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R. C. Liikala et al

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THE PuO_2-UO_2 EXPERIMENT IN THE EBWR

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June 9, 1965

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I. INTRODUCTION

A plutonium experiment is to be performed in the Experimental Boiling Water Reactor (EBWR) at Argonne National Laboratory and is a joint program between Pacific Northwest Laboratory and Argonne National Laboratory. This program which is to demonstrate the utilization of plutonium in a light-water moderated power reactor is entering Phase 2, [1,2] the Startup Experiments. In this phase of the program, the central portion of the core will be loaded with plutonium fuel such that the core reactivity variation with burnup will be caused mainly by burnup of the plutonium zone. Surrounding the plutonium zone are uranium fuel elements which will be used as driver elements. Several rods will be included in the plutonium zone to obtain burnup information from special fuel compositions.

A series of tests will be conducted during the initial loading of the EBWR in order to measure the reactivity worth of fuel rods, safety rods, voids, and boric acid in the moderator.

At various stages of burnup, the series of tests performed at the time of the startup experiments will be repeated. Also, at these stages a series of rods from the plutonium zone will be removed and returned to Battelle Northwest for reactivity measurements in the Plutonium Recycle Critical Facility (PRCF) and subsequently analyzed for plutonium concentration, isotopic composition and to obtain other data which will describe the burnup characteristics. The results of calculations of the reactivity changes expected at startup and throughout the burnup of the core are presented in this report. Information obtained during the

startup experiments will be used to assess the accuracy of the calculational methods and identify areas of uncertainty in the computations.

II. SUMMARY

The maximum exposure at which the plutonium zone can be made critical at low power is expected to be about 5000 MWd/t with the moderator hot and 6000 MWd/t with it cold. However, the plutonium zone is subcritical before reaching 5000 MWd/t at full power because of large negative reactivity effects due to void and xenon concentrations.

A result from this study is that the plutonium fuel exhibits larger variations of negative reactivity with increased moderator temperature and moderator void changes than does the uranium fuel which surrounds it.

Another result is that the moderator temperature coefficient of reactivity for the plutonium zone alone becomes less negative with fuel exposure, and finally goes positive near 5000 MWd/t. At an irradiation which is greater than 7000 MWd/t for this fuel, the reactivity change due to moderator and fuel heating is positive. However, the reactivity change due to moderator void is calculated to be negative throughout burnup with a magnitude large enough to compensate for the positive temperature effect. Thus, the reactivity effects at full power operation are expected to be negative up to very high exposures ($\sim$ 15,000 MWd/t). For a pressurized water reactor loaded like the EBWR the negative reactivity effects of a large void fraction present in the EBWR would be lost, and at exposures greater than 7000 MWd/t the reactivity response to temperature increases would be positive for the pressurized system.

III. CORE CONFIGURATION AND PROGRAM OUTLINE

The EBWR core is divided essentially into three zones. The central portion of the core is the plutonium zone containing 1296 rods (36 elements of 36 rods each), surrounded by zones of enriched and natural UO_2 elements. The core loading and the pattern of special rods within the plutonium zone are shown in Figure 1. There are two fuel elements shown containing special plutonium rods. However, the corresponding elements in the right hand quadrants of the central four quadrants shown containing PuO_2-UO_2 probably will contain special plutonium rods also. The general outline of the experimental program[3] is shown in Figure 2.

A series of startup experiments will be conducted during the initial loading, both at low power and full power operation. These tests will include determining the critical masses of the unirradiated plutonium fuel, the measurement of boron and control rod worths, kinetic studies and foil irradiations.

At the completion of the startup tests the fuel will be irradiated to an approximate 2000 to 3000 MWd/t exposure. At this stage of burnup, the series of critical tests performed at startup will be repeated. Thirteen rods, five of which are special rods, (see Figure 1) will be removed from one of the plutonium-zone quadrants for post irradiation analysis. Using the results of all the experiments, a better estimate of the reactivity lifetime of the plutonium zone can be derived. With this new estimate of reactivity lifetime for the plutonium zone, the frequency at which the critical experiments will be repeated can better be determined.

FIGURE 1

PLUTONIUM LOADING IN EBWR

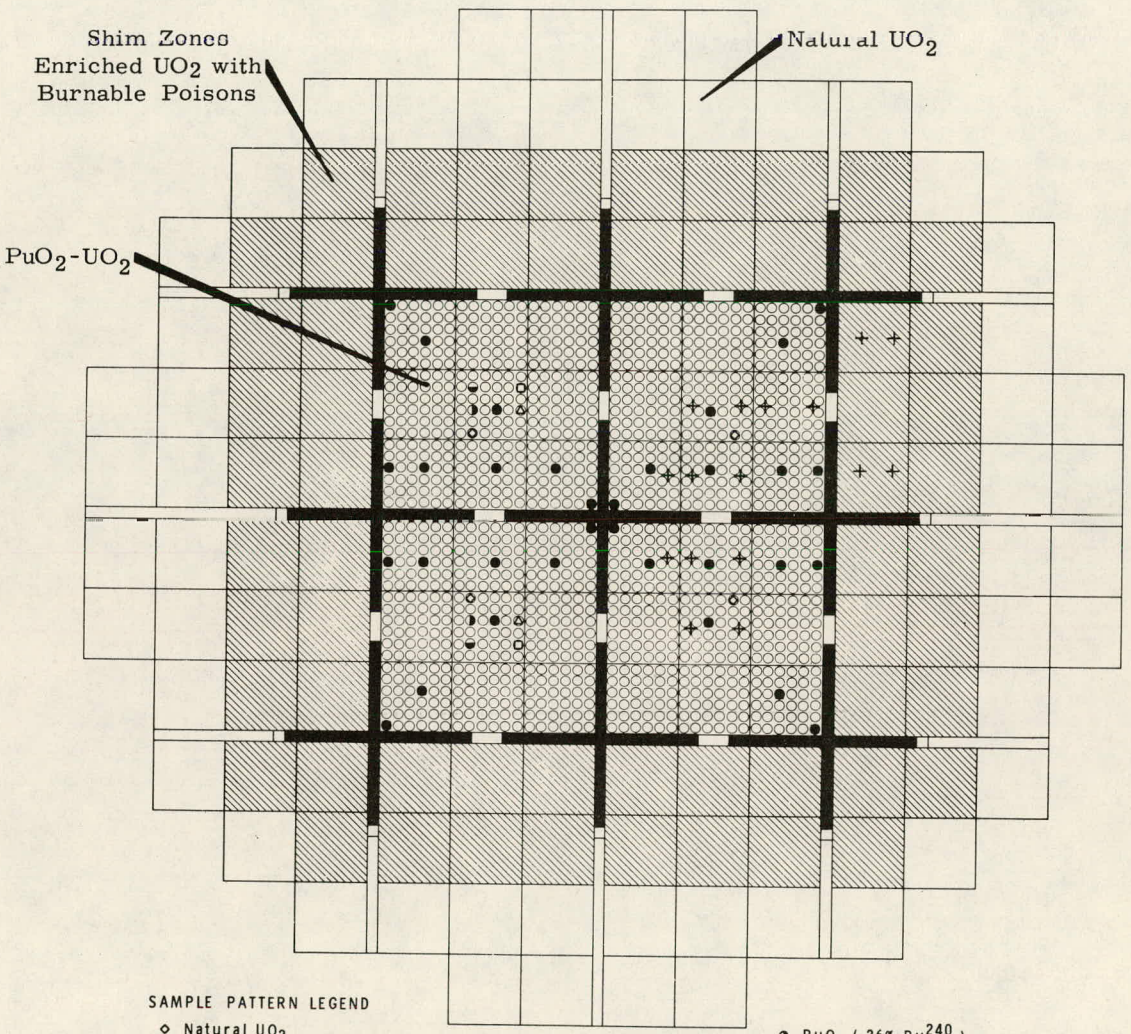
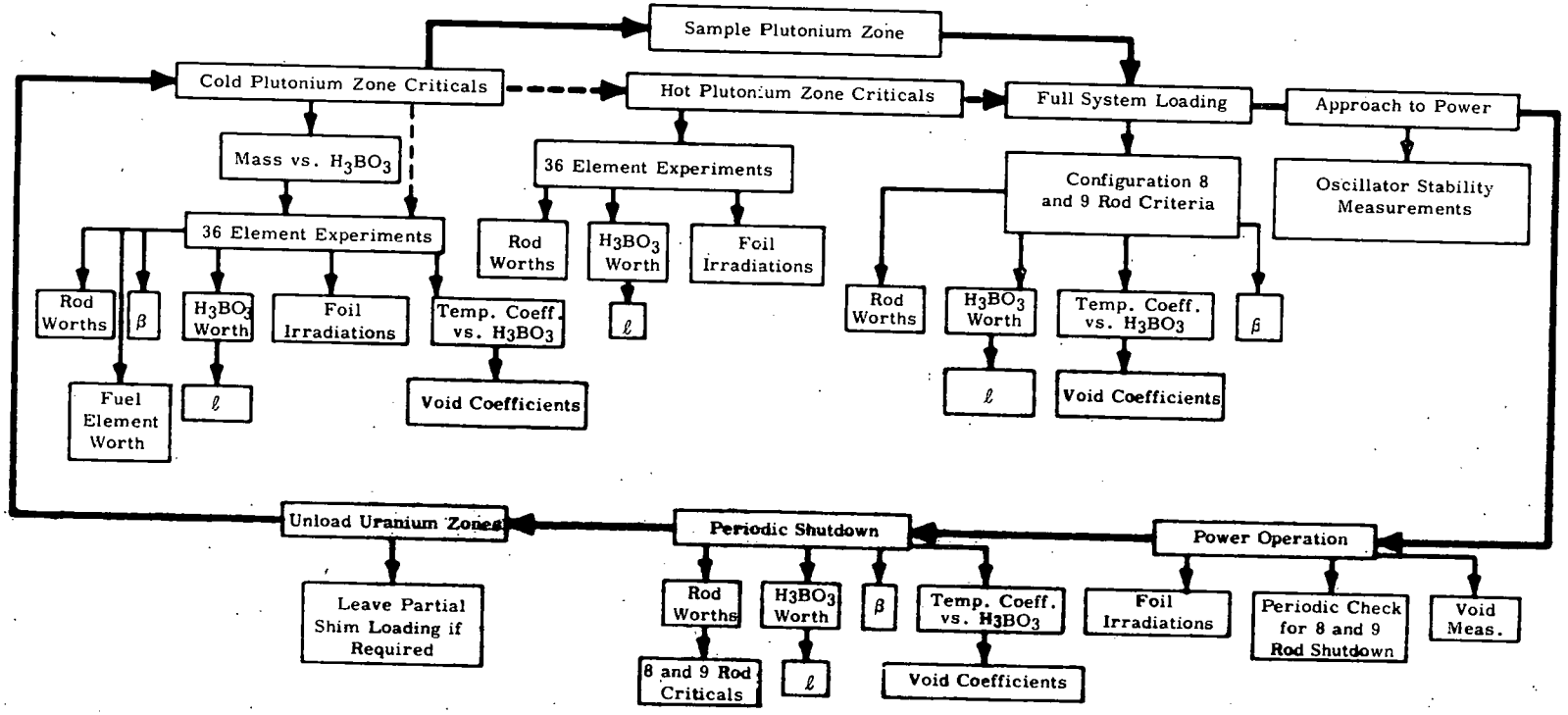


FIGURE 2

EBWR PLUTONIUM RECYCLE PROGRAM OUTLINE



IV. CALCULATIONAL MODELS

Reactivity

The methods utilized in the calculation of effective multiplications, k_{eff}, are the same as that employed in the analysis of the approach-to-critical experiments[4,5] which were conducted using the EBWR fuel. The fact that the calculations and the experiments agree to within 0.5% in k_{eff} lends confidence in applying these calculational methods to the EBWR experiment. These methods consist of using the codes HRG,[6] THERMOS,[7] and TEMPEST[8] to obtain homogenized cross sections for use by a one-dimensional diffusion theory code, HFN.[9] All calculations which were made for the EBWR core assume a four region cylindrical model, as described in Table I. As seen in Figure 1, the EBWR is loaded in square geometry; however, the calculations were made using cylindrical geometry. No quantitative assessment of the effects on reactivity of this square versus cylindrical arrangement has been made; however, the values of k_{eff} are expected to be consistently higher for the cylindrical geometry case. In calculating the reactivity variations as a function of temperature and voids a few values of the independent variable were chosen. The moderator temperatures selected are room temperature (20°C), and expected inlet (195°C) and outlet temperatures (255°C). The fuel temperatures investigated were room temperature and that expected at full power operation (472°C). Moderator void concentrations of no voids ($\rho\ H_2O = 0.791$ gms/cc), 15% and 30% voids were considered in an effort to bracket the expected range of moderator void content.

TABLE I

REGIONAL MATERIAL AND GEOMETRICAL DESCRIPTIONS

Region	Material	Equivalent Outer Radius (cm)
1) PuO_2-UO_2 Zone	1.5 w/o PuO_2 in UO_2 - Uranium containing 0.22% U^{-235} 36 Elements (1296 rods)	36.5425
2) Enriched UO_2 Zone	6.0 w/o U^{235} in UO_2 with 0.158 w/o Eu_2O_3 and 0.0288 w/o Sm_2O_3	59.6736
3) Natural UO_2 Zone	0.7% U^{235} in UO_2	74.0931
4) H_2O Reflector	H_2O	100.0

The reactivity variations with burnup were calculated utilizing concentrations of fuel and psuedo fission products obtained from the burnup calculations. The effects of xenon and samarium on reactivity were omitted in the calculations because of their strong dependence on the actual reactor operation. Cell averaged cross sections were calculated using programs HRG, THERMOS, and TEMPEST for the materials with concentrations corresponding to average exposures of 3030, 5970 and 3840 MWd/t* for the temperature and void conditions already described. These cell averaged constants were then used in one-dimensional calculations with diffusion theory assumptions using program HFN to determine these reactivity variations. The conditions assumed for the calculations are summarized in Table II.

* All exposures quoted are based on a ton (t) equal to 2000 lbs.

TABLE II

CALCULATIONAL TEMPERATURE, VOID AND EXPOSURE POINTS

Effect	Points
Moderator Heating	20°, 195°, and 255° C
Fuel Heating	20° and 472°C
Moderator Voiding	0, 15, and 30%
Burnup	
Plutonium Zone Only	3030, 5970, and 8840 MWd/t.

Burnup

Changes in fuel concentrations with irradiation were obtained from calculations performed with a one-dimensional model in cylindrical geometry using the program ALTHAEA.[10] The reactor is divided into five regions comprising a central cell consisting of fuel, cladding and moderator of radius 0.8150 cm surrounded by the four regions listed in Table I. For the calculations only the central cell and the PuO_2-UO_2 zone were considered as being burnable. The burnup behavior for all special rods was determined by considering each rod as being in the central cell. A constant power of 40 megawatts is assumed for reactor operation and fission products excluding xenon and samarium are accounted for by three psuedo groups of fission products. The values for the thermal cross sections of Pu^{239} and U^{235} suggested by Leonard[11] were utilized. This choice seems reasonable since data obtained from other experiments in which plutonium was irradiated have been compared

to calculations[12,13,14] and the results agree favorably when the Pu^{239} cross sections suggested by Leonard[11,15] are utilized in calculations with the Althaea Model. The thermal flux depression factors and effective resonance integrals used in the burnup calculations (ALTHAEA) were obtained from cell calculations utilizing transport theory (program THERMOS) and slowing down theory (program HRG) respectively.

The burnup calculations in this report were performed to aid in scoping the experiment. Detailed calculations of the burnup behavior for the actual core are underway to aid in defining the experiment.

V. PLUTONIUM ZONE REACTIVITY

Cold Moderator and Fuel

The initial experiment will be the determination of the critical loading for the room temperature, unirradiated zone of PuO_2-UO_2. The number of rods required for the central loading is calculated to be ~ 15.08 elements of 543 rods. Values of the calculated multiplication as a function of the number of elements loaded in the core are shown in Figure 3. Following this initial experiment, all subsequent experiments for this zone will be made with a 36 element loading.

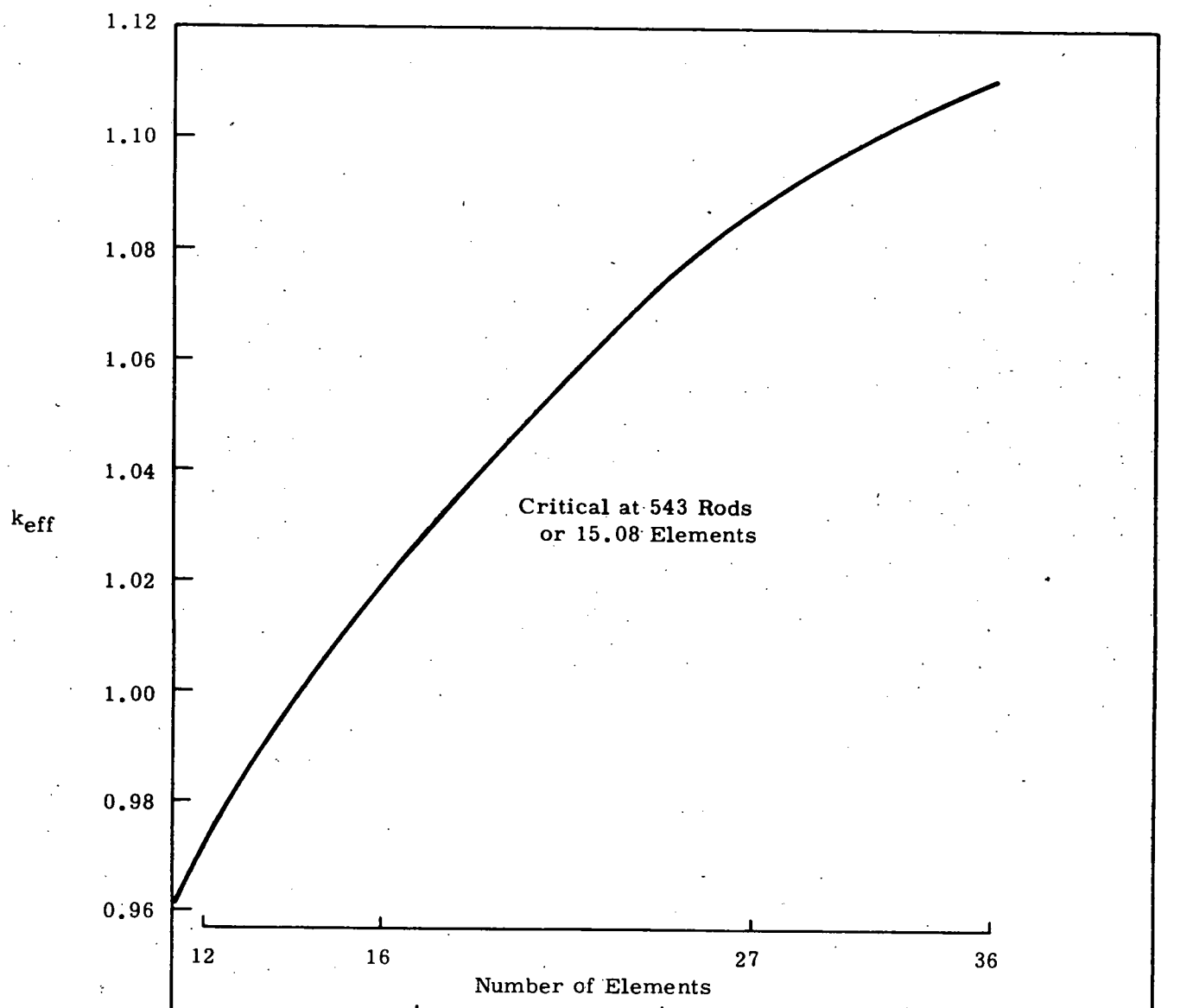


FIGURE 3

k_{eff} versus Numbers of Pu Elements in the EBWR Core for Cold, Clean Conditions

The k_{excess} for 36 elements is calculated to be 115 mk. Boron mixed in the moderator will be utilized in controlling this excess reactivity. The calculated change in multiplication as a function of boron concentration in the moderator is shown in Figure 4. The amount of boron required to maintain a just critical 36 element configuration ($k_{eff} = 1.0$) is calculated to be 410 ppm.* The curve is approximately linear and the reactivity coefficient for boron changes is -2.5×10^{-4} ($\frac{\Delta k}{k}$ / ppm boron) at $k_{eff} = 1.0$.

Moderator and Fuel Heating

The effects of changes in moderator temperature on the reactivity of the plutonium zone are shown in Figure 5. The temperature of the fuel was assumed to be constant at 20°C for these calculations. The moderator temperature reactivity coefficients are listed in Figure 5 and summarized in Table III. The coefficients at 20°C, 195°C (inlet temperature) and 255°C (outlet temperature) are values of the slopes of the curve at these temperatures. The value for the average coefficient is the slope of a straight line connecting the end points of 20°C and 255°C.

The effects of fuel heating on reactivity are also shown in Figure 5 and summarized in Table III for a constant moderator temperature of 255°C. The reactivity variation is assumed to be linear with fuel temperature and the value of the Doppler coefficient for a fuel temperature change from 20°C to 472°C is -2.6×10^{-5} $\frac{\Delta k}{k}$ / °C. The Doppler broadening of the plutonium 240 resonances contributes approximately 27% to this Doppler coefficient.

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* Defined here as atoms of natural boron/million molecules of H_2O.

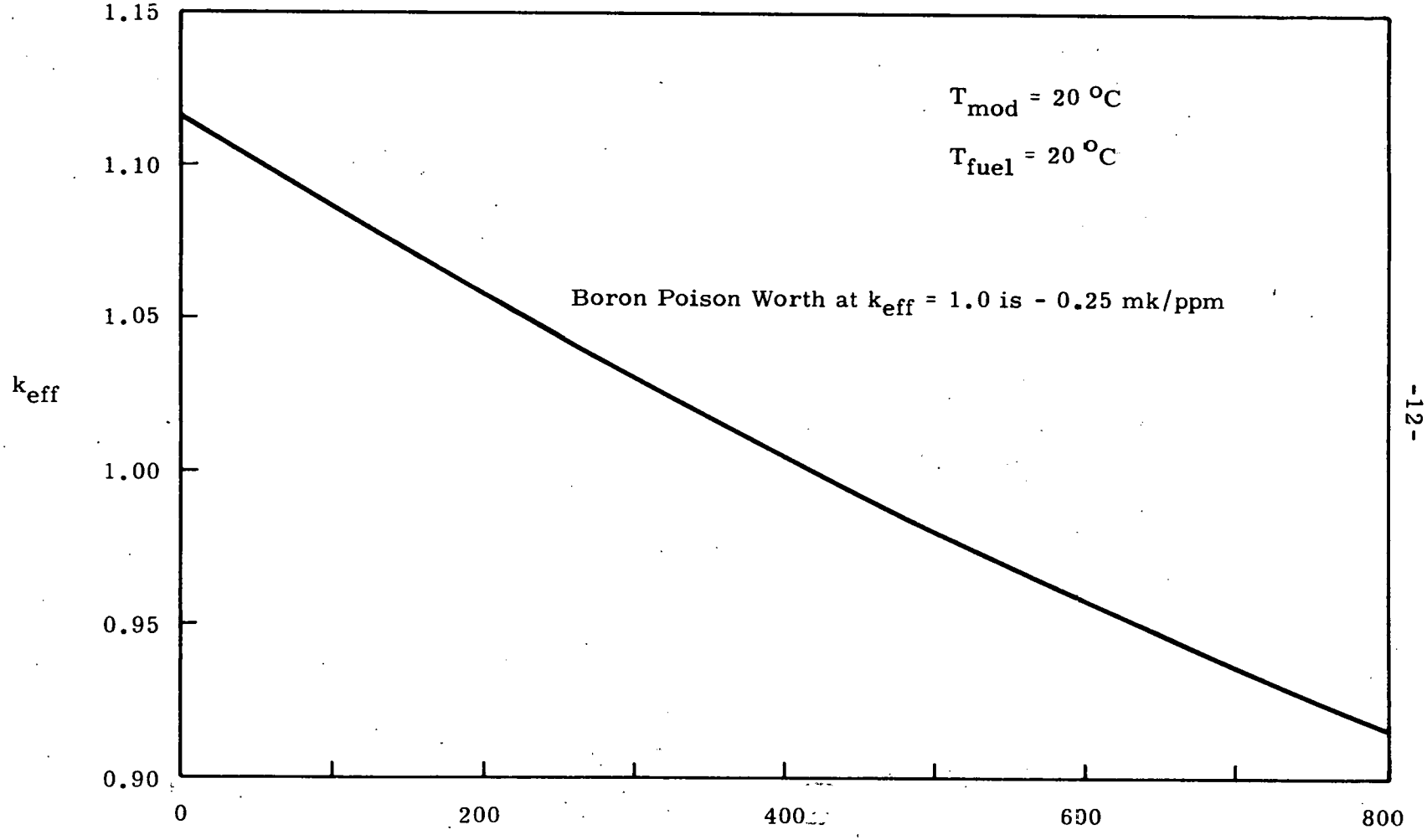

FIGURE 4

Reactivity Variation with Amounts of Boron in Moderator for the 36 Element Pu Zone

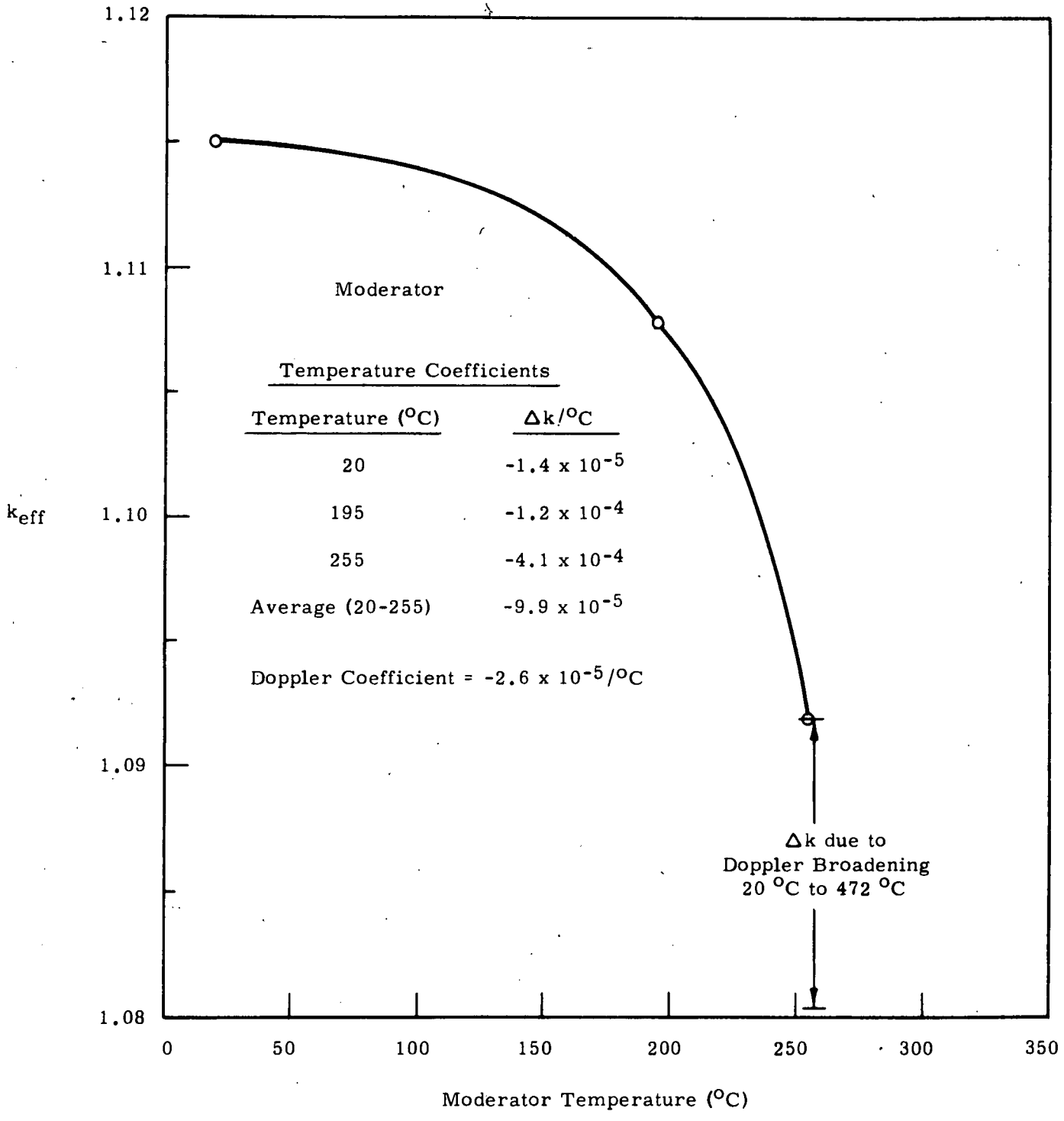

FIGURE 5

Reactivity Variation with Moderator Temperature for the 36 Element Pu Zone

Moderator Voids

The reactivity changes because of void production in the coolant or moderator (the coolant also serves as moderator) of the EBWR have been calculated. Two assumptions used in the calculations are that the voids are represented by a density change in H_2O and that the void concentration is spatially independent. The reactivity changes are shown in Figure 6 and represent the effect of an average void since the actual distribution of voids varies both radially and axially. The void coefficients of reactivity listed in Figure 6 and summarized in Table III are slopes of the curve at the void fractions quoted and the average value is the slope of the line drawn between the end points of 0 and 30% void.

Boron Requirements

Values of the multiplication of the 36 element plutonium zone with various amounts of boron have been calculated for the moderator heated to 255°C (no voids) and compared to the values calculated for the case when the moderator is 20°C in Figure 7. The amount of boron required to control a k_{excess} of 115 mk is calculated to be 410 ppm with cold moderator (20°C). With the moderator heated to 255°C, the amount of boron required to control 80 mk excess reactivity is 450 ppm. The concentration of 410 ppm boron in H_2O at a temperature of 20°C is larger than the concentration of 450 ppm in H_2O at a temperature of 255°C because of the significant change in water density between 20°C and 255°C. The boron concentration in grams of boric acid (H_3BO_3) per gallon of water is independent of water density and these units can be used to compare the relative concentrations of boron that are required. The cold k_{excess} of 115 mk requires ~ 12 gm/gal whereas the hot k_{excess} of 80 mk requires ~ 10.4 gm/gal. Therefore the calculated reactivity coefficients of boron are 9.6 mk/gm/gal at 20°C

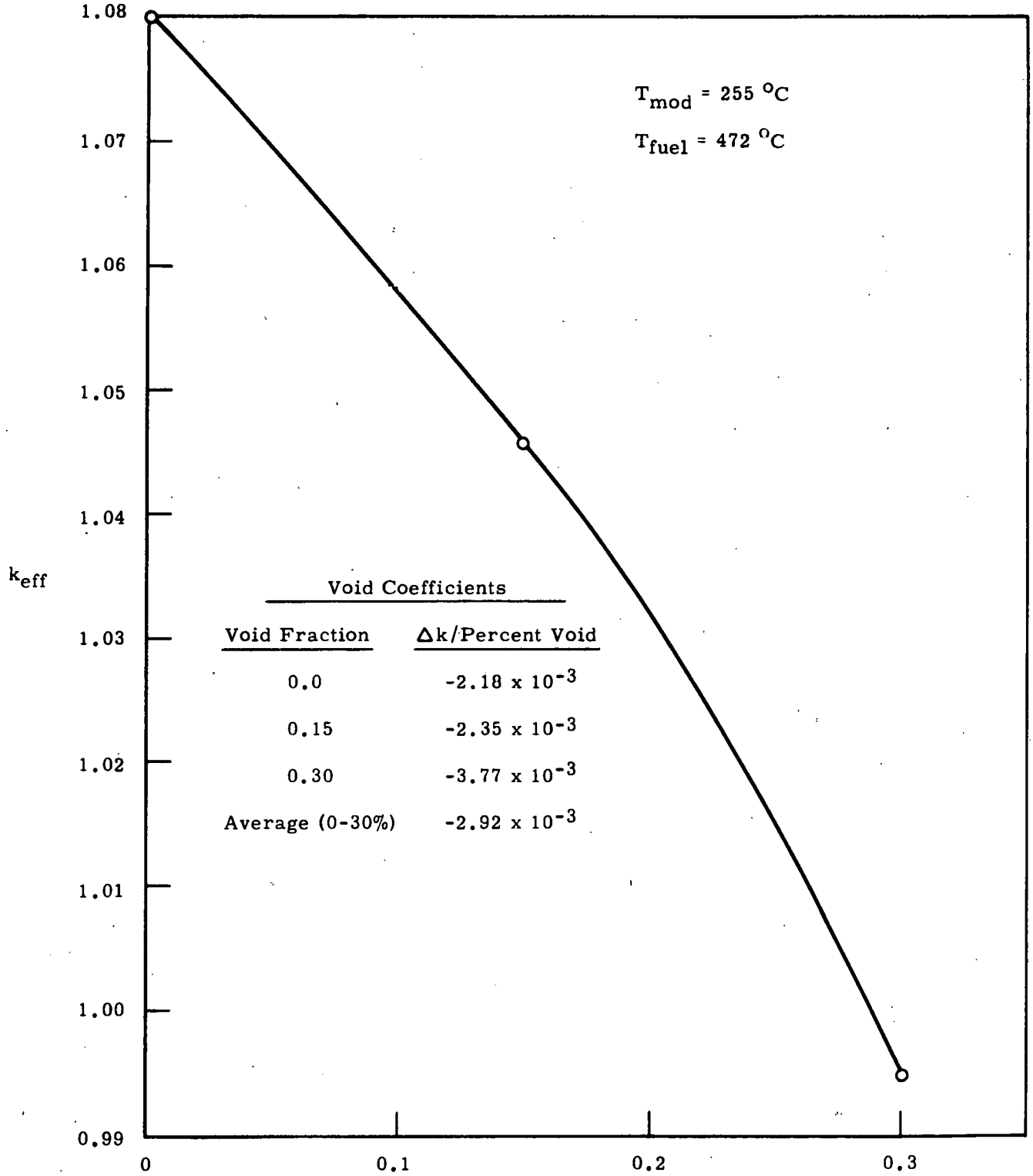

FIGURE 6

Reactivity Variation with Coolant Void for the 36 Element Pu Zone

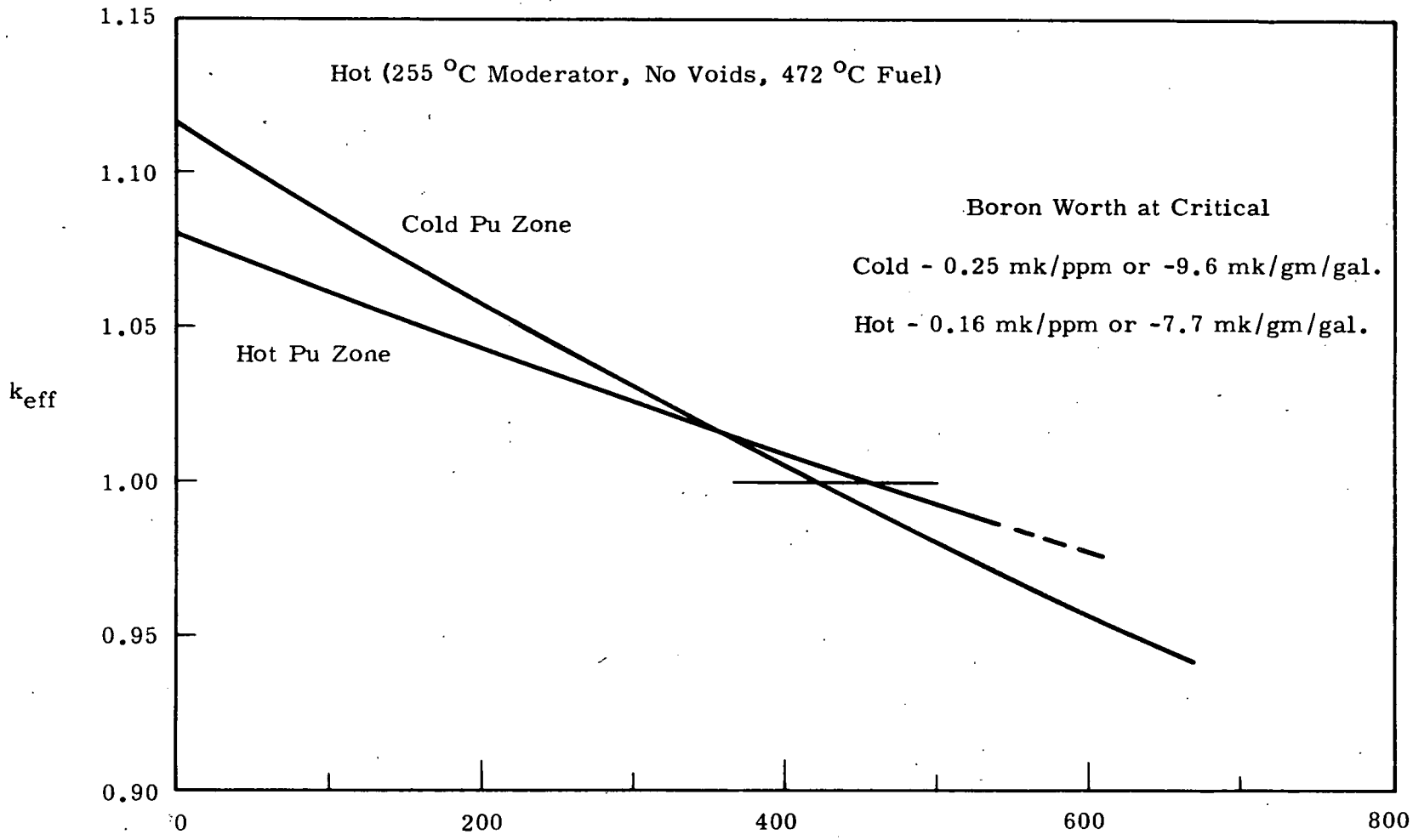

FIGURE 7

Reactivity Variation Worth Amounts of Boron in Moderator for the 36 Element Pu Zone

and 7.7 mk/gm/gal at 255°C. The difference in these coefficients reflects the "spectral hardening" which occurs in going from cold to hot moderator. This hardening results in about a 20% change in $\overline{\eta}f_{thermal}$.

VI. FULL CORE REACTIVITY

Cold Moderator and Fuel

The effective multiplication, k_{eff}, for the core* fully loaded with the PuO_2-UO_2 zone, the enriched UO_2 zone, the natural UO_2 zone and the H_2O reflector is calculated to be 1.159. Comparing this value to the multiplication of 1.115 for the plutonium zone alone shows a 4% increase in reactivity due to the rest of the reactor.

Hot Moderator and Fuel

The effects of moderator heating on the reactivity of the core has been calculated and are compared to those of the plutonium zone in Figure 8. The moderator coefficients of reactivity are slightly smaller for the core than for the plutonium zone (e.g., 9.6×10^{-5}/°C average for the core compared to 9.9×10^{-5}/°C for the plutonium zone). The calculated change in reactivity upon fuel heating alone, at a constant moderator temperature of 255°C, is the same for the core and the plutonium zone. Hence, the identical Doppler coefficients of reactivity are shown in Figure 8 for the two curves.

Moderator Voids

The change in reactivity upon moderator voiding of the core has been calculated and is compared in Figure 9. For a void change of 0 to 30% voids the core has an average void coefficient of -2.58×10^{-3}/% void compared to -2.92×10^{-3}/% void for the plutonium zone.

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*Hereafter denoted as core.

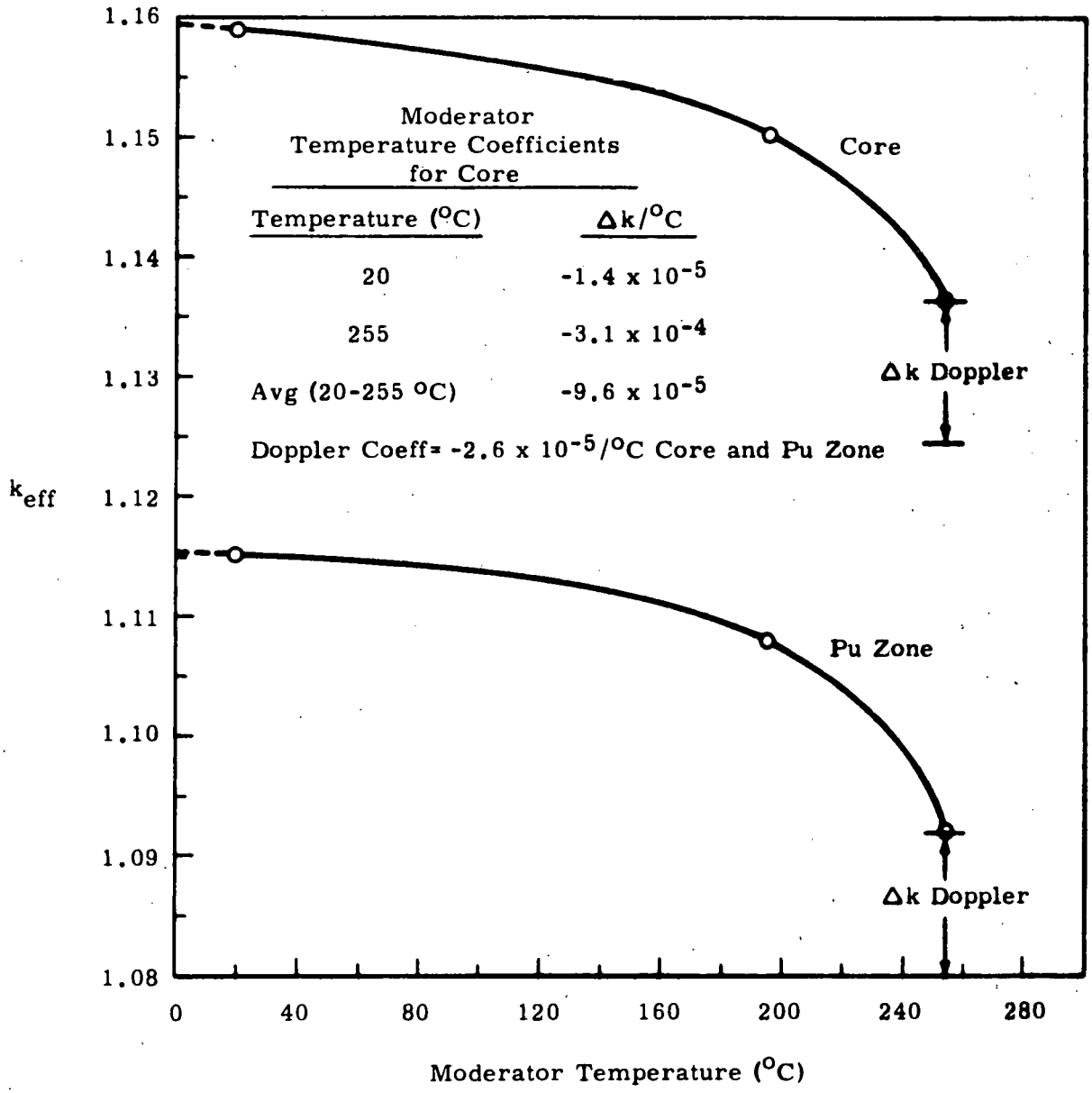

FIGURE 8

Reactivity Variation with Moderator Temperature

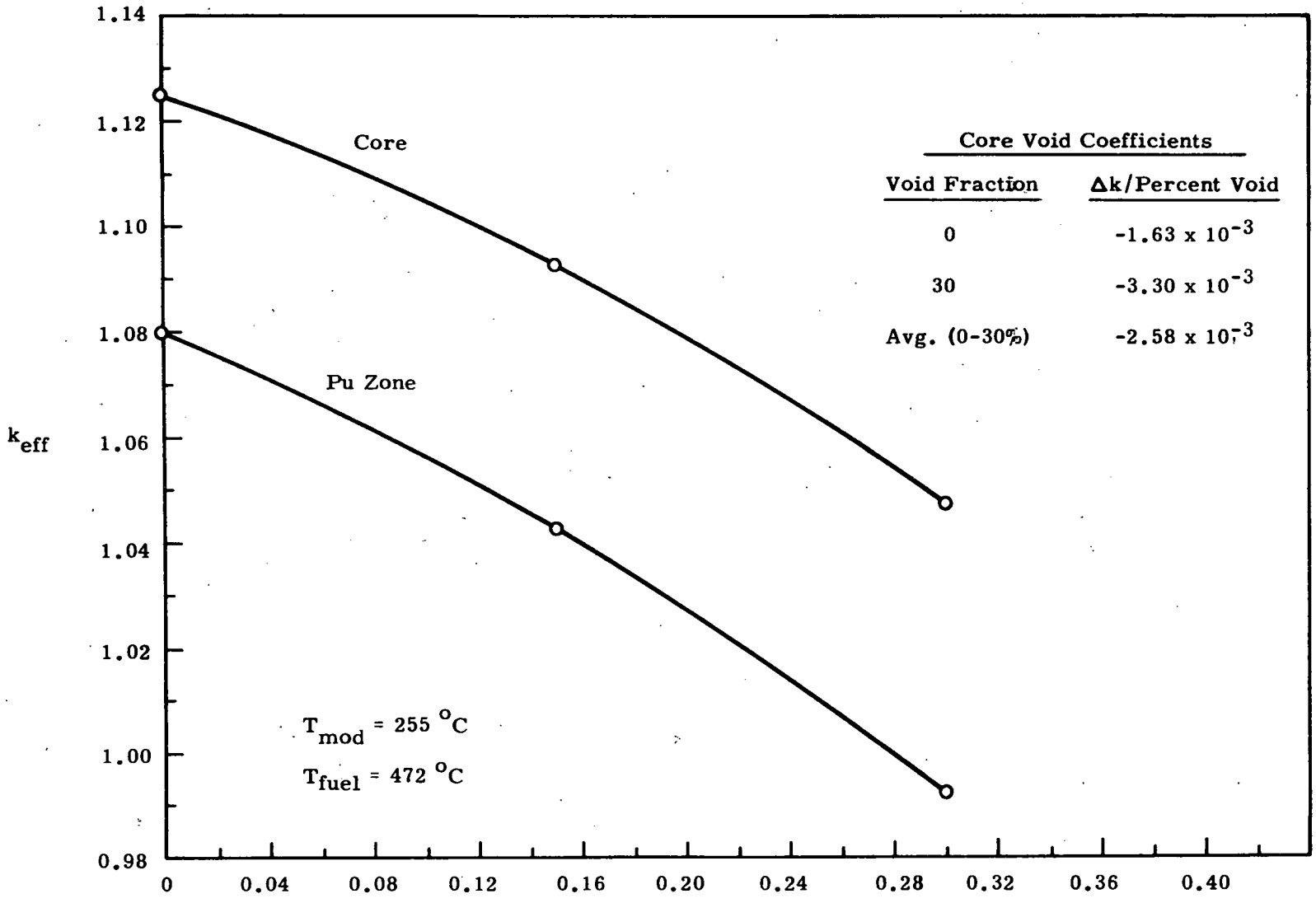

FIGURE 9

Reactivity Variation with Coolant Void

Boron Requirements

The amount of boron required to control the core excess reactivity of 159 mk is calculated to be 615 ppm for cold moderator and 760 ppm for hot moderator. The variation of reactivity with boron content is compared in Figure 10 for the core and plutonium zone. The reactivity coefficients of boron concentrations at $k_{eff} = 1.0$ for each case is also listed in Figure 13. For a constant moderator temperature the boron has a larger effect in the plutonium zone than in the core.

General Trends

The various coefficients of reactivity are summarized in Table III for the plutonium zone and the core. In all cases the reactivity coefficients for the plutonium zone are equal to or larger than those for the core. Hence it is expected that the uranium zones will have coefficients of reactivity which are less negative than that of the plutonium zone. Thus, if the core consisted of only uranium fuel, the temperature and void coefficients of reactivity would be smaller than if the core contained only mixed oxide fuel.

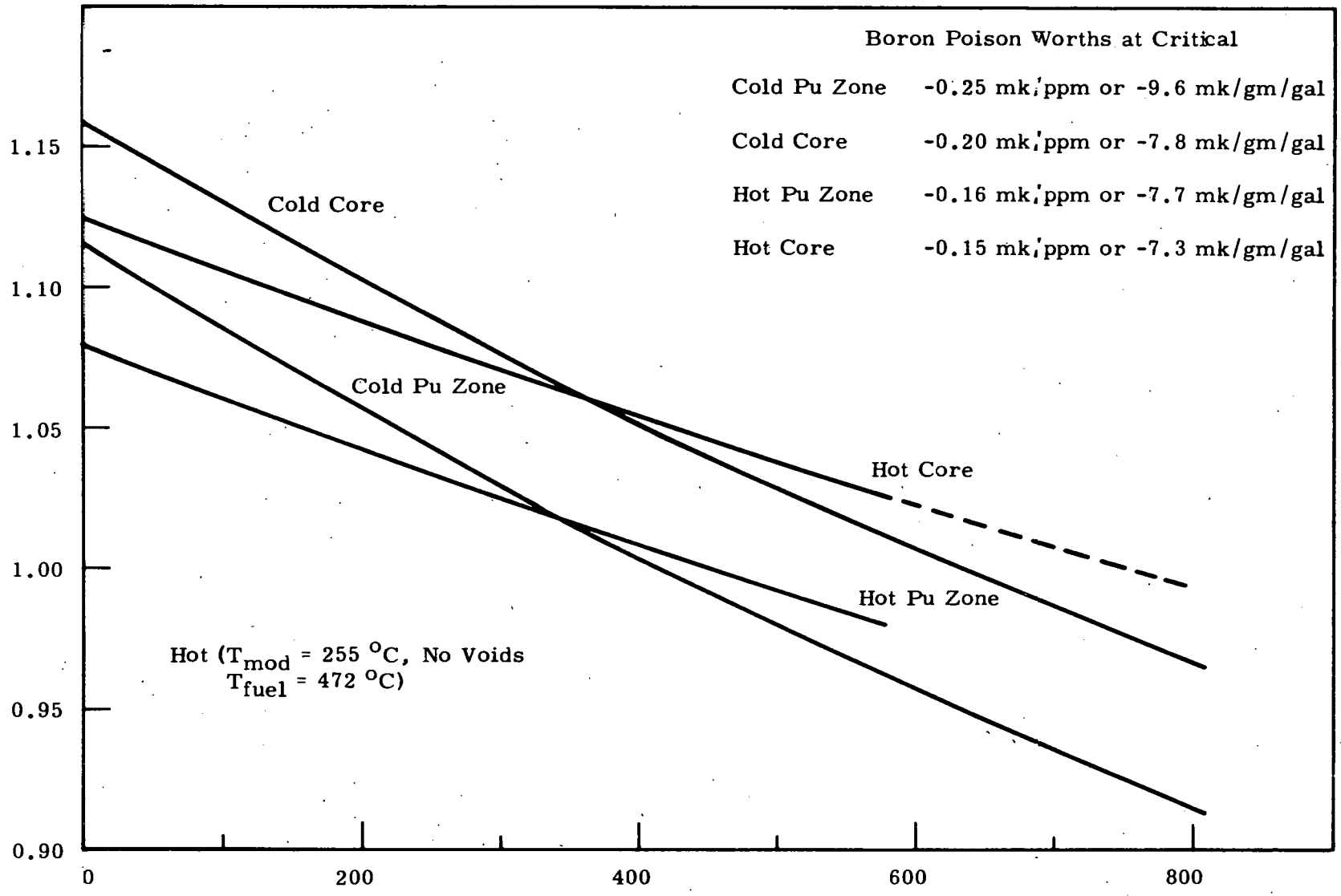

FIGURE 10

Reactivity Variation with Boron Content in Moderator

TABLE III

CALCULATED REACTIVITY COEFFICIENTS

Moderator Reactivity Coefficient - $\Delta k_{eff}/^{\circ}C$

Temperature	Plutonium Zone	Core
20°C	-1.4×10^{-5}	-1.4×10^{-5}
255°C	-4.1×10^{-4}	-3.1×10^{-4}
Avg. (20°C → 255°C)	-1.0×10^{-4}	-9.6×10^{-5}

Doppler Reactivity Coefficient - $\Delta k_{eff}/^{\circ}C$

Temperature	Plutonium Zone	Core
Avg. (20°C → 472°C)	-2.6×10^{-5}	-2.6×10^{-5}

Void Reactivity Coefficient - Δk_{eff}/% Void

% Void	Plutonium Zone	Core
0	-2.18×10^{-3}	-1.63×10^{-3}
30	-3.77×10^{-3}	-3.30×10^{-3}
Avg (0 → 30%)	-2.92×10^{-3}	-2.58×10^{-3}

Boric Acid Worth at Critical - Δk_{eff}/gm/gal

	Core (20°C Mod & Fuel)	Hot(255°C Mod, 472°C Fuel, No void)
Plutonium Zone	-9.6×10^{-3}	-7.7×10^{-3}
Core	-7.8×10^{-3}	-7.3×10^{-3}

VII. REACTIVITY BEHAVIOR WITH IRRADIATION

The variation of reactivity with burnup which was calculated for the plutonium zone is shown in Figure 11. The maximum exposure at which the plutonium zone would still be critical (k_{eff} = 1.0) is approximately 6000 MWd/t for moderator and fuel at room temperature and 5000 MWd/t for moderator at 225°C (no voids) and 472°C fuel. There are negative reactivity effects due to moderator void and xenon + samarium production during power operation. Thus, the plutonium zone would be subcritical at full power with an exposure of 5000 MWd/t. The exact exposure at which the plutonium zone becomes subcritical during full power operation depends on the void content and saturation quantities of xenon and samarium. However, these results show that the uranium fuel in the zones surrounding the plutonium zone must supply reactivity to carry the irradiation of the plutonium fuel to exposures up to and in excess of 5000 MWd/t. An average reactivity loss of 0.01917 mk/MWd/t is derived for the plutonium zone, cold. Assuming that the core will lose reactivity with exposure at the same rate as the plutonium zone, an estimate of the core reactivity lifetime can be made. The k_{excess} for the core is 159 mk and utilizing the above reactivity loss with exposure value, the core would be expected to be subcritical at approximately 8000 MWd/t in the cold condition. Since the burnup characteristics of the core are expected to be different than that of the plutonium zone this number is only an approximation. The reactivity characteristics of the core as a function of exposure are being calculated and will be the subject of another report.

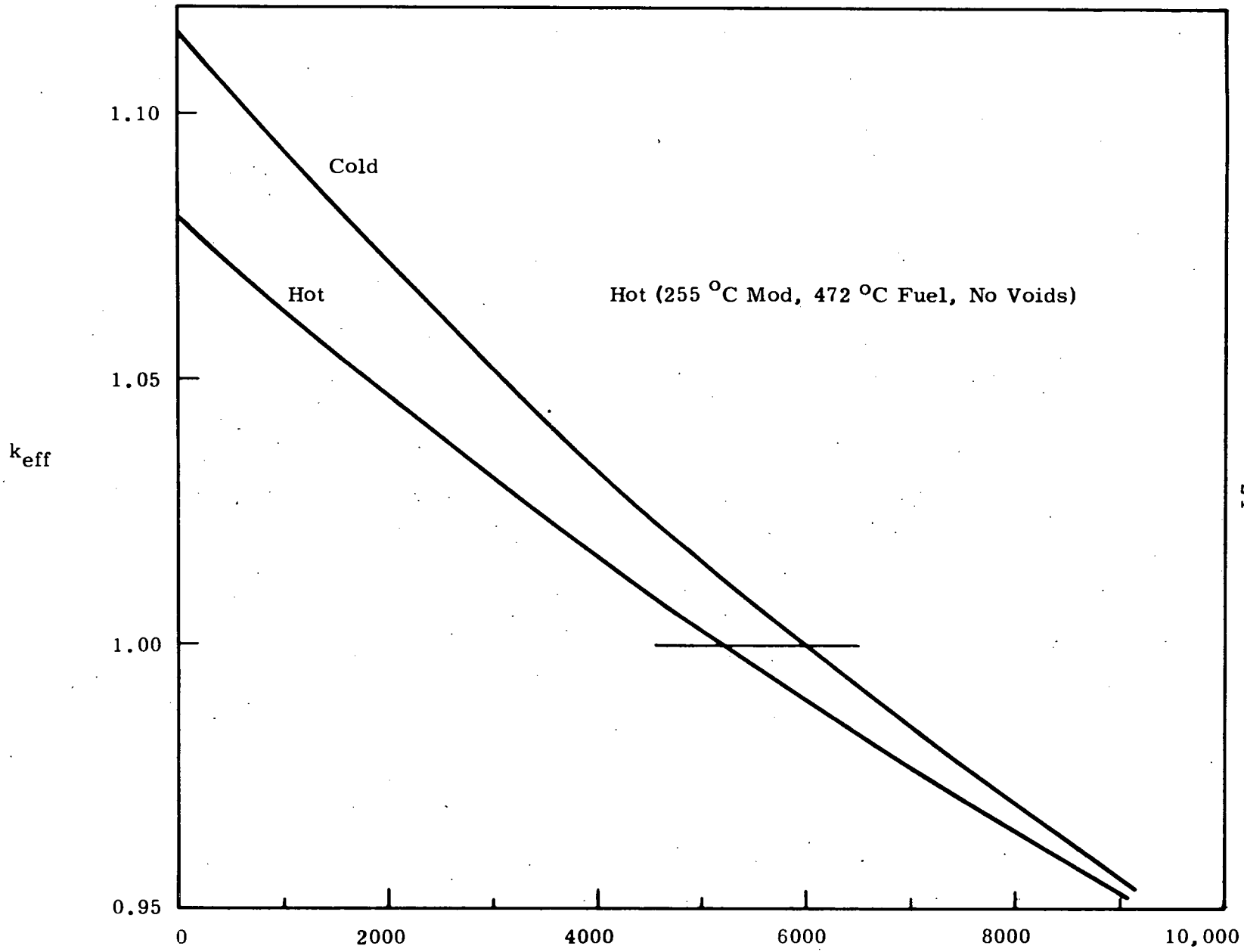

FIGURE 11

Reactivity Variation with Exposure for the 36 Element Pu Zone

The reactivity difference between cold and hot conditions for the plutonium zone decreases with exposure as shown in Figure 11. This difference is ~ 35 mk initially and decreases to ~ 10 mk at 6000 MWd/t. Thus it appears the moderator temperature coefficients become less negative with exposure. Calculations were made to determine the variation of the temperature and void coefficients of reactivity with exposure.

Moderator and Fuel Heating

The effects of moderator and fuel heating on reactivity as a function of exposure are shown in Figure 12. Initially, the moderator temperature coefficient of reactivity (the slope of the curve in Figure 12) is negative throughout the range of moderator temperatures. At 3000 MWd/t , the coefficient is positive up to ~ 140°C where it becomes zero and then negative for higher temperatures. An explanation for the positive moderator temperature coefficient is that the EBWR lattice becomes over-moderated when the coefficient becomes positive. This could result when sufficient plutonium has been destroyed to make the atom ratio of hydrogen to plutonium larger than optimum for a given temperature. The value of the moderator temperature at which the moderator coefficient of reactivity changes from positive to negative (i.e., the slope of the curve of reactivity versus temperature is zero) changes from ~140°C at 3000 MWd/t, to ~ 170°C at 6000 MWd/t, and to 200°C at 9000 MWd/t. This is approximately a 30°C change per 3000 MWd/t of exposure. Using this value of a 30°C increase per 3000 MWd/t to extrapolate to higher exposures, it appears that the moderator reactivity coefficient would be positive throughout the range of moderator temperatures (20°C to 255°C) at exposures of 15,000 MWd/t or greater. Also shown in Figure 12, is the

Figure 12 - Page 26

Circles denoting calculational points should be on the curve at 20°C and 195°C instead of at 40°C and 235°C.

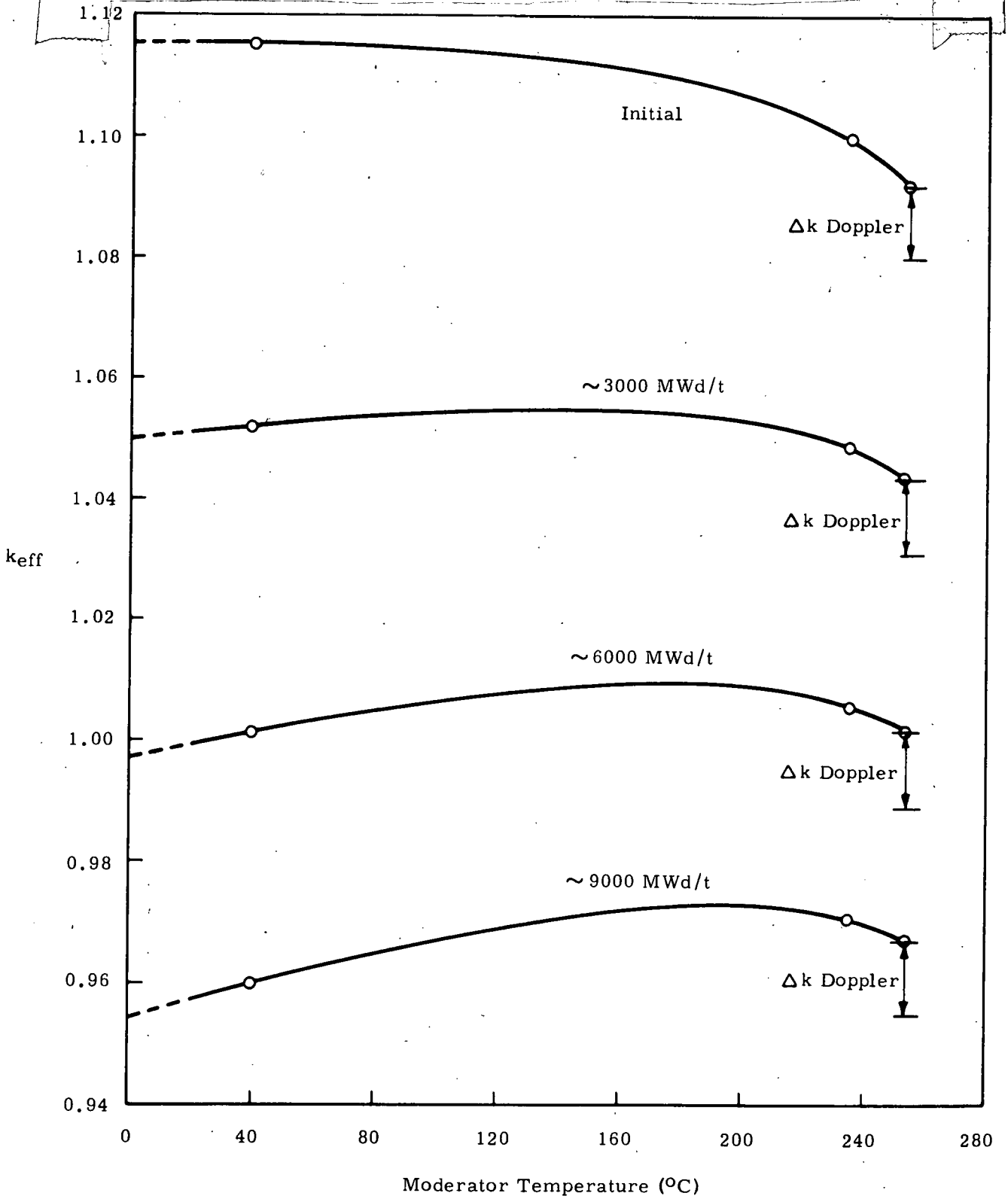

FIGURE 12

Reactivity Variation with Exposure for the 36 Element Pu Zone

reactivity change which occurs because of fuel heating from 20°C to 472°C at a constant moderator temperature of 255°C. The reactivity change due to fuel heating increases slightly with fuel burnup. The reactivity loss due to Doppler broadening is large enough to compensate for any positive effects due to moderator heating at exposures of 3000 and 6000 MWd/t. At 9000 MWd/t, the net reactivity effect due to moderator and fuel heating is almost zero. Thus, for exposures greater than 9000 MWd/t, a positive reactivity effect upon moderator and fuel heating is expected.

Voids

The effect of voids on reactivity are shown in Figure 13 as a function of void fraction and at various stages of burnup. A less negative trend is noted in the void coefficient as the burnup proceeds. The difference in reactivity between 0 and 30% void is ~ 85 mk initially and decreases to ~ 70 mk at 9000 MWd/t.

Variation of Coefficients

The average coefficient of reactivity for moderator temperature changes, void fraction, and Doppler effects are compared in Figure 14 as a function of exposure. The average moderator temperature coefficient is expected to go positive at about 5300 MWd/t. The negative Doppler coefficient is calculated to be equal to the positive moderator temperature coefficient at ~ 7600 MWd/t. The average void coefficient has a slight positive trend which when extrapolated to higher exposures (~ 15,000 MWd/t) is expected to stay negative. Thus though the reactivity could increase upon moderator + fuel heating at high exposures the net reactivity effects for full power operation (temperature, void, xenon and samarium) would be negative. Calculations of the reactivity invested in saturation xenon

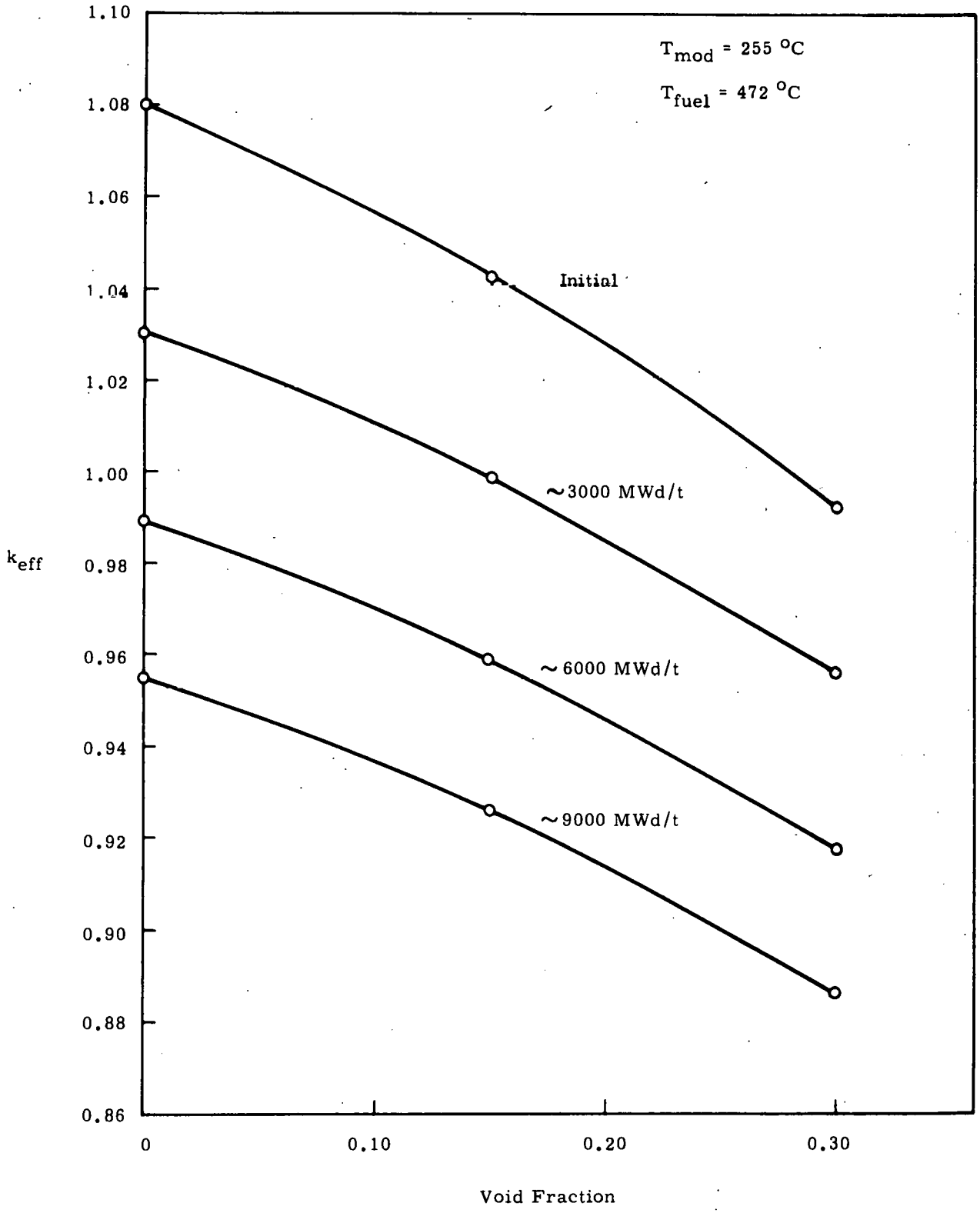

FIGURE 13

Reactivity Variation with Coolant Void for the 36 Element Pu Zone

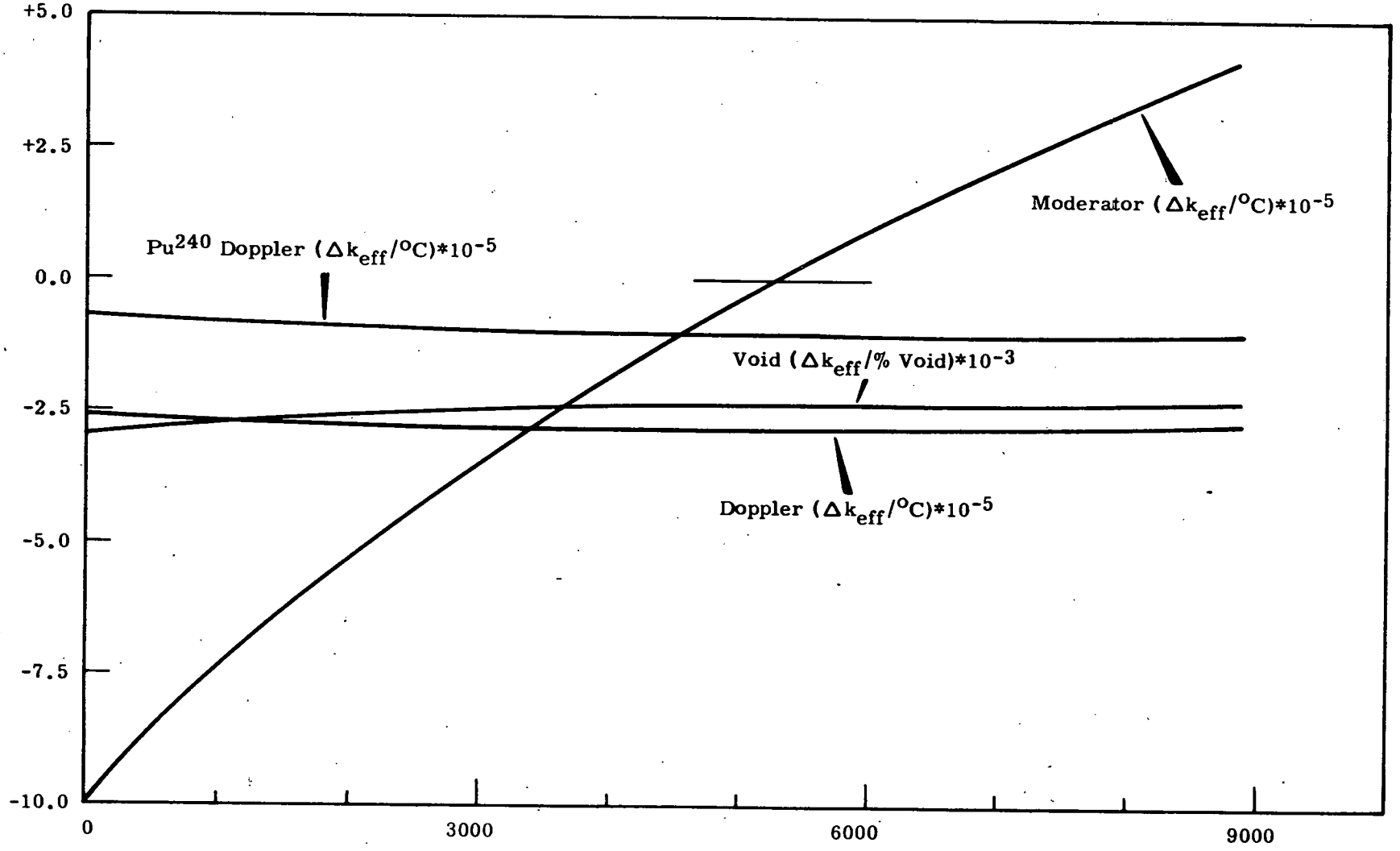

FIGURE 14

Variation of the Average Reactivity Coefficients with Exposure for the 36 Element Pu Zone

and samarium fission products have not been made but is estimated to be about 30 mk.[2] The Pu^{240} Doppler coefficient is also shown in Figure 14. To illustrate the contribution of Pu^{240} to the total Doppler coefficient, the percent contribution versus exposure is shown in Figure 15. This contribution increases from ~ 27% initially to ~ 38% at 9000 MWd/t, and is nearly constant at 40% at an exposure of about 12,000 MWd/t.

Conclusions

The results of calculations show that the reactivity variations with temperature changes and void changes are largest for initial conditions (i.e., startup) of the PuO_2-UO_2 loading proposed for the EBWR and tend to become less negative as fuel burnup proceeds. These trends point out interesting aspects of a reactor design. It appears that care must be taken in selection of a moderator to fuel ratio for the loading. Selecting a ratio too near the optimum one could result in operational difficulties later because of possible positive temperature coefficients at higher exposures. It seems feasible to select a moderator to fuel ratio far enough from the optimum one to ensure undermoderation up to 15,000 MWd/t. This problem could be more acute in a pressurized water power reactor where no large negative void coefficient is present as there is in a boiling water power reactor. This problem is not unique to a plutonium fueled system because the results of Section VI show that the plutonium fuel is expected to have larger negative reactivity coefficients than the uranium fuel. The data obtained from the startup tests when compared to the results of these calculations will be significant for ascertaining the validity of the calculated reactivity trends with increased fuel exposure.

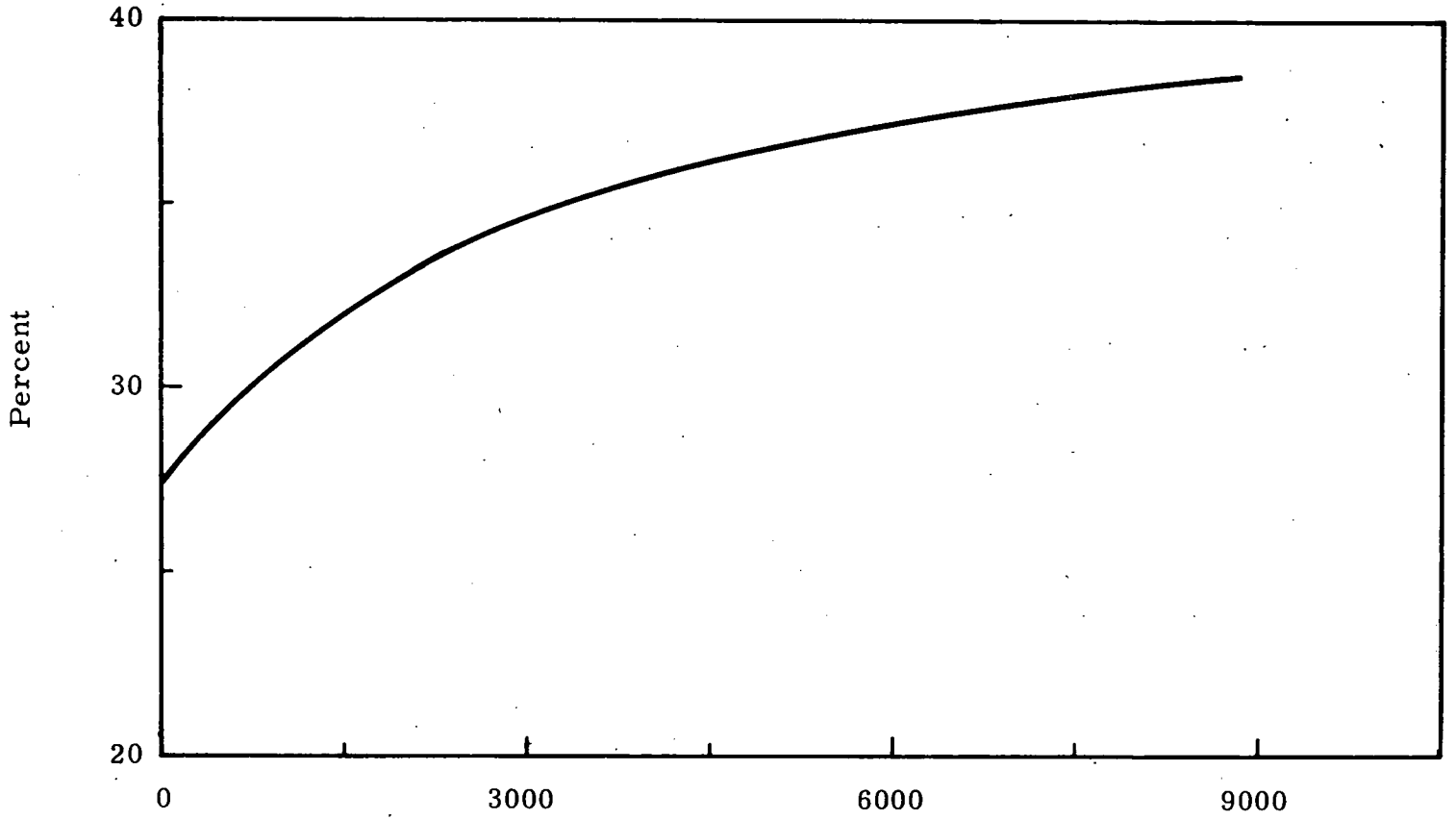

FIGURE 15

Pu^{240} Contribution to the Total Doppler Coefficient as a Function of Exposure

VIII. SPECIAL RODS

Additional useful physics data from this EBWR experiment will be obtained from a series of special rods which are placed in the core as shown in Figure 1. There are five different types of rods. There are rods made of natural UO_2, 3.35 w/o PuAl of which ~ 8 or ~ 26 atom percent of the plutonium is Pu^{240}, and 1.5 w/o PuO_2 in UO_2 of which ~ 20 or ~ 26 atom percent of the plutonium is Pu^{240} and ~ 0.22 atom percent of the uranium is U^{235}. In addition, data will be available from the rods of the base load which are 1.5 w/o PuO_2 in UO_2.

UO_2 Rods

Four rods containing natural uranium dioxide are to be included in the plutonium zone in order to compare uranium and plutonium burnup characteristics. At appropriate irradiation intervals (~ 2000 to 3000 MWd/t) one of these rods shall be removed with a base load (referring to a 1.5 w/o PuO_2 in UO_2 containing 8 percent Pu^{240}) plutonium rod. The simultaneous irradiation of uranium and plutonium fuel in essentially the same neutron spectral environment should lead to a valid comparison of the burnup behavior of these fuels in a reactor moderated with light water. Since natural UO_2 rods have been irradiated and PuO_2-UO_2 rods are being irradiated in the Plutonium Recycle Test Reactor (PRTR) which is D_2O moderated, a comparison between the burnup behavior of this fuel in an H_2O moderated reactor and that in a D_2O moderated reactor can be made.

PuAl Rods

Eight rods made of a plutonium aluminum alloy are included in the EBWR core to obtain physics data for high plutonium burnups over

relatively short irradiation periods (e.g., for a 1.8 w/o PuAl rod with 6 a/o Pu^{240}, 100 MWd corresponds to an average burnup of ~ 38%).[14] The plutonium content of the PuAl rod was chosen such that the heat generation rates in the rods are comparable to the base load rods. A plutonium concentration of 3.35 w/o Pu results in a value for the ratio $\overline{\eta}f(\nu\overline{\Sigma}_f/\overline{\Sigma}_a)_{thermal}$ which is equal to that for the fuel of the base loading. Since the PuAl rods do not contain fertile material, the heat generation of the elements should become less than that of the fuel used for the base loading as the irradiation proceeds. Four PuAl rods containing ~ 8 atom percent Pu^{240} and four rods containing ~ 26 atom percent Pu^{240} will be inserted into the plutonium zone at startup and one of each type taken out at various exposure intervals. The atom ratio of Pu^{240} in Pu as a function of exposure is shown in Figure 16 for the PuAl rods. A rod containing 8% Pu^{240} initially will contain 26 a/o Pu^{240} after being irradiated for about 500 full power days. If the atom concentration ratio (N^{Pu-240}/N^{Pu}) is defined as a measure of burnup, a rod containing 26 a/o Pu^{240} therefore has initially an "equivalent" 500 day irradiation. Thus an attempt to infer what is the behavior of a highly burned plutonium rod will be made by combining the data obtained from the rods containing 8% and 26 a/o Pu^{240} initially. However, the contents of a rod containing 8% Pu^{240} having been irradiated until there is 26% Pu^{240} are somewhat different from those of an unirradiated rod containing 26% Pu^{240}. Therefore corrections will have to be made to combine these data. PuAl rods have been irradiated in the PRTR,[12,13,14] so a comparison of the burnup behavior of this type of fuel in reactors moderated by light or heavy water can also be made.

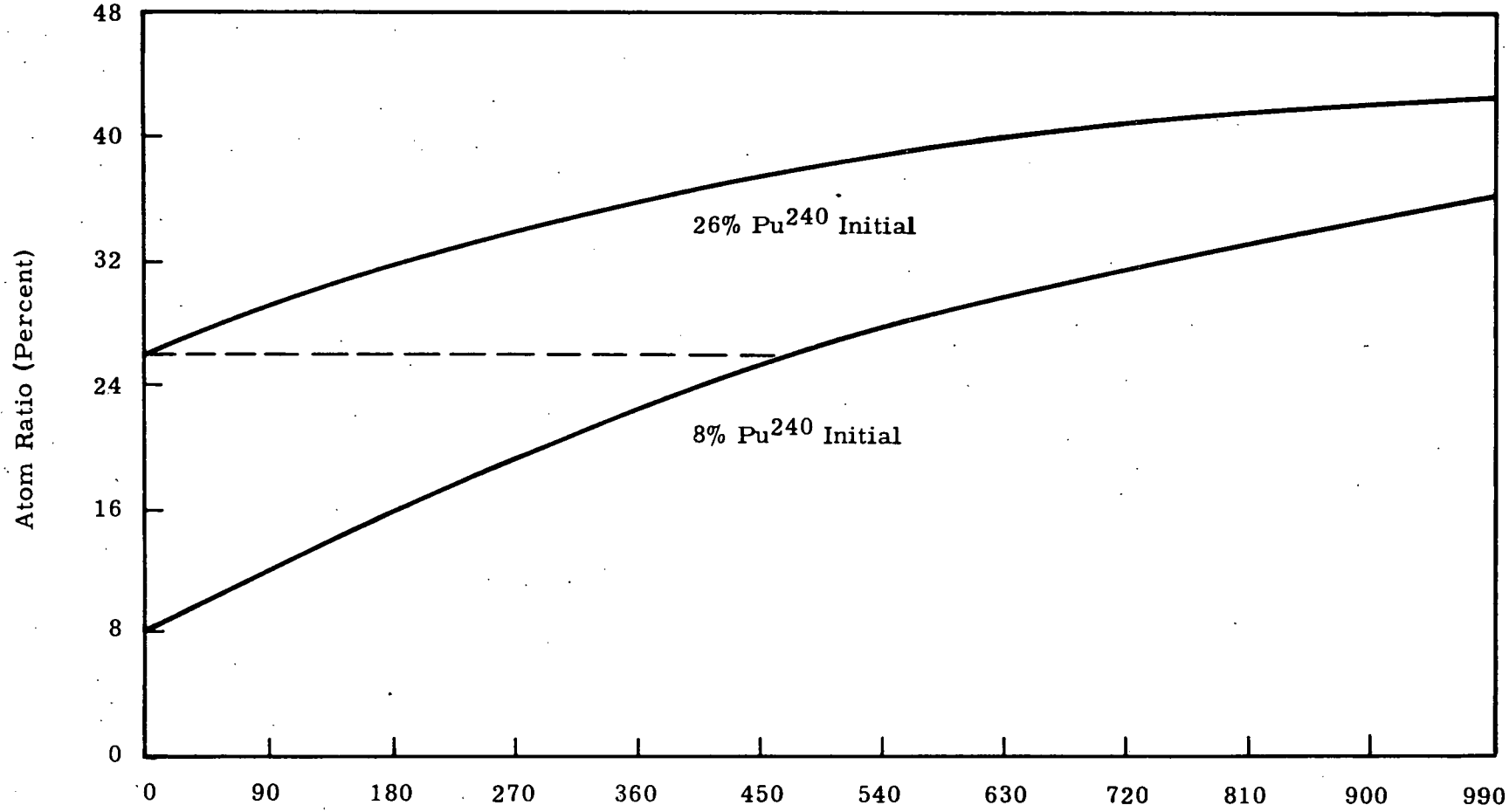

FIGURE 16

Atom Ratio (Plutonium 240/Total Pu) as a Function of Exposure for 3.35 w/o PuAl Rods

PuO_2-UO_2 Rods

Eight special rods containing the mixed oxides of plutonium and uranium will be inserted into the plutonium zone at startup. These rods are included for a comparison of the behavior of this type of fuel with that of the PuAl rods which contain varying concentrations of Pu^{240}. A mixed oxide rod does not burn out as fast as a Pu-Al rod since Pu is being produced from U^{238}. Therefore, to ensure collecting data over a wide range of exposure, four additional mixed oxide rods each containing ~ 20% Pu^{240} will also be irradiated. Using the Pu^{240} to Pu atom ratio defined previously as a measure of inferring burnup, the burnup characteristics of a base load rod (8% Pu^{240}) up to about 15,000 MWd/t can be inferred by an actual irradiation of about only 6000 MWd/t on a special rod containing 26% Pu^{240} initially. This is shown in Figure 17 where a mixed oxide rod with an initial 26% Pu^{240} content undergoing an irradiation of 6000 MWd/t has the same atom ratio of Pu^{240} to total Pu as a mixed oxide rode containing initially 8% Pu^{240} and irradiated to 15,000 MWd/t. A final check on this method of inferring the characteristics of fuel with high burnups will be made by analysis of a rod from the base loading after the end of the irradiation and comparing with the results obtained from a special rod of equivalent exposure.

A typical lifetime for fuel in a light water moderated power reactor would be of the order of 15,000 MWd/t. To accumulate this exposure on the mixed-oxide fuel of the base loading in the EBWR would require an absolute minimum of 1350 days* at full power operation and 100% efficiency.

*Based upon a 40 MW power for the core with 36% of the power coming from the Pu zone, and assuming the power generation independent of exposure.

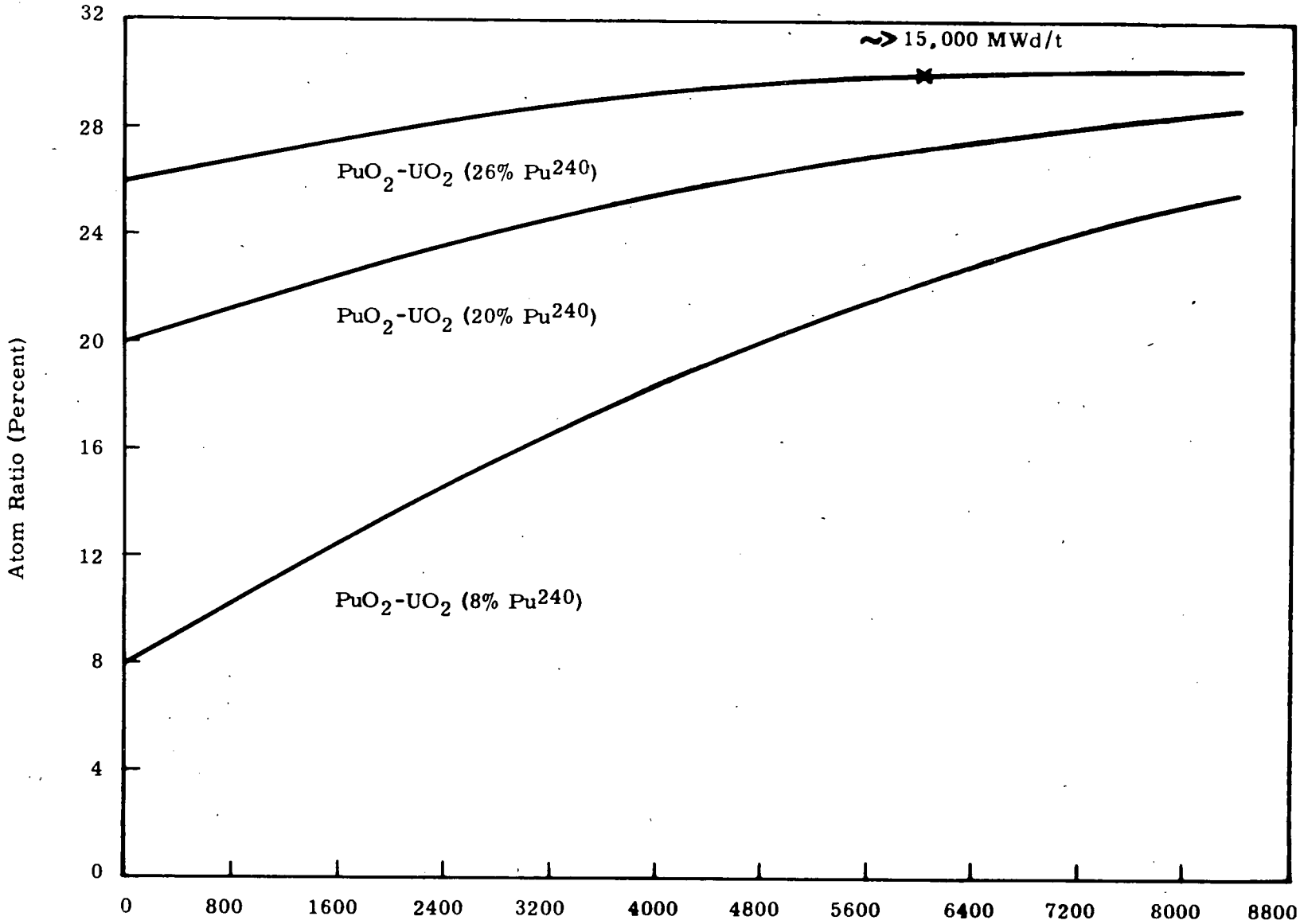

FIGURE 17

Atom Ratio (Plutonium 240/Total Pu) as a Function of Exposure for 1.5 w/o PuO_2 in UO_2 Rods

Since a reasonable estimate of the plant operating efficiency is around 75%, the time involved would be approximately 5 years. For purposes of a demonstration experiment, such a time interval is prohibitive. Thus, if successful, the "inferred burnup" scheme may prove to be very useful in predicting the burnup behavior of PuO_2-UO_2 cores. Also, information about the merits of mixed oxide power reactor fuels containing varying amounts of Pu^{240} can be extracted from the results of these special rod irradiations (e.g., what amount of initial Pu^{240} leads to the most constant reactivity variation with exposure). Mixed oxide rods have been irradiated in the PRTR and the comparison of burnup in reactors moderated by light or heavy water will be made just as for UO_2 and PuAl rods.

The calculated variation of atom concentrations with exposure (from which the data plotted in Figures 16 and 17 were obtained) are included in Appendix A for all special rods.

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APPENDIX A

CALCULATED ISOTOPIC CONCENTRATION VARIATIONS FOR RODS TO BE IRRADIATED IN THE EBWR

The initial isotopic compositions of the special rods and of the base load rod of PuO_2-UO_2 used in the calculations are presented in Table A1. The compositions of the rods actually used in the experiment will probably differ slightly. The isotopic compositions of the rods as a function of burnup of the PuO_2-UO_2 zone are presented graphically in Figures A1 through A7. The curves in Figures 16 and 17 were obtained by taking ratios of these isotopic concentrations.

Burnup of the special rods was calculated with program ALTHAEA[10] which is a two group, one dimension (using cylindrical geometry), time dependent diffusion theory code. The cross sections are based on the Westcott formalism,[16] $\hat{\sigma} = \sigma_{2200} \left[g(T) + rS(T) \right]$, using the Δ4 non-Maxwellian flux shape. In the calculations, the Wescott formalism is modified by

$$g_{eff}(T) = g(T)/F$$

where F is the thermal disadvantage factor and is approximated by:

$$F = \text{FCONST} * \bar{\Sigma}_a + e^{-\text{FEXP} * \bar{\Sigma}_a}$$

and $\bar{\Sigma}_a$ is the macroscopic fuel absorption cross section for the Maxwellian group of neutrons. Values of FCONST and FEXP are listed in Table A2 for the various types of rods. Another modification is

$$S_{eff}(T) = \frac{S(T) + bg(T)}{\sqrt{1 + \frac{\sum_i C^i N^i \sigma_o{}^i}{SCA}}} - bg_{eff}(T)$$

where:

b has the value 1.1762 ($\Delta 4$ non-Maxwellian flux shape)

σ_o^i is the effective resonance peak cross section of the i^{th} isotope corrected for the effect of Doppler broadening,

C^i are interference coefficients between isotopes,

Σ_p is the potential scattering in the fuel region,

$1/\bar{\ell}$ is the surface to volume term, S/4 V, of the fuel region modified by the Bell correction,

N^i is the isotope density,

with

$$SCA = \Sigma_p + 1/\bar{\ell} .$$

The neutron temperature is

$$T_n = T_m \left(1 + 0.62 \frac{\bar{\Sigma}_{a_2}}{\bar{\xi}\bar{\Sigma}_{s_1}} \right)$$

where:

T_m is the moderator absolute temperature and $\bar{\xi}\bar{\Sigma}_{s_1}$ is the slowing down power. The spectral index, r, is determined by

$$r = \frac{\bar{\Sigma}_{a_2}}{\bar{\xi}\bar{\Sigma}_{s_1} - (1 - RAYK1)(\bar{\Sigma}_{a_1} \Delta u_1) + b\, \bar{\Sigma}_{a_2}} .$$

where: Δu_1 is 16.18 lethargy units. Values for $\bar{\Sigma}_{a_1}$, $\bar{\xi}\bar{\Sigma}_{s_1}$, and RAYK1 are also included in Table A2.

The epithermal resonance integral for Pu^{240} is given by:

$$I_{eff} = I_{dilute} \left(1 + \frac{NZ}{SCA}\right)^{-1/2}$$

where:

$$Z = \left(\frac{\bar{\sigma}_o^2}{\sigma_{eff}^2} - 1\right) * SCA/N.$$

Values for the parameters which are listed in Table A2 were obtained from cell computations using the thermalization codes THERMOS[7] and SPECTRUM[17] and the slowing down code HRG.[6]

TABLE A1

FUEL ISOTOPIC COMPOSITIONS ASSUMED IN BURNUP ANALYSIS

Rod		Composition
1) Mixed Oxides $\rho_{PuO_2\text{-}UO_2}$ = 9.873 gm/cc		1.5 w/o PuO_2 in UO_2, 0.22 a/o U^{235} in U.
a) Base Load	8% Pu^{240}	92 a/o Pu^{239} and 8% Pu^{240} in Pu.
b) Special	26% Pu^{240}	69.14 a/o Pu^{239}, 25.96 a/o Pu^{240}, 4.09 a/o Pu^{241}, and 0.804 a/o Pu^{242}.
c) Special	20% Pu^{240}	76.42 a/o Pu^{239}, 20.16 a/o Pu^{240}, 3.08 a/o Pu^{241}, and 0.328 a/o Pu^{242}.
2) PuAl Special $\rho_{Pu\text{-}Al}$ = 2.7 gm/cc		
a)	8% Pu^{240}	92 a/o Pu^{239} and 8 a/o Pu^{240}
b)	26% Pu^{240}	69.14 a/o Pu^{239}, 25.96 a/o Pu^{240}, 4.09 a/o Pu^{241}, and 0.804 a/o Pu^{242}.
3) UO_2 Special ρ_{UO_2} = 10.2 gm/cc		Natural, 0.7115 a/o U^{235} in U.

TABLE A2

PARAMETERS FOR ALTHAEA TO CALCULATE BURNUP OF THE SPECIAL RODS AND THE BASE LOAD PuO_2 ROD

	F_{const}	F_{exp}	$\bar{\Sigma}_{a_1}$	$\bar{\xi}\bar{\Sigma}_{s_1}$	RAYK1
Mixed Oxides	1.4606	0.81079	0.0623	0.22395	1.1423
UO_2	1.4606	0.81079	0.0383	0.24945	1.9901
PuAl	0.96793	0.35510	0.0266	0.25869	1.8820

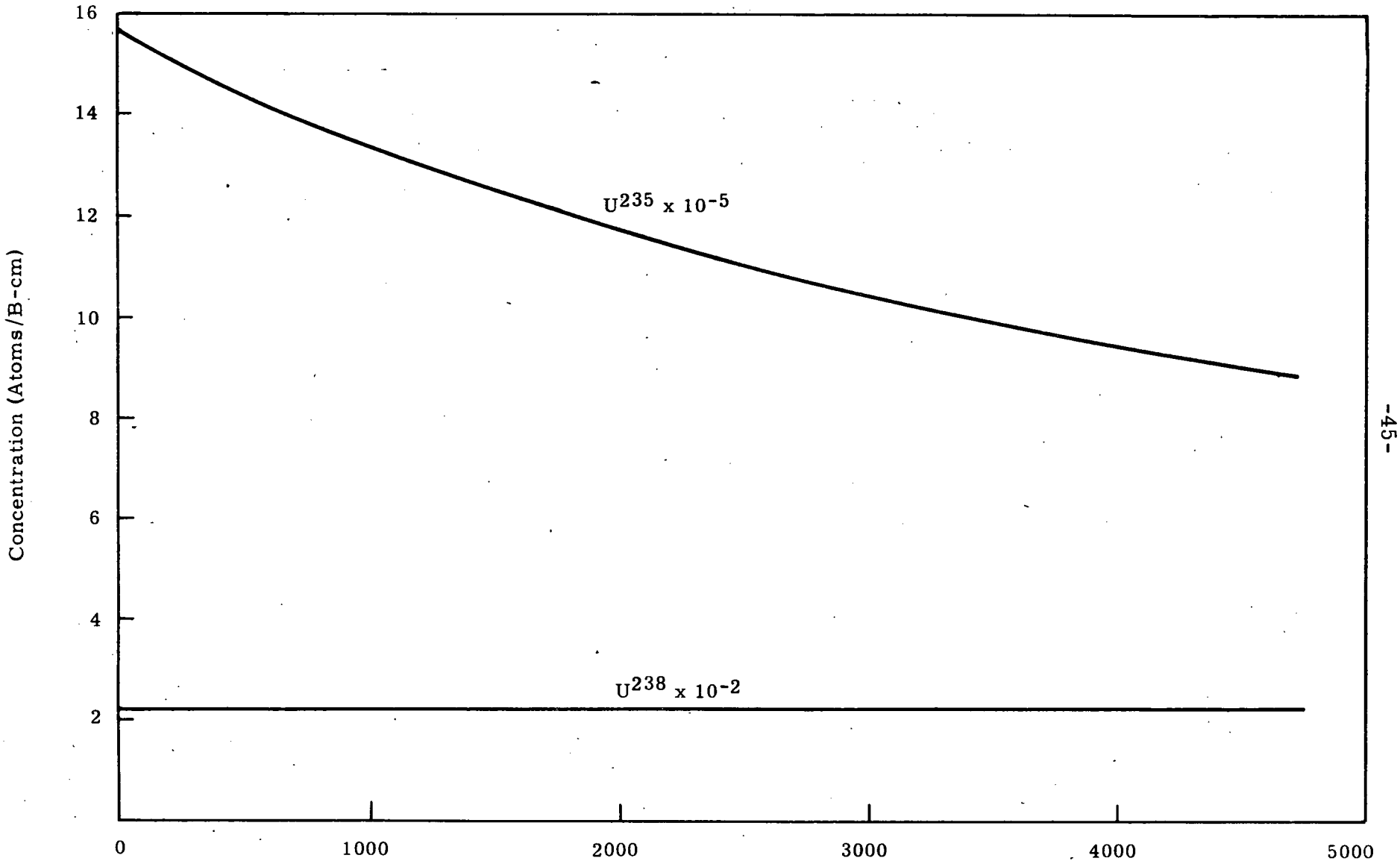

FIGURE A1

Uranium Atom Concentration versus Exposure for a Natural UO_2 Rod

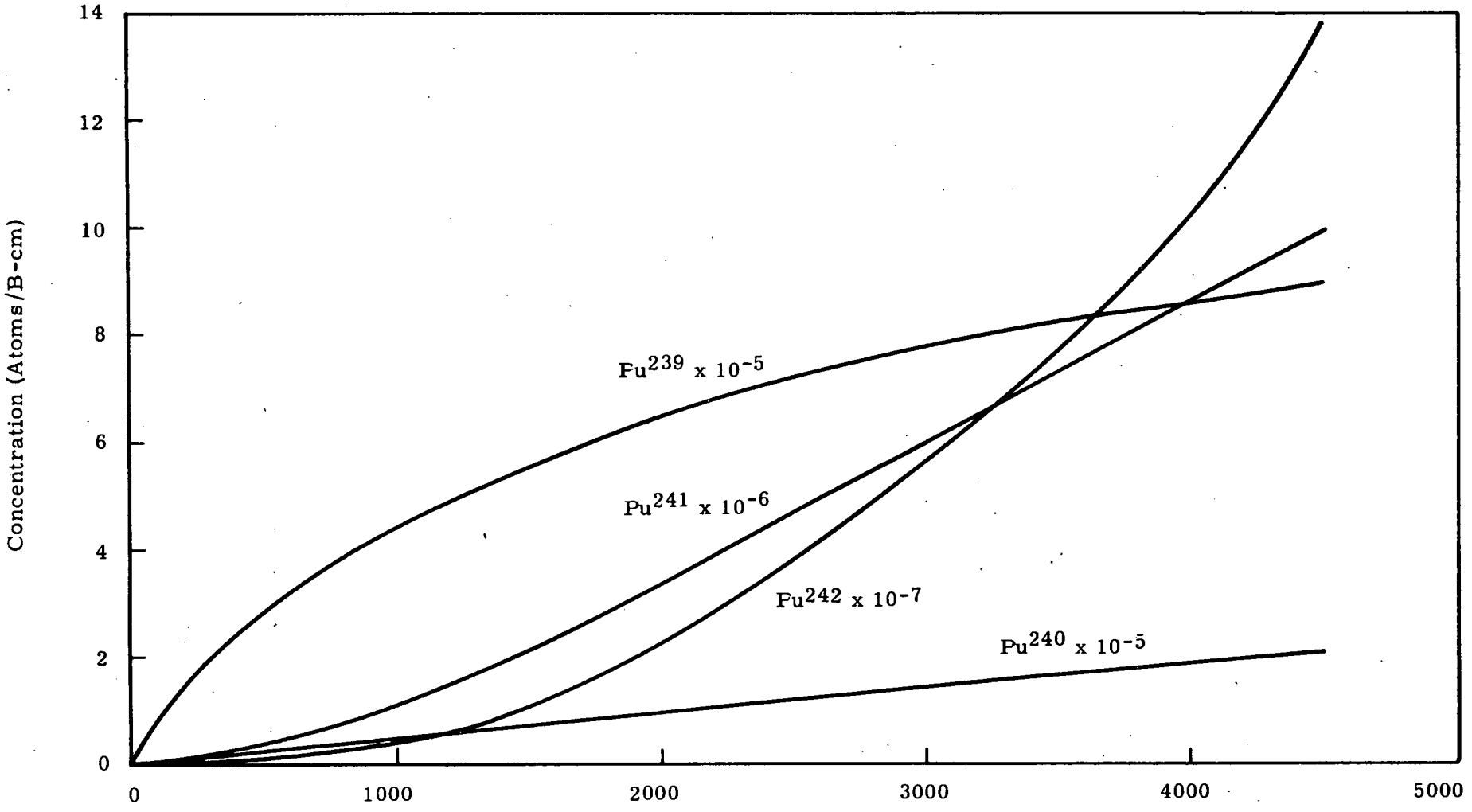

FIGURE A2

Plutonium Atom Concentrations versus Exposure for a Natural UO_2 Rod

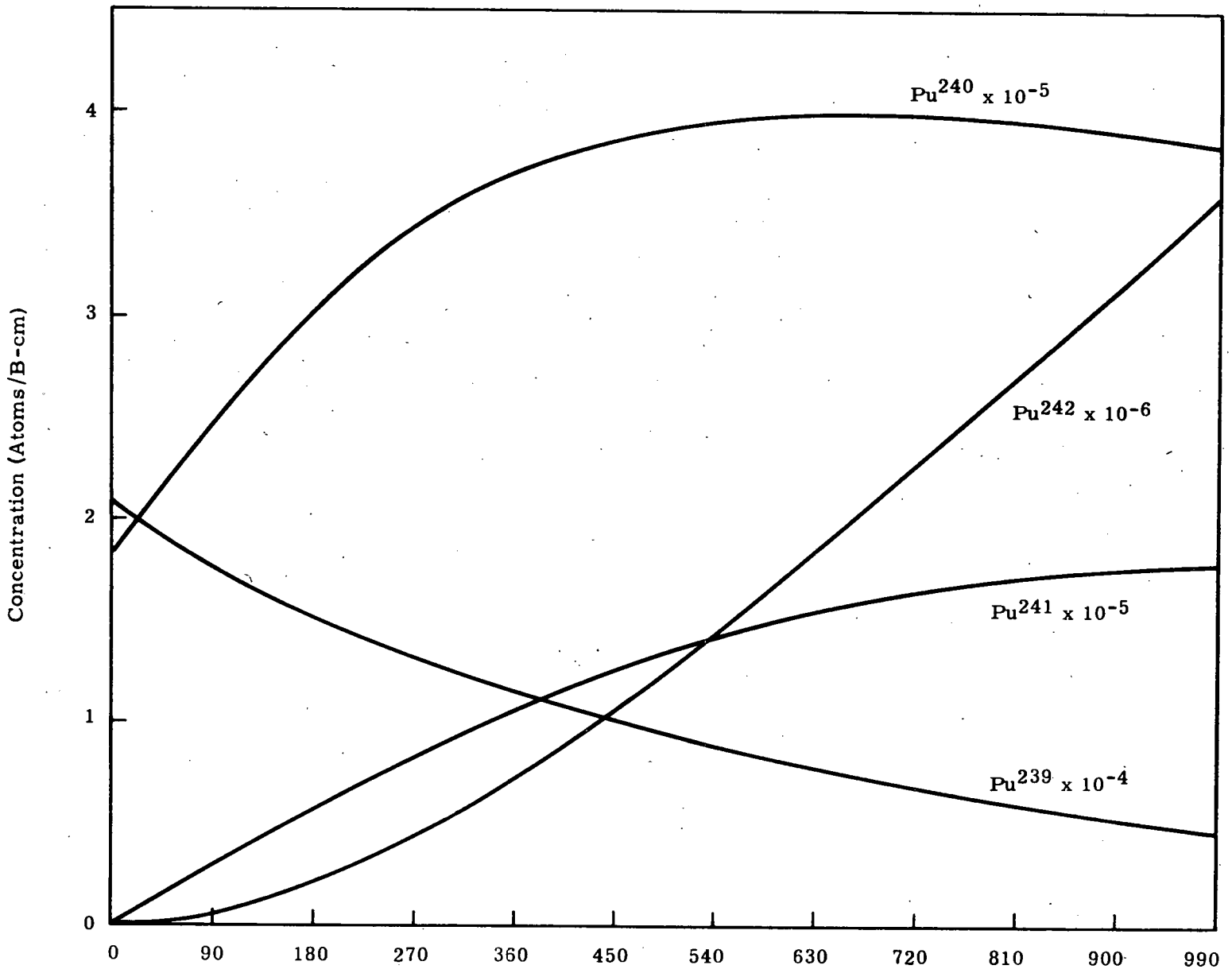

FIGURE A3

Plutonium Atom Concentrations versus Exposure for a 3.35 w/o PuAl Rod with 8% Pu^{240}

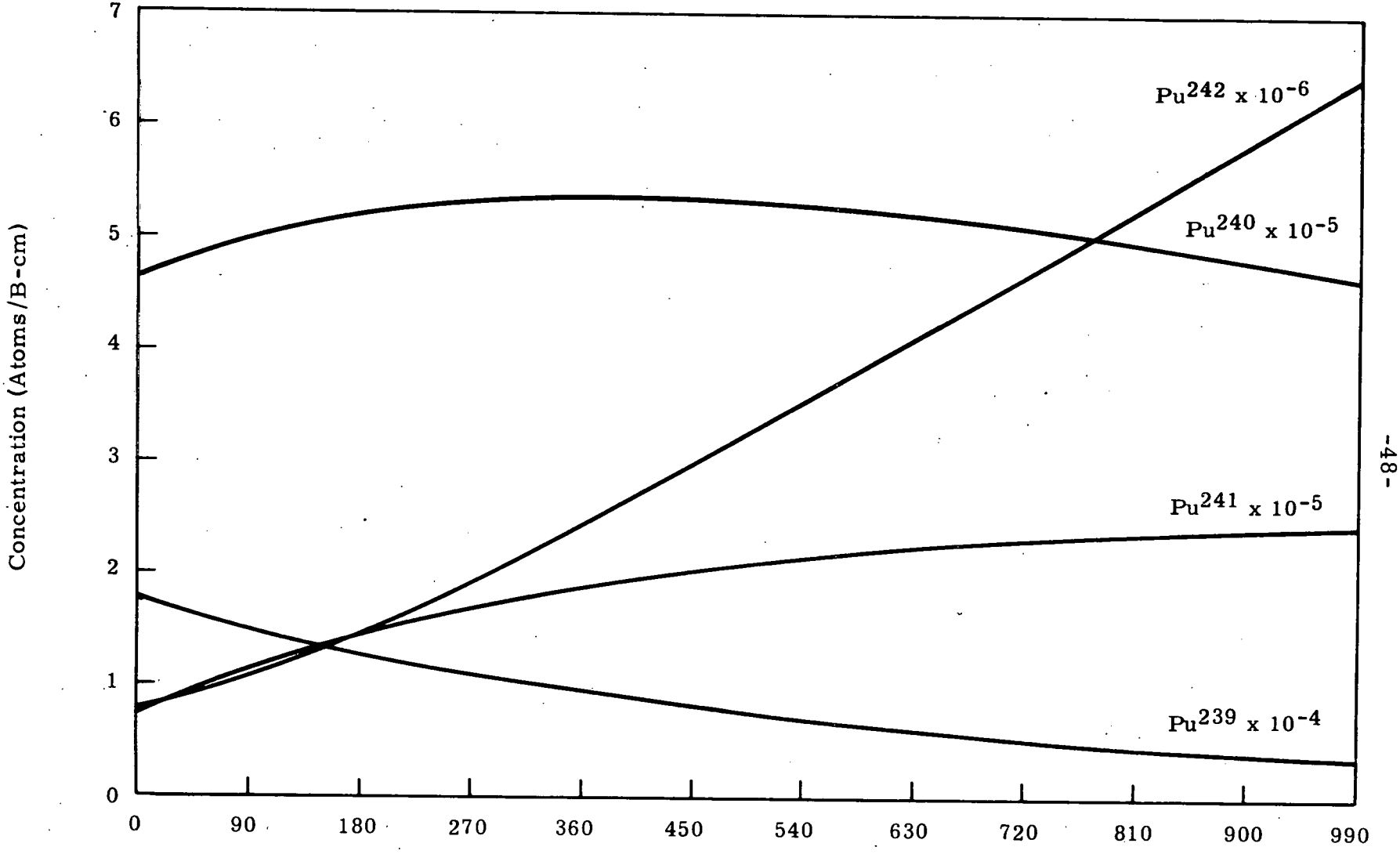

FIGURE A4

Plutonium Atom Concentrations versus Exposure for a 3.35 w/o PuAl Rod with 26% Pu^{240}

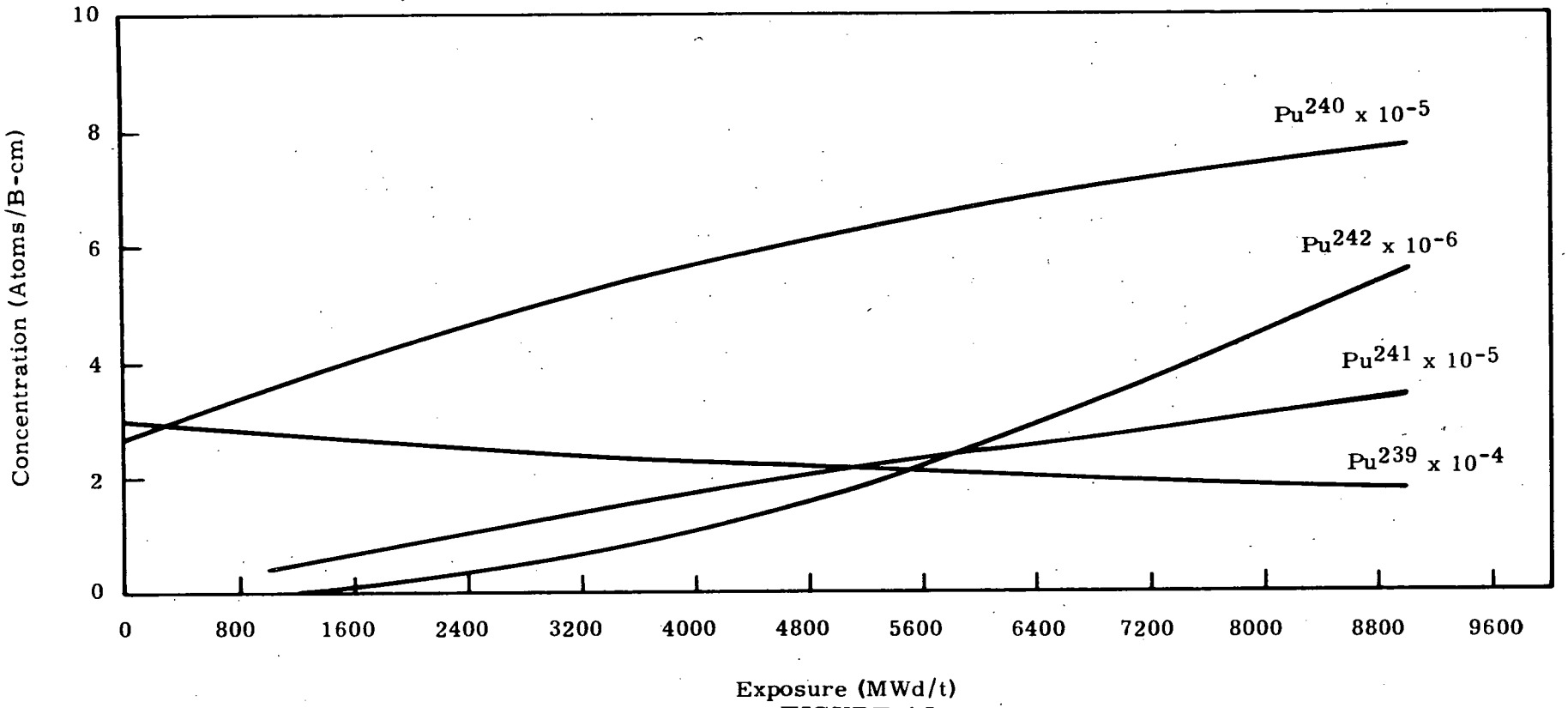

FIGURE A5

Plutonium Concentrations versus Exposure for a 1.5 w/o PuO_2 in UO_2 Rod with 8% Pu^{240}
(Base or Normal Rod)

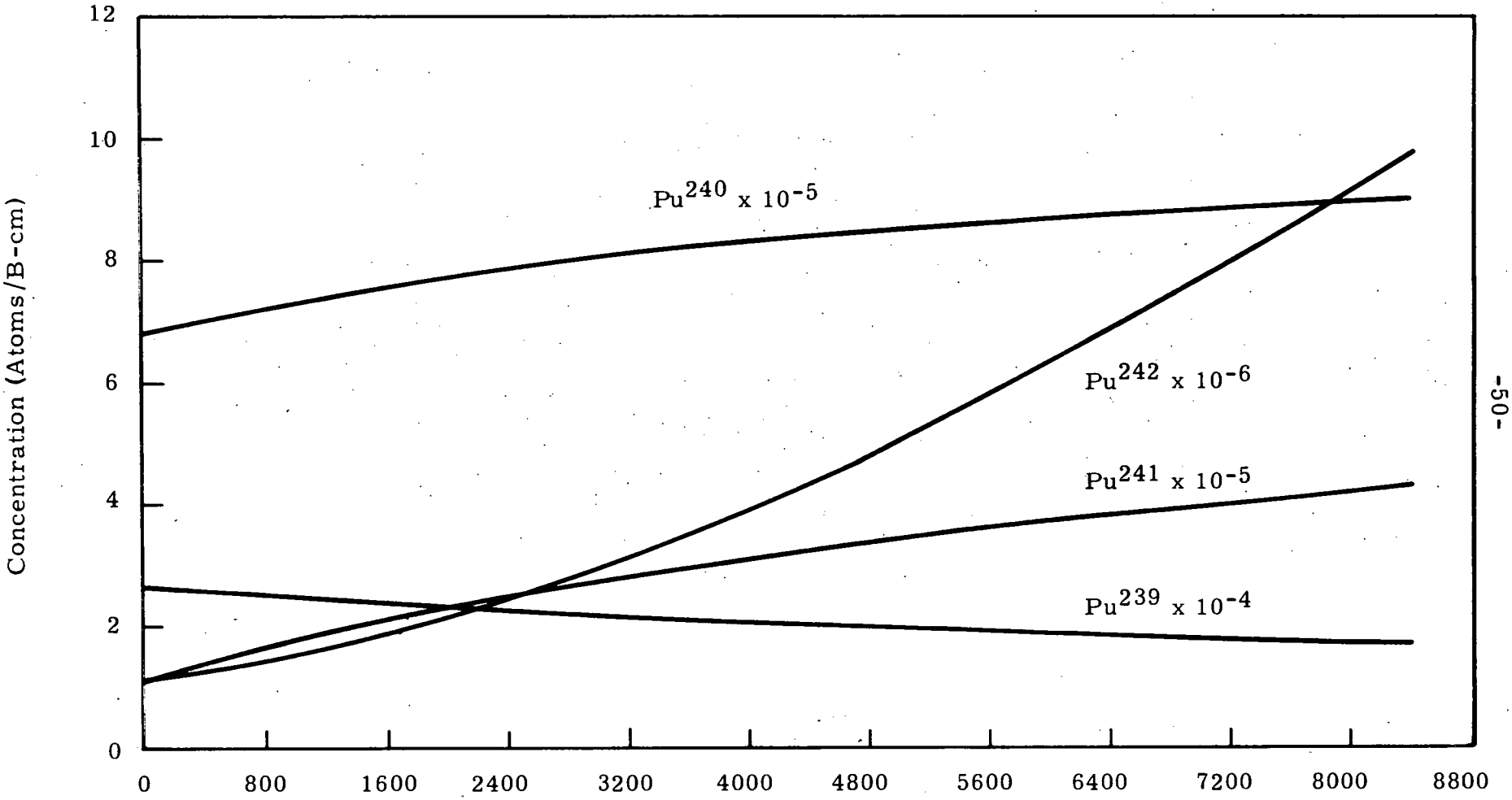

FIGURE A6

Plutonium Atom Concentrations versus Exposure for a 1.5 w/o PuO_2 in UO_2 Rod with 20% Pu^{240}

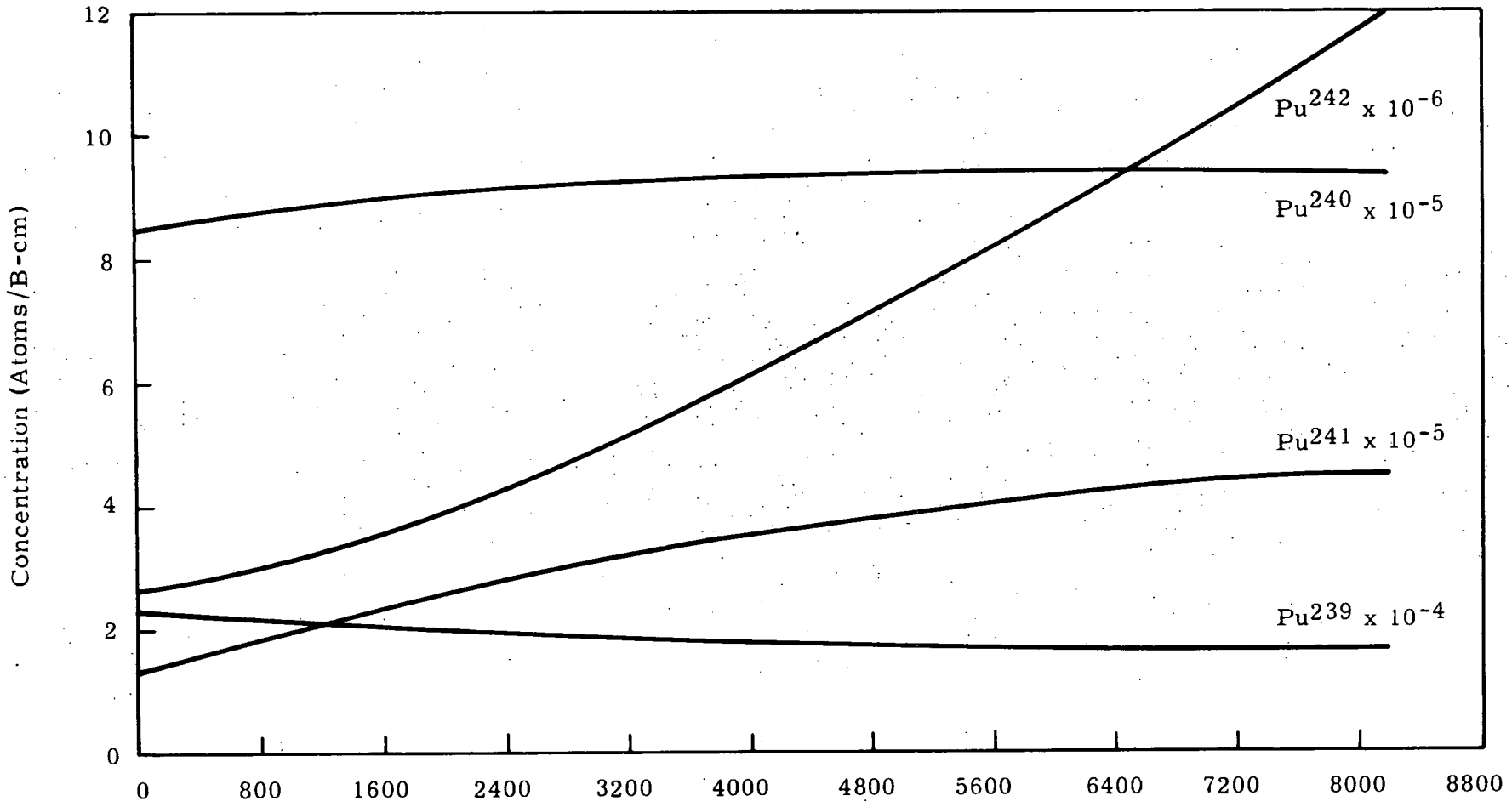

FIGURE A7

Plutonium Atom Concentrations versus Exposure for a 1.5 w/o PuO_2 in UO_2 Rod with 26% Pu^{240}

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