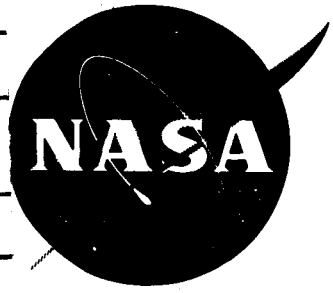

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by

J. C. Peak
J. M. Lovallo

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

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TOPICAL REPORT

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November 8, 1965

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Technical Management
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I. INTRODUCTION

General Atomic is engaged in a program of research for the Lewis Research Center of the National Aeronautics and Space Administration to determine 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 third 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 3.0 in. pitch core with beryllium reflectors.

II. DESCRIPTION OF THE 3.0 IN. PITCH Be REFLECTED CORE

The critical assembly is an hexagonal array of 121 fuel subassemblies. The lattice pitch is three inches. The assembly is water moderated and reflected on the sides and bottom with beryllium metal reflectors. The fuel subassemblies are in the form of concentric cylinders axially divided into twenty-four 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 (9/16 in. o.d. and 1/2 in. i.d.) containing a cadmium nitrate solution. A solution of a 0.232 molar concentration of $CdNO_3$ has been calculated for the poison concentration required for a just critical assembly.

The total loadings in the 3.0 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 2. A detailed description of the critical assembly is given in the 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

3.1 Calculational Methods

The neutronic calculational methods utilized are dictated by the heterogeneous nature of the core. They have been described in detail in Reference 1. Two modifications of the method described in Reference 1 were used in this series of calculations. They are; 1. a two-dimensional transport calculation of the cadmium disadvantage factors, and 2. a special treatment of the boral boundary in the diffusion theory calculations. These two methods are described in detail in Sections 3.3 and 3.4. Otherwise the calculations were similar to those reported for the two previous experiments.[2,4] The entire set of procedures are summarized as follows:

a. 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 4.001 cm. was used in a GAPLSN P_1-S_8 calculation.[5] 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

b. Thermal disadvantage factors for cadmium were obtained from the two-dimensional transport calculations described in Section 3.3. The unit cell was approximated in XY geometry with the cadmium tube shown explicitly. The calculations were made in the S_4 representation of the angular flux. A transport correction to the total cross section was used in the P_0 cross section representation. The disadvantage factors so obtained were corrected for the linearly anisotropic scattering effects by comparison with P_0 and P_1 one-dimensional cases. Disadvantage factors were calculated for $CdNO_3$ solutions of 0.122, 0.244, and 0.325 molar.

c. Thermal and fast spectra were computed in the GATHER-II[6] and GAM-II[7] codes respectively, using the disadvantage factors from the cell calculations. Resonance calculations were performed using Nordheim's integral method. The presence of interstitial aluminum was included in the resonance calculation. Collision probability tables for a cylinder were used with mean chord lengths of 0.1972 and 0.3990 respectively for W and U^{238}. A Dancoff-Ginsburg factor of 0.042 was used. Pointwise microscopic cross sections were averaged over these spectra to obtain self-shielded cross sections for ten broad groups. Scattering cross sections for the beryllium reflector were obtained from a bound kernel model.[8]

d. The effective multiplication factor was computed using the ten broad group cross sections obtained in step c. The final cadmium concentration was found by a search following a one-dimensional buckling iteration sequence in the GAZE-II[9] code. The homogenized atom densities and geometric description used in the GAZE calculations are given in Section 3.2.

Comparison of experiments and analysis in the 3.0 in. pitch core indicate the calculated excess reactivity for these cores is low by about 0.02 $\Delta k/k$ using the techniques presented in this report. This discrepancy has been removed in later calculations using a more sophisticated approach to the fuel disadvantage factors and the resonance calculations. To allow for 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 \$20.73.

3.2 Core Description

The unit cell dimensions and cell description are identical to those for the 3.0 in. pitch water reflected core. The homogenized atom densities and dimensions of the critical assembly used for calculations are listed in Table 3. The inner radius for the cadmium loading is equivalent to a 204 poison tube loading.

Table 3

HOMOGENIZED ATOM DENSITIES FOR THE 3.0 IN. PITCH Be REFLECTED CORE

Radial Description

Nuclide	Atom Density
Core (0 to 44.01 cm)	
H	2.172×10^{-2}
O	1.085×10^{-2}
Al	1.845×10^{-2}
N_i	4.4×10^{-5}

Table 3 (Cont.)

Nuclide	Atom Density
Core (0 to 44.01 cm)	
Zr	9.83×10^{-5}
Cd^{113} (0 to 40.41 cm)	8.627×10^{-7}
Cd^{113} (40.41 to 44.01 cm)	0.0
W^{182}	2.519×10^{-4}
W^{183}	1.374×10^{-4}
W^{184}	2.920×10^{-4}
W^{186}	2.710×10^{-4}
U^{235}	3.735×10^{-4}
U^{238}	1.521×10^{-3}
Side Reflector (44.01 to 53.77 cm)	
Al (44.01 to 45.51 cm)	6.02×10^{-2}
Be (45.51 to 52.79 cm)	1.228×10^{-1}
H (52.79 to 53.77 cm)	7.98×10^{-2}
C (52.79 to 53.77 cm)	3.99×10^{-2}

(The Al region in the side reflector accounts for the scalloped reflector edges and the Be can material. The $(CH_2)_x$ region represents the sheet of polyethylene outside the Be blocks. The boral-aluminum sheet is just outside the polyethylene.)

Axial Description

Bottom Reflector (0 to 23.5 cm)	
H (0 to 10 cm)	6.677×10^{-2}
0 (0 to 10 cm)	3.339×10^{-2}
Be (10 to 20 cm)	1.228×10^{-1}
H (20 to 23.5 cm)	Same as core
0 (20 to 23.5 cm)	Same as core
Al (20 to 23.5 cm)	3.720×10^{-2}
Cd (20 to 23.5 cm)	Same as core

Table 3 (Cont.)

Nuclide	Atom Density
Core (23.5 to 131.5 cm)	
Top Reflector (131.5 to 136.5 cm)	
H	Same as core
O	Same as core
Al	4.740×10^{-3}
Cd	Same as core

(The axial region of 20.0 to 23.5 cms between the core and the bottom Be reflector represents the bottom end plugs and grid plate.)

The cadmium concentration given in Table 3 is equivalent to a Cd^{113} concentration in the poison tubes of 17.13×10^{-6} atoms/b cm or a $CdNO_3$ concentration of 0.232 moles per liter.

3.3 Cadmium Disadvantage Factor Calculation

Calculations of the thermal flux were made in a two-dimensional approximation to the unit cell using a transport code, 2DXY.[10] The 2DXY code allowed reflecting boundary conditions to be applied to the unit cell selected, which is shown in Fig. 1. The internal curved geometry of the cell shown on the right side of Fig. 1 was represented in XY geometry by the configuration on the left side. This stepped approximation to the internal cell surfaces is believed to be entirely adequate for disadvantage factor calculations. The actual calculation covered the entire cell shown in Fig. 1, to obtain reflecting boundary conditions on all four sides. The material comprising the inner four fuel-W rings in the mockup core was homogenized into one region. The material in ring E including the U^{238}, W, and fuel was also homogenized into an outer ring, and the void, the pressure tube, and the cadmium tube were explicitly represented. This homogenization has been shown to give good results in the overall flux distribution. Atom densities in the cell were slightly adjusted when necessary to preserve the correct

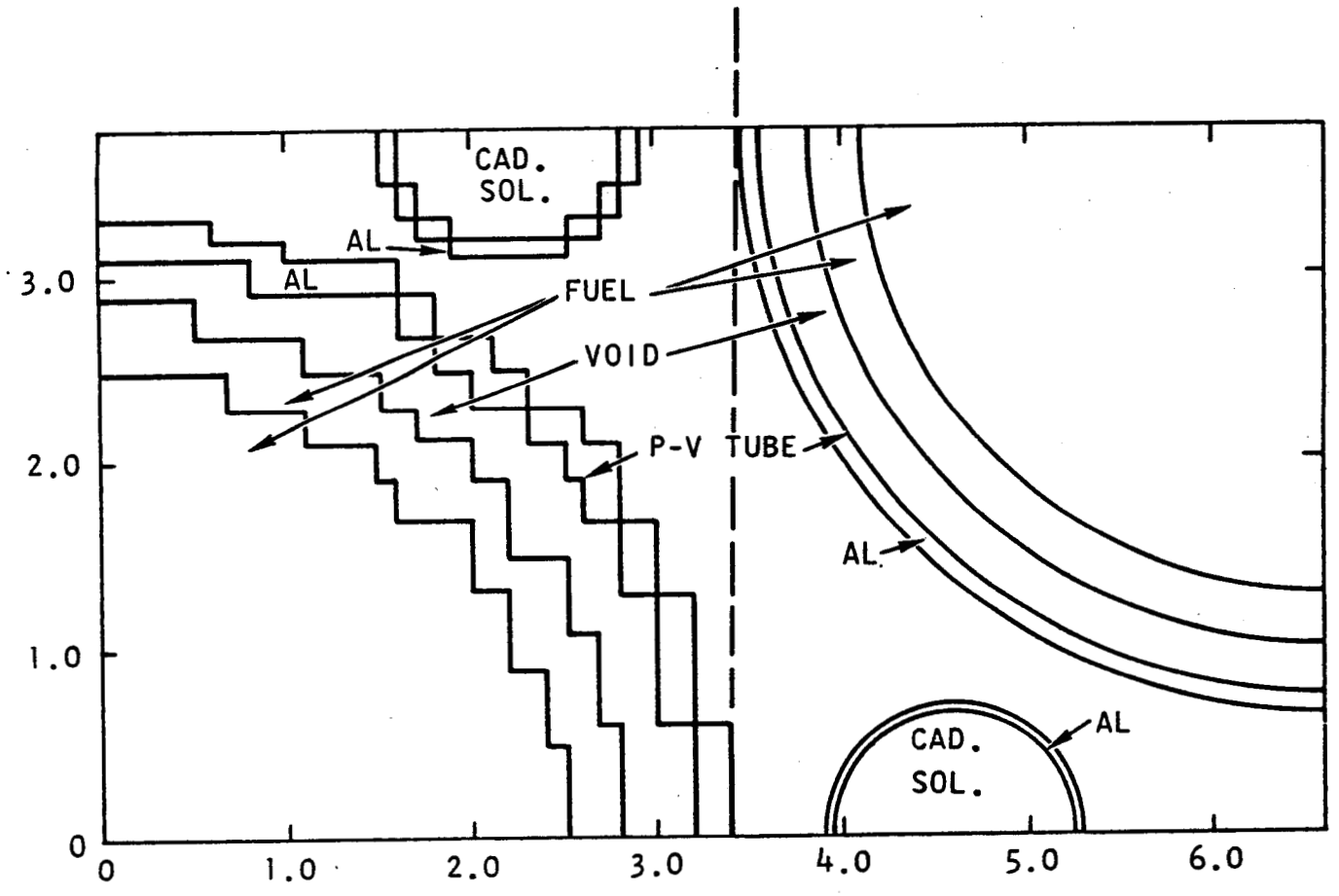

Fig. 1 --Two-dimensional cell description

total material loadings. The calculations were carried out in the S_4 representation of the angular flux and used the transport approximation to the P_0 cross section representation. Five thermal groups were used.

In order to investigate the possible error arising from using the P_0 approximation, calculations were also made on analogous one-dimensional cells using both the P_0 and P_1 representations. These calculations used the poison tube centered geometry and were carried out with the GAPLSN code.

The calculated disadvantage factors are given in Table 4 for three cadmium concentrations. A comparison of the (1-D) P_1 and (1-D)P_0^{tr} columns shows that in one-dimensional calculations the P_0 transport approximation gives results within 2% of those found using a P_1 expansion. Comparison of the (2-D)P_0^{tr} and (1-D)P_0^{tr} columns shows a sizable difference associated with the geometric representation. In this case, it seemed a useful approach to correct the two-dimensional cell results for the slight error arising from the use of the P_0 approximation. This has been done in the $\approx$(2-D)P_1 column by simply multiplying by the ratio of the one dimensional results. (This method may be contrasted to that previously reported in which results from a P_1 one dimensional calculation were multiplied by a one-to two-dimensional correction.) The calculated disadvantage factors were used in a perturbation analysis to obtain the worth of one cadmium poison tube in the center of the 3.0 in. pitch water reflected core. The results are compared in Fig. 2 to a curve drawn through the experimental values. The worst deviation is 8% over the concentration of Cd of 0.122 to 0.325 moles per liter. The comparison between theory and experiment is somewhat better using these modified methods than that previously obtained. The results show a trend, however, which might well lead to an increasing error above 0.325 molar concentration of Cd.

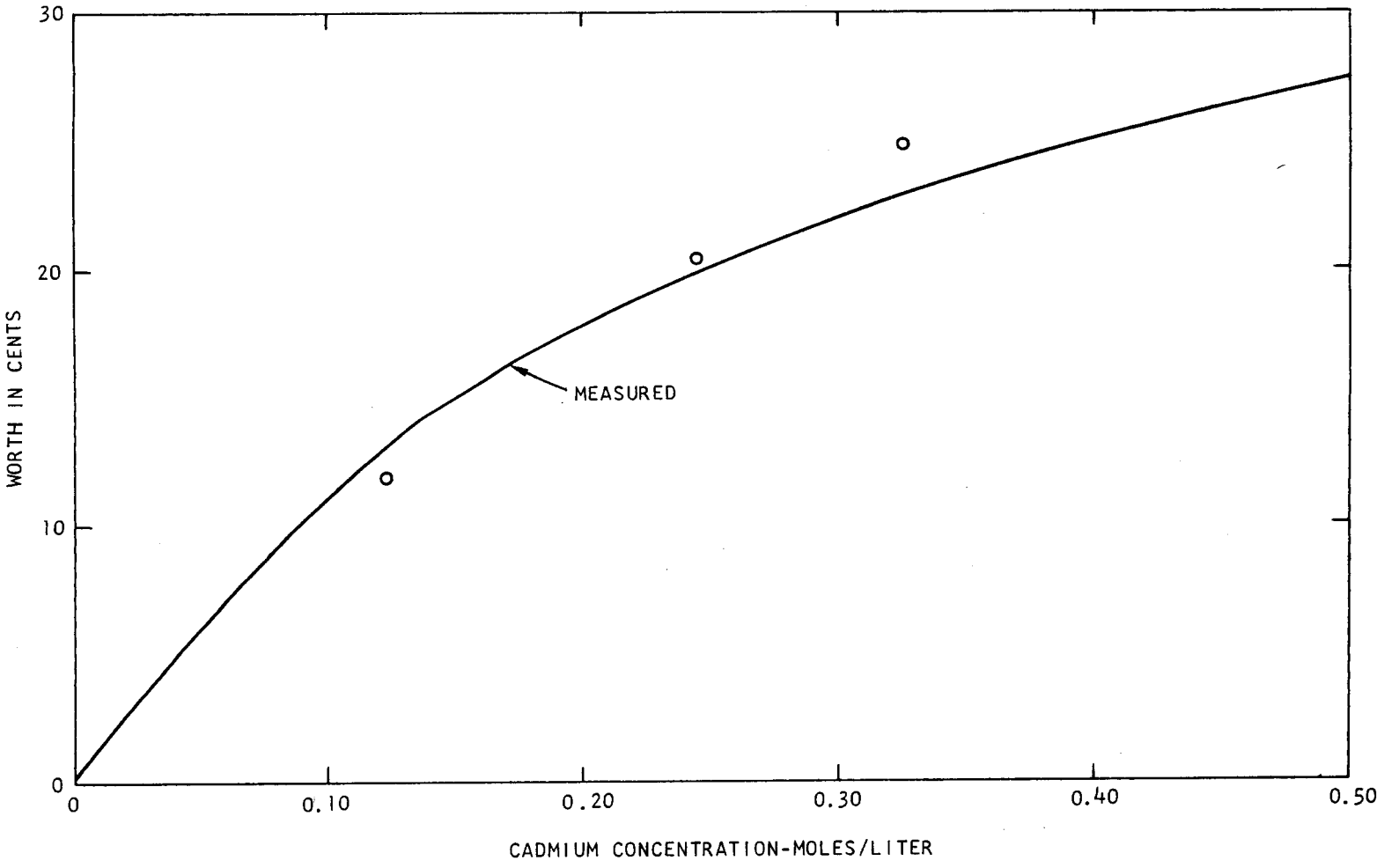

Fig. 2--Worth of cadmium poison tubes vs concentration

Table 4

CADMIUM DISADVANTAGE FACTORS

Group	$(2-D)\,P_0^{tr}$	$(1-D)\,P_1$	$(1-D)\,P_0^{tr}$	$\frac{(1-D)P_1}{(1-D)\,P_0^{tr}}$	$\approx(2-D)\,P_1$
		$Cd^{113} = 9.0 \times 10^{-6}$ atoms/b-cm			
1	1.158	1.134	1.148	0.987	1.143
2	1.303	1.411	1.384	1.019	1.328
3	1.586	1.859	1.839	1.010	1.603
4	1.812	2.182	2.172	1.004	1.820
5	2.147	2.633	2.642	0.996	2.140
		$Cd^{113} = 18.0 \times 10^{-6}$ atoms/b-cm			
1	1.156	1.132	1.146	0.987	1.142
2	1.153	1.238	1.217	1.017	1.172
3	1.365	1.609	1.589	1.012	1.382
4	1.543	1.874	1.868	1.003	1.548
5	1.789	2.216	2.235	0.991	1.774
		$Cd^{113} = 24.0 \times 10^{-6}$ atoms/b-cm			
1	1.155	1.131	1.144	0.988	1.141
2	1.069	1.140	1.126	1.012	1.082
3	1.245	1.466	1.454	1.008	1.256
4	1.399	1.710	1.703	1.004	1.404
5	1.600	2.019	2.017	1.000	1.601

4.2 Treatment of Boundary for Boron-Aluminum Plate

The side Be reflectors have an outside 1/4 inch layer of aluminum mixed with B_4C to represent a non-reentrant boundary to thermal neutrons.

(The average boron atom density in the plate is 0.0269 atoms/b cm.) Outside of the boral plate is a water reflector which is neutronically infinite; this reflector will return some epithermal neutrons through the plate to the beryllium and thus to the core, although the thermal neutron return will be negligible. Due to the inadequacy of diffusion calculations to correctly represent fluxes in a region of high absorption it is necessary to terminate the GAZE diffusion calculations, used to find the critical cadmium loading, at the boral plate. The appropriate boundary condition was determined from transport calculation. The boundary condition required by GAZE for each group is the quantity ℓ_i, defined by

$$\ell_i = \phi_i \left(\frac{1}{D_i \text{ grad } \phi_i}\right) .$$

The quantity $D_i \ell_i$ corresponds to the extrapolation distance in diffusion theory, while the value of ℓ_i is the ratio of the flux to the current in diffusion theory.

A P_1S_4 transport calculation representing the radial core, and extending through the boral plate into a 15 cm water reflector was made using the GAPLSN code. The same ten energy groups were used for this case as for the diffusion calculations; values of the extrapolation distance, $\phi_i / \text{grad } \phi_i$, were then calculated from the transport solution at the boral plate and used to find the required values of ℓ_i for the GAZE boundary. The results obtained using these boundary parameters showed a significant improvement in the accuracy of the diffusion calculations in the regions near the boundary. This may be seen in Figs. 3 and 4 which represent an epithermal group flux and a thermal group flux over the entire core and reflector. The top line in each case represents the transport solution while the bottom line represents a diffusion solution when a non-reentrant boundary condition was applied to each group; the middle line is the diffusion solution using the calculated extrapolation distances. It should be noted that the transport core flux solution is closely represented in the

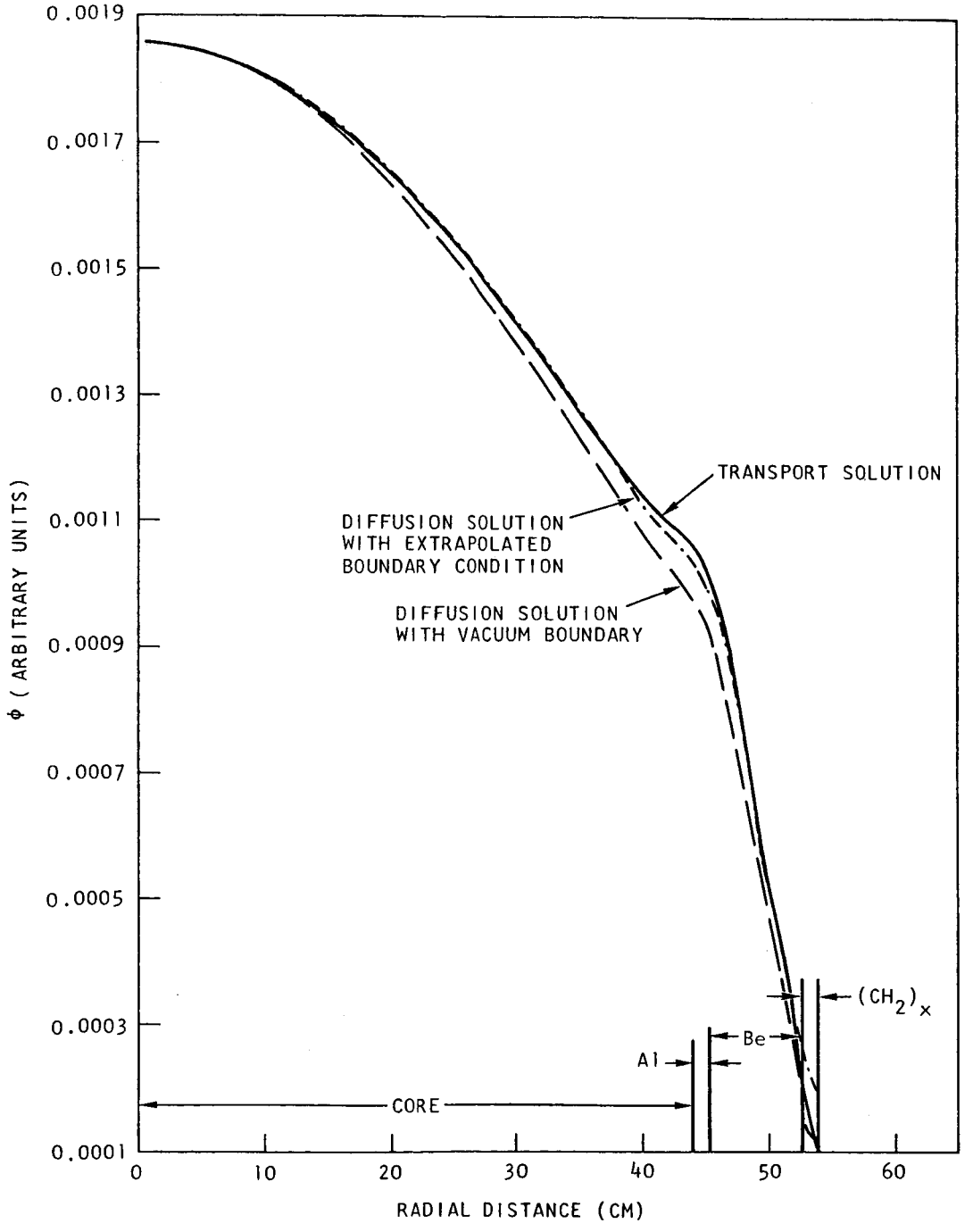

Fig. 3--Neutron flux in energy region of 500 to 67 keV

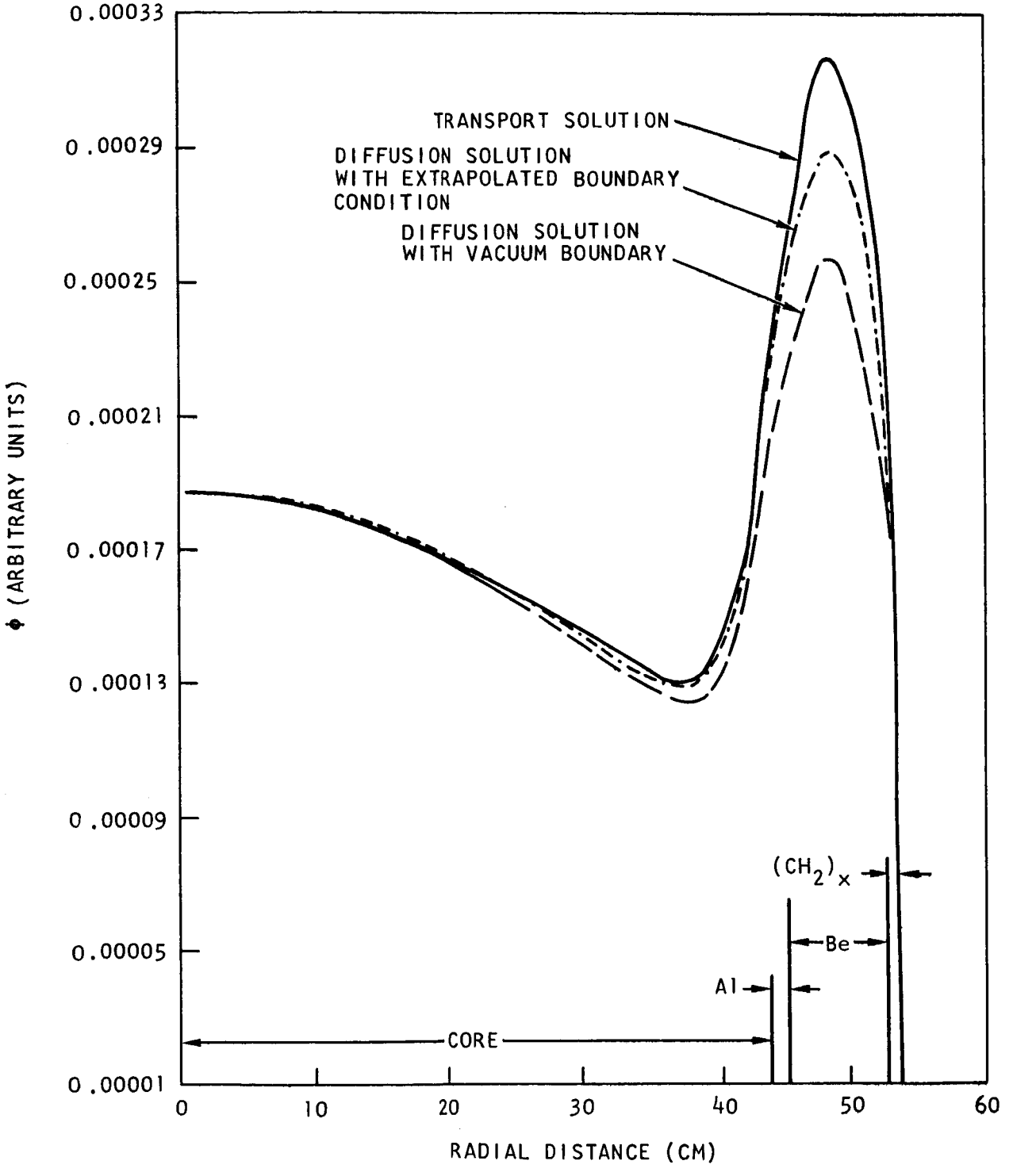

Fig. 4--Neutron flux in energy region of 0.05 to 0.09 eV

case where the calculated extrapolation distances were used, and that accurate determination of the core fluxes are most important in determining the multiplication factor. The improvement in the thermal flux is caused by the better description of the epithermal flux which serves as a source to the thermal region, rather than a change in the thermal flux boundary condition.

IV. ESTIMATE OF ACCURACY

Previous experiments in the 3.0 in. pitch water reflected core deviated from the results of a similar analysis by + 1.9% $\Delta k/k$. Since the reasons for the previous discrepancies are now understood, and since the error has been compensated for in the converged eigenvalue in this analysis, the present calculations have been assigned an uncertainty of about \$1.00 in the estimate of k_{ex}.

V. FLUX DISTRIBUTIONS

Radial and axial flux distributions in three energy groups are given in Figs. 5 and 6 for the full size 3.0 in. pitch beryllium reflected core.

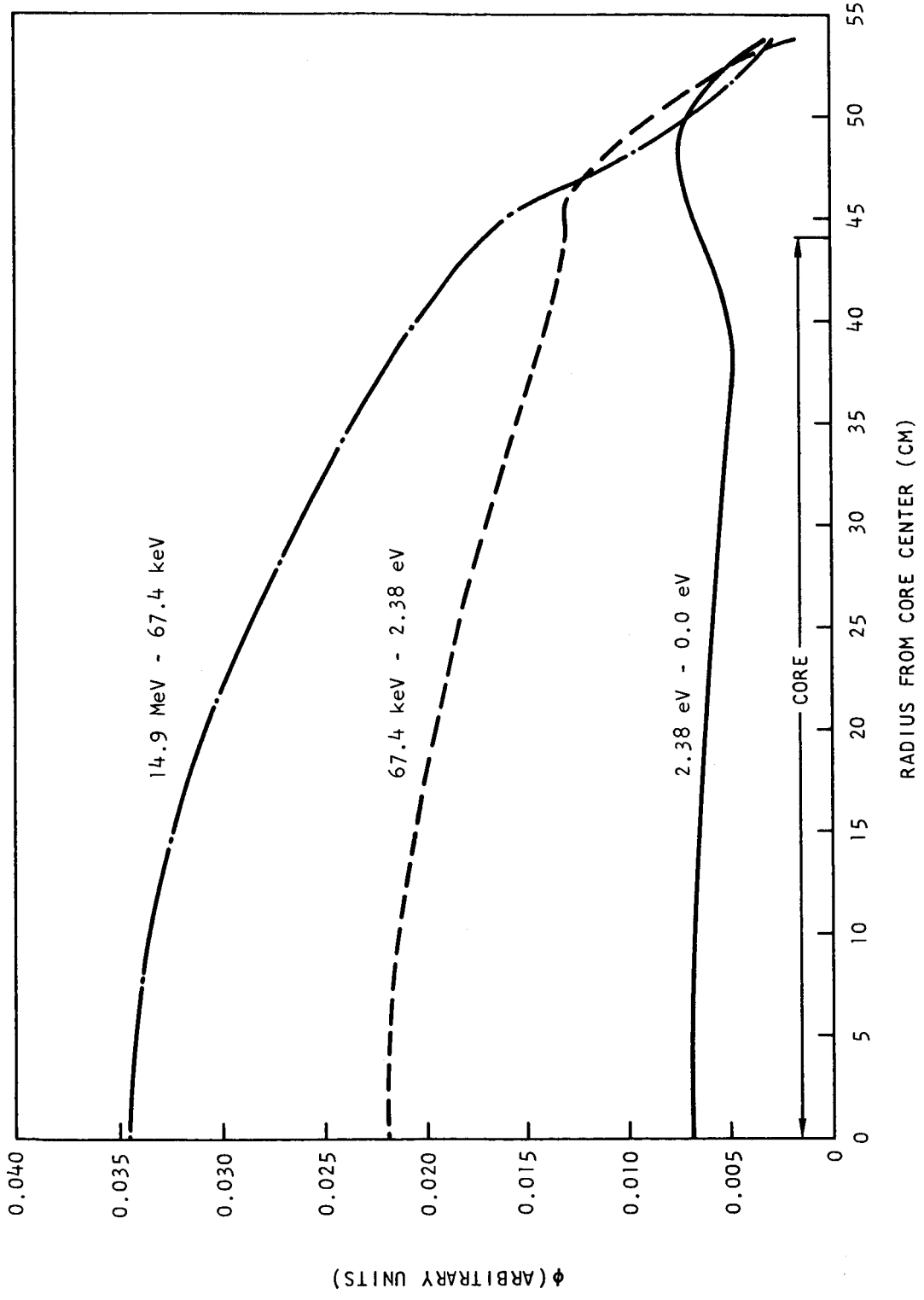

Fig. 5 -- Flux vs radius, 3.0 in. pitch, Be reflected core

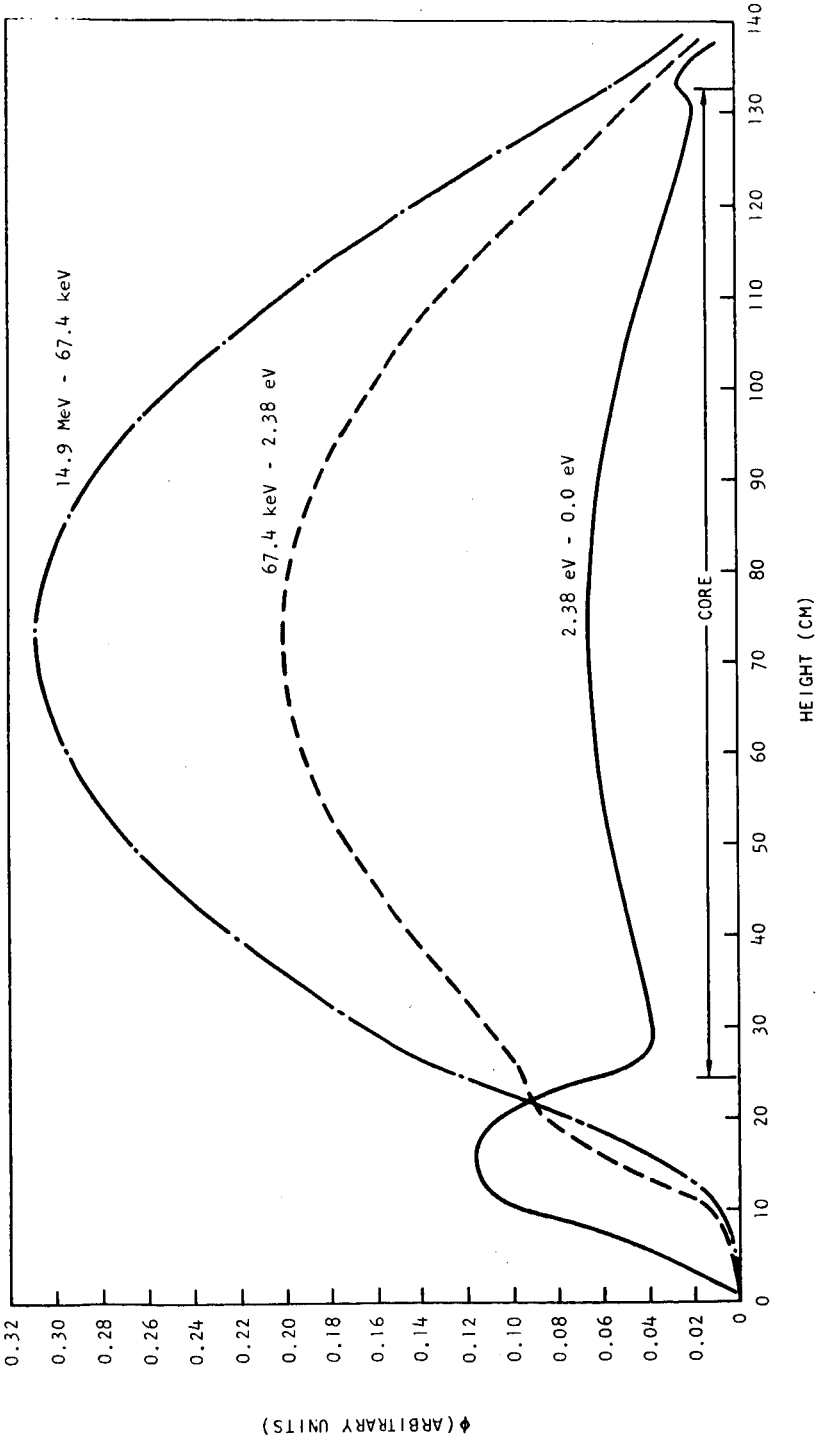

Fig. 6--Flux vs height, 3.0 in. pitch, Be reflected core

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