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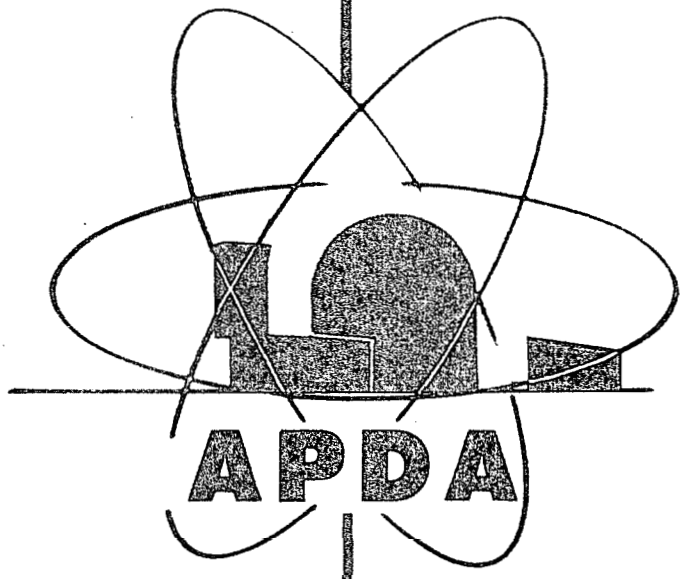

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PRELIMINARY REPORT ON SODIUM TEMPERATURE COEFFICIENTS IN LARGE FAST REACTORS

J. B. Nims
P. F. Zweifel

November, 1959

ATOMIC POWER
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November 1959

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ABSTRACT

Present practice in fast reactor design is to eliminate any known positive temperature coefficients of reactivity. This approach has been feasible for the fast power reactors now being constructed. In recent considerations of advanced fast reactor designs at APDA, some cases were encountered in which the sodium temperature coefficient of reactivity was positive. Because of the serious implications of this result, a study of the sodium temperature coefficient of a design in which the problem appears to be most severe has been made. The principle objective of the study was to obtain a better understanding of the problem. Simply stated, reducing the sodium density causes spectral reactivity effects which can, in some situations, be positive and larger in magnitude than the negative leakage effect, thereby causing a positive temperature coefficient of reactivity. In addition, some attention has also been given to possible methods of influencing the sign of the sodium coefficient. Although the results indicate that these methods could be successfully applied, there are penalties involved with their use.

The results given are believed to be qualitatively correct, but the uncertainties in the cross section data on which they are based cast some doubt on the quantitative accuracy.

GENERAL DISCUSSION

The component of the total temperature coefficient of reactivity which is attributable to density changes of the sodium coolant is of importance to fast reactors now in operation and under construction. Power and coolant temperature are closely coupled, and the sodium temperature coefficient of reactivity is, therefore, prompt. In the Enrico Fermi reactor, the sodium temperature coefficient is -4.4×10^{-6} $\Delta k/k/C$, which is the same magnitude as the other important temperature coefficients, and the time response associated with sodium heating is 0.2 second. The only effects that exhibit faster response are Doppler broadening and fuel expansion. From the standpoint of reactor control and safety, this temperature coefficient is, therefore, of particular advantage because of its sign, magnitude, and prompt response.

In some recent considerations of advanced fast reactor designs, some cases have been encountered in which the sodium temperature coefficient is positive and of significant magnitude. This is a matter of considerable concern in the light of present fast reactor safety philosophy because the building of a fast reactor with a known prompt positive temperature coefficient is not consistent with present practice. In the design of the Enrico Fermi reactor, a considerable effort was made to eliminate such effects. In this case it was possible to eliminate the only significant positive coefficient, due to a delayed structural expansion, by a simple alteration of the mechanical design.

In a fast reactor, the magnitude and sign of the sodium temperature coefficient is affected by the amount of threshhold fission material that is present, by the size of the core, and by the type of fissionable material that is present, i.e., U-235 or Pu-239. The tendency in advanced fast reactor designs is toward

larger cores, increased concentrations of fertile or threshhold fission material, and the use of Pu-239 rather than U-235 as the fuel. All of these factors tend to make the sodium temperature coefficient more positive.

Because the possibility of a positive sodium coefficient could play an important part in future plans, it was felt that an effort was warranted to attempt to gain a better understanding of the problem and, beyond this, to make a preliminary study of means of adjusting this coefficient. In the work described here, consideration has been limited to fast reactors which use cermet fuel. Thus, although the results do yield a better understanding of the basic effects that are involved, they do not provide any information as to how these effects may be manifested among other promising types of fast reactor fuels. Furthermore, it should be pointed out that there is considerable doubt as to the accuracy of the results obtained because of uncertainties in the cross sections. This uncertainty includes not only the sodium inelastic and elastic scattering data which are primarily involved, but also the cross sections of all other materials in the reactor because these cross sections determine the dependence of the neutron importance on energy and, hence, the sign of the spectral component of the sodium temperature coefficient. An early reevaluation of the currently formulated multigroup cross-sectional data is certainly warranted. Because this reevaluation will undoubtedly include a considerable amount of theoretical results that have not been checked experimentally, sodium danger coefficient measurements that are designed for this particular problem should also be made at an early date in a fast reactor critical experiment.

THE SIGN OF THE SODIUM TEMPERATURE COEFFICIENT

There are three components of the sodium temperature coefficient of reactivity of which only two are usually significant. There is a leakage component

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which is negative, a spectral component which can be either positive or negative, and an absorption component which is positive but usually comparatively insignificant.

The explanation of the leakage component is obvious. A reduction in sodium density makes the core more transparent to neutrons and thereby enables more neutrons to escape from the core to regions of lower neutron importance. The spectral component is caused by the reduced sodium inelastic and elastic scattering that occurs when the sodium density is decreased. Sodium degrades the neutron spectrum at the high end as a result of inelastic scattering and builds up the low end of the spectrum by elastic scattering; thus, a decrease in sodium density tends to harden the spectrum through the reduction in the sodium inelastic and elastic scattering. This hardening of the spectrum can constitute a positive or negative reactivity effect depending on the reactor composition. Hardening the spectrum at the high energy end increases the probability of threshhold fission. In addition, the probability of fission absorption in the normal fissile material can change either positively or negatively depending on the core composition and on whether U-235 or Pu-239 is used. In one sense, the elastic spectral effect depends on the relative change in the fission cross section with energy compared to the change in the absorption cross sections of other materials present. Viewed in this manner, the elastic spectral component to the sodium coefficient tends to be more positive with Pu-239 than with U-235 because the fission cross section of Pu-239 is much less sensitive than that of U-235 to the change in spectrum as compared to the energy sensitivity of the cross sections of the other materials present. This can be seen in Figure 1 in which a comparison is made of the fission cross-sections of Pu-239 and U-235 with the U-238 capture cross-sections.

The net result is that the spectral component may be positive and larger in absolute magnitude than the negative leakage term, thus giving a positive sodium temperature coefficient.

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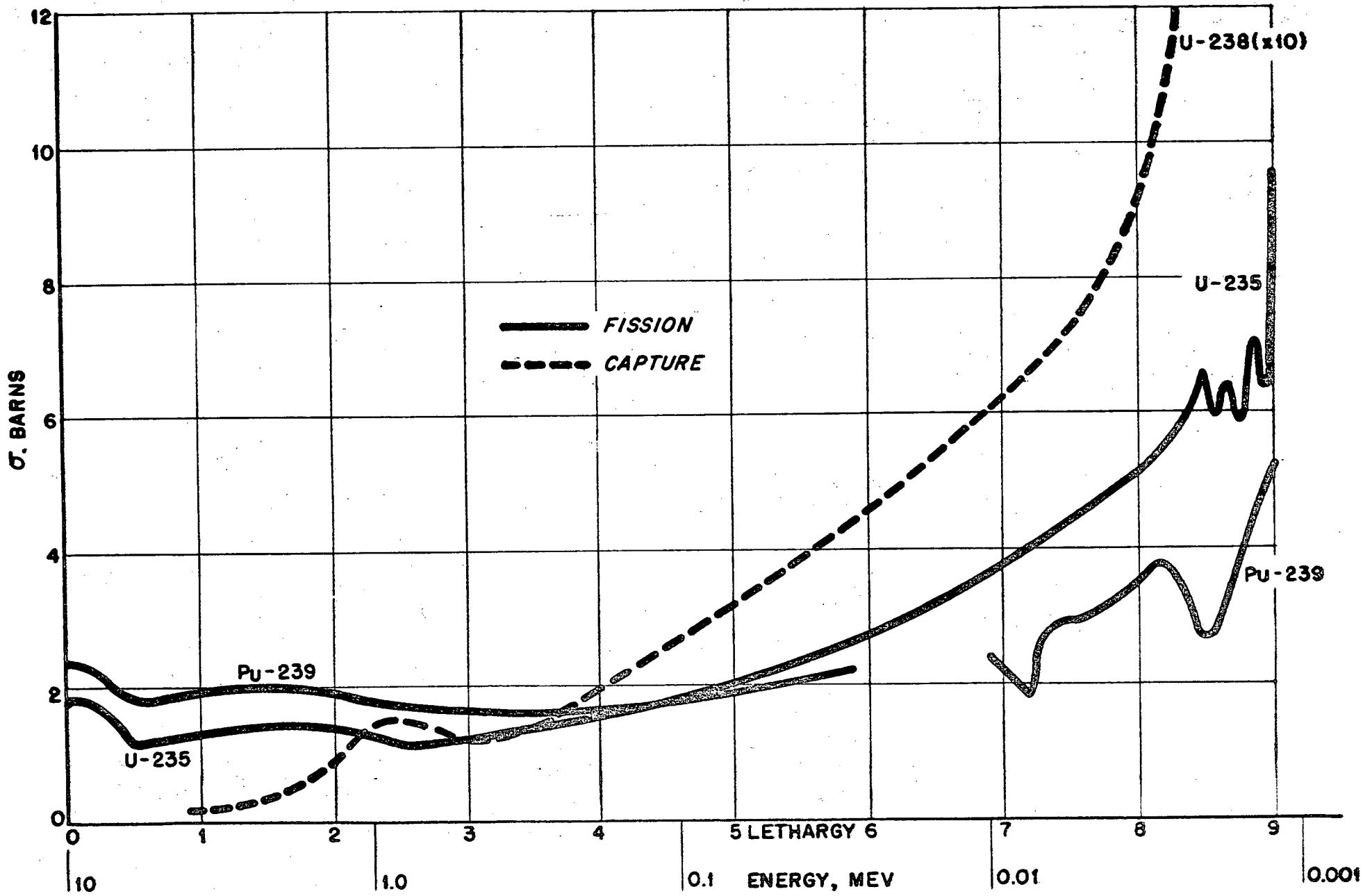

FIG. 1 ENERGY DEPENDENCE OF PERTINENT FISSION AND CAPTURE CROSS SECTIONS

DETAILED CONSIDERATION OF A CERMET-FUELED FAST REACTOR

In order to obtain a better insight into this problem, a detailed study has been made of a fairly large fast reactor having a cermet fuel. The cermet fuel was chosen because, by its nature, the use of such a fuel permits high concentrations of fertile material in the core and, therefore, is the type of fuel in which the positive coefficient problem is the most severe.

In obtaining the results presented, multigroup diffusion theory and spherical reactor models have been used. The multigroup codes used are PROD for the IBM 650 and DMM for the Datatron 205. The flux adjoints were computed by means of modified versions of these codes. In addition, an IBM 650 program that calculates the individual terms of the material danger coefficient, i.e. leakage, inelastic scattering, elastic scattering, and absorption, was used.

The group constants were obtained by modifying the constants for fast reactors given in Report ANL-5800 from 11 to 10 energy groups.

A description of the reactor is given in Table I. Two cases were considered: one with Pu-239 as the fissionable material and the other with U-235. In both cases the fuel is representative of a recycled material and, therefore, includes appropriate amounts of either Pu-240 or U-236. It is important to include these materials because they undergo threshhold fission and, therefore, contribute to the positive component of the sodium temperature coefficient. The significance of the kind of primary fissile material is seen from the isothermal temperature coefficients given in Table I, which are positive for the plutonium case and negative for the uranium case.

The reason for the difference in the sign of the sodium temperature coefficient between the Pu and U systems can be understood better by considering the neutron importance functions shown in Figure 2. The importance functions shown are for the PuO_2 and UO_2 cermet designs described in Table I and for the

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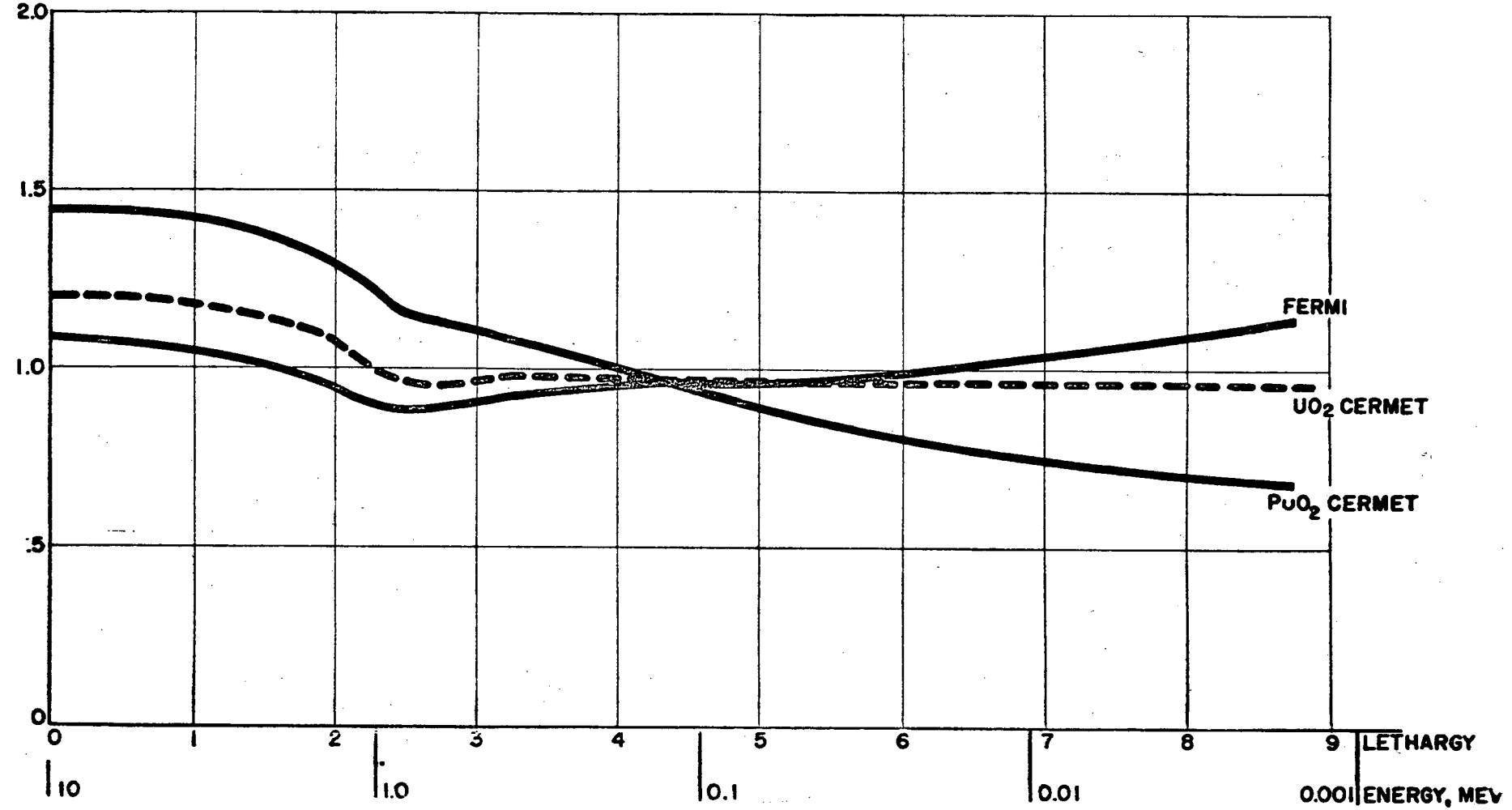

FIG. 2 COMPARISON OF NEUTRON IMPORTANCE IN Pu & U-235 SYSTEMS

Enrico Fermi reactor, which uses a U-10 w/o Mo alloy as fuel material. These importance functions are normalized core values that contain only volume weighting. The liberty of showing the multigroup results as smoothly varying continuous curves has been taken in order to make the significance of these results clear.

TABLE I

DESCRIPTION OF REACTOR

Fuel: PuO_2-U.15 w/o Mo Cermet or
UO_2-U.15 w/o Mo Cermet

Core Volume: 800 liters

Core Composition, Volume Per Cent:

Fuel	40
Coolant	40
Clad	5
Structure	15

Blanket Thickness: 18 inches

Blanket Composition, Volume Per Cent:

Fertile Material	45
Structure and Clad	15
Coolant	40

Isothermal Na Temperature Coefficient

With Pu fuel	$+4 \times 10^{-6}$ $\Delta k/k/C$
With U fuel	-3×10^{-6} $\Delta k/k/C$

For the plutonium fuel, neutron importance is an increasing function of energy over the entire spectrum. Thus, any type of energy degradation, whether elastic or inelastic, will tend to decrease reactivity and, conversely, hardening of the spectrum by lowering the sodium density increases the reactivity. Therefore, both the elastic and inelastic scattering components of the sodium temperature coefficient will be positive. In addition, it is seen that the difference in importance between energies above and below the U-238 fission threshhold is

COY 011

large; therefore, the inelastic portion of the spectral component will be relatively significant.

For the UO_2 cermet core, neutron importance is a much less sensitive function of neutron energy. Inelastic scattering to energies below threshhold fission energies still decreases reactivity, but much less significantly with a UO_2 cermet core than with a plutonium core. In the low energy range, degradation of energy hardly affects importance at all. Thus, with U-235 as the primary fissionable isotope, it is to be expected that the spectral component will be positive but small.

In the Enrico Fermi reactor, neutron importance shows another effect due to reactor composition. The inelastic scattering effect is of much smaller significance than in even the UO_2 cermet core. But in the low energy range, neutron importance is a decreasing function of energy. Thus, in the Enrico Fermi reactor, the elastic component due to the temperature coefficient will be negative rather than positive. This important difference can be attributed to the lower U-238/U-235 ratio, which is about 3:1 in the Enrico Fermi reactor as compared to about 5:1 in the UO_2 cermet system. Thus, in the Enrico Fermi reactor, it is expected that the spectral component will be negative rather than positive.

The effect of removing sodium on neutron absorption is given in Table II. This shows the effect of removing 40% of the sodium in the core for both the Pu-239 and the U-235 cermet-fueled reactors. Note that the removal of sodium reduces core absorptions by about 2% in both cases due to increased leakage. Despite this increase in leakage, the threshhold fissions increase. This increase is most pronounced in the Pu-240, which has the lowest fission threshhold energy. Furthermore, it is seen that the U-235 fissions tend to decrease almost in the same ratio as the core absorptions, indicating little spectral effect. On the other hand, the Pu-239 fissions, while decreased, are decreased to a much smaller extent than would

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be expected from the increase in leakage alone. The other significant point is that the nonfission absorptions are reduced far more than leakage increases.

TABLE II

CORE NEUTRON ABSORPTION REDISTRIBUTION

(40% of Core Sodium Removed)

Fuel		U-235			Pu-239		
		A	ΔA	ΔA(%)/A	A	ΔA	ΔA(%)/A
Fission	U-235	0.2877	-0.0052	-1.8	--	--	--
	U-236	0.0117	+0.0003	+2.2	--	--	--
	U-238	0.0390	+0.0005	+1.2	0.0412	+0.0006	+1.5
	Pu-239	--	--	--	0.02364	-0.0015	-0.6
	Pu-240	--	--	--	0.0223	+0.0008	+3.5
Capture	U-235	0.0621	-0.0027	-4.4	--	--	--
	U-236	0.0332	-0.0003	-0.8	--	--	--
	U-238	0.1840	-0.0052	-2.8	0.2096	-0.0076	-3.6
	Pu-235	--	--	--	0.0495	-0.0025	-5.0
	Pu-240	--	--	--	0.0226	-0.0010	-4.3
	Mo	0.0295	-0.0011	-3.7	0.0351	-0.0020	-5.7
	Zr	0.0034	-0.0003	-7.6	0.0042	-0.0004	-8.6
	SS	0.0070	-0.0001	-1.7	0.0078	-0.0002	-2.1
	Na	0.0010	-0.0004	-43.2	0.0012	-0.0005	-44.6
	FP	0.0020	-0.0001	-5.9	0.0025	-0.0002	-7.3
	O_2	0.0000	--	--	--	--	--
		0.6607	-0.0146	-2.2	0.6323	-0.0144	-2.3

The components of the sodium danger coefficients are given in Figures 3, 4, and 5 for the two different cermet cases considered and for the Enrico Fermi reactor.

In Figure 3, which gives results for the PuO_2 cermet core, it is seen that the scattering components are both negative as would be predicted from consideration of the importance functions. The elastic term is approximately twice the magnitude of the inelastic term. Neutron capture is of minor importance. Leakage is positive and achieves its maximum value in the vicinity of the core boundary. The net effect is strongly negative near the center of the core but

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$\beta_{eff} \simeq 0.0038$

AVERAGE WORTH – 1.4¢/kg

RADIUS NORMALIZED TO CORE RADIUS

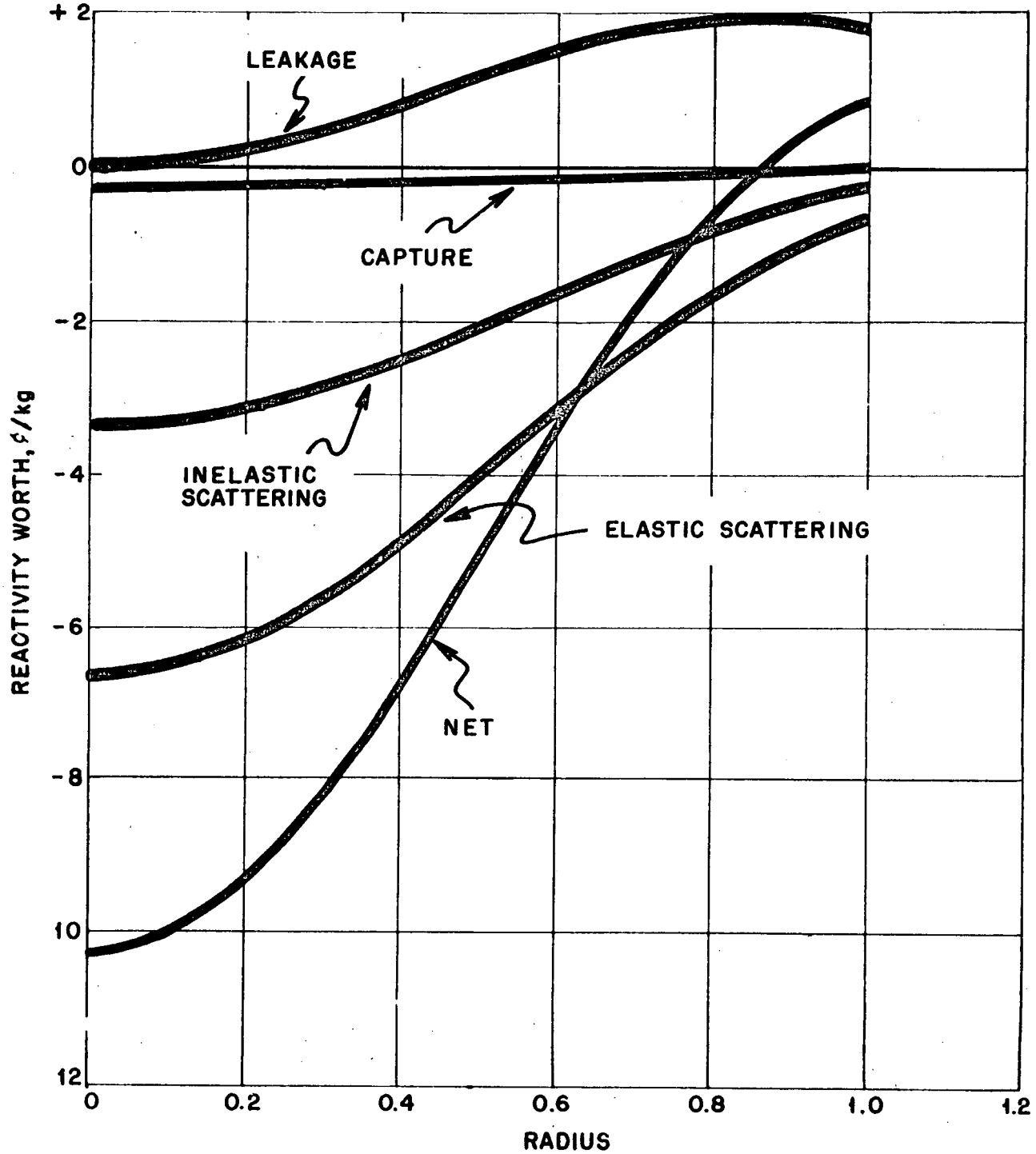

FIG. 3 COMPONENTS OF THE SODIUM DANGER COEFFICIENT IN THE PuO_2– UMo SYSTEM

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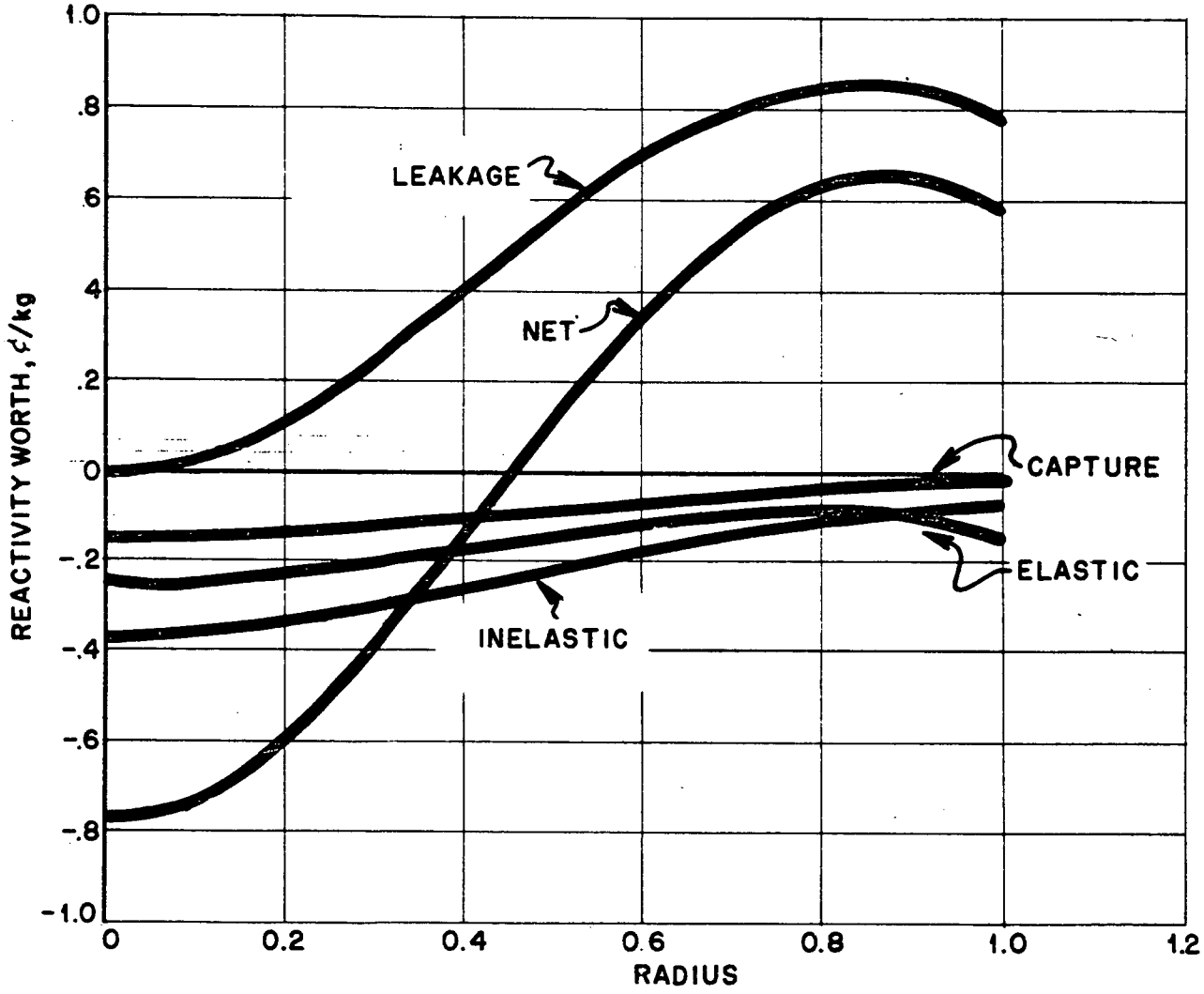

FIG. 4 COMPONENTS OF THE SODIUM DANGER COEFFICIENT IN THE UO_2-UMo SYSTEM

$\beta_{eff} = 0.0069$

AVERAGE WORTH = 3.3¢/kg
RADIUS NORMALIZED TO CORE RADIUS

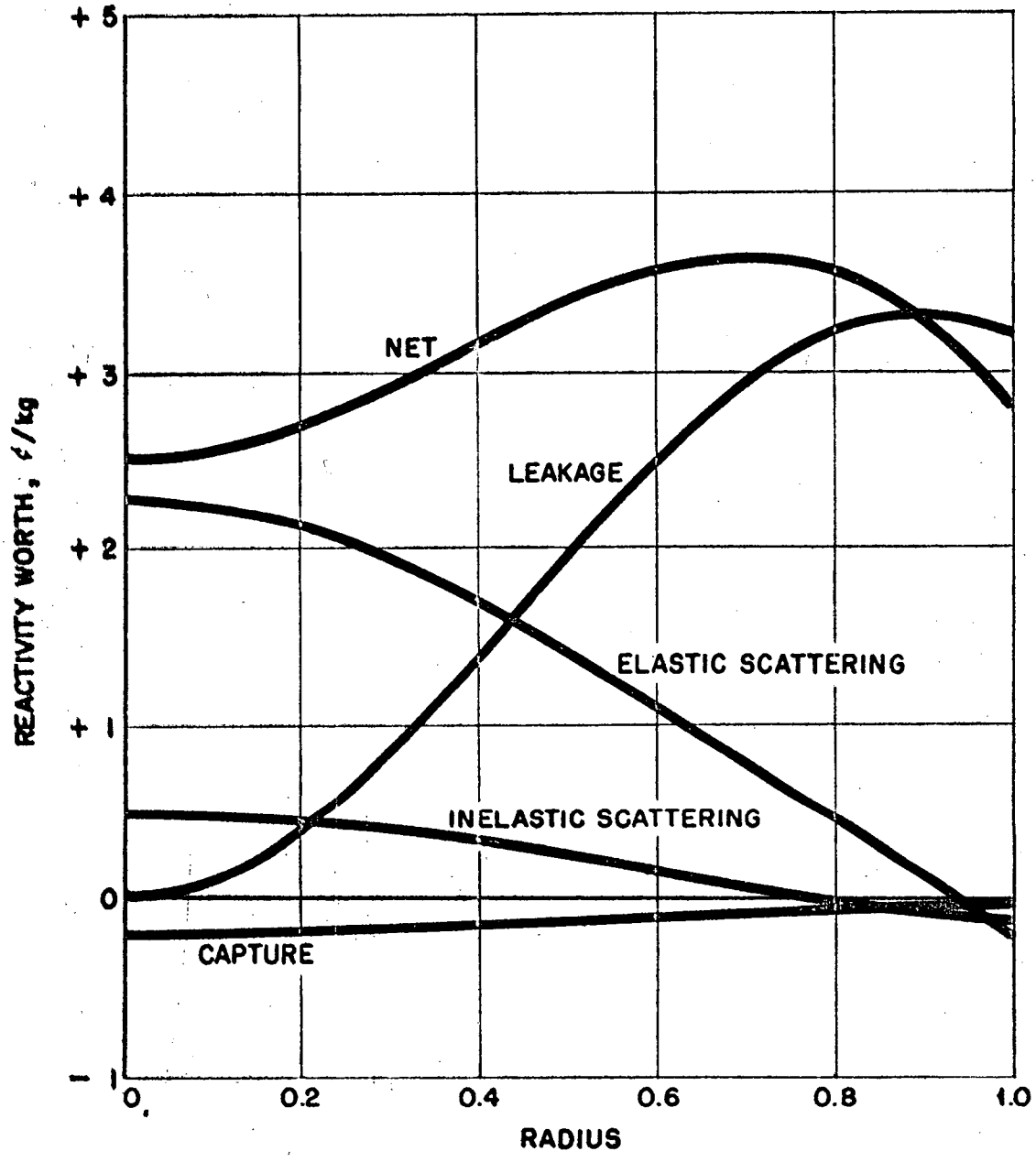

FIG. 5 COMPONENTS OF THE SODIUM DANGER COEFFICIENT IN THE FERMI REACTOR

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becomes more positive as the core boundary is approached. In the vicinity of the core boundary, the leakage term becomes the dominant one and sodium has a positive worth. The average sodium worth in the core is, however, negative. This corresponds to a positive temperature coefficient.

The sodium danger coefficient components for the UO_2 cermet core are given in Figure 4. The leakage term is scarcely different than in the PuO_2 cermet core. However, the spectral effects are very much reduced in magnitude, now being roughly of the same order of magnitude as the capture effect. The elastic component is smaller than the inelastic, although still negative. The leakage term now is much larger than the spectral effect, with the result that the average sodium worth in the core is positive and the temperature coefficient is negative.

In the case of the Enrico Fermi reactor, as shown in Figure 5, the inelastic scattering term is very small, and the sign of the elastic scattering component is reversed so that the spectral component adds to rather than detracts from the leakage effect. Leakage is much more important in this case because of the smaller core size and the sodium worth is relatively large.

A comparison of the various components of the sodium temperature coefficient is given in Table III. As indicated by the danger coefficient components, the leakage terms in the Pu and U systems are approximately the same. The spectral components are positive in both cases but considerably reduced in magnitude in the U system. In the Pu system, the spectral terms more than compensate for the negative leakage effect and result in a net positive temperature coefficient. In comparison, the leakage term is the dominant one in the U system and accounts for a negative coefficient.

One of the more disconcerting things about this problem comes from a comparison of the calculated worth of sodium and the value measured in the ZPR-III Fermi critical experiments. This comparison shows that the calculations

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overestimate the worth of sodium in a positive sense, that is, the calculated temperature coefficient is far less negative than the experiments indicate. The components of the calculated core averaged sodium danger coefficient are shown in Table IV.

TABLE III

COMPARISON OF COMPONENTS OF SODIUM TEMPERATURE COEFFICIENTS

Units $\Delta k/k \times 10^{-6}/C$

System	PuO_2 Cermet	UO_2 Cermet
Component		
Leakage	-4.7	-4.3
Elastic Scattering	+5.6	+0.6
Inelastic Scattering	+2.8	+0.7
Capture	+0.2	+0.2
Net	+3.9	-2.8

TABLE IV

COMPONENTS OF SODIUM DANGER COEFFICIENT IN FERMI REACTOR

Component	Worth (cents/kg)
Leakage	+2.83
Elastic Scattering	+0.57
Inelastic Scattering	+0.02
Capture	-0.08
Net	+3.34

The calculated value is +3.34 cents per kilogram and the measured worth is 2 cents per kilogram. One possible explanation of this discrepancy is that the spectral components of the danger coefficient are much more negative than the calculations indicate. In the case of the Enrico Fermi reactor, the sodium temperature coefficient is negative; but if the calculations are inaccurate in the way described above, the positive coefficient problem may be even more serious in the advanced designs than theory presently indicates.

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METHODS OF ADJUSTING THE SODIUM COEFFICIENT

Although, in the main, efforts have been directed toward understanding the reasons for the positive coefficient, some preliminary work has been done to investigate methods of adjusting this coefficient. One obvious way of accomplishing this is to vary the core shape so that the leakage effect is enhanced. The effect of varying L/D and core size is shown in Figure 6. As is to be expected, the smaller the core the larger the leakage component and the less positive the sodium temperature coefficient. However, the trend in advanced reactor design is not in the direction of smaller cores, so this is not a suitable answer to the problem. Increasing the neutron leakage component by flattening the core is also a step in the right direction. However, in order to achieve a significant improvement, the flattening must be carried to an extreme, such as an L/D of 0.2 or 0.3. This is probably not acceptable because it means unusually large in-pile inventories as well as an abnormally large number of fuel elements to be fabricated.

Another possible method of adjusting the sodium temperature coefficient is to decrease the ratio of fertile to fissionable material. This accomplishes two things -- it makes the threshhold fission effect less important and it makes the elastic scattering effect less positive or even negative. In Figure 7 the sodium temperature coefficient is shown as a function of the ratio of U-238 to Pu-239. This approach can be carried to the point where the sodium temperature coefficient is at least a negligible one. In doing this, there is a penalty paid in terms of breeding. In the base calculation, the breeding ratio is 1.42, whereas at the point where the sodium temperature coefficient is zero, the breeding ratio is 1.27. The results given here assume that the fertile material is replaced by a completely inert material as far as neutrons are concerned. Therefore, they do not reflect the full effect of this nonfertile diluent material on breeding. Through neutron capture and spectrum degradation, the breeding ratio would be reduced even more.

$\frac{N28}{N49} = 8/1$

FUEL: PuO_2 - UMo CERMET

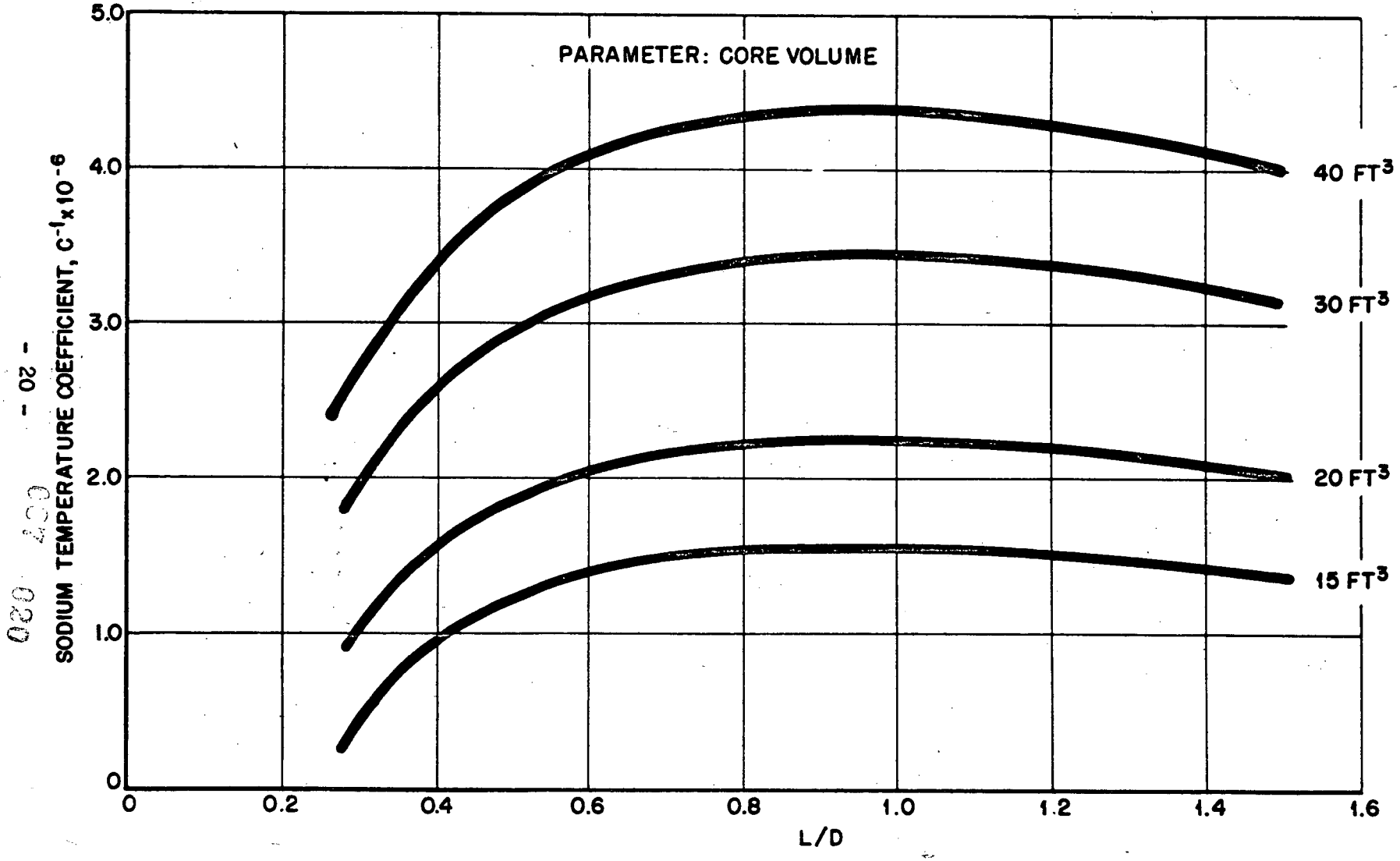

FIG. 6 SODIUM TEMPERATURE COEFFICIENT AS FUNCTION OF L/D

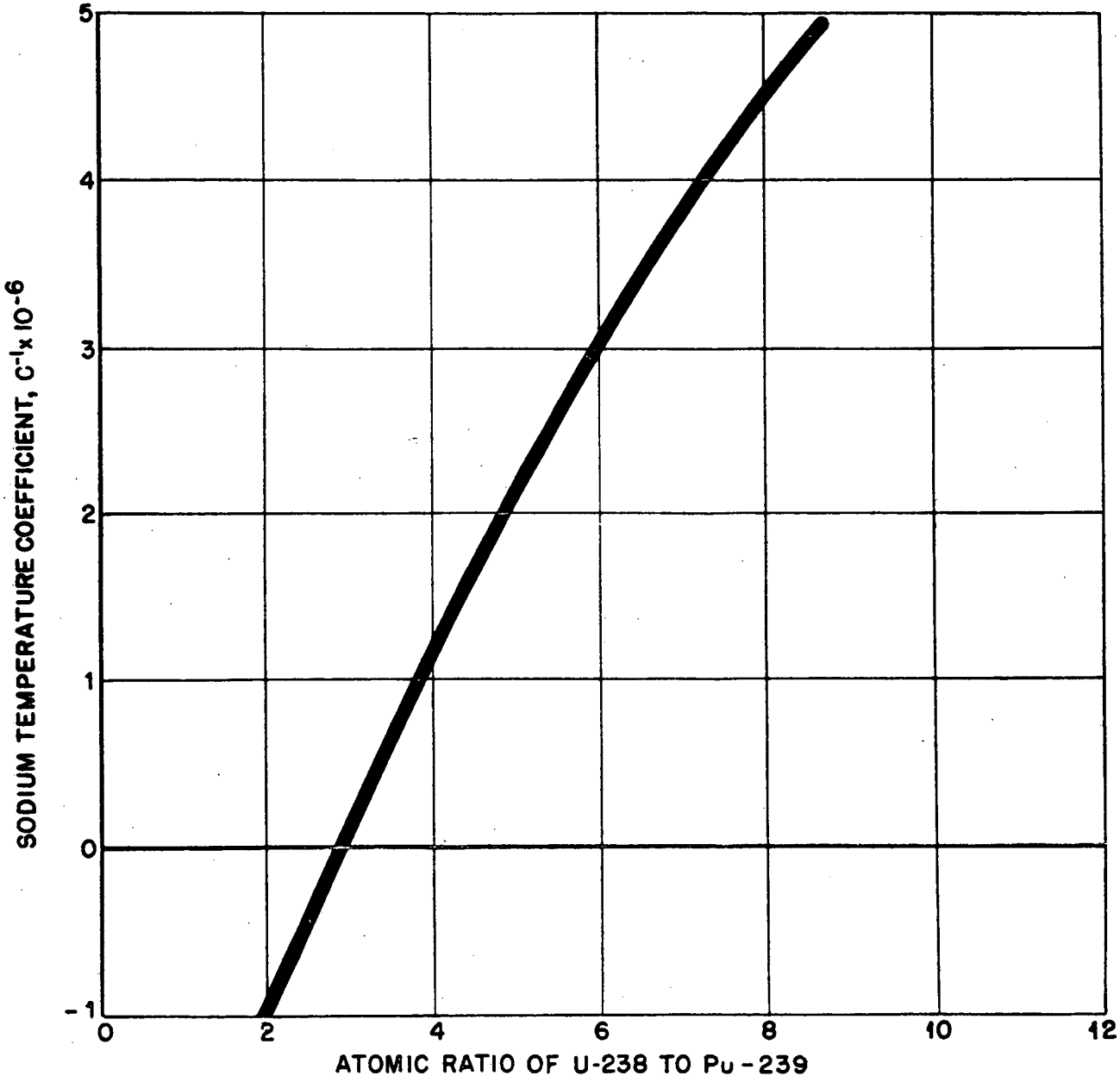

FIG. 7 VARIATION OF NA TEMPERATURE COEFFICIENT WITH ATOMIC RATIO OF U-238 TO Pu-239

Apparently either of these two methods could be successfully used to adjust the sodium temperature coefficient if one wishes to pay the penalty involved. There is one other possibility that should be considered in the future. That is to accept a positive sodium coefficient in preference to using the above methods. Since other contributions to the overall temperature coefficient, such as fuel expansion and Doppler broadening, have a faster response and are large negative coefficients, the reactor can be designed with an overall negative power coefficient. Whether this leads to an unstable situation under practical conditions is a matter that remains to be investigated.

ACKNOWLEDGMENT

The authors wish to acknowledge the contributions to this effort made by G. R. Thomas and D. R. Hostetler of The Babcock & Wilcox Company, who were involved in the initial investigations. The authors also appreciate and acknowledge the assistance of Yvonne Wilson and Agnes Liedel of APDA, who performed the necessary machine and hand calculations and prepared many of the figures.

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