08.80.20

APPENDIX F-7

BENCHMARK CORE CALCULATIONS

performed by

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1. INTRODUCTION

In order to compare reactor physics calculational methods used in various research centers we have calculated the benchmark problems proposed by the Consultants Meeting on "Preparation of a Programme on Research Reactor Conversions to LEU Instead of HEU", IAEA, June 1979 in Vienna using our current methods.

In this preliminary report we describe the generation of cross sections, burn-up and x-y diffusion calculations.

2. CROSS SECTIONS

Cell cross sections for burn-up at 10 MW were obtained up to 50% of consumed U-235 in steps of 5% for 93% and 20% enrichment cases.

The WIMS-D code /1/ and its 69 group library were used in the pin cell option with condensation to the five energy groups of Table I.

The main transport calculation was performed with the S4 option in the above mentioned group structure. The actual cell geometry has been adapted to the code assuming the cell composed of three kinds of infinite layers (Fig. 9).

Fuel (Al + U)
Clad + Lateral Support (Al)
Coolant (H_2O)

so that

a) the volume ratios of the different materials are conserved.

b) option 1): the cell pitch is conserved (see Fig. 9.1)
option 2): the meat thickness is conserved (see Fig. 9.2).

A buckling of 0.008 cm^{-2} corresponding to a cylinder with a fuel volume equivalent to that of the benchmark configurations was used.

Three group cross sections for water and carbon reflectors were obtained by condensation of the 200 groups GCTC-ENEL /2/ library with a slowing down U-235 fission spectrum in water. The cross sections for the trap were those obtained for the coolant in the cell calculation. The control rod channels were represented by a weighted mixture of coolant and clad cross sections.

Tables II and III give the atomic densities in the fuel meat for the 93% and 20% enriched fuel elements with various stages of burn-up.

Table IV shows the k_∞ obtained for the different burn-ups.

Tables II to IV correspond to the option 1) in the cell transformation, i.e. pitch conservation.

Tables II' to IV' correspond to the option 2) i.e. meat thickness conservation.

3. REACTOR CALCULATIONS

The two dimensional three group (see Table 1), x-y diffusion calculation was performed with EXTERMINATOR-II code /3/ using one quarter reactor geometry.

A total of 48 and 52 mesh intervals was used in the x and y directions respectively.

The fluxes were normalized to 10 MW in the whole core. The axial buckling of 1.709×10^{-3} cm^{-2} corresponds to a chopped cosine axial flux distribution with a 8 cm reflector savings.

The control rod channels were represented as H_2O + Al zones at both sides of the corresponding fuel elements.

In Table V the k_{eff} values for fresh-fuels, BOL and EOL situations for 93% and 20% enrichments are shown. Table V refers to cross sections obtained with pitch conservation in the transformed cell (option 1), Table V" refers to the meat thickness conservation (option 2).

Table VI presents fluxes in different regions of the reactor (with option 1). Average fluxes were averaged both over x-y plane and along the axial direction which has a chopped cosine distribution.

Plots of the fluxes in midplanes along the x and y-axis for the 93% BOL and EOL cases are shown in Fig. 1 to 4.

Flux ratios of the 20% and 93% cases are shown in Fig. 5 to 8.

4. FINAL REMARKS

The present report is a first draft useful for preliminary comparisons. More detailed descriptions of methods, microscopic and macroscopic cross sections and general discussions will be included in a final report.

REFERENCE

/1/ M. J. ROTH, J. D. MAC'DOUGALL, P. B. KEMSHELL, "The preparation of input data for WIMS" AEEW-R-538,

/2/ O. CHIOVATO, F. DI PASQUANTONIO. "GGTC - ENEL", CNA - CPL, 1977.

/3/ T. B. FOWLER et al, "EXTERMINATOR-II a FORTRAN 4 code for solving multigroup neutron diffusion equations in two dimensions", ORNL - 4078, 1967.

TABLE I: Energy Groups Used in the cell calculations.

Five-group structure	Three-group structure	E_U (eV)	E_L (eV)
1	1	1.000+07	8.210+05
2		8.210+05	5.530+03
3	2	5.530+03	1.500+00
4		1.500+00	0.625+00
5	3	0.625+00	0.

TABLE II: Atom Densities in 93% Enriched Fuel Meat vs ^{235}U Burnup.
Atom Densities ($cm^{-3} \times 10^{24}$) (Pitch conservation).

Burnup (%)	Al	^{135}Xe	^{149}Sm	^{235}U	^{236}U	^{238}U
0	5.7013-02	0.0	0.0	1.6180-03	0.0	1.2025-04
5	5.7013-02	1.6313-08	1.4041-07	1.5371-03	1.3750-05	1.1977-04
10	5.7013-02	1.5569-08	1.4175-07	1.4562-03	2.7395-05	1.1929-04
15	5.7013-02	1.4812-08	1.4150-07	1.3753-03	4.0903-05	1.1880-04
20	5.7013-02	1.4043-08	1.4040-07	1.2944-03	5.4269-05	1.1830-04
25	5.7012-02	1.3263-08	1.3848-07	1.2135-03	6.7506-05	1.1779-04
30	5.7013-02	1.2472-08	1.3578-07	1.1326-03	8.0613-05	1.1728-04
35	5.7013-02	1.1669-08	1.3235-07	1.0517-03	9.3565-05	1.1675-04
40	5.7013-02	1.0854-08	1.2822-07	9.7091-04	1.0636-04	1.1621-04
45	5.7013-02	1.0028-08	1.2342-07	8.9015-04	1.1899-04	1.1565-04
50	5.7013-02	9.1899-09	1.1799-07	8.0947-04	1.3144-04	1.1508-04

Burnup (%)	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
0	0.0	0.0	0.0	0.0
5	4.3948-07	8.3958-09	3.6393-10	3.1461-12
10	8.3459-07	3.2001-08	2.7710-09	5.0353-11
15	1.1846-06	6.8361-08	8.8647-09	2.5478-10
20	1.4910-06	1.1519-07	1.9835-08	8.0297-10
25	1.7555-06	1.7046-07	3.6461-08	1.9538-09
30	1.9793-06	2.3230-07	5.9118-08	4.0370-09
35	2.1633-06	2.9887-07	8.7761-08	7.4488-09
40	2.3089-06	3.6863-07	1.2205-07	1.2663-08
45	2.4170-06	4.4012-07	1.6129-07	2.0232-08
50	2.4887-06	5.1196-07	2.0448-07	3.0798-08

TABLE II': Atom Densities in 93% Enriched Fuel Meat vs ^{235}U Burn-up.
Atom Densities ($cm^{-3} \times 10^{24}$) (Meat thickness conservation).

Burnup (%)	Al	^{135}Xe	^{149}Sm	^{235}U	^{236}U	^{238}U
0						
5	5.7013-02	1.6298-08	1.4017-07	1.5370-03	1.3755-05	1.1977-04
10	5.7013-02	1.5554-08	1.4150-07	1.4560-03	2.7405-05	1.1929-04
15	5.7013-02	1.4796-08	1.4125-07	1.3751-03	4.0918-05	1.1880-04
20	5.7013-02	1.4028-08	1.4014-07	1.2941-03	5.4290-05	1.1831-04
25	5.7013-02	1.3248-08	1.3822-07	1.2132-03	6.7533-05	1.1780-04
30	5.7013-02	1.2456-08	1.3552-07	1.1322-03	8.0646-05	1.1729-04
35	5.7013-02	1.1653-08	1.3209-07	1.0512-03	9.3604-05	1.1676-04
40	5.7013-02	1.0839-08	1.2797-07	9.7032-04	1.0641-04	1.1622-04
45	5.7013-02	1.0012-08	1.2317-07	8.8949-04	1.1905-04	1.1567-04
50	5.7013-02	9.1745-09	1.1775-07	8.0873-04	1.3152-04	1.1510-04

Burnup (%)	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
0				
5	4.3802-07	8.3692-09	3.6284-10	3.1390-12
10	8.3181-07	3.1902-08	2.7628-09	5.0242-11
15	1.1807-06	6.8151-08	8.8390-09	2.5424-10
20	1.4860-06	1.1484-07	1.9778-08	8.0138-10
25	1.7495-06	1.6996-07	3.6358-08	1.9501-09
30	1.9724-06	2.3162-07	5.8952-08	4.0299-09
35	2.1557-06	2.9801-07	8.7518-08	7.4366-09
40	2.3006-06	3.6759-07	1.2171-07	1.2643-08
45	2.4082-06	4.3889-07	1.6084-07	2.0202-08
50	2.4793-06	5.1054-07	2.0390-07	3.0756-08

TABLE III: Atom Densities in 20% Enriched Fuel Meat vs ^{235}U Burnup
Atom Densities ($cm^{-3} \times 10^{24}$). (Pitch conservation).

Burnup(%)	Al	^{135}Xe	^{149}Sm	^{235}U	^{236}U	^{238}U
0	3.8177-02	0.0	0.0	2.2539-03	0.0	8.9016-03
5	3.8177-02	2.2146-08	2.0380-07	2.1412-03	1.9932-05	8.8872-03
10	3.8177-02	2.1415-08	2.0983-07	2.0286-03	3.9690-05	8.8729-03
15	3.8177-02	2.0643-08	2.1289-07	1.9158-03	5.9253-05	8.8582-03
20	3.8177-02	1.9837-08	2.1434-07	1.8031-03	7.8576-05	8.8430-03
25	3.8177-02	1.8999-08	2.1424-07	1.6904-03	9.7683-05	8.8272-03
30	3.8177-02	1.8113-08	2.1268-07	1.5777-03	1.1655-04	8.8109-03
35	3.8177-02	1.7208-08	2.0970-07	1.4650-03	1.3519-04	8.7939-03
40	3.8177-02	1.6270-08	2.0538-07	1.3523-03	1.5358-04	8.7762-03
45	3.8177-02	1.5298-08	1.9977-07	1.2396-03	1.7170-04	8.7577-03
50	3.8177-02	1.4276-08	1.9290-07	1.1270-03	1.8953-04	8.7382-03

Burnup (%)	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
0	0.0	0.0	0.0	0.0
5	1.2153-05	2.5179-07	1.3570-08	1.2152-10
10	2.3173-05	9.5224-07	1.0321-07	1.9461-09
15	3.3067-05	2.0205-06	3.2904-07	9.8268-09
20	4.1854-05	3.3816-06	7.3116-07	3.0777-08
25	4.9587-05	4.9748-06	1.3330-06	7.4305-08
30	5.6293-05	6.7463-06	2.1418-06	1.5219-07
35	6.2008-05	8.6513-06	3.1521-06	2.7845-07
40	6.6756-05	1.0650-05	4.3464-06	4.6935-07
45	7.0559-05	1.2708-05	5.6966-06	7.4325-07
50	7.3439-05	1.4793-05	7.1669-06	1.1214-06

TABLE III': Atom Densities in 20% Enriched Fuel Meat Vs ^{235}U Burnup.
Atom Densities ($cm^{-3} \times 10^{24}$) (Meat thickness conservation).

Burnup (%)	Al	^{135}Xe	^{149}Sm	^{235}U	^{236}U	^{238}U
0						
5	3.8177-02	2.2118-08	2.0338-07	2.1411-03	1.9936-05	8.8877-03
10	3.8177-02	2.1382-08	2.0929-07	2.0283-03	3.9701-05	8.8737-03
15	3.8177-02	2.0603-08	2.1225-07	1.9154-03	5.9276-05	8.8593-03
20	3.8177-02	1.9792-08	2.1361-07	1.8026-03	7.8614-05	8.8443-03
25	3.8177-02	1.8948-08	2.1342-07	1.6896-03	9.7741-05	8.8289-03
30	3.8177-02	1.8057-08	2.1177-07	1.5767-03	1.1663-04	8.8129-03
35	3.8177-02	1.7147-08	2.0872-07	1.4637-03	1.3530-04	8.7962-03
40	3.8177-02	1.6204-08	2.0433-07	1.3507-03	1.5373-04	8.7788-03
45	3.8177-02	1.5226-08	1.9864-07	1.2377-03	1.7189-04	8.7606-03
50	3.8177-02	1.4199-08	1.9171-07	1.1248-03	1.8976-04	8.7415-03

Burnup (%)	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
0				
5	1.1899-05	2.4643-07	1.3280-08	1.1898-10
10	2.2689-05	9.3212-07	1.0102-07	1.9060-09
15	3.2376-05	1.9782-06	3.2205-07	9.6273-09
20	4.0980-05	3.3115-06	7.1564-07	3.0160-08
25	4.8549-05	4.8730-06	1.3047-06	7.2838-08
30	5.5113-05	6.6101-06	2.0962-06	1.4922-07
35	6.0703-05	8.4791-06	3.0849-06	2.7311-07
40	6.5344-05	1.0442-05	4.2536-06	4.6049-07
45	6.9058-05	1.2463-05	5.5745-06	7.2949-07
50	7.1865-05	1.4513-05	7.0127-06	1.1011-06

TABLE IV: WIMS K_∞ vs. ^{235}U Burnup for 93% and 20% Enrichments. (Pitch conservation).

Burnup (%)	Enrichment 93%	20%
0	1.74221	1.65257
5	1.64377	1.56348
10	1.62233	1.54330
15	1.60020	1.52226
20	1.57691	1.50026
25	1.55212	1.47710
30	1.52541	1.45276
35	1.49643	1.42701
40	1.46476	1.39954
45	1.42983	1.37008
50	1.39089	1.33820

TABLE V: Values of Keff from X - Y Diffusion Theory Calculations. (Pitch conservation).

Enrichment	Description	Keff
93%	BOL Benchmark	1.03765
93%	EOL Benchmark	1.01425
93%	Fresh Fuel in All Fuel Regions	1.20018
20%	BOL Benchmark	1.03316
20%	EOL Benchmark	1.01300
20%	Fresh Fuel in All Fuel Regions	1.18150

TABLE IV': WIMS k_∞ vs. ^{235}U Burnup For 93% and 20 % Enrichments
Enrichment (Meat thickness conservation).

Burnup (%)	93%	20%
0		
5	1.64231	1.56537
10	1.62085	1.54515
15	1.59870	1.52409
20	1.57540	1.50205
25	1.55058	1.47884
30	1.52384	1.45446
35	1.49480	1.42861
40	1.46313	1.40101
45	1.42817	1.37137
50	1.38916	1.33926

TABLE V': Values of k_{eff} from X-Y Difussion theory Calculations.

Enrichment	Description	k_{eff}
93%	BOL Benchmark	1.03620
93%	EOL Benchmark	1.01278
93%	Fresh fuel in all fuel regions	
20%	BOL Benchmark	1.03334
20%	EOL Benchmark	1.01348
20%	Fresh fuel in all fuel regions	

TABLE VI: Fluxes from the DIF2D Problems (n/cm^2 sec). (Pitch conservation).

Case	Core Average Fluxes ϕ_1	ϕ_2	ϕ_f	ϕ_{th}	Flux Trap Average ϕ_{th}	Center Ave. ϕ_{th}	Center Midplane ϕ_{th}
93% BOL	1.1403+14	5.2846+13	1.6688+14	5.9785+13	1.9813+14	2,5734+14	3.3743+14
93% EOL	1.1655+14	5.4041+13	1.7059+14	6.3787+13	2.0507+14	2.6409+14	3.4627+14
20% BOL	1.1332+14	5.0669+13	1.6399+14	4.1533+13	1.7220+14	2.3668+14	3.1033+14
20% EOL	1.1550+14	5.1662+13	1.6716+14	4.3701+13	1.7691+14	2.4156+14	3.1673+14

FIG. 1: IAEA 10 Mw. BENCHMARK 93% U-235 BOL
FLUXES AT MIDPLANE ALONG X - AXIS.

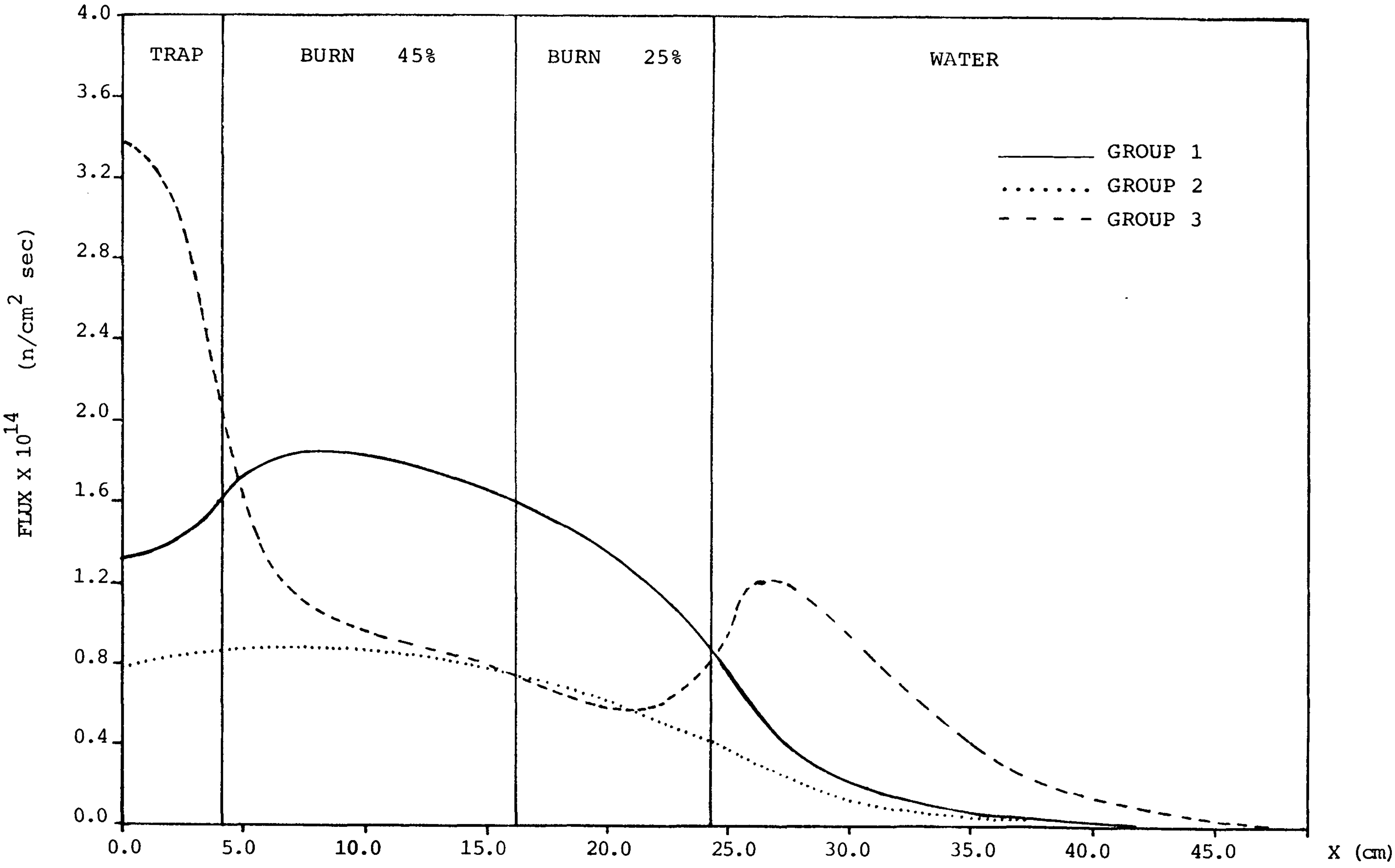

FIG. 2: IAEA 10 Mw BENCHMARK 93% U-235 BOL
FLUXES AT MIDPLANE ALONG Y - AXIS

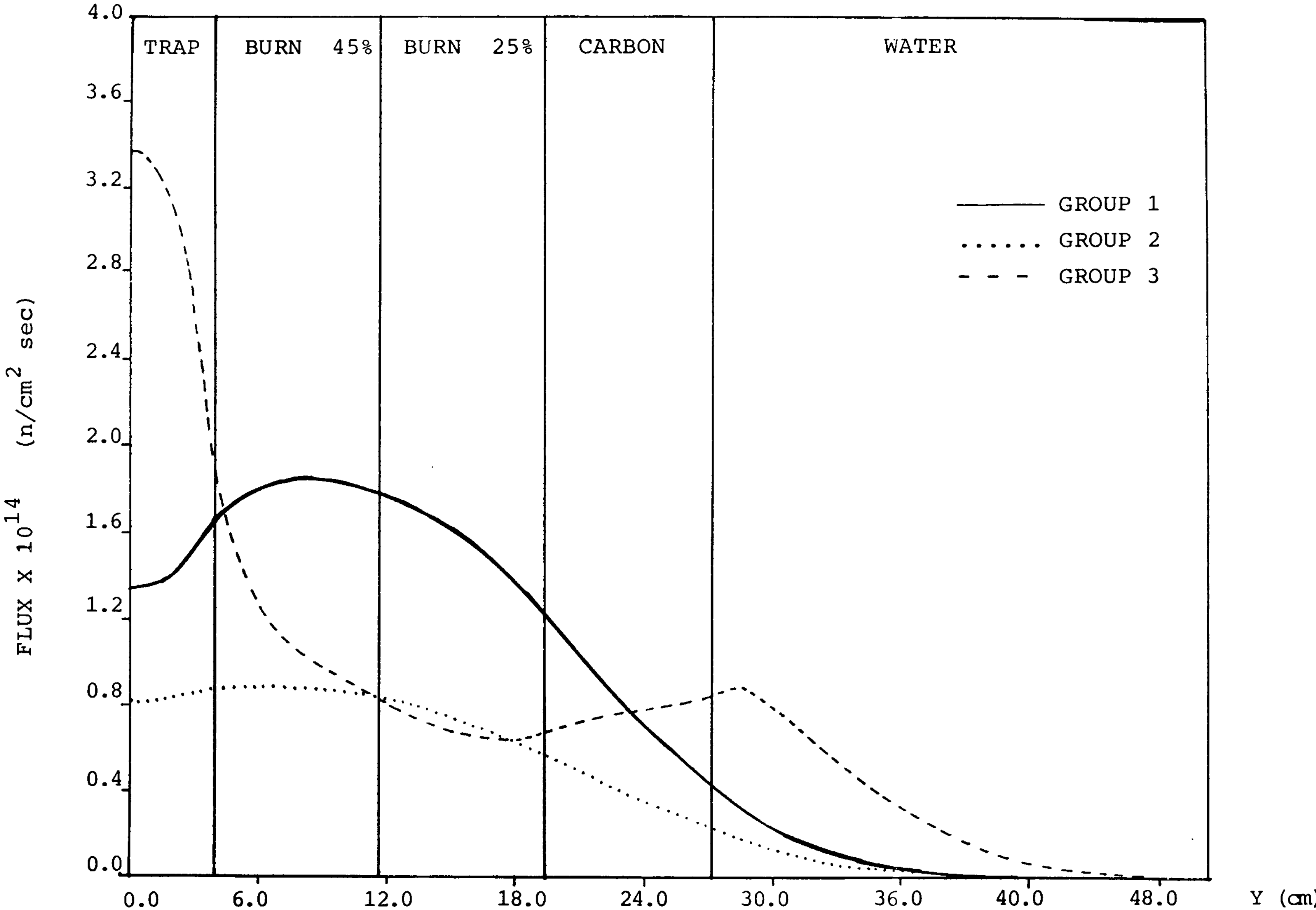

FIG. 3: IAEA 10 Mw BENCHMARK 93% U-235 EOL
FLUXES AT MIDPLANE ALONG X-AXIS.

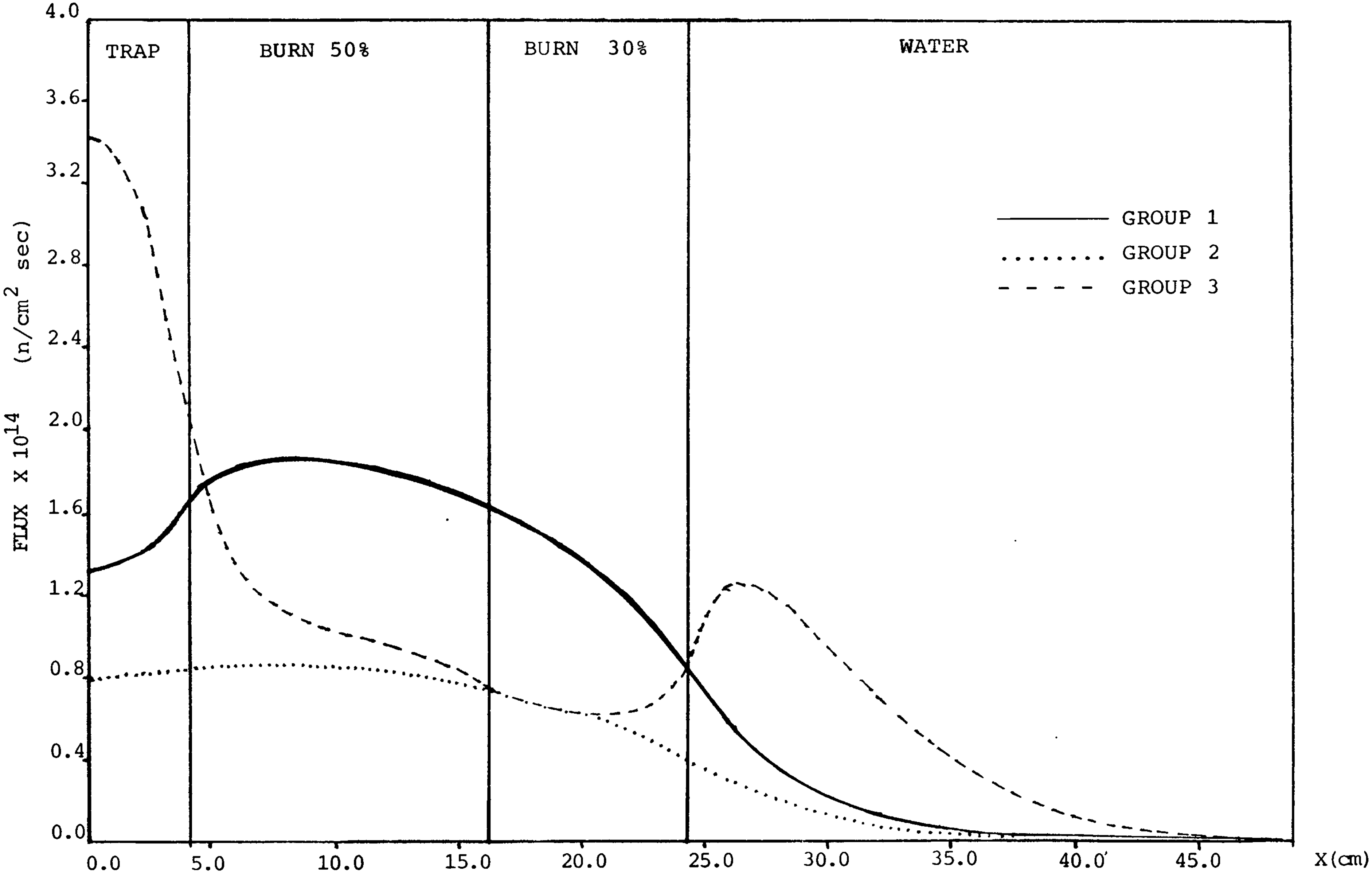

FIG. 4: IAEA BENCHMARK 93% U-235 EOL
FLUXES AT MIDPLANE ALONG Y-AXIS

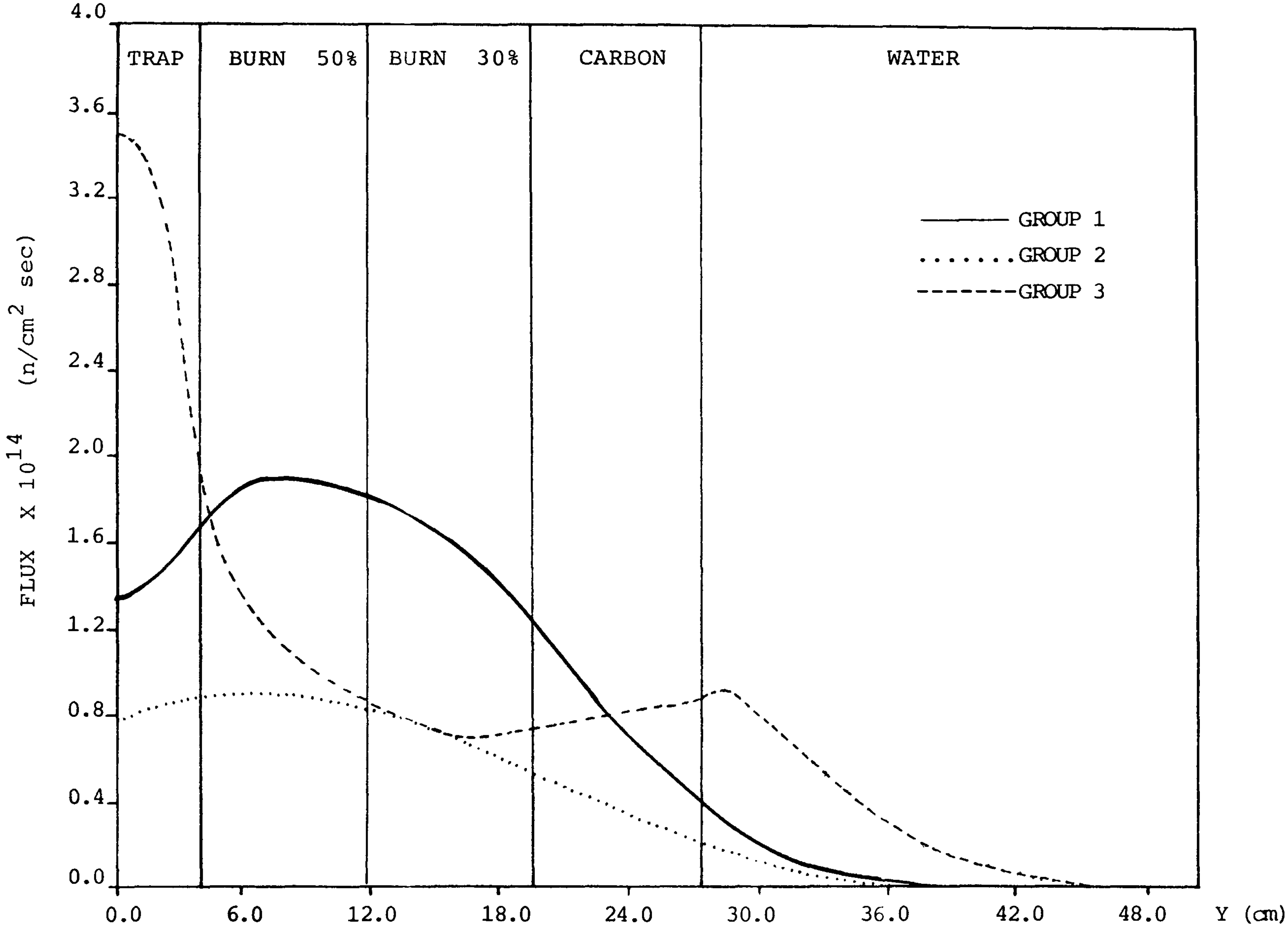

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FIG. 5: FLUX RATIOS FOR 20% U-235 / 95% U-235 BOL MIDPLANE ALONG X-AXIS.

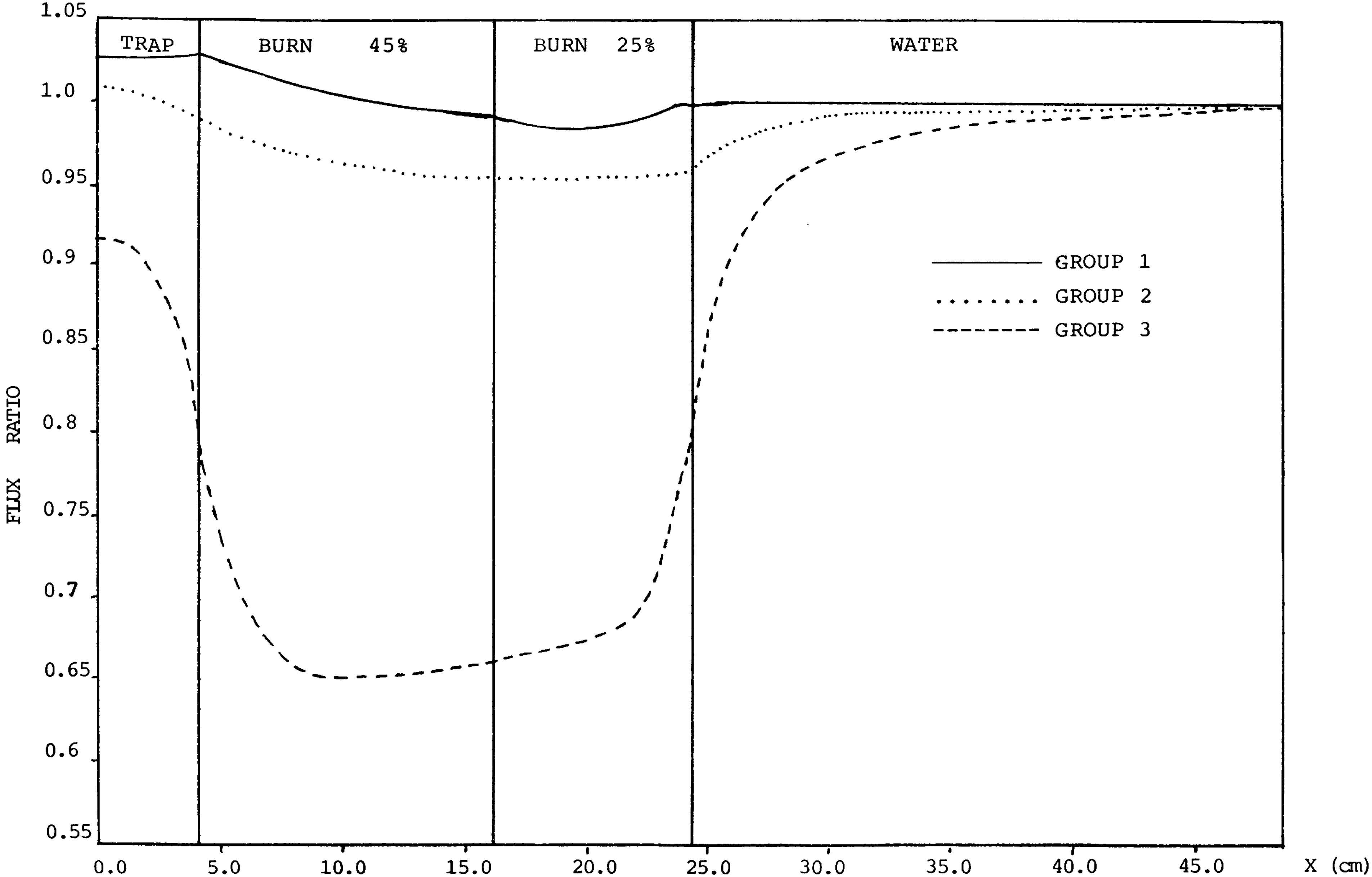

FIG. 6: FLUX RATIOS FOR 20% U-235 / 93% U-235 BOL
MIDPLANE ALONG Y-AXIS.

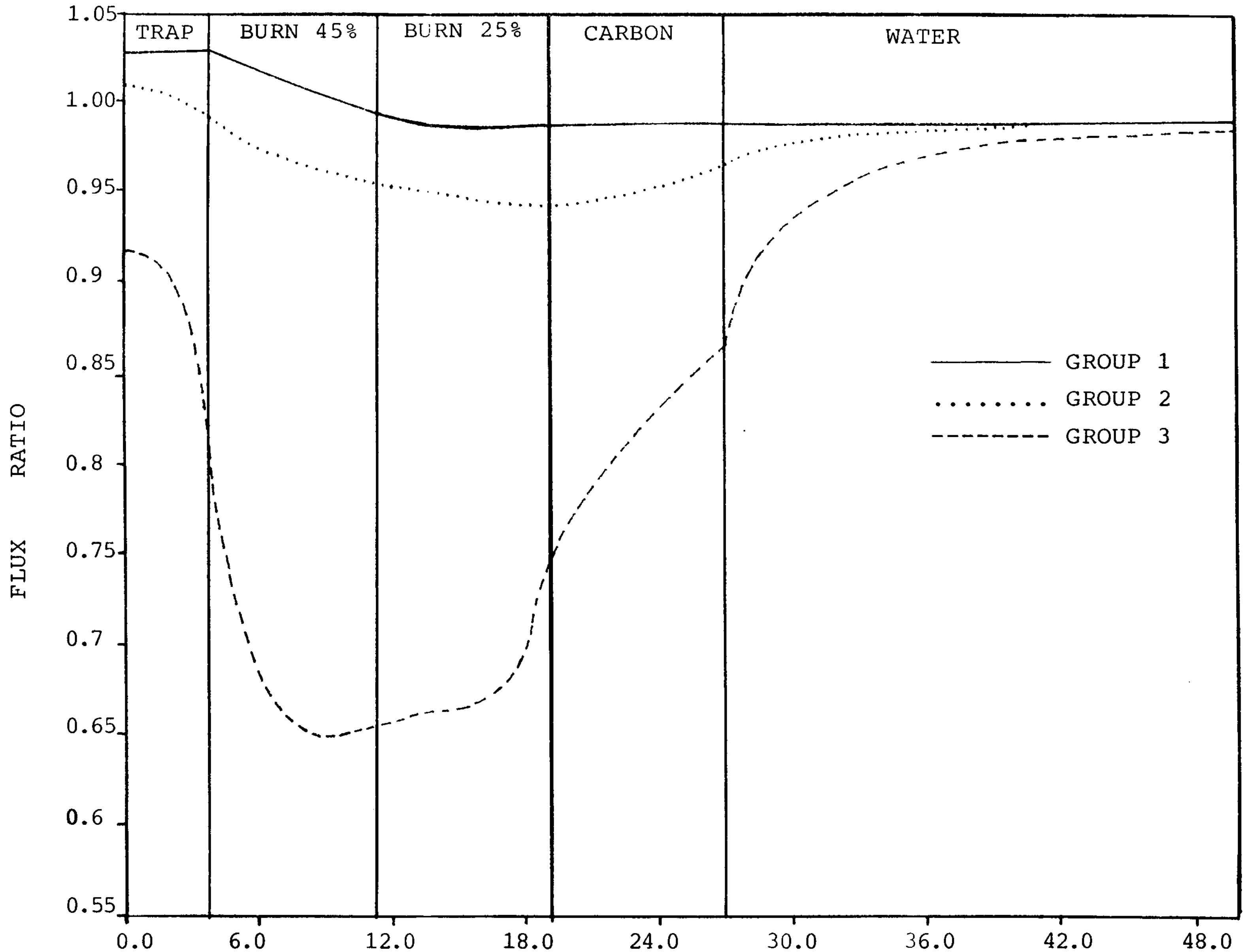

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FIG. 7: FLUX RATIOS FOR 20% U-235 / 93% U-235 EOL MIDPLANE ALONG X-AXIS.

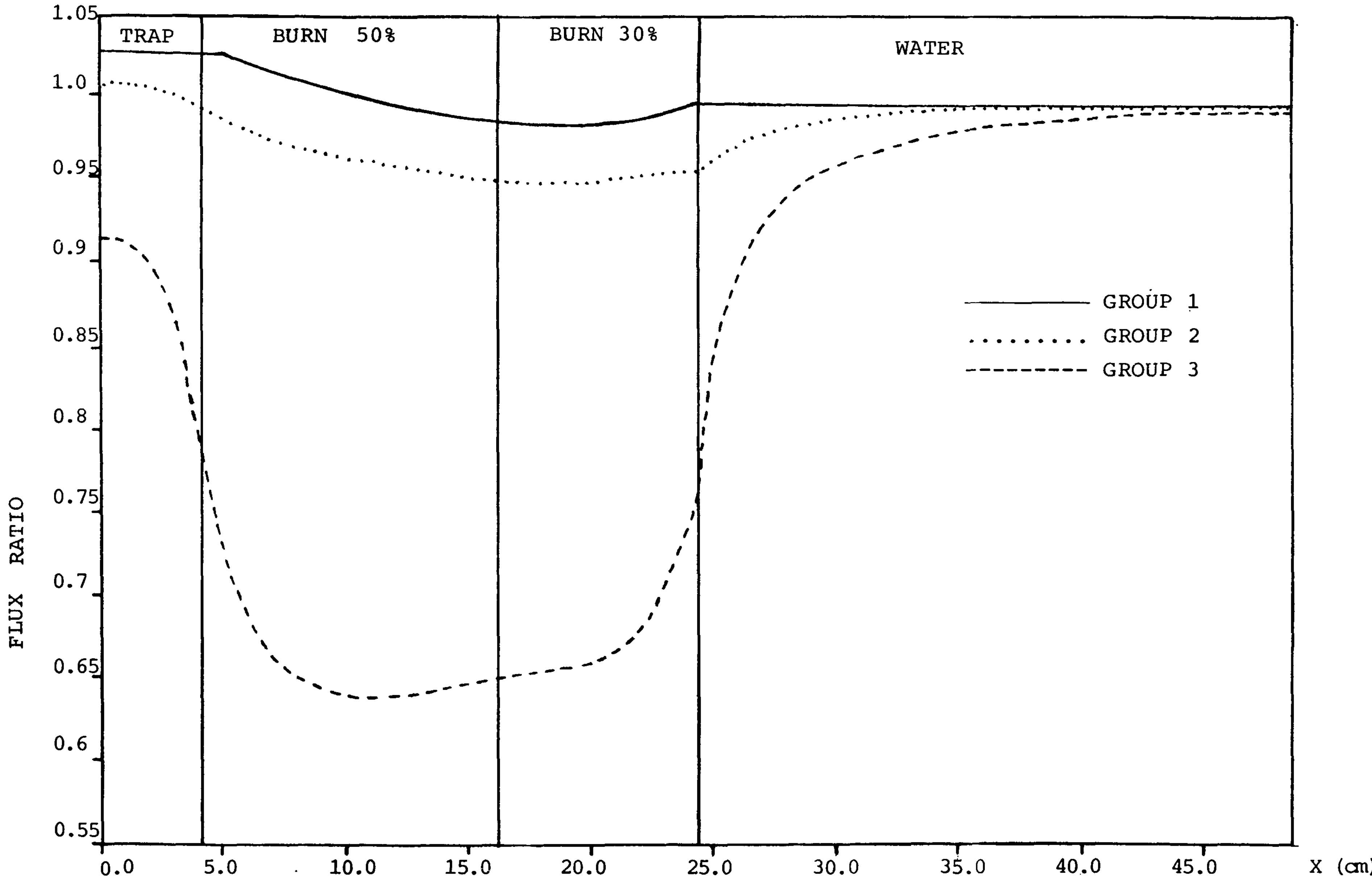


FIG. 8: FLUX RATIOS FOR 20% U-235 / 93% U-235 EOL FOR MIDPLANE ALONG Y-AXIS.

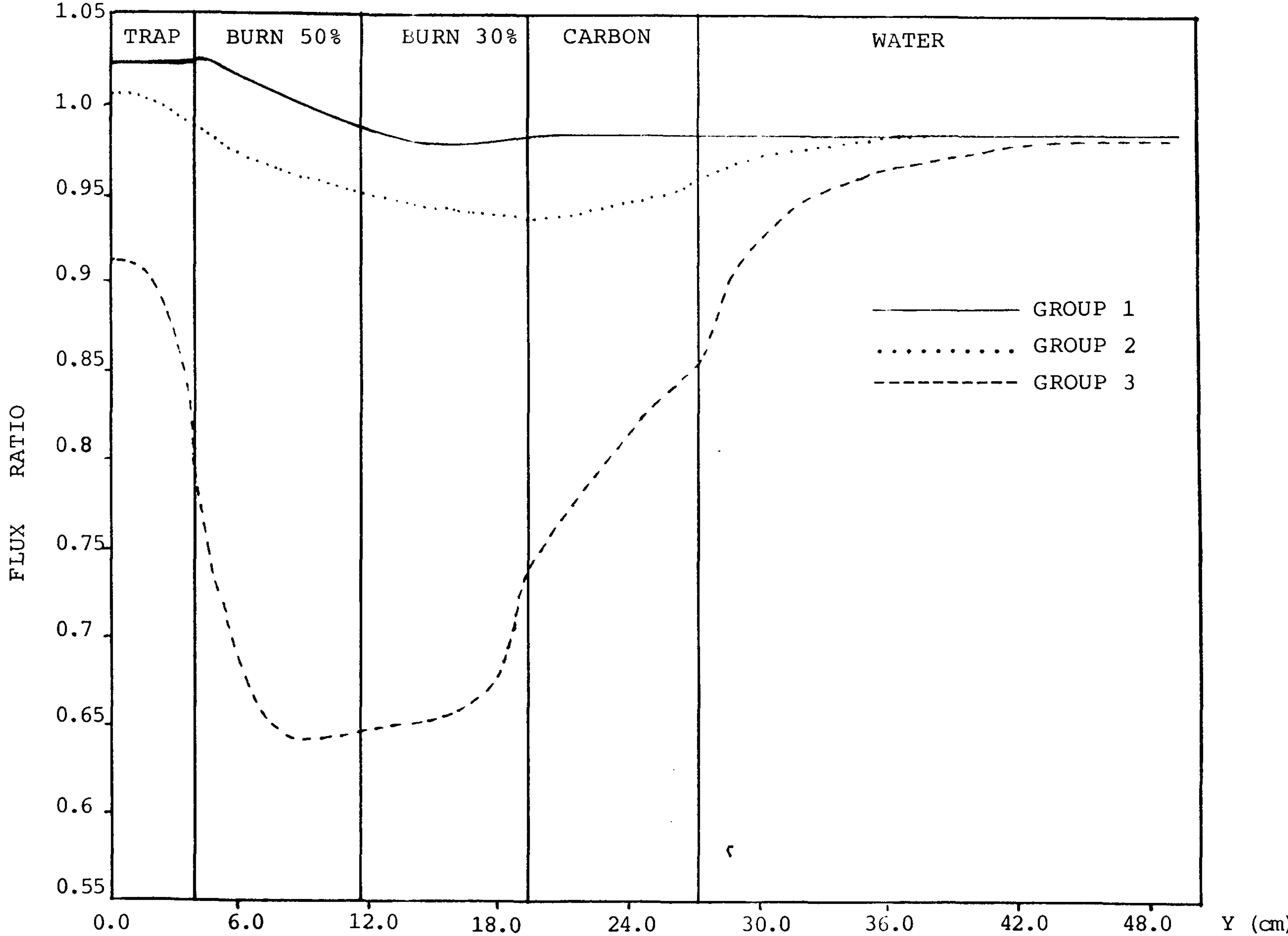
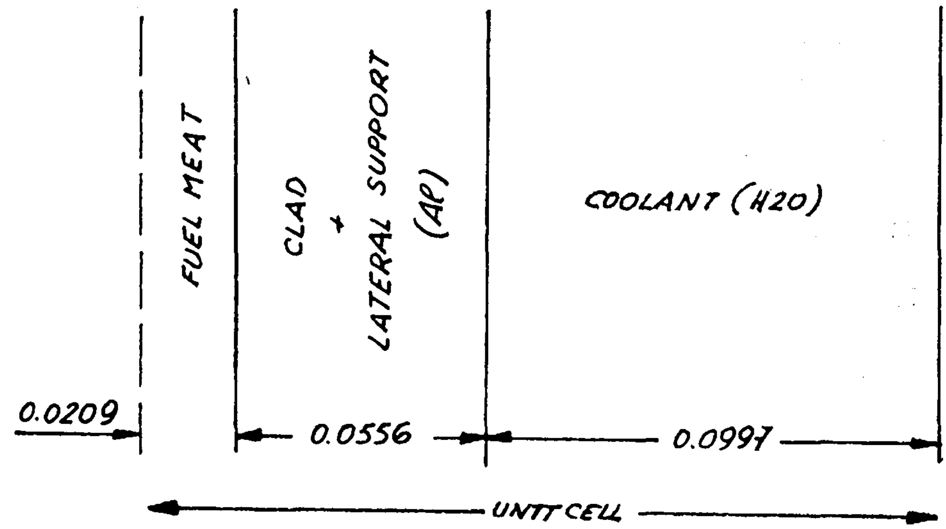
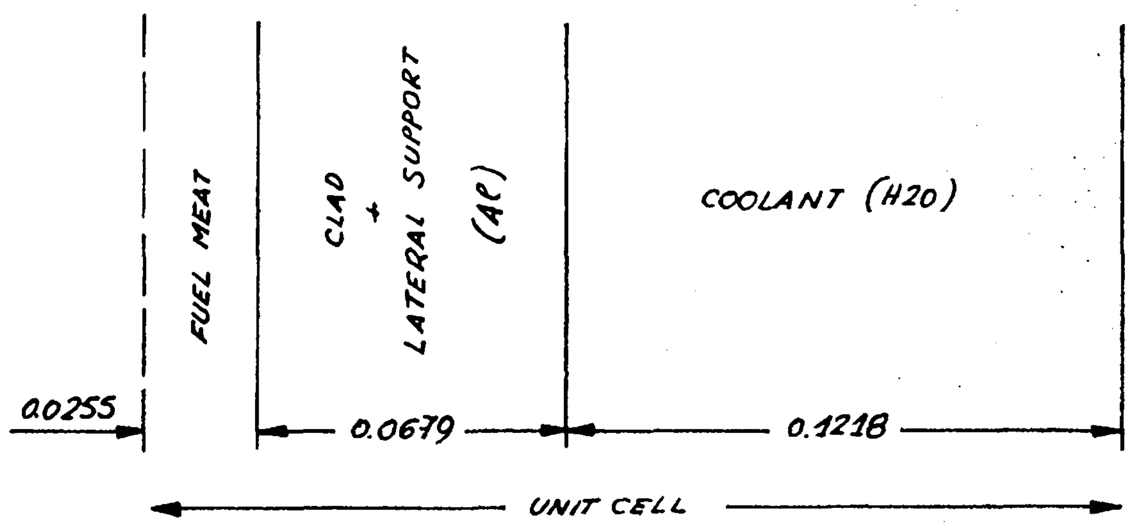


FIGURE 9: SLAB GEOMETRY USED IN WIMS



1) WITH PITCH CONSERVATION



2) WITH MEAT THICKNESS CONSERVATION