ANL-6212
Physics
(TID-4500, 16th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

SOME PHYSICS CALCULATIONS ON THE PERFORMANCE OF LARGE FAST BREEDER POWER REACTORS

by

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December 1960

*On leave from the Israel Atomic Energy Commission

Operated by The University of Chicago
under
Contract W-31-109-eng-38

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ABSTRACT

Critical mass, spectrum, breeding ratio and coolant removal coefficients have been calculated for a series of large, Pu-U^{238}-fueled, sodium-cooled, fast breeder, power reactors, using a new 16-group cross section set based in part on recent, microscopic cross-section measurements. The parameters studied include reactor size, plutonium isotopic content, and type of structural material. Reactors cooled with Pb-Bi eutectic and those containing U^{233}-Th fuel were also examined.

I. INTRODUCTION

The recent completion of a new 16-group set of fast reactor cross sections by Yiftah, Okrent and Moldauer(1) has made it of interest to examine the change in previous predictions(2) of performance and to study various additional characteristics of large, fast breeder, power reactors. The limited series of calculations reported herein* was used to study some large, sodium-cooled, metal, oxide and carbide-fueled systems, paying particular attention to the effect of plutonium isotopic content on critical mass, breeding ratio, and sodium reactivity coefficient. Also examined are reactors with the nonmoderating lead-bismuth coolant, reactors with various structural materials other than stainless steel, and a few reactors having a fuel alloy of U^{233}-thorium.

All the calculations were made in spherical geometry by means of diffusion theory. Each reactor was assumed to consist of three regions, namely, core, blanket, and external reflector. The core size and composition were varied while maintaining the same thickness and composition for all blankets and reflectors. Only a small fraction of the possible permutations of parameters were calculated, since only trends were sought.

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*These calculations were made with the set of cross sections of Reference 1 prior to some final numerical corrections of a relatively minor nature in the cross sections of several materials. As a consequence, the group fluxes and performance predictions may differ slightly (~1%) from the results of calculations made with the final cross sections.

The specifications of the systems studied are as follows:

Core Volume: 800, 1500 or 2500 liters

(where necessary, some additional core volumes were used.)

Core Volume Fractions:		
	Fuel and Fertile Material	0.25
	Structural Material	0.25
	Coolant	0.50

Fuels:	Density, g/cc
Pu-U^{238}	19
PuO_2-UO_2	8.4
PuC-UC	11.39
U^{233}-Th	18.57 (for U^{233}) 11.58 (for Th)
$U^{233}O_2$-ThO_2	8.4
U^{233}C-ThC	11.39

Plutonium Composition:

	Atom Per cent			
Type	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}
A	100	0	0	0
B	74.7	10.2	12.4	2.7
C	40	10	25	25

Coolants		
	Liquid Sodium	0.84 g/cc
	The liquid lead-bismuth eutectic (44.5 wt-% Pb - 55.5 wt-% Bi), 10.46 g/cc	

Structural Materials: Stainless Steel and

- Titanium
- Vanadium
- Zirconium
- Niobium
- Molybdenum
- Tantalum

Blanket Thickness:

45 cm (Uranium)
54 cm (Thorium)

Blanket Volume Fractions:		
	U^{238} or Th	0.6
	Na or Pb-Bi	0.2
	Fe	0.2

Reflector Thickness: 30 cm

Reflector Volume Fractions:		
	Fe	0.6
	Na or Pb-Bi	0.4

II. METAL, OXIDE AND CARBIDE PLUTONIUM FUELS

The comparative performance of fast reactors fueled with metal, oxide, and carbide fuels is shown in Table 1. It is seen that the critical masses (M_C) of oxides are 15-20% lower than those of the corresponding metal systems, whereas the critical masses of carbides lie between those of the metals and oxides. For plutonium "A" the breeding ratio with metallic fuel is about 1.8. With oxide, it is about 20% lower, whereas values for the carbides again lie between the two.

The reduced breeding ratio with ceramic fuels can be traced partly to the reduced fast fission bonus in U^{238} which accompanies a reduction in the U^{238} content of the core, and partly to the increased alpha ($=\sigma_c/\sigma_f$) which accompanies the softened neutron spectrum resulting from increased moderation and reduced overall low energy absorption.

Details of the neutron energy spectrum and the neutron balance for these reactors are given in the Appendix in Tables A-1, A-2 and A-3. It should be noted that the fluxes listed are the integrals over the core or blanket, and that they have been normalized to an average fission neutron source in the core of unity.

III. EFFECT OF ISOTOPIC COMPOSITION OF PLUTONIUM

The plutonium feed material for fueling fast reactors in a power economy may in principle come from different sources:

a) Natural uranium-fueled thermal reactors whose fuel elements can be run only to relatively small burnups before reprocessing and separation of built-in plutonium from the uranium takes place.

b) Thermal reactors fueled with either natural uranium or enriched uranium, where plutonium is produced as a byproduct to the electric power, should provide a considerable source in the future whose size is proportional to the number of thermal power reactors. The bigger the volume of a nuclear power industry based on thermal reactors, the larger will become the quantities of plutonium produced.*

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*It has been estimated by Sir John Cockcroft of Britain (in a talk during the dedication of the Plutonium Fuel Fabrication Facility at the Argonne National Laboratory, May 14, 1959), that by the end of the 1960's the United Kingdom will produce from its commercial reactors about five tons of plutonium per year, which, if not used, will constitute a waste of about seventy-five million dollars per year ($15 per gram of Pu).

Table 1

EFFECT OF ISOTOPIC COMPOSITION OF PLUTONIUM IN 800, 1500 AND 2500-LITER REACTORS FUELED WITH METAL, OXIDE, AND CARBIDE FUELS HAVING SODIUM COOLANT AND STEEL STRUCTURE

Reactor Size (liters)	Fuel	Pu "A"(a)				Pu "B"(a)					Pu "C"(a)				
		M_c (kg)	IBR(c)	BR(c)	$\bar{\alpha}$(b)	M_c (kg)		IBR	Br	$\bar{\alpha}$	M_c (kg)		IBR	Br	$\bar{\alpha}$
						Total Pu	Pu^{239} + Pu^{241}				Total Pu	Pu^{239} + Pu^{241}			
800	Metal	431	0.73	1.82	0.188	458	399	0.79	1.93	0.173	533	346	0.86	2.12	0.150
	Oxide	372	0.31	1.55	0.230	392	341	0.35	1.65	0.209	452	294	0.37	1.81	0.178
	Carbide	396	0.46	1.62	0.224	417	363	0.51	1.73	0.204	480	312	0.55	1.90	0.174
1500	Metal	686	0.91	1.79	0.198	729	635	0.97	1.90	0.182	849	552	1.05	2.08	0.156
	Oxide	562	0.44	1.47	0.251	590	514	0.48	1.57	0.228	680	442	0.51	1.72	0.192
	Carbide	613	0.61	1.56	0.241	645	562	0.66	1.67	0.218	743	483	0.71	1.82	0.185
2500	Metal	1025	1.04	1.76	0.205	1089	949	1.11	1.87	0.187	1269	825	1.21	2.05	0.161
	Oxide	806	0.54	1.42	0.267	845	736	0.59	1.52	0.240	973	632	0.64	1.65	0.203
	Carbide	897	0.73	1.52	0.253	943	821	0.79	1.62	0.229	1086	706	0.85	1.77	0.192

(a)

	239	240	241	242
Pu "A"	100	0	0	0
Pu "B"	74.7	10.2	12.4	2.7
Pu "C"	40	10	25	25

(b) $$\bar{\alpha} = \frac{Pu^{239} \text{ and } Pu^{241} \text{ Captures}}{Pu^{239} \text{ and } Pu^{241} \text{ Fissions}}$$

(c) As defined herein the breeding ratio is the rate at which Pu^{239} and Pu^{241} are being formed to the rate at which they are being destroyed, that is

$$\text{Breeding Ratio} = \frac{U^{238} \text{ and } Pu^{240} \text{ Captures in Reactor}}{(Pu^{239} \text{ and } Pu^{241}) \text{ Captures + Fissions in Reactor}}$$

$$\text{Internal Breeding Ratio} = \frac{\text{Production of Thermally Fissionable Isotopes in Core}}{\text{Destruction of Thermally Fissionable Isotopes in Entire Reactor}}$$

The isotopic composition of plutonium from source (b) will depend on the kind of reactor and, in general, on the irradiation history of the fuel, before it reaches the plants for plutonium extraction.

c) In the future, if many fast breeders are in operation, a third source will become the blankets of the fast reactor themselves. Such plutonium, again, is likely to be low in higher isotopic content.(3)

In addition to the variation in isotopic content of plutonium resulting from the core feed material, the recycling of core plutonium in the reactor will result in changing isotopic concentrations approaching an equilibrium condition which is a function of core design, feed material, and fuel-cycle characteristics.

To examine the effect of higher plutonium isotopes on reactor performance, three representative isotopic compositions were chosen so as to bracket the range of interest.

Plutonium A is pure Pu^{239}.

Plutonium B corresponds to the composition of the recycled plutonium extracted from a thermal reactor fueled with enriched uranium, in this case the pressurized-water, oxide-fueled Yankee reactor, as calculated by Jaye, Bennett and Lietzke.(4)

Plutonium C corresponds to the plutonium which might result from not one, but several, recycles in a thermal reactor with large burnup, and provides some sort of extreme condition of potential feed material.

The comparative results obtained with the different types of plutonium are summarized in Table 1. When one charges himself only for the thermally fissionable isotopes Pu^{239} and Pu^{241}, one finds that the "dirtier" the plutonium, the smaller the critical mass and the higher the breeding ratio. These are both a direct consequence of the fact that Pu^{240} is preferable to U^{238} as a fertile material, due to its larger fission cross section, and that Pu^{241} is preferable to Pu^{239}, at least within the assumptions made in developing this set of cross sections. In particular, the alpha of Pu^{241} itself has been taken to be considerably lower than that for Pu^{239}, automatically yielding an average alpha which decreases as the content of higher isotopes increases.

Details of the neutron balance and the neutron energy spectra for all these systems are given in Tables A-1, A-2 and A-3.

IV. EFFECT OF VARIOUS STRUCTURAL MATERIALS

The effect of substituting titanium, vanadium, zirconium, niobium, molybdenum, and tantalum for steel as the structural material in the 800-liter plutonium-metal-fueled reactors is shown in Table 2.

Table 2

EFFECT OF VARIOUS STRUCTURAL MATERIALS ON 800-LITER PLUTONIUM-METAL-FUELED REACTORS

Structural Material	Critical Mass, kg	Breeding Ratio	Alpha
Fe (Stainless Steel)	431	1.82	0.188
Ti	425	1.92	0.180
V	456	1.68	0.222
Zr	415	1.89	0.181
Nb	494	1.51	0.169
Mo	502	1.46	0.185
T	716	1.02	0.170

The effect of substituting niobium for steel in metal, oxide, and carbide-fueled reactors of all three core sizes is shown in Table 3. The neutron energy spectra and the neutron balances obtained for the various structural materials are given in the Appendix in Table A-4, and similar data for the niobium-containing reactors of various sizes are given in Table A-5.

For the 800-liter, metal-fueled core, there is only a small difference in performance between iron, zirconium, and titanium. The higher inelastic scattering cross section in vanadium apparently reduces the fast fission bonus and increases the alpha of plutonium enough to reduce the breeding ratio appreciably. Niobium and molybdenum show a still lower breeding ratio, due particularly to the significant parasitic capture in these materials. The niobium shows slightly better performance than the molybdenum for an 800-liter, metal-fueled core. For larger, ceramic-fueled cores, however, the softer spectrum is expected to accentuate the higher capture in niobium at low neutron energies, leading to a slightly higher critical mass and lower breeding ratio for this structural material than for molybdenum.

Table 3

EFFECT OF THE STRUCTURAL MATERIAL NIOBIUM REPLACING IRON IN 800, 1500, AND 2500-LITER PLUTONIUM REACTORS FUELED WITH METAL, OXIDE, AND CARBIDE FUELS

Reactor Size (ℓ)	Fuel	Critical Mass		T.B.R.		$\alpha(Pu^{239})$	
		Niobium	Iron	Niobium	Iron	Niobium	Iron
800	Metal	494	431	1.51	1.82	0.169	0.188
	Oxide	462	372	1.23	1.55	0.195	0.230
	Carbide	480	396	1.29	1.62	0.194	0.224
1500	Metal	809	686	1.43	1.79	0.180	0.198
	Oxide	739	562	1.09	1.47	0.205	0.251
	Carbide	786	613	1.17	1.56	0.201	0.241
2500	Metal	1247	1025	1.36	1.76	0.183	0.205
	Oxide	1109	829	0.99	1.42	0.212	0.267
	Carbide	1178	946	1.09	1.52	0.208	0.253

The breeding ratio drops nearly to unity with tantalum as the structural material, in spite of a slight reduction in the average alpha for Pu^{239}. The latter is the result of a hardening of the spectrum by the rapid absorption of neutrons of lower energy in tantalum.

With niobium as the structural material, the breeding ratio drops appreciably below that of steel, and a sharp falloff with reactor size is also noted. For the largest oxide system the breeding ratio falls just below unity.

V. SODIUM REACTIVITY COEFFICIENT

Positive sodium reactivity coefficients for some large fast reactor designs were first reported by Nims and Zweifel(5) and have since been calculated by others.(6) These calculations were done rather crudely, with improper allowance for the effects on spectrum due to elastic scattering resonances in sodium. New, more powerful techniques to treat the problem more adequately are under development.(7)

However, there is some information to be gained by rough calculations of this effect, and some such results are reported herein. In most instances, the effect was calculated by removing uniformly 40% of the sodium originally present in the core. This was augmented by calculations with 20 and 60% removals on occasion. The reactivity change is reported in terms of $\delta M_c/M_c$, the fractional increment in critical mass which would produce the same reactivity effect as the removal of the sodium. (The constant of proportionality, $\delta k/k / \delta M_c/M_c$, was observed to be between 0.5 and 0.7 for these reactors.)

The reactivity effects upon partial sodium removal from an 800-liter, metallic plutonium core with steel structure are given in Table 4,and the effects for a 1500-liter oxide core, again with steel structure, are given in Table 5. The results in both cases were negative, and the reactivity effect changed somewhat more rapidly than linearly with sodium removal.

Table 4

REACTIVITY CHANGE UPON REMOVING 20, 40, AND 60% OF SODIUM FROM 800-LITER CORES FUELED WITH METALLIC PLUTONIUM (STAINLESS STEEL STRUCTURE)

Percentage of Sodium Removed from Core	$\delta M_c/M_c$ to Produce Same Reactivity Change
20	-0.0021
40	-0.0047
60	-0.0080

Table 5

REACTIVITY CHANGE UPON REMOVING 20, 40, AND 60% OF SODIUM FROM 1500-LITER CORES FUELED WITH PLUTONIUM OXIDE (STAINLESS STEEL STRUCTURE)

Percentage of Sodium Removed from Core	$\delta M_c/M_c$ to Produce Same Reactivity Change
20	-0.0067
40	-0.0140
60	-0.0222

The sodium removal reactivity effects for a series of reactors of differing sizes, with metal, oxide, and carbide fuel (Type A plutonium), and with both steel or niobium structural material, are given in Table 6, and are plotted in Figs. 1 and 2. The following observations can be made from these results:

a) All the reactors calculated with niobium structure exhibited a positive reactivity effect. Extrapolations of the curves in Figs. 1 and 2 suggest a threshold size for the positive effect of about 400 liters for the metal-fueled system chosen, namely, 700-800 liters for the oxide and carbide systems.

b) All reactors having steel as the structural material exhibit a threshold size for a positive effect which is three or four times that of niobium for the reactor models chosen.

Table 6

REACTIVITY CHANGE UPON REMOVING 40% OF SODIUM FROM CORES OF VARIOUS SIZES FUELED WITH METAL, OXIDE, OR CARBIDE PLUTONIUM FUEL WITH STEEL AND NIOBIUM STRUCTURES

$\delta M_c/M_c$ To Produce Same Reactivity Change

Core Volume (ℓ)	Metal		Oxide		Carbide	
	Steel	Niobium	Steel	Niobium	Steel	Niobium
800	-0.0047	+0.0057	-0.0211	+0.0003	-0.0143	+0.0022
1500	+0.0041 (+0.0014)	+0.0144	-0.0140 (-0.0162)	+0.0260	-0.0058 (-0.0076)	+0.0210
2000			-0.0094	+0.0136		
2500	+0.0120	+0.0306	-0.0056	+0.0168	+0.0022	+0.0176
3000			-0.0025	+0.0194	+0.0051	+0.0200
3500			+0.000048	+0.0215	+0.0076	+0.0220

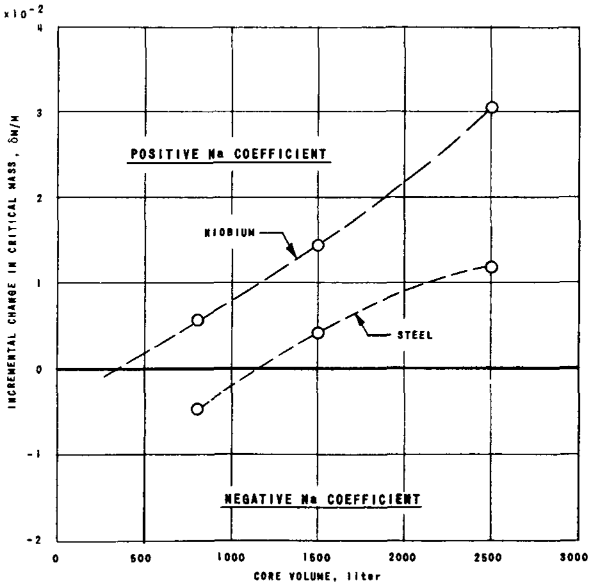

FIG. 1

REACTIVITY CHANGE EFFECTED BY REMOVAL OF 40% OF SODIUM FROM PLUTONIUM METAL-FUELED CORES WITH STEEL OR NIOBIUM STRUCTURE.

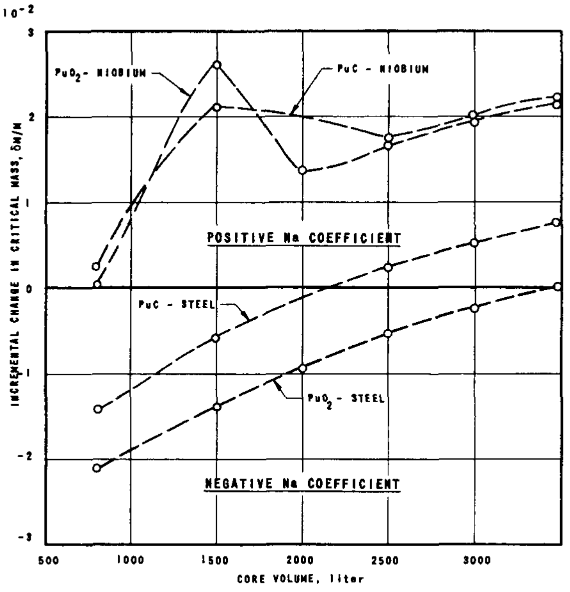

FIG. 2

REACTIVITY CHANGE EFFECTED BY REMOVAL OF 40% OF SODIUM FROM PLUTONIUM OXIDE-AND PLUTONIUM CARBIDE-FUELED CORES WITH STEEL OR NIOBIUM STRUCTURE.

The "wiggle" observed in the curves for niobium structure with oxide or carbide fuel is thought to be real. However, detailed justification based on microscopic cross-section data has not been attempted.

The sodium reactivity effects were also computed for the 1500-liter reactors fueled with Plutonium "C" in the metallic, oxide, and carbide forms, with steel structure. The results are given in parentheses in Table 6. In all cases the contents of the higher plutonium isotopes made the reactivity change upon removal of 40% of the sodium initially present in the core more negative.

For the 800-liter, metal-fueled reactor, sodium reactivity coefficients were also computed for the other structural materials. Tantalum was similar to niobium, molybdenum was positive but much less so, whereas zirconium, vanadium, and titanium gave negative coefficients of the same size as obtained for stainless steel.

The sodium reactivity coefficients for niobium-containing reactors were calculated using an early set of capture cross sections for niobium, which were too low at very low energies. When these cross sections were corrected upwards to provide agreement with recent experimental microscopic data [that is, using the final niobium cross sections assigned in Reference (1)], the sodium reactivity coefficients for the niobium-bearing systems were found to become more positive by 10-20% in the few cases tested.

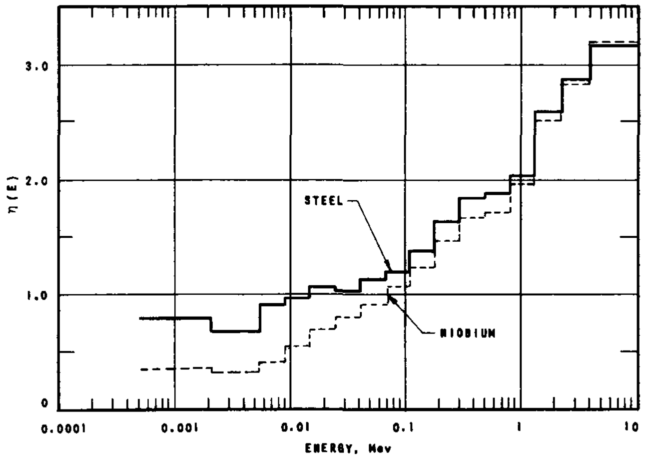

FIG. 3
η AS A FUNCTION OF NEUTRON ENERGY FOR 1500-LITER PLUTONIUM CARBIDE-FUELED REACTORS WITH STEEL OR NIOBIUM STRUCTURE.

For a specific oxide-fueled reactor design, Nims and Zweifel(5) have broken the sodium reactivity coefficient into several components, showing that both elastic moderation and inelastic scattering in sodium were producing spectral effects leading to a gain in reactivity upon sodium removal. The manner in which hardening of the spectrum can add reactivity is well illustrated in Fig. 3, wherein $\eta(E)$, the average number of neutrons emitted per absorption in all core materials, is plotted versus energy for two 1500-liter, plutonium carbide reactors, one using stainless steel structure, the other niobium.

The average $\overline{\eta}$ has also been computed for most of the reactor types considered herein, and this k_∞-like parameter is presented in Table 7.

Table 7

$\bar{\eta}$, THE NEUTRONS EMITTED PER ABSORPTION IN THE CORE

$\left(\bar{\eta} = \int \eta(E)\sigma_a(E)\phi(E)dE / \int \sigma_a(E)\phi(E)dE\right)$

Core Volume (ℓ)	Structural Material	$\bar{\eta}$		
		Metal	Oxide	Carbide
800	Iron	1.525	1.796	1.662
	Niobium	1.406	1.552	1.480
	Tantalum	1.263		
	Molybdenum	1.387		
	Zirconium	1.545		
	Vanadium	1.438		
	Titanium	1.566		
1500	Iron	1.390	1.611	1.498
	Niobium	1.323	1.527	1.387
2500	Iron	1.301	1.479	1.386
	Niobium	1.238	1.315	1.269

VI. LEAD-BISMUTH EUTECTIC AS COOLANT

The effect of substituting the heavy coolant, lead-bismuth eutectic, for sodium was calculated for the 800, 1500 and 2500-liter core reactors fueled with metal, oxide, and carbide. The results are shown in Table 8, taking iron as the structural material. The results with sodium as the coolant are also presented for comparison purposes.

The critical mass with the heavy coolant is always slightly less, ranging from 6 to 12%. The breeding ratios are almost identical, despite small shifts in alpha.

The group-wise neutron energy spectra and the neutron balance for the heavy coolant systems can be found in the Appendix in Table A-6, which provides more details on these reactors.

The changes in reactivity on removing 40% of the coolant in the core were computed for the lead-bismuth systems. As can be seen in Table 9, the reactivity effect was substantially negative in all cases calculated.

Table 8

EFFECT OF THE COOLANT LEAD-BISMUTH REPLACING SODIUM IN 800, 1500, AND 2500-LITER PLUTONIUM REACTORS FUELED WITH METAL, OXIDE, AND CARBIDE FUELS

Reactor Size (ℓ)	Fuel	Critical Mass		T.B.R.		α	
		Lead-Bismuth	Sodium	Lead-Bismuth	Sodium	Lead-Bismuth	Sodium
800	Metal	403	431	1.79	1.82	0.173	0.188
	Oxide	337	372	1.52	1.55	0.217	0.230
	Carbide	363	396	1.59	1.62	0.211	0.224
1500	Metal	642	686	1.76	1.79	0.181	0.198
	Oxide	508	562	1.45	1.47	0.237	0.251
	Carbide	564	613	1.54	1.56	0.226	0.241
2500	Metal	962	1025	1.74	1.76	0.186	0.205
	Oxide	730	829	1.40	1.42	0.252	0.267
	Carbide	828	946	1 50	1.52	0.237	0.253

Table 9

REACTIVITY CHANGES UPON REMOVING 40% OF LEAD-BISMUTH COOLANT FROM 800, 1500 OR 2500-LITER CORES FUELED WITH METAL, OXIDE AND CARBIDE PLUTONIUM FUEL (STAINLESS STEEL STRUCTURE)

Core Volume (ℓ)	$\delta M_c/M_c$ To Produce Same Reactivity Change		
	Metal	Oxide	Carbide
800	-0.0249	-0.0519	-0.0398
1500	-0.0165	-0.0449	-0.0309
2500	-0.0083	-0.0360	-0.0222

VII. COMPARISON WITH PREDICTIONS OF 11-GROUP SET

To compare the performance predictions of the newer, 16-group set with the 11-group set utilized by Loewenstein and Okrent in their 1958 Geneva Conference paper,(2) a series of reactors were calculated with both sets. Using steel as the structural material, and plutonium-U^{238} in the metallic, oxide, or carbide form, reactors having core volumes of 1500 and 2500 liters were examined. The critical masses and breeding ratios predicted by the two sets of cross sections are compared in Table 10. It can be seen that the older 11-group set gives consistently higher critical masses, ranging from 10% for the metal-fueled systems to 3% for the oxides.

Table 10

COMPARISON OF PERFORMANCE PREDICTIONS FOR LARGE METAL, OXIDE AND CARBIDE REACTORS USING NEW 16-GROUP SET (YOM)* AND OLDER ELEVEN GROUP SET (LO)**

1500-liter Core						2500-liter Core					
Critical Mass		B.R.		α		Critical Mass		B.R.		α	
YOM	LO	YOM	LO	YOM	LO	YOM	LO	YOM	LO	YOM	LO
Plutonium Metal											
686	755	1.79	1.60	0.198	0.221	1025	1139	1.76	1.58	0.205	0.228
Plutonium Oxide											
562	577	1.47	1.33	0.251	0.287	806	829	1.42	1.28	0.267	0.304
Plutonium Carbide											
613	643	1.56	1.41	0.241	0.271	897	946	1.52	1.37	0.253	0.284

* Yiftah, Okrent and Moldauer, Reference 1

** Loewenstein and Okrent, Reference 2

The breeding ratios are consistently higher in the 16-group calculations. This is mainly attributed to the higher value of ν for U^{238} in the newer 16-group set.

VIII. REMARKS ON U^{233}-THORIUM SYSTEMS

A limited number of calculations have been performed on large reactors fueled with thorium-U^{233} in the metallic, oxide, and carbide form. The results for 800, 1500 and 2500-liter cores are presented in Table 11. Details of the spectra are given in the Appendix in Table A-7.

The breeding ratios for the thorium systems (using steel as the structural material) all lie well above unity, but considerably below the results obtained with corresponding plutonium-U^{238} systems. The critical masses for the two systems are very similar.

Table 11

PERFORMANCE OF LARGE REACTORS FUELED WITH U^{233}-THORIUM MIXTURE AS METAL, OXIDE OR CARBIDE FUEL, HAVING SODIUM COOLANT AND STEEL STRUCTURE

Reactor Size (ℓ)	Fuel	Critical Mass (kg)	Internal Breeding Ratio	Breeding Ratio	α
800	Metal	453	0.38	1.29	0.085
	Oxide	371	0.27	1.23	0.099
	Carbide	410	0.38	1.26	0.096
1500	Metal	679	0.50	1.28	0.089
	Oxide	539	0.39	1.21	0.106
	Carbide	616	0.52	1.24	0.102
2500	Metal	968	0.61	1.28	0.092
	Oxide	755	0.49	1.19	0.112
	Carbide	890	0.62	1.23	0.106

The thorium blanket had been taken to be somewhat thicker than the blanket of the uranium counterparts, due to the lower density of thorium. However, there was still a significant net leakage from the blanket. If one assumes that about 80% of the leakage neutrons could be captured in a more efficient blanket, all the breeding ratios for these systems would be enhanced by 0.03-0.05.

The sodium coefficients, which are tabulated in Table 12, are all negative.

Table 12

REACTIVITY CHANGE UPON REMOVING 40% OF SODIUM COOLANT FROM 800, 1500 AND 2500-LITER CORES FUELED WITH METAL, OXIDE, OR CARBIDE U^{233}-Th FUEL (STAINLESS STEEL STRUCTURE)

Core Volume (ℓ)	$\delta M_c/M_c$ To Produce Same Reactivity Effect		
	Metal	Oxide	Carbide
800	-0.0437	-0.0506	-0.0415
1500	-0.0387	-0.0436	-0.0336
2500	-0.0323	-0.0339	-0.0246

IX. CONCLUSIONS

The recent 16-group set of cross sections developed by Yiftah, Okrent, and Moldauer predicts somewhat higher breeding ratios for U^{238}-plutonium-fueled fast reactors than were calculated by Loewenstein and Okrent in 1958. This effect is attributed primarily to the higher $\nu(E)$ values now used for U^{238}.

The addition of higher isotopes of plutonium to the fuel raises the breeding ratio and apparently makes the sodium reactivity coefficient more negative (or less positive). However, for all the structural materials studied in the particular reactor configuration chosen, the sodium coefficient becomes more positive as reactor size is increased and attains a positive value upon 40% removal of sodium coolant from the core, if the fuel is plutonium. The threshold core volume for a positive sodium coefficient with niobium as the structure in the metal-fueled reactor was found to be only of the order of 400 liters for the reactor composition studied. Thus, a considerable likelihood of difficulties of this type can be anticipated for large, central-station reactors having metal fuel elements jacketed in niobium, molybdenum, or other strongly absorbing materials. If positive sodium coefficients are to be avoided for metal-fueled reactors, it would appear that titanium, vanadium, or zirconium offer the best alternates to steel for structure and cladding from the physics point of view. Also, one might surmise that a somewhat reduced volume fraction both of structure and of fuel alloy, with a corresponding increase in sodium volume fraction above the 0.5 used herein, might help to keep the sodium coefficient negative.

Negative sodium coefficients were computed in all sizes for U^{233}-thorium systems using steel for structure Negative coolant coefficients were also calculated for plutonium-U^{238}-steel systems using lead-bismuth as coolant.

APPENDIX

Table A-1: Study of 800-liter Spherical Reactors Fueled with Metal, Oxide, and Carbide Plutonium Fuels with Different Isotopic Compositions of Plutonium.

Table A-2: Study of 1500-liter Spherical Reactors Fueled with Metal, Oxide and Carbide Plutonium Fuels with Different Isotopic Compositions of Plutonium.

Table A-3: Study of 2500-liter Spherical Reactors Fueled with Metal, Oxide and Carbide Plutonium Fuels with Different Isotopic Compositions of Plutonium.

Table A-4: Effect of Various Structural Materials on Performance of 800-liter, Plutonium-U^{238}-metal-fueled Reactors.

Table A-5: Study of 800, 1500 and 2500-liter Spherical Reactors Fueled with Metal, Oxide and Carbide Plutonium Fuels with Niobium as the Structural Material in the Core.

Table A-6: Study of 800, 1500 and 2500-liter Spherical Reactors Fueled with Metal, Oxide and Carbide Plutonium Fuels with Lead-Bismuth Eutectic Alloy as Coolant.

Table A-7: Study of 800, 1500 and 2500-liter Spherical Reactors Fueled with U^{233}-Thorium as Metal, Oxide or Carbide, Having Steel Structure and Sodium Coolant.

Table A-1

STUDY OF 800 LITER SPHERICAL REACTORS FUELED WITH METAL OXIDE AND CARBIDE PLUTONIUM FUELS WITH DIFFERENT ISOTOPIC COMPOSITIONS OF PLUTONIUM

Fuel		Pu A						Pu B						Pu C					
		Metal		Oxide		Carbide		Metal		Oxide		Carbide		Metal		Oxide		Carbide	
Ratio of Fuel Atoms to Diluent Atoms (Pu/U^{238})		0.128		0.336		0.222		0.137		0.360		0.237		0.163		0.439		0.283	
Critical Mass of Fuel (kg)		431		372		396		399 (458)[a]		341 (392)[a]		363 (417)[a]		346 (533)[a]		294 (452)[a]		312 (480)[a]	
Flux Integrals																			
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3.668 10.00	1.62	0.21	2.13	0.30	1.92	0.26	1.62	0.21	2.13	0.30	1.92	0.26	1.62	0.21	2.13	0.29	1.92	0.26
2	2.225 3.668	3.16	0.38	4.37	0.56	3.90	0.49	3.16	0.38	4.37	0.56	3.90	0.49	3.16	0.38	4.38	0.56	3.91	0.49
3	1.35 2.225	5.66	0.80	8.00	1.18	7.14	1.05	5.66	0.80	8.00	1.18	7.15	1.05	5.67	0.80	8.02	1.18	7.16	1.05
4	0.825 1.35	9.51	2.22	11.02	2.86	10.58	2.69	9.50	2.22	11.03	2.86	10.58	2.69	9.47	2.21	11.00	2.85	10.55	2.68
5	0.5 0.825	16.18	5.72	16.30	6.83	15.75	6.41	16.16	5.72	16.31	6.84	15.75	6.41	16.08	5.70	16.24	6.81	15.69	6.39
6	0.3 0.5	20.15	8.60	18.93	9.75	18.63	9.24	20.19	8.61	18.99	9.76	18.68	9.25	20.17	8.59	18.98	9.74	18.68	9.24
7	0.18 -0.3	18.22	8.94	19.80	10.43	17.62	9.56	18.34	8.96	19.95	10.47	17.74	9.59	18.46	8.96	20.07	10.47	17.85	9.59
8	0.11 0.18	14.80	8.23	17.17	9.87	15.09	8.88	14.94	8.26	17.34	9.91	15.23	8.91	15.11	8.28	17.53	9.94	15.40	8.94
9	0.067 0.11	8.10	4.53	11.73	5.77	10.28	5.14	8.17	4.55	11.86	5.81	10.38	5.17	8.28	4.57	12.02	5.83	10.52	5.19
10	0.0407 0.067	7.40	5.76	10.26	7.35	9.10	6.54	7.46	5.79	10.34	7.40	9.20	6.58	7.54	5.81	10.47	7.43	9.33	6.61
11	0.025 0.0407	3.24	2.33	5.53	3.12	5.02	2.78	3.26	2.34	5.60	3.14	5.08	2.80	3.30	2.35	5.68	3.16	5.15	2.81
12	0.015 -0.025	3.73	2.80	6.79	4.00	5.88	3.50	3.75	2.81	6.86	4.03	5.94	3.52	3.77	2.82	6.94	4.06	6.01	3.55
13	0.0091 0.015	1.42	1.05	3.50	1.65	3.10	1.44	1.41	1.05	3.52	1.66	3.12	1.45	1.41	1.06	3.53	1.67	3.13	1.45
14	0.0055-0.0091	0.61	0.40	1.93	0.70	1.73	0.61	0.60	0.40	1.93	0.71	1.73	0.62	0.59	0.40	1.91	0.71	1.72	0.62
15	0.0021 0.0055	0.26	0.18	1.12	0.34	0.96	0.30	0.26	0.18	1.12	0.34	0.96	0.30	0.25	0.18	1.11	0.34	0.95	0.30
16	0.0005 0.0021	0.20	0.070	1.54	0.19	1.21	0.16	0.20	0.070	1.55	0.19	1.22	0.16	0.19	0.070	1.56	0.19	1.22	0.16
Neutron Balance																			
Pu^{239}	Fissions	0.282		0.313		0.301	-	0.224		0.247		0.238	-	0.140		0.153		0.148	
Pu^{239}	Captures	0.0532		0.0720		0.0676		0.0424		0.0570		0.0536		0.0266		0.0355	-	0.0333	
Pu^{240}	Fissions		-	-	-			0.00690		0.00702		0.00694		0.00786	-	0.00788	-	0.00782	
Pu^{240}	Captures					-	-	0.00599		0.00768		0.00724		0.00686	-	0.00869	-	0.00822	
Pu^{241}	Fissions	-						0.0469		0.0549		0.0524		0.110		0.128	-	0.122	-
Pu^{241}	Captures				-	-		0.00473		0.00629		0.00591		0.0111	-	0.0147	-	0.0138	
Pu^{242}	Fissions		-				-	0.00177		0.00177	-	0.00180	-	0.0191		0.0191		0.0190	
Pu^{242}	Captures	-				-		0.00158		0.00199		0.00193		0.0171		0.0217		0.0205	-
U^{238}	Fissions	0.0583	0.0214	0.0264	0.0311	0.0379	0.0277	0.0578	0.0214	0.0259	0.0311	0.0375	0.0276	0.0366	0.0214	0.0245	0.0310	0.0362	0.0276
U^{238}	Captures	0.245	0.364	0.120	0.476	0.171	0.427	0.244	0.366	0.119	0.479	0.170	0.429	0.240	0.366	0.113	0.480	0.165	0.430
Coolant (Na) Captures		0.00144	0.000353	0.00502	0.000635	0.00433	0.000555	0.00142	0.000353	0.00500	0.000637	0.00431	0.000556	0.00139	0.000353	0.00495	0.000637	0.00427	0.000556
Structural Captures		0.0149	0.00637	0.0179	0.00805	0.0179	0.00728	0.0150	0.00639	0.0200	0.00810	0.0180	0.00731	0.0150	0.00641	0.0202	0.00813	0.0182	0.00933
Internal Breeding Ratio		0.73		0.31		0.46		0.79		0.35		0.51		0.86		0.37		0.55	
Breeding Ratio		1.82		1.55		1.62		1.93		1.65		1.73		2.12		1.81		1.90	
Ratio Captures to Fissions in Pu^{239} + Pu^{241}		0.188		0.230		0.224		0.173		0.209		0.204		0.150		0.178		0.174	
Escape from Blanket		0.0118		0.0143		0.0135		0.0118		0.0144		0.0133		0.0118		0.0143		0.0134	

[a] The figures of critical mass represent the critical mass of the two fissionable isotopes Pu^{239} and Pu^{241} The values in parentheses give the total mass of all four plutonium isotopes Pu^{239} Pu^{240} Pu^{241} and Pu^{242}

Table A-2

STUDY OF 1500-LITER SPHERICAL REACTORS FUELED WITH METAL, OXIDE, AND CARBIDE PLUTONIUM FUELS WITH DIFFERENT ISOTOPIC COMPOSITIONS OF PLUTONIUM

Fuel		Pu A						Pu B						Pu C					
		Metal		Oxide		Carbide		Metal		Oxide		Carbide		Metal		Oxide		Carbide	
Ratio of Fuel Atoms to Diluent Atoms (Pu/U^{238}) Critical Mass of Fuel (kg)		0.106 686		0.253 562		0.176 613		0.113 635 (729)[a]		0.269 514 (590)[a]		0.187 562 (645)[a]		0.135 552 (849)[a]		0.323 442 (680)[a]		0.222 483 (743)[a]	
Flux Integrals																			
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3.668 -10.00	1.68	0.15	2.24	0.22	2.00	0.19	1.68	0.15	2.24	0.22	2.00	0.19	1.68	0.15	2.24	0.22	2.01	0.19
2	2.225 -3.668	3.28	0.28	4.62	0.42	4.10	0.37	3.28	0.28	4.62	0.42	4.10	0.37	3.28	0.28	4.63	0.42	4.10	0.37
3	1.35 -2.225	5.95	0.60	8.61	0.90	7.63	0.79	5.96	0.60	8.62	0.90	7.64	0.79	5.96	0.60	8.63	0.90	7.65	0.79
4	0.825 -1.35	10.23	1.67	12.06	2.20	11.52	2.05	10.22	1.67	12.07	2.20	11.52	2.05	10.19	11.67	12.04	2.19	11.50	2.05
5	0.5 -0.825	17.84	4.38	18.19	5.31	17.47	4.95	17.83	4.38	18.21	5.31	17.48	4.96	17.74	4.37	18.15	5.30	17.43	4.94
6	0.3 -0.5	22.85	6.70	21.63	7.67	21.15	7.24	22.90	6.70	21.69	7.68	21.22	7.25	22.88	6.69	21.69	7.67	21.22	7.24
7	0.18 -0.3	21.21	7.07	23.38	8.38	20.52	7.60	21.35	7.09	23.54	8.41	20.65	7.62	21.47	7.09	23.66	8.42	20.77	7.63
8	0.11 -0.18	17.66	6.60	20.90	8.08	18.00	7.16	17.81	6.63	21.10	8.12	18.16	7.19	18.00	6.65	21.31	8.14	18.34	7.21
9	0.067 -0.11	7.84	3.68	14.69	4.82	12.55	4.21	9.93	3.69	14.85	4.85	12.68	4.24	10.05	3.71	15.03	4.87	12.83	4.25
10	0.0407-0.067	9.23	4.72	13.22	6.21	11.43	5.42	9.31	4.74	13.37	6.25	11.55	5.45	9.41	4.76	13.53	6.29	11.69	5.47
11	0.025 -0.0407	4.13	1.92	7.38	2.68	6.47	2.33	4.17	1.94	7.46	2.70	6.54	2.35	4.21	1.94	7.56	2.72	6.62	2.36
12	0.015 -0.025	4.96	2.36	9.54	3.57	7.91	3.02	4.99	2.37	9.65	3.59	7.99	3.04	5.02	2.38	9.76	3.62	8.08	3.06
13	0.0091-0.015	1.94	0.90	5.14	1.52	4.33	1.28	1.94	0.90	5.17	1.53	4.36	1.28	1.94	0.90	5.20	1.53	4.38	1.29
14	0.0055-0.0091	0.86	0.35	2.94	0.67	2.50	0.56	0.85	0.35	2.94	0.67	2.50	0.56	0.83	0.35	2.93	0.67	2.49	0.56
15	0.0021-0.0055	0.39	0.16	1.77	0.33	1.43	0.28	0.37	0.16	1.76	0.33	1.42	0.28	0.37	0.16	1.75	0.34	1.41	0.28
16	0.0005-0.0021	0.31	0.062	2.76	0.21	1.98	0.16	0.31	0.061	2.79	0.21	2.00	0.16	0.30	0.061	2.82	0.21	2.01	0.16
Neutron Balance																			
Pu^{239}	Fissions	0.278	-	0.310	-	0.299	-	0.222	-	0.244	-	0.236	-	0.139	-	0.151	-	0.146	-
Pu^{239}	Captures	0.0553	-	0.0780	-	0.072	-	0.0441	-	0.0616	-	0.0569	-	0.0276	-	0.0383	-	0.0354	-
Pu^{240}	Fissions	-	-	-	-	-	-	0.00631	-	0.00615	-	0.00621	-	0.00719	-	0.00691	-	0.00701	-
Pu^{240}	Captures	-	-	-	-	-	-	0.00614	-	0.00816	-	0.00758	-	0.00705	-	0.00923	-	0.00861	-
Pu^{241}	Fissions	-	-	-	-	-	-	0.0471	-	0.0558	-	0.0530	-	0.111	-	0.130	-	0.124	-
Pu^{241}	Captures	-	-	-	-	-	-	0.00490	-	0.00679	-	0.00628	-	0.0115	-	0.0158	-	0.0147	-
Pu^{242}	Fissions	-	-	-	-	-	-	0.00162		0.00156	-	0.00162	-	0.0175	-	0.0168	-	0.0170	-
Pu^{242}	Captures	-	-	-	-	-	-	0.00162	-	0.00212	-	0.00202	-	0.0176	-	0.0230	-	0.0215	
U^{238}	Fissions	0.0621	0.0159	0.0300	0.0235	0.0417	0.0208	0.0617	0.0159	0.0296	0.0235	0.0413	0.0208	0.0606	0.0159	0.0284	0.0235	0.0402	0.0208
U^{238}	Captures	0.302	0.295	0.169	0.404	0.226	0.354	0.302	0.297	0.168	0.406	0.225	0.355	0.297	0.297	0.162	0.407	0.220	0.357
Coolant (Na) Captures		0.00192	0.000303	0.00774	0.000606	0.00629	0.000507	0.00194	0.000303	0.00772	0.000608	0.00628	0.000509	0.00171	0.000303	0.00767	0.000609	0.00623	0.000509
Structural Captures		0.0178	0.00513	0.0251	0.00673	0.0220	0.00595	0.0179	0.00515	0.0253	0.00676	0.0221	0.00598	0.0180	0.00516	0.0255	0.00678	0.0223	0.00599
Internal Breeding Ratio		0.91		0.44		0.61		0.97		0.48		0.66		1.05		0.51		0.71	
Breeding Ratio		1.79		1.47		1.56		1.90		1.57		1.67		2.08		1.72		1.82	
Ratio Captures to Fissions in Pu^{239} + Pu^{241}		0.198		0.251		0.241		0.182		0.228		0.218		0.156		0.192		0.185	
Escape from Blanket		0.00865		0.0104		0.00972		0.00866		0.0104		0.00974		0.00865		0.0104		0.00971	

[a] The figures of critical mass represent the critical mass of the two fissionable isotopes Pu^{239} and Pu^{241}. The values in parentheses give the total mass of all four plutonium isotopes, Pu^{239}, Pu^{240}, Pu^{241}, and Pu^{242}.

Table A 3

STUDY OF 2500-LITER SPHERICAL REACTORS FUELED WITH METAL, OXIDE AND CARBIDE PLUTONIUM FUELS WITH DIFFERENT ISOTOPIC COMPOSITIONS OF PLUTONIUM

Fuel		Pu A						Pu B						Pu C					
		Metal		Oxide		Carbide		Metal		Oxide		Carbide		Metal		Oxide		Carbide	
Ratio Fuel Atoms to Diluent Atoms (Pu/U^{238})		0 0945		0 210		0 152		0 100		0 223		0 161		0 119		0 265		0 190	
Critical Mass of Fuel (kg)		1026		806		897		949 (1089)[a]		736 (845)[a]		821 (943)[a]		825 (1269)[a]		632 (973)[a]		706 (1086)[a]	
Flux Integrals																			
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3 668 -10 00	1 72	0 12	2 31	0 17	2 06	0 15	1 72	0 12	2 31	0 17	2 06	0 15	1 72	0 12	2 31	0 17	2 06	0 15
2	2 225 -3 668	3 36	0 22	4 79	0 33	4 22	0 29	3 36	0 22	4 79	0 33	4 23	0 29	3 36	0 22	4 80	0 33	4 23	0 29
3	1 35 -2 225	6 15	0 46	9 02	0 70	7 96	0 62	6 15	0 46	9 03	0 70	7 96	0 62	6 15	0 46	9 04	0 70	7 97	0 62
4	0 825 1 35	10 71	1 31	12 78	1 74	12 16	1 62	10 70	1 31	12 79	1 73	12 18	1 62	10 67	1 30	12 76	1 73	12 14	1 61
5	0 5 -0 825	18 98	3 45	19 53	4 22	18 68	3 93	18 97	3 45	19 54	4 22	18 69	3 93	18 89	3 44	19 49	4 21	18 63	3 92
6	0 3 0 5	24 77	5 33	23 58	6 16	22 96	5 79	24 82	5 34	23 64	6 16	23 03	5 80	24 81	5 33	23 64	6 15	23 03	5 79
7	0 18 0 3	23 41	5 69	26 05	6 82	22 65	6 14	23 55	5 71	26 21	6 84	22 78	6 16	23 68	5 71	26 35	6 85	22 90	6 16
8	0 11 -0 18	19 81	5 37	23 78	6 67	20 19	5 85	19 98	5 39	23 99	6 69	20 36	5 87	20 17	5 41	24 21	6 71	20 54	5 89
9	0 067 0 11	11 18	3 01	17 03	4 03	14 30	3 48	11 27	3 03	17 20	4 05	14 44	3 49	11 40	3 04	17 40	4 07	14 59	3 51
10	0 0407 0 067	10 67	3 89	15 65	5 24	13 25	4 50	10 77	3 91	15 82	5 27	13 39	4 52	10 87	3 92	16 00	5 30	13 53	4 54
11	0 025 0 0407	4 85	1 60	8 90	2 29	7 63	1 96	4 89	1 61	9 00	2 30	7 71	1 97	4 94	1 61	9 11	2 32	7 80	1 98
12	0 015 -0 025	5 98	1 99	11 92	3 12	9 59	2 59	6 02	2 00	12 06	3 15	9 69	2 60	6 05	2 00	12 18	3 17	9 78	2 62
13	0 0091 0 015	2 39	0 76	6 61	1 36	5 38	1 11	2 39	0 76	6 66	1 37	5 42	1 12	2 38	0 77	6 70	1 37	5 44	1 12
14	0 0055-0 0091	1 07	0 30	3 87	0 61	3 17	0 50	1 06	0 30	3 88	0 62	3 17	0 50	1 05	0 30	3 87	0 62	3 16	0 50
15	0 0021-0 0055	0 48	0 13	2 37	0 31	1 83	0 25	0 48	0 13	2 37	0 31	1 83	0 25	0 47	0 13	2 36	0 31	1 82	0 25
16	0 0005 0 0021	0 41	0 054	4 03	0 21	2 72	0 15	0 40	0 054	4 08	0 21	2 75	0 15	0 40	0 053	4 13	0 21	2 77	0 15
Neutron Balance																			
Pu^{239}	Fissions	0 276	-	0 308	-	0 296		0 220		0 243		0 234	-	0 138		0 150	-	0 145	
Pu^{239}	Captures	0 0568	-	0 0823	-	0 0750		0 0452		0 0650	-	0 0593		0 0283		0 0404	-	0 0368	
Pu^{240}	Fissions		-	-		-	-	0 00593		0 00560	-	0 00575		0 00677	-	0 00628	-	0 00649	-
Pu^{240}	Captures		-		-	-		0 00625	-	0 00851	-	0 00782	-	0 00718		0 00962		0 00888	-
Pu^{241}	Fissions			-	-	-		0 0473		0 0564		0 0534		0 111	-	0 131		0 125	-
Pu^{241}	Captures			-		-	-	0 00501		0 00715		0 00653	-	0 0118	-	0 0167		0 0153	-
Pu^{242}	Fissions		-	-	-			0 00153		0 00142		0 00150	-	0 0165	-	0 0153	-	0 0158	-
Pu^{242}	Captures		-	-	-	-		0 00165		0 00221	-	0 00208	-	0 0179	-	0 0240	-	0 0222	
U^{238}	Fissions	0 0646	0 0122	0 0323	0 0184	0 0442	0 0162	0 0642	0 0122	0 0320	0 0184	0 0439	0 0162	0 0632	0 0122	0 0310	0 0184	0 0428	0 0162
U^{238}	Captures	0 347	0 242	0 212	0 342	0 271	0 295	0 347	0 243	0 212	0 344	0 271	0 296	0 342	0 244	0 206	0 345	0 266	0 297
Coolant (Na) Captures		0 00242	0 000259	0 0102	0 000558	0 00802	0 000452	0 00240	0 000259	0 0102	0 000560	0 00801	0 000454	0 00236	0 000258	0 0102	0 000561	0 00796	0 000454
Structural Captures		0 0200	0 00419	0 0298	0 00563	0 0252	0 00491	0 0201	0 00421	0 0297	0 00565	0 0254	0 00493	0 0202	0 00421	0 0299	0 00567	0 0255	0 00494
Internal Breeding Ratio		1 04		0 54		0 73		1 11		0 59		0 79		1 21		0 64		0 85	
Total Breeding Ratio		1 76		1 42		1 52		1 87		1.52		1 62		2 05		1 65		1 77	
Ratio Captures to Fissions in $Pu^{239} + Pu^{241}$		0 205		0 267		0 253		0 187		0 240		0 229		0 161		0 203		0 192	
Escape from Blanket		0 00620		0 00811		0 00718		0 00623		0 00812		0 00720		0 00620		0 00811		0 00718	

[a] The figures of critical mass represent the critical mass of the two fissionable isotopes Pu^{239} and Pu^{241} The values in parentheses give the total mass of all four plutonium isotopes, Pu^{239} Pu^{240} Pu^{241} and Pu^{242}

Table A-4

EFFECT OF VARIOUS STRUCTURAL MATERIALS ON PERFORMANCE OF 800-LITER PLUTONIUM-U^{238}-METAL-FUELED REACTORS

Structural Material		Fe		Ta		Mo		Zr		Nb		Ti		V	
Ratio Fuel Atoms to Diluent Atoms (Pu/U^{238})		0.126		0.232		0.152		0.122		0.149		0.125		0.136	
Critical Mass of Fuel		431		716		502		415		494		425		456	
Flux Integrals															
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3.668 -10.00	1.62	0.21	1.45	0.17	1.51	0.18	1.81	0.24	1.71	0.21	1.85	0.25	1.66	0.20
2	2.225 -3.668	3.16	0.38	2.42	0.28	2.72	0.32	3.36	0.42	2.87	0.35	3.58	0.46	3.00	0.36
3	1.35 -2.225	5.66	0.80	3.66	0.53	4.46	0.62	6.00	0.87	4.82	0.68	6.21	0.92	4.89	0.71
4	0.825 -1.35	9.51	2.22	6.03	1.41	7.52	1.68	10.47	2.42	8.12	1.84	10.98	2.64	7.85	1.88
5	0.5 -0.825	16.18	5.72	9.93	3.52	14.25	4.50	16.30	5.92	14.71	4.86	16.43	6.42	11.54	4.49
6	0.3 -0.5	20.15	8.60	13.52	5.42	18.22	6.87	21.31	8.99	19.79	7.55	21.41	9.87	14.58	6.63
7	0.18 -0.3	18.22	8.94	12.10	5.58	16.63	7.12	18.31	9.16	17.33	7.77	17.00	9.76	14.63	6.94
8	0.11 -0.18	14.80	8.23	11.49	5.34	13.91	6.62	14.96	8.38	13.84	7.11	14.01	8.86	16.10	6.95
9	0.067 -0.11	8.10	4.53	6.27	3.01	9.44	3.90	9.06	4.75	8.35	4.03	7.92	4.90	11.42	4.26
10	0.0407-0.067	7.40	5.76	4.99	3.74	7.00	4.84	7.20	5.91	6.06	4.96	5.56	5.92	9.63	5.45
11	0.025 -0.0407	3.24	2.33	1.81	1.49	3.70	2.05	4.09	2.51	3.10	2.06	3.11	2.43	5.72	2.42
12	0.015 -0.025	3.73	2.80	0.69	1.54	2.08	2.22	2.60	2.75	1.67	2.21	0.96	2.49	2.73	2.54
13	0.0091-0.015	1.42	1.05	0.18	0.54	0.83	0.81	1.18	1.03	0.62	0.80	1.47	1.04	1.14	0.93
14	0.0055-0.0091	6.07	0.40	0.037	0.18	0.29	0.30	0.47	0.39	0.19	0.29	1.29	0.47	0.79	0.37
15	0.0021-0.0055	2.64	0.18	0.0070	0.078	0.081	0.13	0.14	0.17	0.047	0.12	0.55	0.22	0.71	0.19
16	0.0005-0.0021	2.00	0.070	0.0016	0.029	0.041	0.046	0.10	0.064	0.022	0.045	0.45	0.098	0.85	0.11
Neutron Balance															
Pu^{239}	Fissions	0.282	-	0.299	-	0.292	-	0.277	-	0.282	-	0.274	-	0.287	-
Pu^{239}	Captures	0.0532	-	0.0511	-	0.0543	-	0.0503	-	0.0476	-	0.0495	-	0.0640	-
U^{238}	Fissions	0.0593	0.0214	0.0390	0.0152	0.0478	0.0173	0.0629	0.0236	0.0520	0.0192	0.0654	0.0254	0.0532	0.0196
U^{238}	Captures	0.245	0.364	0.133	0.224	0.211	0.296	0.244	0.373	0.194	0.308	0.235	0.387	0.266	0.325
Coolant (Na) Captures		0.00144	0.000353	0.000258	0.000166	0.000644	0.0000670	0.000949	0.000337	0.000524	0.000252	0.00262	0.000425	0.00320	0.000357
Structural Captures		0.0149	0.00637	0.268	0.00401	0.113	0.00522	0.0133	0.00659	0.117	0.00548	0.0102	0.00685	0.0211	0.00563
Internal Breeding Ratio		0.73		0.38		0.61		0.75		0.59		0.73		0.76	
Breeding Ratio		1.82		1.02		1.46		1.89		1.51		1.92		1.68	
Ratio Fuel Captures to Fuel Fissions		0.188		0.170		0.185		0.181		0.169		0.180		0.222	
Escape from Blanket		0.0118		0.00757		0.00932		0.0125		0.0103		0.0136		0.00954	

Table A-5

STUDY OF 800, 1500 AND 2500-LITER SPHERICAL REACTORS FUELED WITH METAL, OXIDE AND CARBIDE PLUTONIUM FUELS WITH NIOBIUM AS THE STRUCTURAL MATERIAL IN THE CORE

Fuel		Metal		Oxide		Carbide		Metal		Oxide		Carbide		Metal		Oxide		Carbide	
Core Volume (liters)		800		800		800		1500		1500		1500		2500		2500		2500	
Ratio Fuel Atoms to Diluent Atoms (Pu/U^{238})		0.149		0.452		0.283		0.128		0.362		0.238		0.117		0.314		0.209	
Critical Mass of Fuel (kg)		494		462		480		809		739		788		1247		1109		1178	
Flux Integrals																			
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3.668 -10.00	1.71	0.21	2.28	0.31	2.04	0.27	1.78	0.15	2.41	0.23	2.14	0.20	1.82	0.12	2.50	0.18	2.21	0.16
2	2.225 -3.668	2.87	0.35	3.86	0.51	3.49	0.45	2.97	0.26	4.06	0.38	3.65	0.34	3.04	0.20	4.20	0.30	3.75	0.26
3	1.35 -2.225	4.82	0.68	6.47	0.98	5.90	0.88	5.04	0.50	6.89	0.74	6.23	0.66	5.18	0.39	7.16	0.58	6.46	0.51
4	0.825 -1.35	8.12	1.84	9.01	2.34	8.78	2.21	8.63	1.37	9.69	1.77	9.40	1.66	8.96	1.06	10.14	1.39	9.83	1.29
5	0.5 -0.825	14.71	4.86	14.29	5.71	13.98	5.38	16.03	3.67	15.67	4.37	15.25	4.10	16.89	2.85	16.61	3.44	16.15	3.21
6	0.3 -0.5	19.79	7.55	18.27	8.42	18.07	8.02	22.13	5.78	20.48	6.52	20.15	6.18	23.72	4.55	22.03	5.17	21.67	4.89
7	0.18 -0.3	17.33	7.77	18.72	8.95	16.75	8.26	19.76	6.02	21.53	7.03	19.04	6.43	21.44	4.77	23.55	5.63	20.74	5.12
8	0.11 -0.18	13.84	7.11	15.88	8.40	4.08	7.63	16.12	5.57	18.76	6.70	16.32	6.00	17.72	4.45	20.88	5.42	18.04	4.82
9	0.067 -0.11	8.35	4.03	11.81	5.09	10.36	4.55	9.94	3.20	14.38	4.14	12.00	3.61	10.71	2.55	16.33	3.40	13.85	2.96
10	0.0407-0.067	6.06	4.96	8.26	6.23	7.57	5.60	7.36	3.95	10.32	5.10	8.98	4.47	8.09	3.16	11.92	4.21	10.50	3.68
11	0.025 -0.0407	3.10	2.06	5.17	2.76	4.78	2.47	3.90	1.67	6.73	2.31	5.87	2.01	4.37	1.34	7.98	1.94	7.03	1.68
12	0.015 -0.025	1.67	2.21	3.15	3.01	2.98	2.71	2.10	1.78	4.18	2.54	3.72	2.21	2.36	1.44	5.03	2.14	4.52	1.86
13	0.0091-0.015	0.62	0.80	1.47	1.15	1.44	1.04	0.79	0.65	2.02	0.98	1.85	0.86	0.90	0.52	2.48	0.84	2.29	0.73
14	0.0055-0.0091	0.19	0.29	0.62	0.44	0.63	0.40	0.25	0.23	0.87	0.38	0.83	0.34	0.29	0.19	1.09	0.33	1.04	0.29
15	0.0021-0.0055	0.047	0.12	0.20	0.19	0.21	0.18	0.062	0.099	0.29	0.17	0.28	0.15	0.070	0.080	0.37	0.14	0.35	0.13
16	0.0005-0.0021	0.022	0.044	0.13	0.071	0.14	0.66	0.030	0.035	0.20	0.062	0.19	0.055	0.035	0.028	0.26	0.054	0.25	0.048
Neutron Balance																			
Pu^{239}	Fissions	0.282	-	0.317	-	0.306	-	0.284	-	0.314	-	0.304	-	0.283	-	0.313	-	0.302	-
Pu^{239}	Captures	0.0476	-	0.0620	-	0.0595	-	0.0514	-	0.0647	-	0.0609	-	0.0521	-	0.0664	-	0.0631	-
U^{238}	Fissions	0.0520	0.0192	0.0213	0.0276	0.0321	0.0247	0.0551	0.0141	0.0241	0.0208	0.0351	0.0185	0.0572	0.0109	0.0259	0.0162	0.0371	0.0143
U^{238}	Captures	0.194	0.308	0.0796	0.387	0.122	0.353	0.240	0.243	0.102	0.314	0.148	0.281	0.266	0.195	0.120	0.258	0.172	0.229
Coolant (Na) Captures		0.000524	0.000252	0.00118	0.000373	0.00118	0.000344	0.000622	0.000202	0.00159	0.000321	0.00129	0.000278	0.000619	0.000161	0.00193	0.000274	0.00184	0.00244
Structural Captures		0.117	0.00548	0.162	0.00677	0.151	0.00618	0.138	0.00431	0.201	0.00546	0.190	0.00490	0.157	0.00345	0.231	0.00446	0.208	0.00397
Internal Breeding Ratio		0.59		0.21		0.33		0.71		0.27		0.41		0.79		0.32		0.47	
Breeding Ratio		1.51		1.23		1.29		1.43		1.09		1.17		1.37		0.99		1.09	
Ratio Fuel Captures to Fuel Fissions		0.169		0.195		0.194		0.180		0.205		0.200		0.184		0.212		0.208	
Escape from Blanket		0.0103		0.0126		0.0106		0.00727		0.00878		0.00820		0.00529		0.00660		0.00598	

Table A-6

STUDY OF 800, 1500, AND 2500-LITER SPHERICAL REACTORS FUELED WITH METAL, OXIDE, AND CARBIDE PLUTONIUM FUELS WITH LEAD-BISMUTH EUTECTIC ALLOY AS COOLANT

Fuel		Metal		Oxide		Carbide		Metal		Oxide		Carbide		Metal		Oxide		Carbide	
Core Volume, (liters)		800		800		800		1500		1500		1500		2500		2500		2500	
Ratio: Fuel Atoms to Diluent Atoms (Pu/U^{238})		0.118		0.294		0.200		0.099		0.223		0.160		0.088		0.187		0.138	
Critical Mass of Fuel (kg)		403		337		363		642		508		564		962		730		828	
Flux Integrals																			
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3.668 -10.00	1.24	0.13	1.53	0.17	1.41	0.16	1.27	0.094	1.58	0.13	1.45	0.11	1.29	0.072	1.61	0.095	1.48	0.087
2	2.225 -3.668	2.83	0.28	3.79	0.38	3.43	0.34	2.91	0.20	3.94	0.28	3.55	0.25	2.97	0.15	4.04	0.21	3.63	0.192
3	1.35 -2.225	5.58	0.64	7.77	0.91	6.98	0.82	5.82	0.47	8.25	0.67	7.37	0.61	5.97	0.36	8.56	0.52	7.62	0.47
4	0.825 -1.35	11.37	2.19	13.19	2.72	12.70	2.59	12.22	1.63	14.39	2.05	13.81	1.96	12.79	1.27	15.19	1.60	14.55	1.52
5	0.5 -0.825	22.34	6.74	22.20	7.60	21.27	7.20	25.05	5.18	25.06	5.88	23.88	5.55	26.94	4.10	27.08	4.65	25.71	4.39
6	0.3 -0.5	23.71	9.21	22.52	10.04	21.95	9.59	27.24	7.18	25.98	7.86	25.16	7.48	29.78	5.73	28.47	6.27	27.47	5.96
7	0.18 -0.3	20.64	9.22	23.74	10.58	20.40	9.67	24.31	7.30	28.36	8.47	23.96	7.66	27.02	5.88	31.81	6.85	26.58	6.16
8	0.11 -0.18	15.22	7.99	19.12	9.54	16.32	8.55	18.29	6.40	23.52	7.76	19.59	6.86	20.60	5.20	26.91	6.36	22.05	5.56
9	0.067 -0.11	7.64	4.15	12.60	5.35	10.76	4.74	9.31	3.35	15.93	4.43	13.21	3.85	10.59	2.74	18.55	3.68	15.08	3.16
10	0.0407-0.067	7.72	5.63	11.83	7.28	10.20	6.42	9.74	4.59	15.56	6.12	12.93	5.28	11.31	3.77	18.58	5.13	15.06	4.36
11	0.025 -0.0407	2.55	1.96	5.38	2.70	4.83	2.39	3.28	1.61	7.29	2.31	6.28	1.99	3.86	1.33	8.87	1.96	7.44	1.66
12	0.015 -0.025	3.20	2.43	7.07	3.59	5.95	3.12	4.30	2.03	10.15	3.18	8.09	2.67	5.20	1.69	12.81	2.76	9.86	2.26
13	0.0091-0.015	1.05	0.85	3.46	1.40	3.02	1.21	1.45	0.72	5.22	1.28	4.27	1.07	1.78	0.60	6.79	1.14	5.33	0.92
14	0.0055-0.0091	0.41	0.30	1.93	0.58	1.70	0.50	0.59	0.26	3.03	0.55	2.50	0.46	0.74	0.22	4.06	0.51	3.20	0.41
15	0.0021-0.0055	0.27	0.18	2.21	0.47	1.60	0.38	0.41	0.15	3.84	0.50	2.51	0.37	0.54	0.13	5.48	0.49	3.35	0.34
16	0.0005-0.0021	0.027	0.020	0.56	0.065	0.54	0.058	0.043	0.017	1.10	0.073	0.94	0.060	0.058	0.014	1.70	0.076	1.33	0.059
Neutron Balance																			
Pu^{239}	Fissions	0.286	-	0.315	-	0.305	-	0.283	-	0.313	-	0.302	-	0.282	-	0.312	-	0.301	-
Pu^{239}	Captures	0.0495	-	0.0687	-	0.0645	-	0.0514	-	0.0745	-	0.0687	-	0.0526	-	0.0787	-	0.0716	-
U^{238}	Fissions	0.0544	0.0163	0.0245	0.0225	0.0352	0.0204	0.0574	0.0119	0.0723	0.0166	0.0381	0.0150	0.0593	0.00917	0.0290	0.0127	0.0399	0.0115
U^{238}	Captures	0.255	0.347	0.132	0.451	0.184	0.404	0.313	0.279	0.185	0.379	0.242	0.332	0.357	0.228	0.231	0.319	0.288	0.274
Coolant Captures		0.00396	0.000697	0.00511	0.000857	0.00458	0.000778	0.00465	0.000554	0.00632	0.000701	0.00551	0.000626	0.00516	0.000449	0.00731	0.000578	0.00622	0.000509
Structural Captures		0.0156	0.00615	0.0218	0.00771	0.0194	0.00695	0.0187	0.00493	0.0276	0.00637	0.0237	0.00564	0.0209	0.00401	0.0323	0.00528	0.0272	0.00461
Internal Breeding Ratio		0.76		0.35		0.50		0.93		0.48		0.65		1.06		0.59		0.77	
Breeding Ratio		1.79		1.52		1.59		1.76		1.45		1.54		1.74		1.40		1.50	
Ratio Fuel Captures to Fuel Fissions		0.173		0.217		0.211		0.181		0.237		0.226		0.186		0.252		0.237	
Escape from Blanket		0.00992		0.0115		0.0109		0.00684		0.00831		0.00766		0.00517		0.00624		0.00568	

Table A 7

STUDY OF 800, 1500 AND 2500 LITER SPHERICAL REACTORS FUELED WITH U^{233}-THORIUM AS METAL OXIDE OR CARBIDE, HAVING STEEL STRUCTURE AND SODIUM CONTENT

Fuel		Metal		Oxide		Carbide		Metal		Oxide		Carbide		Metal		Oxide		Carbide	
Core Volume (liters)		800		800		800		1500		1500		1500		2500		2500		2500	
Ratio Fuel Atoms to Diluent Atoms (Pu/U^{238})		0 138		0 332		0 232		0 107		0 240		0 178		0 0909		0 194		0 149	
Critical Mass of Fuel, (kg)		453		371		410		679		539		616		968		755		890	
Flux Integrals																			
Group	Energy Interval (Mev)	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket
1	3 668 10 00	1 90	0 30	2 11	0 33	1 91	0 29	2 00	0 23	2 23	0 24	2 01	0 21	2 07	0 18	2 31	0 19	2 07	0 17
2	2 225 -3 668	3 83	0 59	4 36	0 64	3 91	0 57	4 06	0 45	4 63	0 48	4 12	0 43	4 21	0 36	4 80	0 38	4 26	0 33
3	1 35 2 225	6 89	1 34	7 91	1 44	7 08	1 30	7 46	1 03	8 55	1 10	7 60	0 98	7 84	0 82	8 98	0 87	7 94	0 77
4	0 825 1 35	11 52	4 39	11 31	4 23	11 10	4 07	12 86	3 46	12 51	3 26	12 23	3 13	13 81	2 78	13 34	2 59	13 01	2 48
5	0 5 0 825	17 09	9 15	16 00	8 63	15 55	8 24	19 68	7 33	18 17	6 76	17 56	6 42	21 56	5 97	19 69	5 40	18 96	5 12
6	0 3 0 5	20 01	13 88	17 98	12 68	17 71	12 20	24 04	11 39	21 06	10 11	20 61	9 68	27 12	9 44	23 27	8 18	22 68	7 81
7	0 18 0 3	17 26	14 15	18 32	13 63	16 17	12 56	21 55	11 90	22 30	11 15	19 39	10 16	24 96	10 04	25 28	9 18	21 76	8 30
8	0 11 -0 18	12 87	11 65	15 11	11 81	13 10	10 62	16 61	10 00	19 10	9 89	16 18	8 74	19 71	8 56	22 20	8 28	18 51	7 23
9	0 067 0 11	7 11	6 63	10 17	7 16	8 80	6 37	9 39	5 77	13 28	6 12	11 15	5 33	11 33	4 99	15 75	5 20	12 97	4 46
10	0 0407 0 067	5 45	7 09	8 26	7 95	7 19	7 03	7 52	6 26	11 27	6 94	9 48	5 98	9 35	5 47	13 77	5 97	11 30	5 06
11	0 025 0 0407	2 29	2 86	4 31	3 38	3 80	2 98	3 27	2 56	6 11	3 00	5 17	2 57	4 17	2 25	7 63	2 61	6 30	2 20
12	0 015 0 025	2 34	3 31	4 75	4 24	3 96	3 66	3 60	3 05	7 23	3 94	5 72	3 27	4 80	2 74	9 45	3 55	7 21	2 86
13	0 0091 0 015	0 78	1 18	2 26	1 71	1 91	1 46	1 27	1 10	3 67	1 66	2 92	1 36	1 77	1 01	5 00	1 54	3 82	1 22
14	0 0055 0 0091	0 31	0 50	1 13	0 79	0 97	0 67	0 53	0 48	1 94	0 79	1 55	0 64	0 77	0 44	2 74	0 75	2 09	0 58
15	0 0021 0 0055	0 13	0 26	0 61	0 42	0 50	0 36	0 23	0 25	1 11	0 43	0 83	0 35	0 34	0 23	1 60	0 41	1 15	0 32
16	0 0005 0 0021	0 11	0 15	0 78	0 27	0 57	0 22	0 22	0 14	1 62	0 29	1 08	0 22	0 36	0 13	2 59	0 30	1 60	0 21
Neutron Ba'ance																			
U^{233}	Fissions	0 380	-	0 385		0 383		0 380		0 386		0 383		0 380		0 386		0 383	
U^{233}	Captures	0 0322	-	0 0380		0 0368		0 0338		0 0411		0 0392		0 0351	-	0 0433		0 0408	
Thorium Fissions		0 00885	0 00414	0 00550	0 00450	0 00782	0 00401	0 00972	0 00317	0 00632	0 00340	0 00868	0 00301	0 0102	0 00252	0 00684	0 00267	0 00923	0 00235
Thorium Captures		0 157	0 377	0 115	0 409	0 161	0 368	0 208	0 325	0 166	0 353	0 217	0 309	0 252	0 280	0 212	0 303	0 264	0 260
Coolant (Na) Captures		0 000876	0 000521	0 00288	0 000788	0 00238	0 000678	0 00136	0 000486	0 00498	0 000784	0 00382	0 000640	0 00188	0 000444	0 00709	0 000742	0 00517	0 000582
Structural Captures		0 0132	0 00905	0 0168	0 00960	0 0150	0 00868	0 0169	0 00777	0 0219	0 00818	0 0190	0 00723	0 0200	0 00666	0 0262	0 00695	0 0221	0 00604
Internal Breeding Ratio		0 38		0 27		0 38		0 50		0 39		0 52		0 61		0 49		0 62	
Total Breeding Ratio		1 29		1 23		1 26		1 28		1 21		1 24		1 28		1 19		1 23	
Ratio Fuel Captures to Fuel Fissions		0 0847		0 0986		0 0962		0 0890		0 106		0 102		0 0922		0 112		0 106	
Escape from Blanket		0 0264		0 0254		0 0237		0 0199		0 0187		0 0173		0 0155		0 0143		0 0133	

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ACKNOWLEDGMENT

Considerable assistance in the numerical analysis of the results of the multigroup diffusion theory calculations was provided by Louis Kvitek.