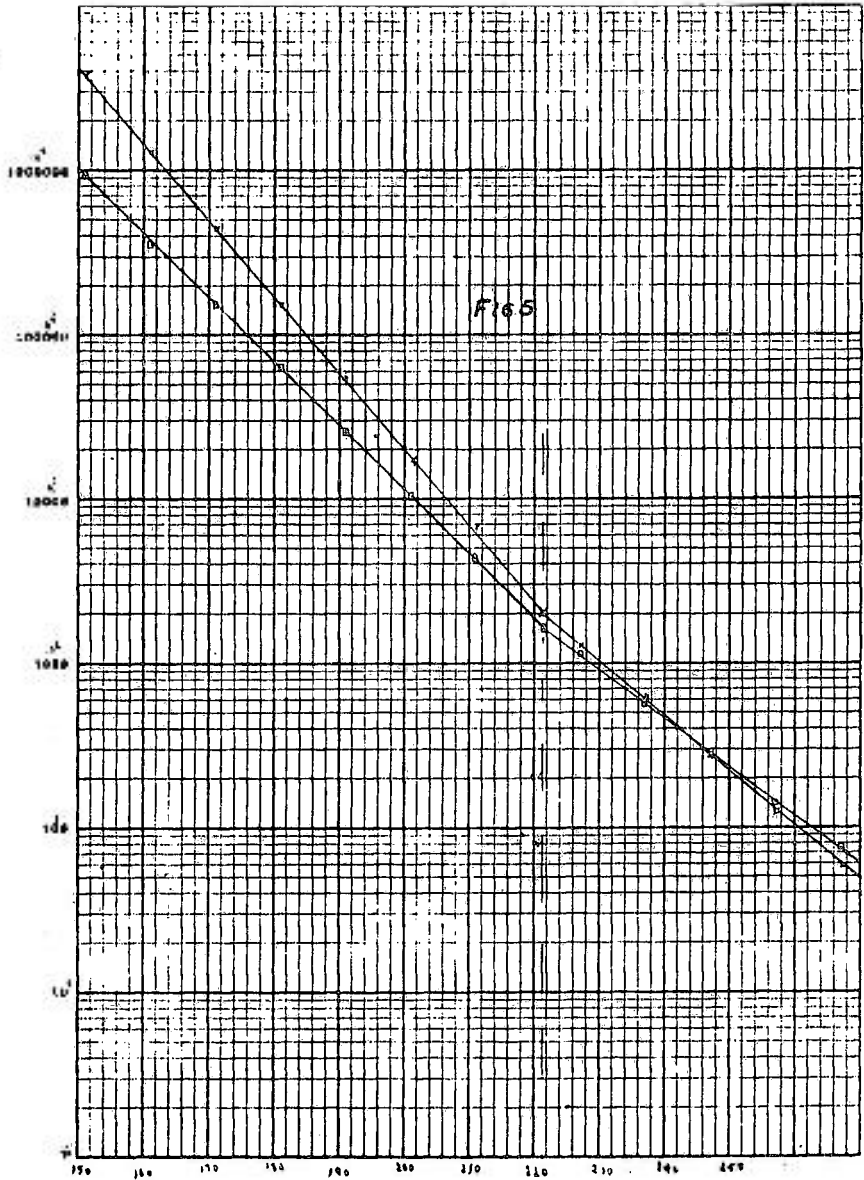
KSE
 MILITARY/NAVY
 AIR FORCE
 VEHICLES BY ENGINE

heavy trucks

MODEL

DATE

45



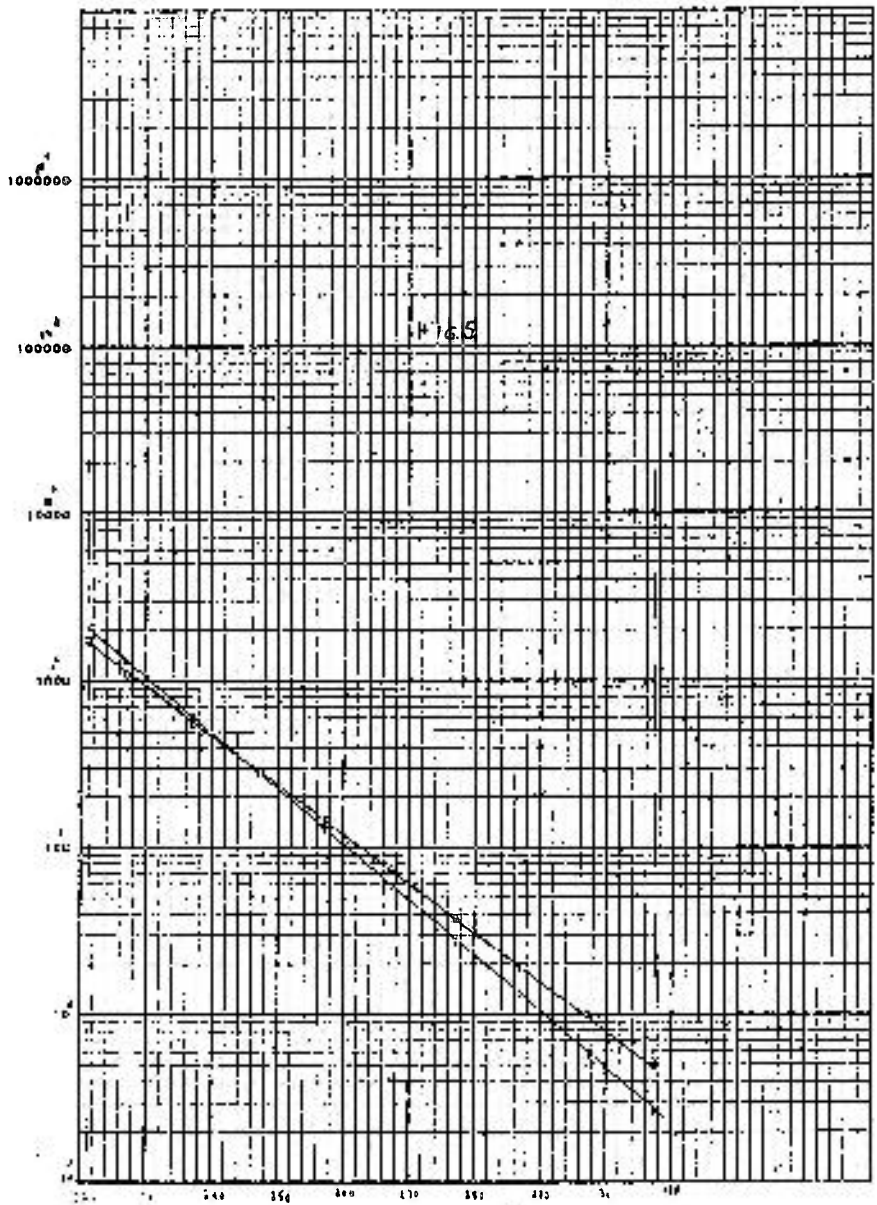
K&E SEMI-LOGARITHMIC 358-00
BRUNNEN & CO. MADE IN U.S.A.
7 CIRCLE 7 80 SHEPPARD

August 10 1945

Fig.

MODEL

DATE



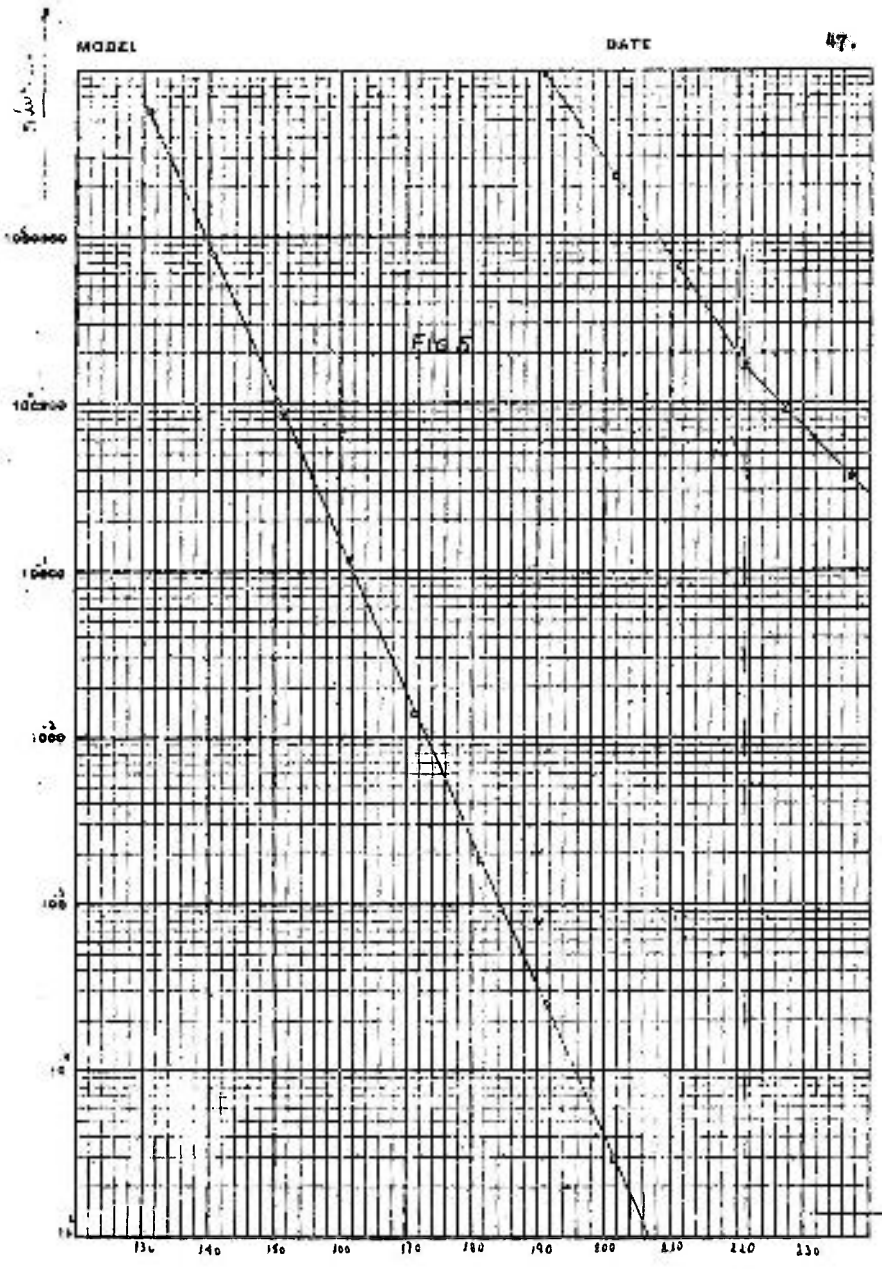
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220 240 260 280 300 320 340 360

16.5

Fig. MODEL DATE

light source



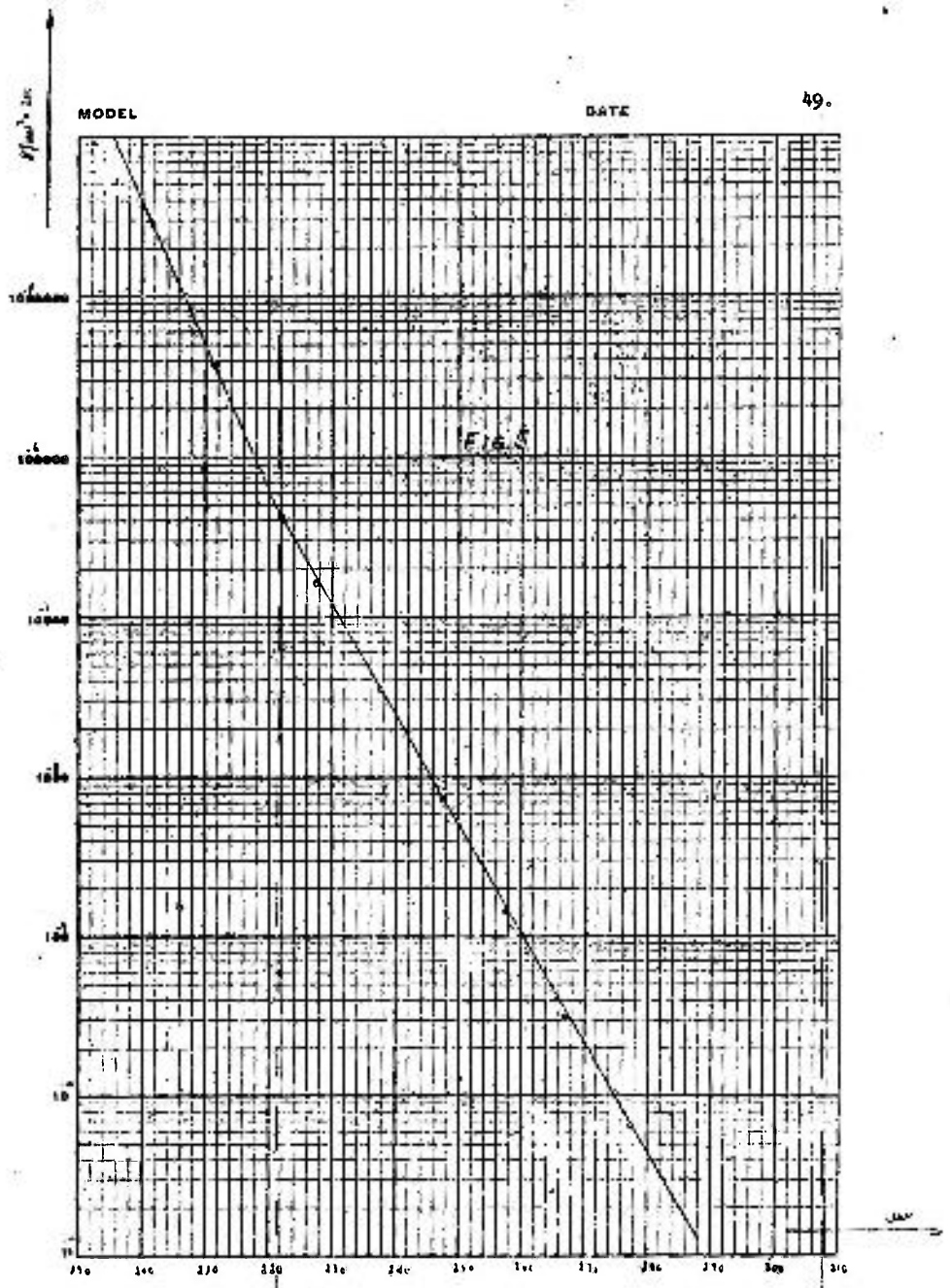
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 48 952
 31

heavy minute

light minute

MODEL

DATE

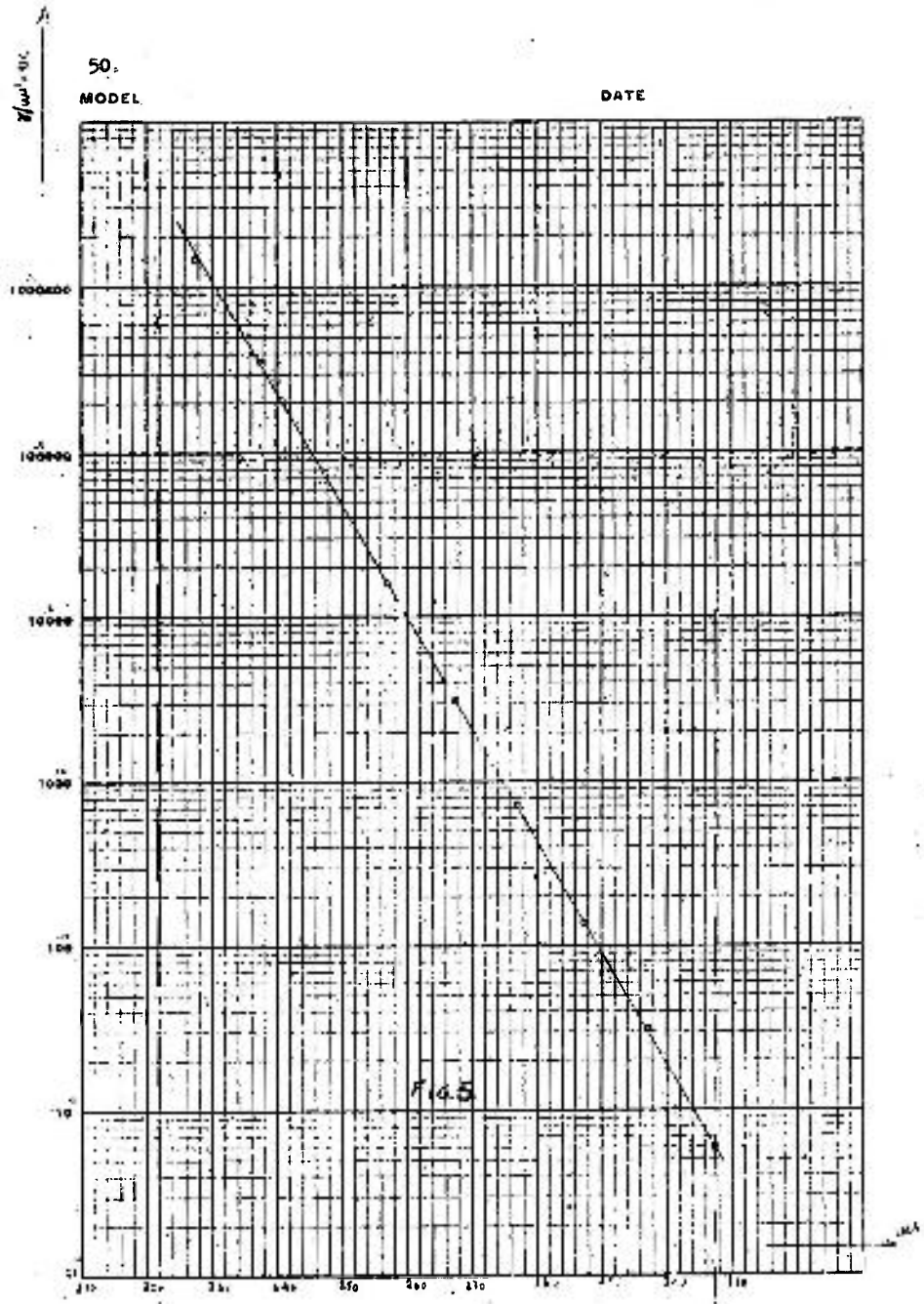


100E SEMI-LOG GRAPHIC 356-DC
 ENGINEERING SUPPLY CO.
 10000 100000 1000000

Time (min)

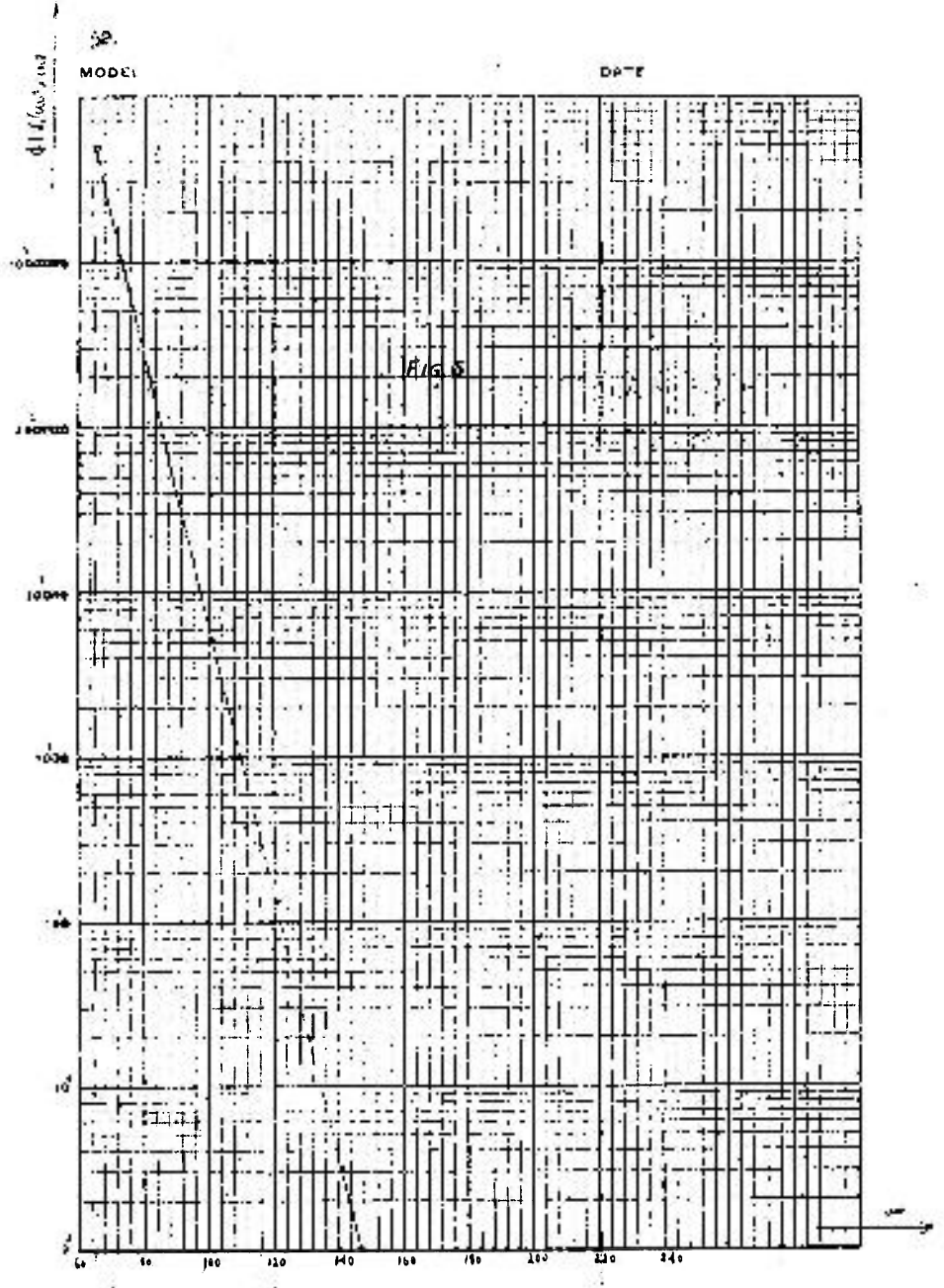
K (mm^2/sec)

W.C. SIMMONS INC. 396 DC
PHILADELPHIA, PA.
SERIALS DIVISION



log f

NOTE: This is a preliminary report and should not be used for final design purposes.

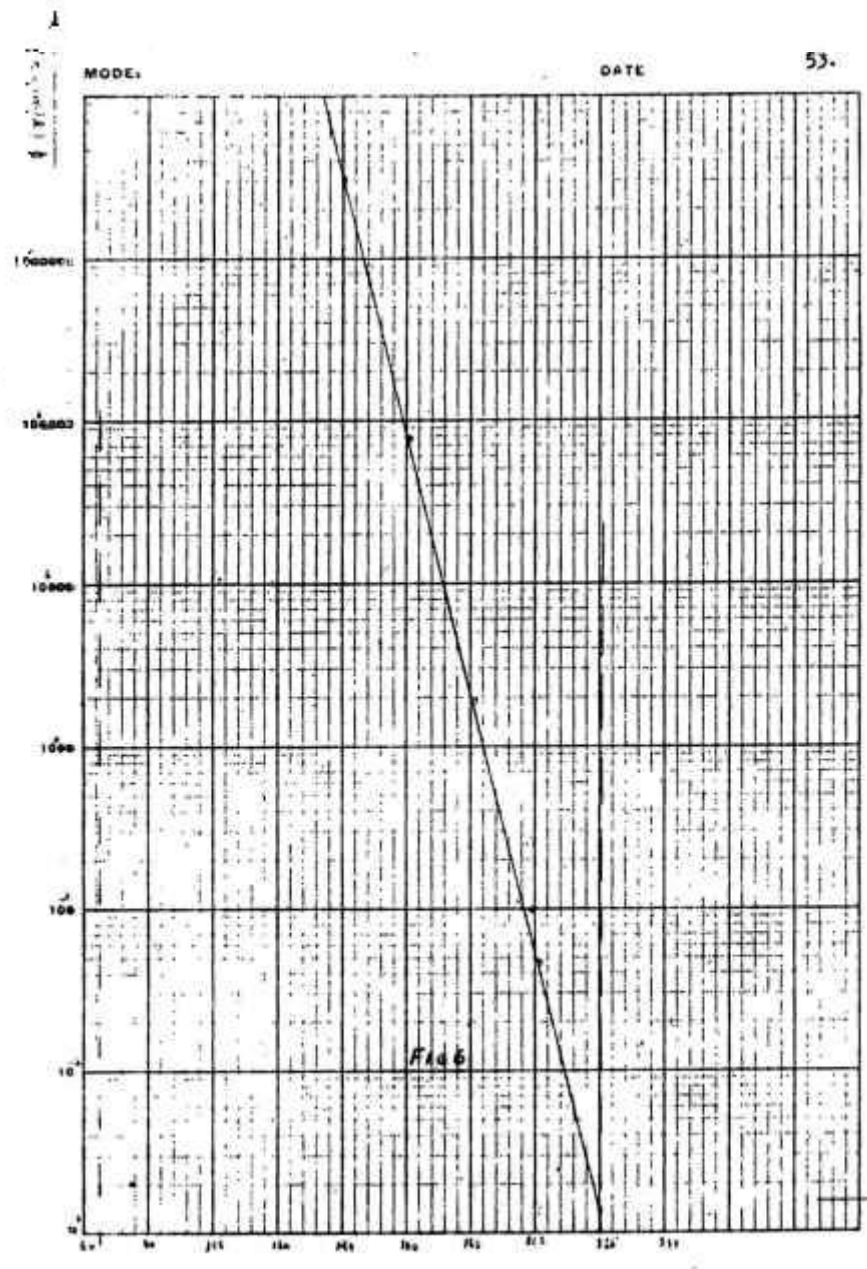


13

10000

1000

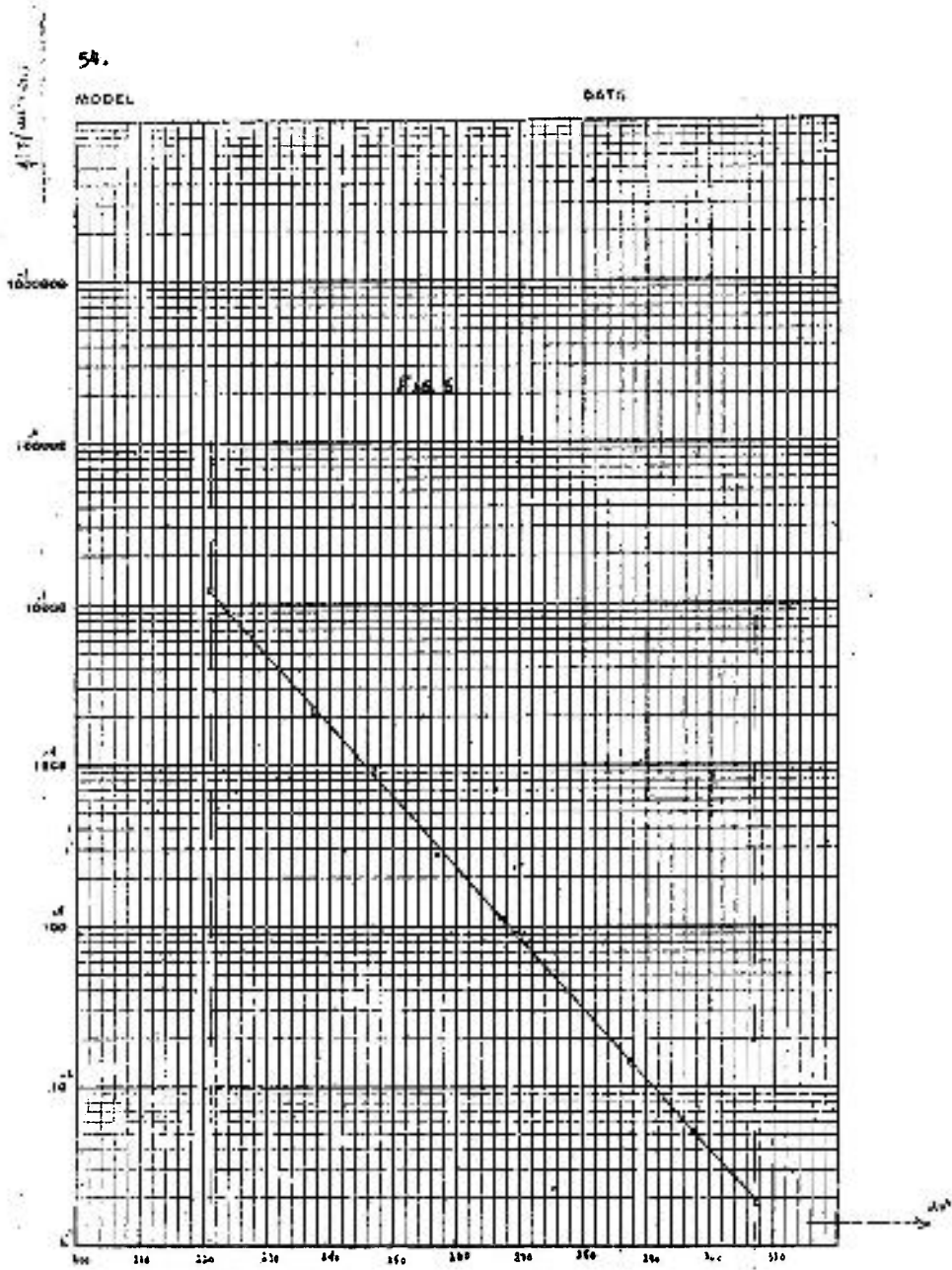
KOE SCHEIDEGARITHMIC 3100 ME
SCURLE COME CO. 1117 N. J. A.
BICYCLES & CO. BOSTON, U.S.A.



Time (seconds)

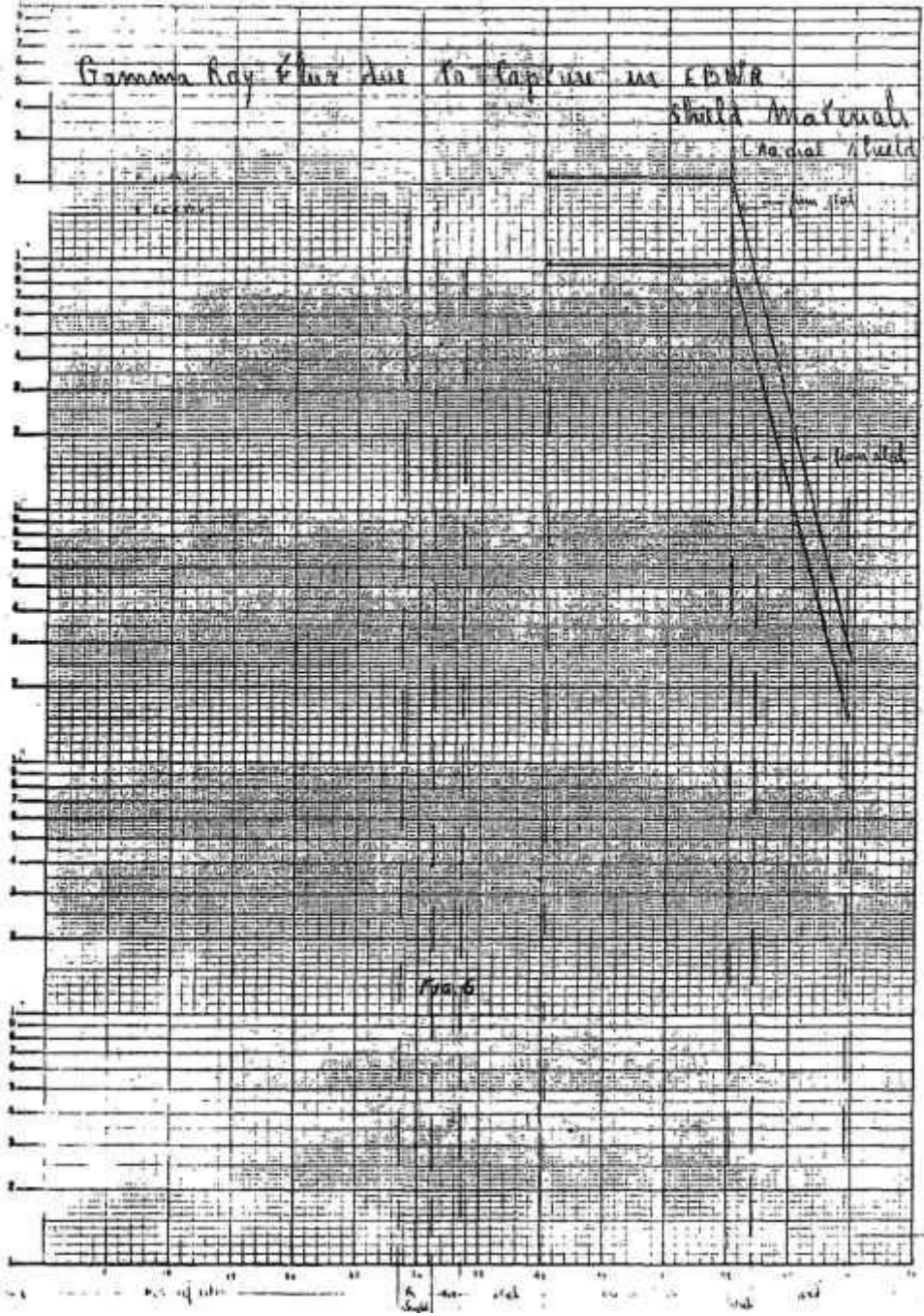
1967 22000

K&E SEMI-LOGARITHMIC 350-06
HEUPFL & ESSER CO. MODEL 1112
CIRCLE 10 DIVISION



Input current

Gamma Ray Flux Due to Capture in EDWR
Shield Materials
(Normal Shield)



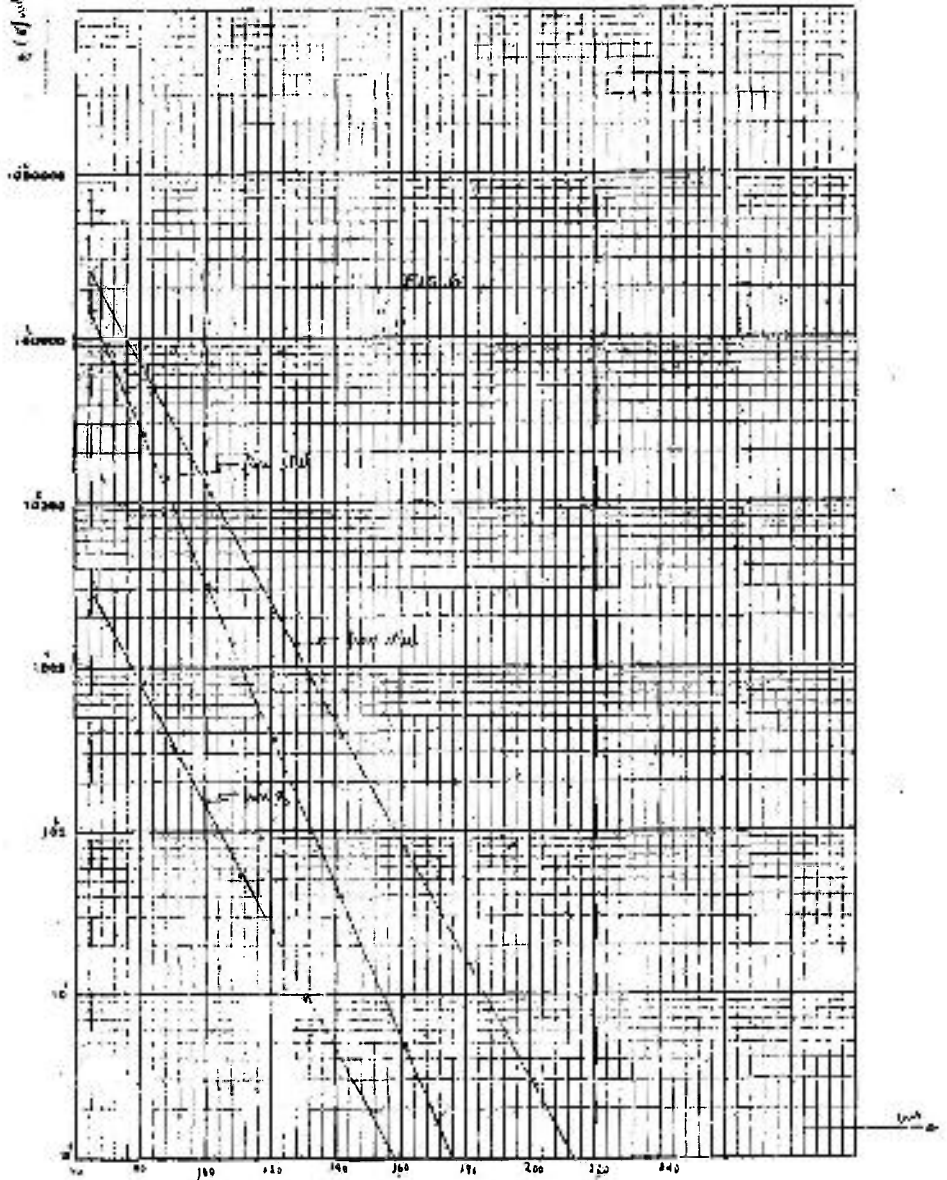
K&E SEMILOGOGRAPHIC 350 (B)
RAUFIC & SULLIVAN CO. NEW YORK, N.Y.
DESIGNS & DIVISIONS

Fig. 6

K&E SEMI-LOGARITHMIC 35% HP
KUPFLY & BEER CO. MADE IN U.S.A.
7 CYCLES PER DIVISION

56.
MODEL

DATE



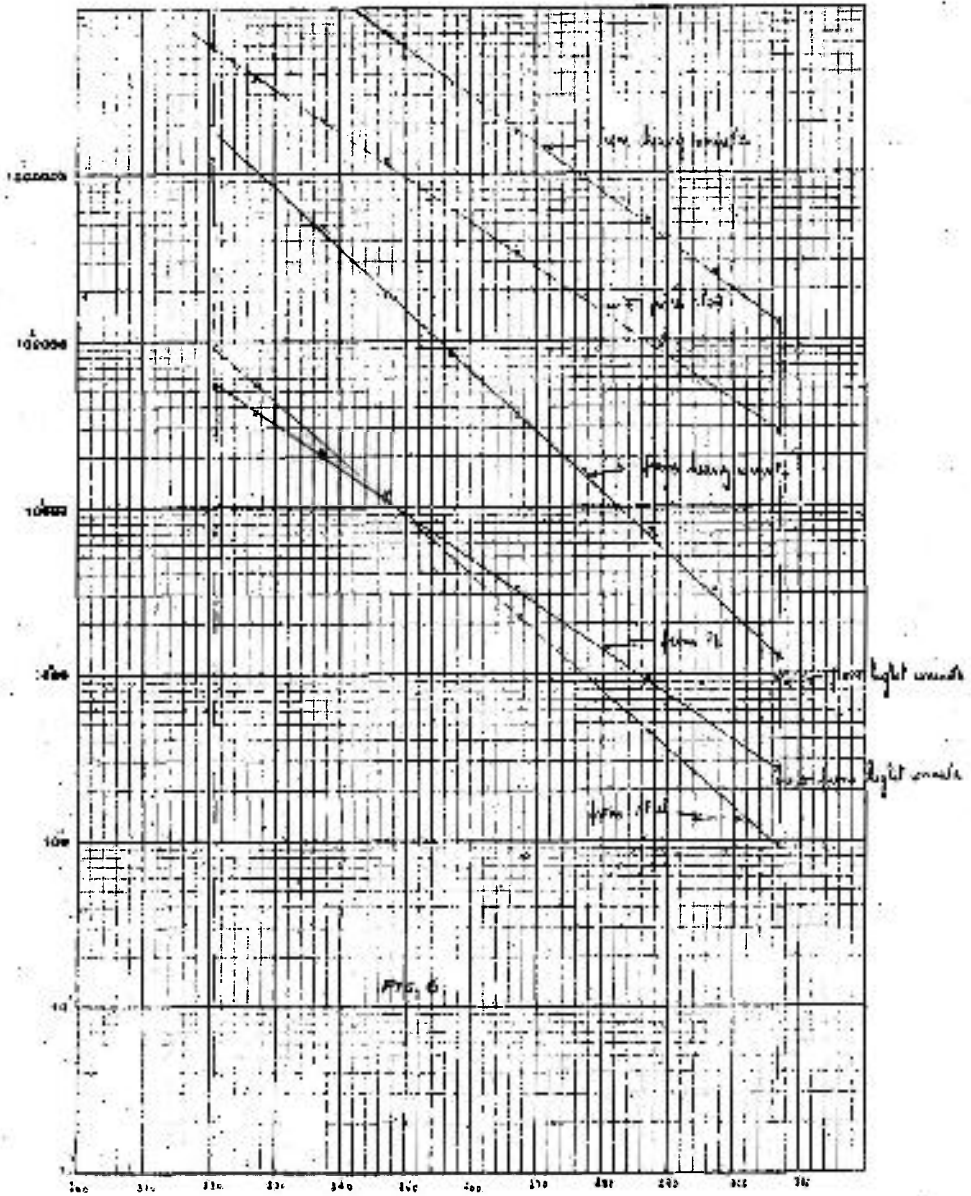
copy 10/16

copy 10/16

58.

MODEL

PARA



KODAK SEMI-LOGARITHMIC 35B-50
RECORDED PAPER CO. 441
YONGE ST. TORONTO, CAN.

light waves