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PRECRITICAL CALCULATIONS FOR THE 2.9 IN. PITCH, TWMR CRITICAL ASSEMBLY

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J. C. Peak
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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract SNPC-27

GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE

P.O. BOX 608, SAN DIEGO 12, CALIFORNIA

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TOPICAL REPORT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

August 1, 1965

Contract SNPC-27

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Nuclear Reactor Division
D. Bogart

GENERAL ATOMIC

DIVISION OF

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I. INTRODUCTION

General Atomic is engaged in a program of research aimed at assisting the Lewis Research Center of the National Aeronautics and Space Administration in determining the feasibility of an isotopically enriched tungsten, water moderated reactor for use as a nuclear rocket. General Atomic's role in this program is to generate accurate and detailed information from reactor analysis and basic critical experiments for the corroboration of the calculated nuclear characteristics of the reactor concept. In compliance with this program, the first of a series of critical assemblies has been fabricated and the necessary precritical neutronic calculations have been performed. This report presents the critical loadings and summarizes the precritical calculations for the 2.9 in. pitch core with water reflectors.

II. DESCRIPTION OF THE 2.9 IN. PITCH CORE

The critical assembly is a hexagonal array of 121 fuel subassemblies. The lattice pitch is 2.90 inches. The assembly is water moderated and reflected by 25 cms of interstitial water on the top and bottom, and by an effectively infinite water reflector on the sides. The fuel subassemblies are in the form of concentric cylinders axially divided into twenty-one 1-5/8 in. long stages which are separated by 1/8 in. long corrugated aluminum spacers. A fuel stage consists of five concentric aluminum-uranium alloy fuel rings wrapped on the inside with 5 mils of natural tungsten. The outer ring is surrounded by an additional 3 mils of tungsten and a 40 mil thickness of U^{238}. The fuel alloy consists of approximately 35 wt. percent enriched uranium. The exact dimensions of a fuel stage are given in Table 7 of Reference 1.

At the midpoint of each triangle formed by the hexagonal array is a sealed aluminum tube containing a 0.0474 molar cadmium nitrate solution.

Each poison tube is 9/16 in. o.d. and 1/2 in. i.d. A detailed description of the critical assembly is given in the Hazards Analysis.[2]

The total loadings for the 2.9 in. pitch core are given in Table 1. The average weights of the components in the individual subassemblies as well as their weight distributions, are given in reference 3.

Table 1

TOTAL CORE LOADING

Nuclide	Loading (kg)
Al	544.099
W	191.301
U^{235}	95.831
U^{238}	395.264
Ni	2.835
Zr	9.801

III. PRECRITICAL CALCULATIONS

The neutronic calculational methods are structured by the heterogeneous nature of the core. They have been described in detail in Reference 1. 1. A major problem in the analysis is the proper weighting of the cadmium cross section for use in the homogeneous eigenvalue calculations. The method presently in use has been previously described for the 3.0 in. pitch core. This description is included as Appendix A. The entire set of procedures can be summarized as follows;

1. Thermal and high energy disadvantage factors were obtained for all the core components except cadmium from a cell transport calculation. An equivalent Wigner-Seitz cylindrical cell of radius 3.867 cm. was used in a GAPLSN P_1-S_8 calculation.[4] The ten-group structure of Table 2 was carried throughout these calculations.

Table 2

ENERGY GROUP STRUCTURE

Group	Bottom Energy	Top Energy
1	2.73 MeV	14.9 MeV
2	0.498 MeV	2.73 MeV
3	67.4 keV	0.498 MeV
4	61.4 eV	67.4 keV
5	2.38 eV	61.4 eV
6	0.414 eV	2.38 eV
7	0.090 eV	0.414 eV
8	0.050 eV	0.090 eV
9	0.030 eV	0.050 eV
10	0.0 eV	0.030 eV

2. Thermal and fast spectra were computed in the GATHER-II [5] and GAM-II [6] codes respectively, using the disadvantage factors from the cell calculations. Resonance calculations were performed by Nordheim's integral method. The presence of interstitial aluminum was included in the resonance calculation. Collision probability tables for a cylinder were used with the mean chord lengths given in Reference 4, and a Dancoff-Ginsburg factor of 0.066. Pointwise microscopic cross sections were averaged over these spectra to obtain self-shielded cross sections for ten broad groups.

3. Thermal disadvantage factors for cadmium were obtained from a series of cell transport calculations using the GAPLSN code. An equivalent cell which was centered on the cadmium tube was chosen. The moderator water and fuel were homogenized into two annular regions outside the tube. The disadvantage factors so obtained were corrected group by group for the neglected two-dimensional aspect of the problem using ratios previously obtained for a 3.0 inch pitch lattice. These ratios are given in Appendix A. Separate sets of disadvantage factors were obtained for Cd NO_3 solutions ranging from 0.0 to 0.163 molar, and broad group cross sections were computed for various cadmium concentrations.

4. The effective multiplication factor was computed using the ten broad group cross sections obtained in Steps 2 and 3. The final cadmium concentration was found by a search following a one-dimensional buckling iteration sequence in the GAZE-II[7] code. The homogenized atom densities and geometric description used in the GAZE calculations is given in Table 3.

Comparison of experiments and analysis in the 3.0 in. core, indicate that the calculated excess reactivity for these cores may be low by about .02 $\Delta k/k$, using the present data and techniques. Pending further investigation of this discrepancy, the final eigenvalue calculations were converged on a multiplication factor of 0.9800. On the same basis the predicted k_{ex} without cadmium is \$6.08.

Table 3

HOMOGENIZED ATOM DENSITIES FOR THE 2.9 IN. PITCH, WATER REFLECTED CORE

Nuclide	Atom density (atoms/b-cm)
Core (height = 108. cm, radius = 42.54 cm)	
H	1.856×10^{-2}
O	0.928×10^{-2}
Al	1.974×10^{-2}
Ni	4.708×10^{-5}
Zr	1.052×10^{-4}
Cd^{113} (0 to 39.43 cm Radius)	1.885×10^{-7}
Cd^{113} (39.43 to 42.54 cm radius)	0.0
W^{182}	2.695×10^{-4}
W^{183}	1.470×10^{-4}
W^{184}	3.124×10^{-4}
W^{186}	2.899×10^{-4}
U^{235}	3.996×10^{-4}
U^{238}	1.627×10^{-3}

Nuclide	Atom density (atoms/b-cm)
Side Reflector (42.54 to 57.54 cm radius)	
H	6.677×10^{-2}
O	3.339×10^{-2}
Top and Bottom Reflectors (25. cm thick)	
H	1.856×10^{-2}
O	0.928×10^{-3}
Al	0.908×10^{-3}
Cd^{113}	1.885×10^{-7}

IV. ESTIMATE OF ACCURACY

Previous experiments in the 3.0 in. pitch core deviated from the results of a similar analysis by + 1.9% $\Delta k/k$. Although this error has been compensated for in the present analysis, the cause is, at present, not understood. Therefore the present calculations have been assigned an uncertainty of 2.0% $\Delta k/k$.

V. MEASUREMENT OF THE ASYMPTOTIC DECAY CONSTANT

It is expected that some pulsed neutron measurements will be made on subcritical 2.9 in. pitch cores. The asymptotic decay constant, α, will be measured as a function of radius with the critical cadmium concentration in the poison tubes. The subcritical cores will be water reflected. Values of α, calculated by the method of 1/v poison removal, are shown in Fig. 1. Finally, radial and axial flux distributions in three energy groups are given in Figs. 2 and 3 for the full size 2.9 in. pitch core.

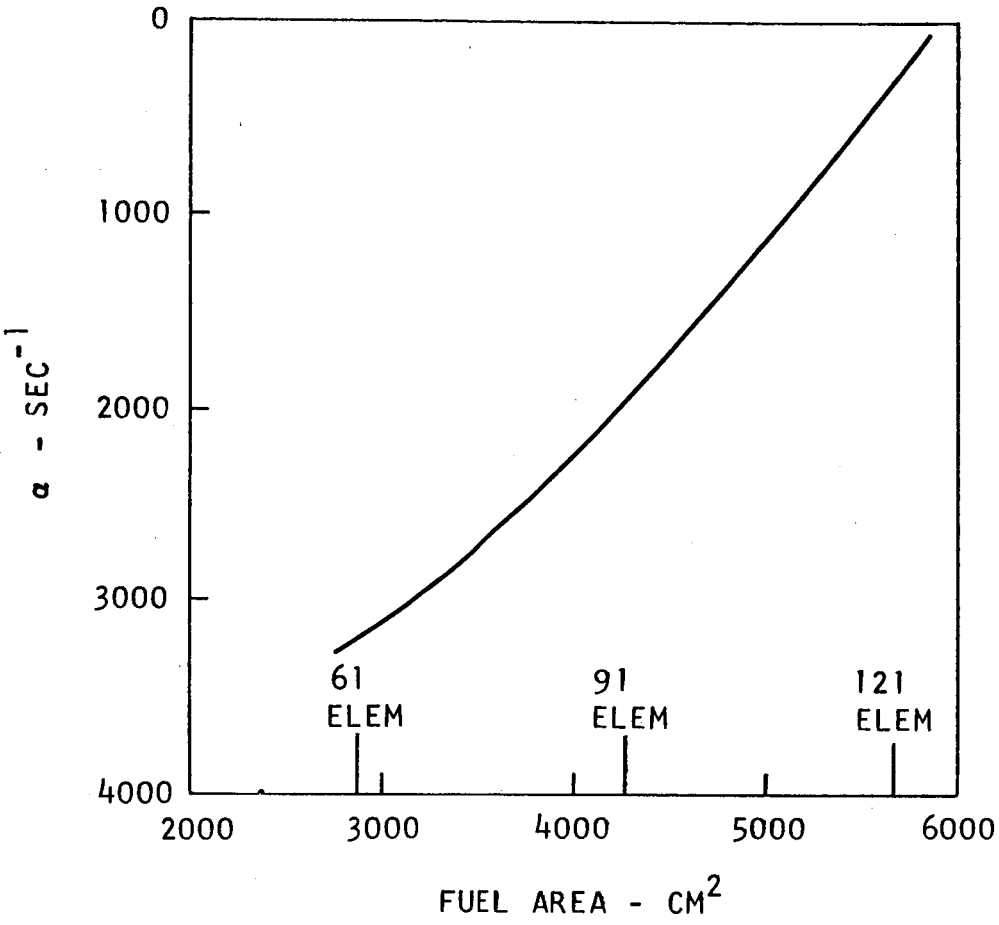

Fig. 1 -- Prompt Neutron Decay Constant α as a Function of the Number of Fuel Elements Loaded

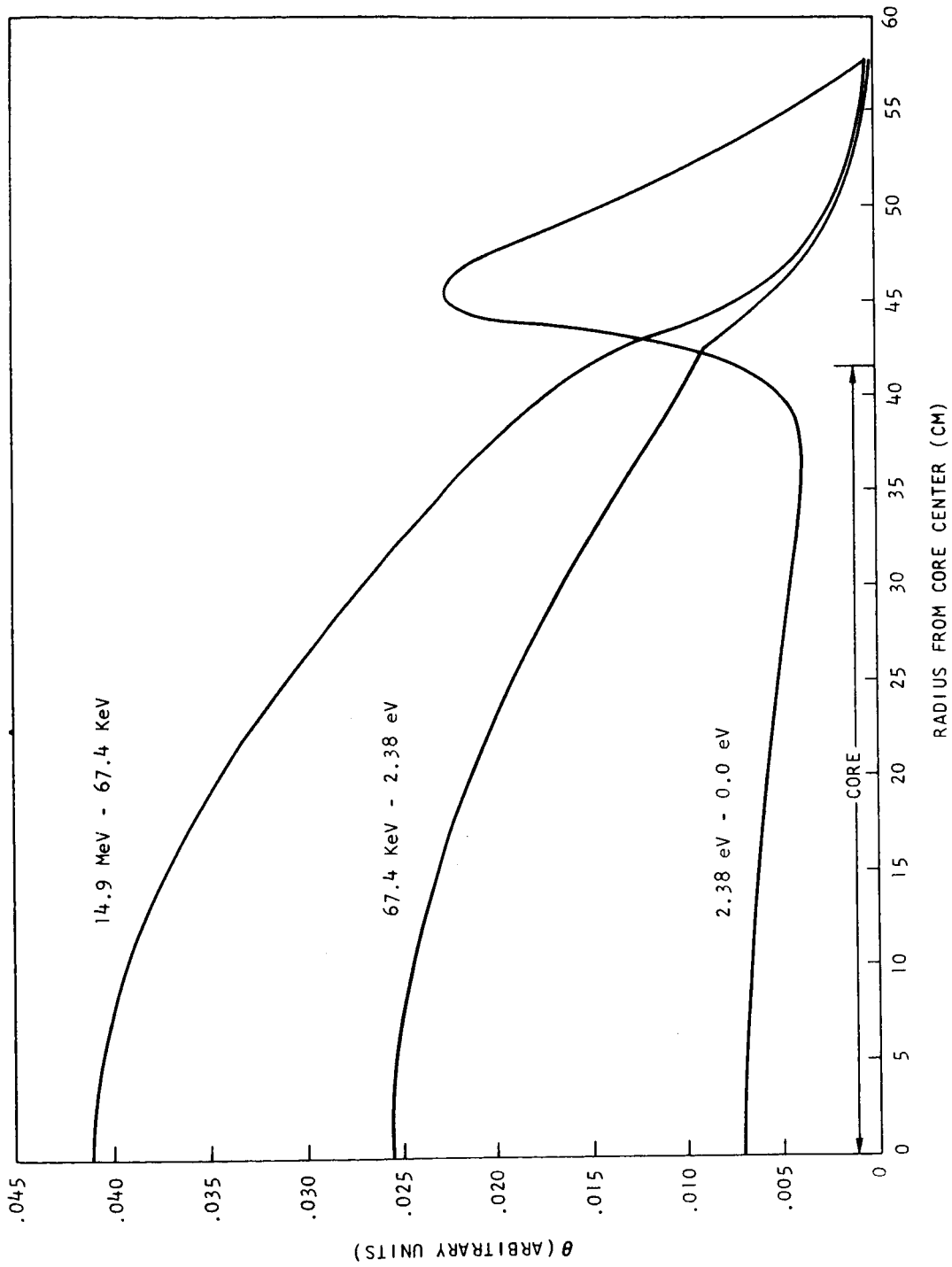

Fig. 2 -- Direct Flux Versus Radius 2.9 In. Pitch

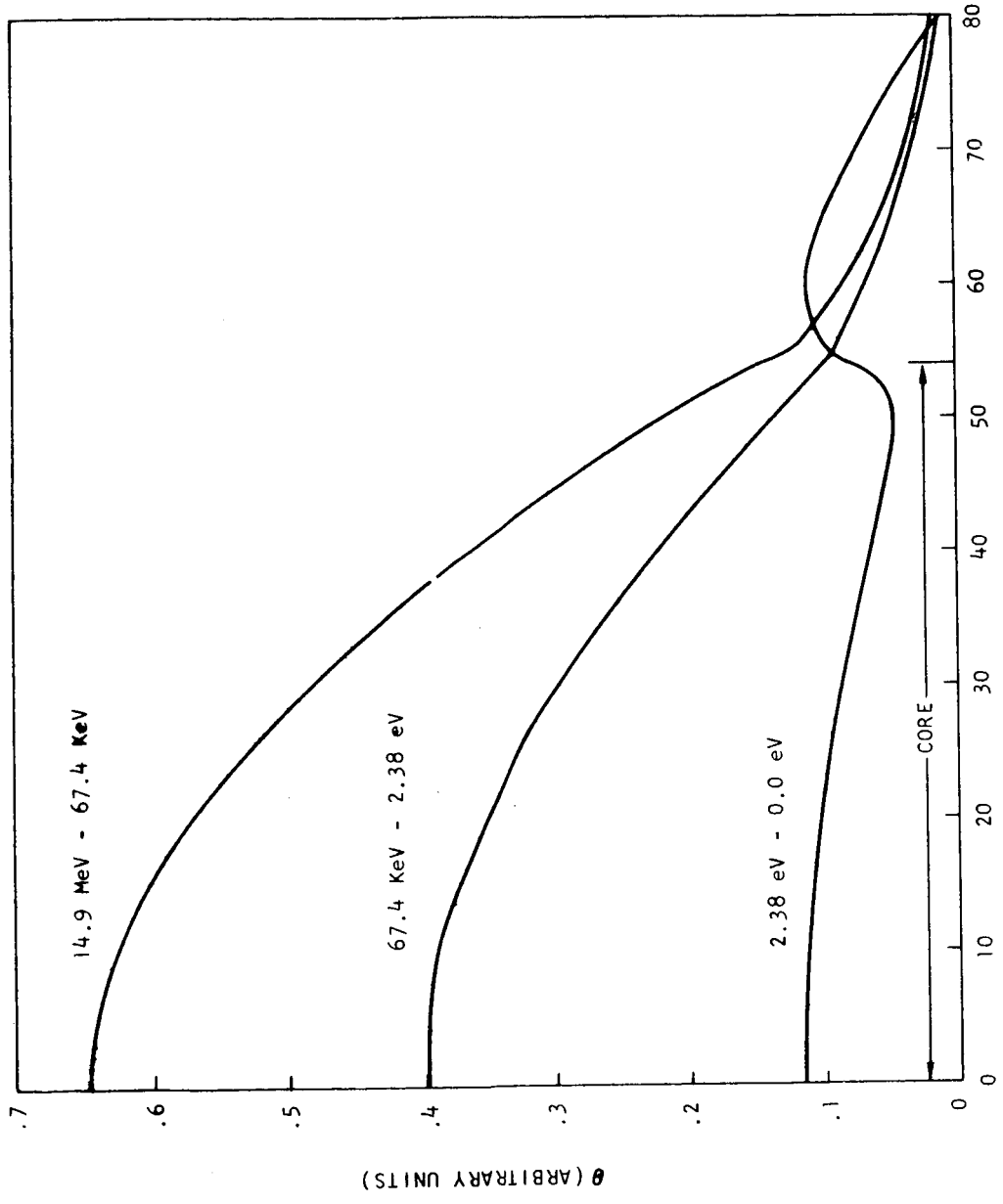

Fig. 3 -- Direct Flux Versus Height, 2.9 In. Pitch

REFERENCES

1. Cohen, S. C., G. D. Joanou, R. A. Moore, and J. C. Peak, "Neutronic Simulation of the Tungsten Water Moderated Nuclear Rocket Reactor (U)," National Aeronautics and Space Administration Report NASA CR-54293, General Atomic Division, General Dynamics Corporation, February 22, 1965, 55 p. (C/RD)

2. Tungsten Nuclear Rocket Critical Facility, Description and Hazards Analysis, General Atomic report GA-5846, October 30, 1964.

3. Peak, J. C., et al., "Criticality Calculations for the Three Inch Pitch As-Built Core," NASA report CR-54431, June 18, 1965.

4. Alexander, J. H., G. W. Hinman, and J. R. Triplett, "GAPLSN: A Modified DSN Program for the Solution of the One-dimensional Anisotropic Transport Equation," General Atomic report GA-4972, March 16, 1964.

5. Joanou, G. D., C. V. Smith, and H. A. Vieweg,"GATHER II, An IBM-7090 Fortran-II Program for the Computation of Thermal Neutron Spectra and Associated Multigroup Cross Sections," General Atomic report GA-4132, July, 1963.

6. Joanou, G. D., and J. S. Dudek, "GAM-II, A B_3 Code for the Calculation of Slowing Down Spectrum and Associated Multigroup Constants," General Atomic report GA-4265, July, 1963.

7. Lenihan, S. R., "GAZE-II, A One-Dimensional, Multigroup, Neutron Diffusion Theory Code for the IBM-7090, General Atomic report GA-3152, August 3, 1962.

APPENDIX A

Extract from Topical Report Entitled

CRITICALITY CALCULATIONS FOR THE THREE-INCH PITCH AS-BUILT CORE

4. 5. Two-Dimensional Effect on Cadmium Thermal Disadvantage Factors

Thermal group disadvantage factors for cadmium 113 have been computed for the 3. 0 inch as-built core for five concentrations of cadmium in the poison tubes. Previous transport theory calculations[5] of these factors for a core of 3. 156 in. pitch were done with the GAPLSN code using a cylindrical cell centered around the poison tube. The three fuel elements surrounding each poison tube and the water in between were homogenized into annuli of the proper volume. This type of calculation was repeated for the 3. 0 inch core. In addition, the accuracy of the annular representation was investigated with two-dimensional diffusion theory GAMBLE cell calculations which could represent the exact configuration in XY geometry.

The adequacy of a diffusion theory calculation to determine this geometric effect was first established by comparing a series of GAZE diffusion calculations identical in geometry to the GAPLSN transport calculations for the geometry of Fig. 6-b. Table 5 shows the cadmium disadvantage factors obtained from GAZE and GAPLSN for the thermal group structure of Table 3. Comparison of the disadvantage factors in Table 5 between GAZE diffusion and GAPLSN transport calculations shows that the diffusion calculations are reasonably representative of the transport calculations over a wide range of Cd^{113} concentrations. This might be expected since the cadmium poison tube solutions have thermal scattering cross sections several times larger than the thermal absorption cross

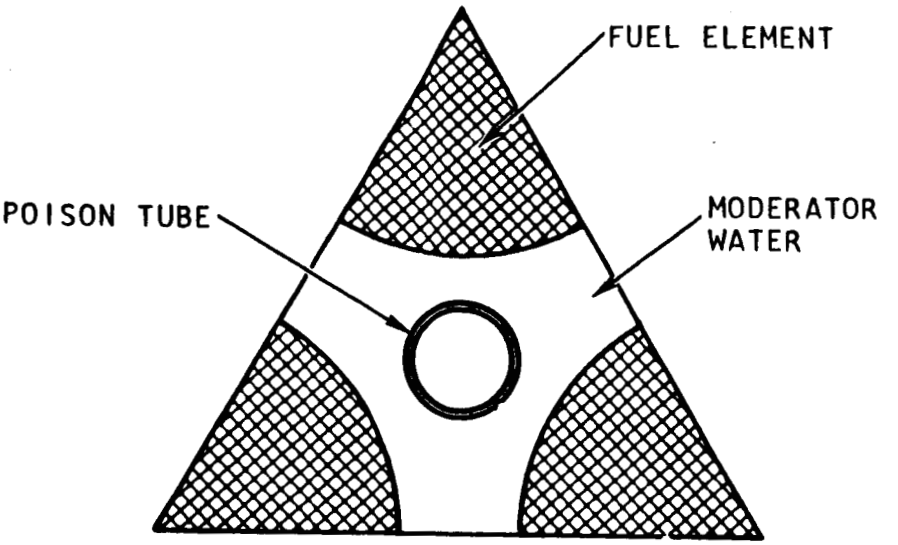

Fig. 6a--Actual Geometry of Poison Tube in Lattice

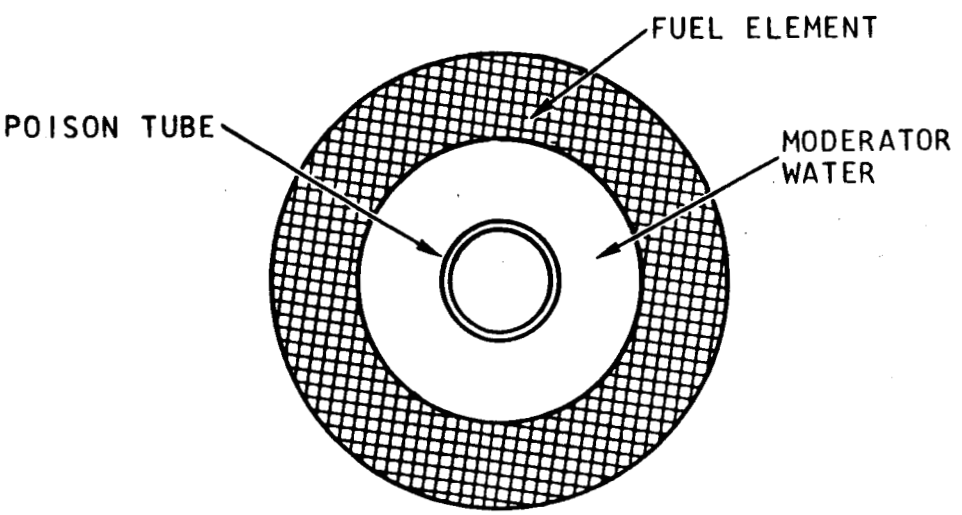

Fig. 6b--One Dimensional Approximation
For Disadvantage Factor Calculation

Table 5

CADMIUM DISADVANTAGE FACTORS COMPUTED BY GAZE AND GAPLSN FOR 5 THERMAL GROUPS (3.0 IN. PITCH)

$Cadmium^{113}$ Atom Dens— in Tube	0.0 atom/b cm		6.0-6		12.0-6		24.0-6		30.0-6	
Group	GAZE	GAPLSN	GAZE	GAPLSN	GAZE	GAPLSN	GAZE	GAPLSN	GAZE	GAPLSN
6	1.063	1.136	1.062	1.135	1.065	1.133	1.061	1.131	1.061	1.130
7	1.387	1.643	1.314	1.481	1.245	1.346	1.116	1.140	1.058	1.058
8	1.972	2.187	1.833	1.959	1.706	1.763	1.487	1.466	1.392	1.351
9	2.412	2.571	2.226	2.295	2.060	2.065	1.777	1.710	1.657	1.572
10	3.084	3.138	2.811	2.768	2.569	2.486	2.165	2.019	1.998	1.837

sections. The reasonable agreement led to the use of the GAMBLE diffusion theory code in an investigation of the two-dimensional effect in a cell. A symmetric slice of the cell with reflecting boundaries was represented as shown in Fig. 7. The fuel assembly was homogenized over the region designated as fuel; otherwise the representation is that appropriate for a fuel rod and poison tube in a 3.0 inch pitch lattice.

The disadvantage factors for cadmium resulting from the two-dimensional GAMBLE diffusion theory cell calculation are compared to those from the one dimensional GAZE diffusion theory cell calculations in Table 6. Two concentrations in the region of interest for the 3.0 inch pitch core were calculated using GAMBLE. The ratio between the results for each energy group is called the "geometric factor" and is seen to be insensitive to the cadmium concentration in this range.

It has been assumed that this geometric factor can be applied as a multiplicative correction factor to the one dimensional disadvantage factors obtained from GAPLSN. This assumption can only be checked by the use of a two-dimensional transport code. The geometric effect does not appear to be large enough to warrant such a calculation.

An average thermal group disadvantage factor for cadmium may be defined as

$$\bar{g} = \frac{\sum_i \sigma_i \phi_i g_i}{\sum_i \sigma_i \phi_i}$$

where σ_i is the cadmium microscopic absorption cross section, ϕ_i is the total flux in the GAPLSN cell, g_i is the group disadvantage factor, and the summation is over the 5 thermal groups used. (This definition is slightly different than the "effectiveness" defined in a previous Monthly Report,[2] where an average flux spectrum from the homogenized problem was used for all concentrations). The average thermal group disadvantage factor before correction for the geometric factor is plotted in Fig. 8 as a function

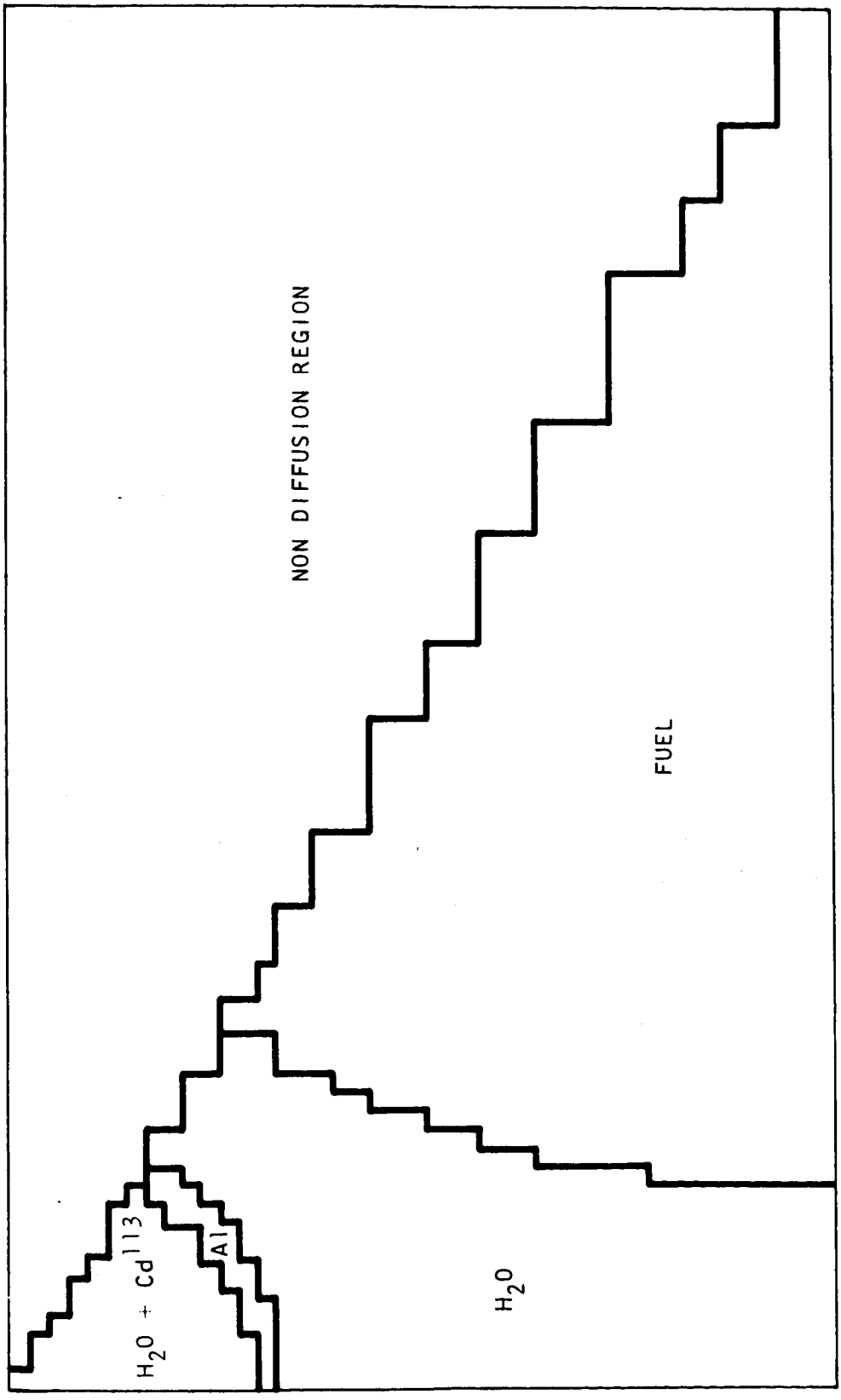

Fig. 7--Geometry of Gamble xy Cell Calculation

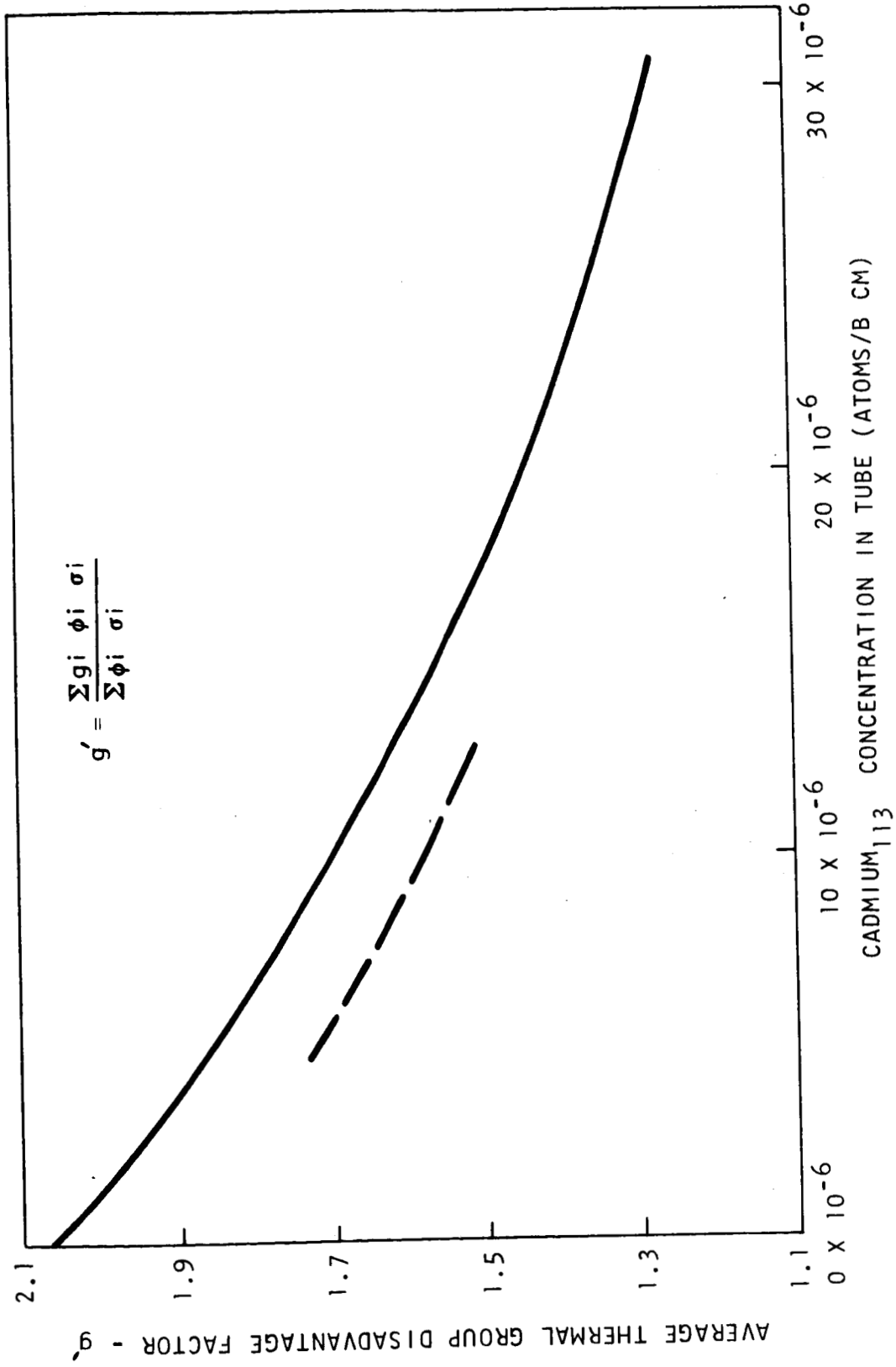

Fig. 8--Average Thermal Group Disadvantage Factor of Cadmium as a Function of Cadmium Atom Density

of cadmium concentration. The corrected curve incorporating the geometric factor is also given, and at present is the best estimate of the ratio between the homogenized - unshielded - and the homogenized - shielded - Cd^{113} concentration in the 3.0 in. pitch core.

Table 6

CADMIUM DISADVANTAGE FACTORS COMPUTED BY GAZE AND GAMBLE FOR 5 THERMAL GROUPS

Cadmium Atom Dens—	6.0-6			12.0-6		
Group	GAZE	GAMBLE	RATIO	GAZE	GAMBLE	RATIO
1	1.062	1.060	.9981	1.065	1.062	.9972
2	1.314	1.264	.9619	1.245	1.204	.9671
3	1.833	1.662	.9067	1.706	1.553	.9103
4	2.226	1.991	.8944	2.060	1.844	.8951
5	2.811	2.531	.9004	2.569	2.308	.8984

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