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A CRITICAL EXPERIMENTAL STUDY OF INTEGRAL PHYSICS PARAMETERS IN SIMULATED LMFBR MELTDOWN CORES*

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S. K. Bhattacharyya, D. C. Wade, R. G. Bucher
D. M. Smith, R. D. McKnight and L. G. LeSage

Argonne National Laboratory
Applied Physics Division
9700 South Cass Avenue
Argonne, Illinois 60439

*Work performed under the auspices of the U. S. Nuclear Regulatory Commission.

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ABSTRACT

Integral physics parameters of several representative, idealized meltdown LMFBR configurations were measured in mockup critical assemblies on the ZPR-9 reactor at Argonne National Laboratory. The experiments were designed to provide data for the validation of analytical methods used in the neutronics part of LMFBR accident analyses. Large core distortions were introduced in these experiments (involving 18.5% core volume) and the reactivity worths of configuration changes were determined. The neutronics parameters measured in the various configurations showed large changes upon core distortion. Both diffusion theory and transport theory methods were shown to mispredict the experimental configuration eigenvalues. In addition, diffusion theory methods were shown to result in a non-conservative misprediction of the experimental configuration change worths.

INTRODUCTION

A program of measurements designed to provide experimental data for the validation of analytical methods used in the neutronics part of LMFBR accident analyses has recently been completed at Argonne National Laboratory. A considerable volume of critical experimental data already exists for normal, undamaged LMFBR cores, and the sizes of the calculational and cross-section data errors are well established. However, this knowledge cannot be easily extrapolated to severely distorted accident configurations because of the large changes in neutron spectrum and system leakage properties (including streaming in large cavities) which are induced by redistribution of materials. The

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available experimental data on the physics of damaged LMFBR cores[1,2,3] are inadequate for use in the systematic validation of calculational methods for a variety of reasons. The present program provides a clean, set of benchmark experiments with large reactivity changes (involving ∿18.5% core volume distortions) for use in the methods validation.

The reference configuration for the measurements consisted of a single-zone core with an LMFBR outer core composition. A sequence of idealized configurations was designed to follow from this reference to simulate, in a static or "snap-shot" sense, the sequence of configurations that might result from a loss-of-flow transient. Both axially symmetric and asymmetric configuration distortions were included in the program; all configurations were rotationally symmetric around the Z axis. Figure 1 shows a schematic view of the sequence of configurations studied. The major distortions in the cores consisted of fuel slumping into the center of the core and outward toward the core/blanket interface, both cases being accompanied by corresponding void cavities in the core. The large volume fraction of fuel redistributed represents an upper limit of expected core volume distortions under accident conditions.

DESCRIPTION OF EXPERIMENTAL PROGRAM

The assemblies were built on the Zero Power Reactor -9 (ZPR-9) split table critical facility having an 8 ft × 8 ft × 8 ft array of stainless steel matrix tubes each with a cross section approximately 2 in. square. Drawers containing fuel platelets, clad solidified sodium coolant, and structural material were loaded into this matrix to simulate the composition of the reactor being studied. The measurements performed in each of the configurations shown in Fig. 1 are listed below. The measurements were designed to characterize the neutronics of

the distorted cores as completely as possible in the short time available for the measurement program.

Configuration	k_{eff}[a]	Neutron Spectrum	Central Reactivity Worth	Axial Reactivity Worth Profiles	$^{235}U(n,f)$ Reaction Rate Profiles (Axial)	$^{235}U(n,f)$ Reaction Rate Profiles (Radial)	^{238}U Doppler Worth	B_4C Control Rod Worth	β/ℓ[d]	β[e]
1. Reference Core	✓	Core Center	^{239}Pu, ^{240}Pu ^{238}U, ^{235}U, ^{10}B, Na, SST[f]	^{239}Pu, ^{238}U, SST[f]	✓	✓	Core Center	Core Center	✓	✓
2. Sodium Voided Reference	✓									
3. Symmetric fuel Slump-Out	✓		"	"	✓					
4. Symmetric fuel Slump-in	✓	Core Center	"	"	✓	✓	Core Center	Core Center	✓	
5. Asymmetric fuel Slump-in	✓		^{239}Pu, ^{238}U, SST, ^{10}B	"	✓					
6. Asymmetric fuel Slump-in with blanket collapse	✓				✓					
7. Asymmetric fuel Slump-out	✓		^{239}Pu, ^{238}U, SST	"	✓					

[a]The changes in k between the configurations gave the worths of these configuration changes.
[b]The foil locations were determined based on Monte Carlo code validation requirements.
[c]The control rod height was kept equal to core height.
[d]Ratio of beta effective to prompt neutron lifetime.
[e]Beta effective.
[f]Stainless Steel.

The reference core shown in Fig. 1 had a radius of 44.19 cm, a height-to-diameter ratio of one, an enrichment* of 22%, and was surrounded by a 40.89 cm radial and 38.18 cm axial blanket of depleted uranium oxide with a stainless steel reflector (14.32 cm thick radially and 12.82 cm thick axially). All the fuel slumping was made in a central test zone of radius 18.96 cm. These dimensions remained unchanged for all configurations except that for all fuel slump-in configurations, the core radius was reduced to 42.39 cm and the core/radial blanket interface moved closer to the center of the core.

The slumped fuel composition had double the fuel density of the reference core obtained at the expense of sodium (enrichment remaining the same at 22%).

*Enrichment here refers to the ratio of number densities (^{239}Pu + ^{241}Pu)/total heavy metal.

The k_∞ of the reference and slumped compositions were 1.71 and 1.86 respectively. The fissile Pu atom concentration was 1.4795×10^{-3} atoms/cm-barn in the reference configuration and 2.9643×10^{-3} atoms/cm-barn in the slumped composition. The corresponding heavy metal atom concentrations in the two cases were 6.7231×10^{-3} and 13.4701×10^{-3} atoms/cm-barn respectively. The void cavities consisted of empty ZPR matrix tubes (a steel volume fraction of 7.2%).

EXPERIMENTAL AND ANALYTICAL METHODS

All experimental methods used for the program have been used with success in a large number of previous critical experiments programs. The worths of the configuration changes were determined in inhours from the experimentally-determined configuration reactivities. The conversion of experimental reactivity in Inhours to the % Δk reactivity scale was based on a computed value of β_{eff}. A measurement was made to check this conversion.

Analyses of the measurements were performed using ENDF/B-IV nuclear data and two-dimensional diffusion theory methods in 29 energy groups. Cross-sections were generated for appropriate compositions using the MC^2-2/SDX codes[4,5]. Eigenvalue calculations were performed using conventional diffusion coefficients ($D = 1/3\ \Sigma_{tr}$), and with bi-directional Benoist diffusion coefficients[6] to account for neutron streaming effects in the non-cavity regions. The final calculations used Gelbard diffusion-coefficients[7] in core regions for neutron energies above 2 keV (to apply a transport correction to the leakage calculation), and Benoist coefficients elsewhere in the core and blanket. The cavity regions were treated with isotropic diffusion coefficients based on the transport cross-sections of the low density structural material comprising the ZPR-9 matrix.

A second phase of the analysis, based on S_4/P_0 transport theory in RZ geometry is in progress, and some results are reported here. The cross section

sets and geometric models used for the diffusion theory and S_4/P_0 analyses were identical so as to isolate the cavity and transport effects from multigroup cross section homogenization effects.

EXPERIMENTAL RESULTS AND COMPARISON WITH CALCULATIONS

A. Eigenvalues of the Configurations

Figure 2 shows the calculated-to-experiment (C/E) eigenvalue biases plotted versus configuration for all configurations in the program. The experimentally determined eigenvalue and the calculated Ih/%Δk/k reactivity scale conversion factor are also listed. The diffusion theory C/E values all lie within the range observed in earlier critical experiments on undamaged cores (C/E ≈ 0.980 to 0.995). The diffusion theory to S_4/P_0 bias, however, ranges from a familiar value of ∿1%Δk for the undamaged core to ∿2.5 to 3.0% Δk for the fuel slump configurations. This increase in bias is presumed to derive from both the greater leakage from the damaged cores and from a failure of $D = 1/3\Sigma_{tr}$ to represent neutron transport adequately in the diffusion theory representation of the internal cavities.

The value of β_{eff} is shown in Fig. 2 to contrast it with the change in the C/E eigenvalue bias from one configuration to another. For the calculational prediction of kinetics effects associated with severe core damage, the bias should change from one configuration to another by less than β_{eff} to ensure that super prompt critical bursts are neither spuriously predicted nor spuriously overlooked. Such is not the case for either the diffusion or the S_4/P_0 calculations -- suggesting that currently, core disassembly accident calculations must be viewed with skepticism based on reactor physics aspects alone.

B. Reactivity Worths Due to Material Rearrangement

Table I displays the experimental reactivity worths of core rearrangements caused by fuel slumping. The worth of fuel removed to decrease the core radius from 44.19 to 42.39 before construction of the slump-in configurations is included where appropriate. Also presented in the Table are calculated predictions based on diffusion theory. It is seen that the calculated predictions of the worths are quite poor. The trend of overprediction of the fuel slump-out negative worth and underprediction of fuel slump-in positive worth with diffusion theory methods shown in Table I has been observed in earlier experiments.[2] These results follow from the increased C/E biases in the slumped configurations relative to the reference configurations as shown in Fig. 2.

Figure 2 shows that the transport theory calculations yield C/E values greater than 1 for all configurations where a diffusion theory underpredicts experimental eigenvalues (C/E < 1). Additionally, in constrast to diffusion theory, the transport theory worth predictions are in a conservative direction.

C. Reactivity Coefficients

Material reactivity coefficients are of prime interest in safety calculations. Table II lists the results of measurements of small sample reactivity worths and associated calculations using first order perturbation theory (diffusion theory with Gelbard D's). The worth per kg of ^{239}Pu at core center is overpredicted by 30% and 50% in the undamaged and slumped-in cores respectively. (Typical C/E values in undamaged LMFBR cores of larger size and lower enrichment are $\sim$1.2.) All other worths in the table are normalized to the ^{239}Pu central worth to extract out global perturbation denominator effects and focus on spectrum-related effects. Only the worths of ^{235}U and ^{10}B are reasonably consistently predicted in both the undamaged and slumped configurations. The results suggest

that high uncertainties must be assigned to computational predictions of reactivity accompanying sodium, pin clad, and fuel motion.

Given that the amplitudes of material worths are poorly predicted, it is still of interest to know whether the shape of the axial distribution can be accurately computed. Figures 3-5 show the C/E values for the ^{239}Pu worth per kg as a function of axial position within the test zone for the reference, symmetric fuel slump-out and symmetric fuel slump-in configurations. The C/E values in the reference configuration remain fairly constant in the core and show deviations near the core/blanket interfaces. For the slumped configurations there are large variations in the C/E values within the compacted fuel zones and the void regions. Clearly, predictions of material worth axial profile using diffusion theory are unpredicted with compacted fuel cavity regions.

For materials like ^{238}U and stainless steel, which have net reactivity worth values depending upon cancellations among position-dependent effects of downscatter, leakage, and absorption components, the calculated worth shape predictions were found to be poorer than for ^{239}Pu.

D. ^{238}U Doppler Reactivity Worth

The central Doppler reactivity worth of a small ($\sim$1.1 g) $^{238}UO_2$ sample was measured in the reference and symmetric slump-in configurations. The measurements were analyzed using a modified First Order Perturbation theory method[8] with the two dimensional diffusion theory fluxes. The normalized Doppler reactivity worths, displayed in Table II, show a 58% decrease in the slump-in configuration relative to the reference configuration because of the hardened neutron spectrum. Preliminary results of the analysis of the reference measurement yields a C/E ratio (0.89) that is in the range of earlier experience for LMFBR cores.[8] The

C/E ratio for the normalized Doppler Worth (ρ^{238}U Doppler/ρ^{49}) however is smaller than earlier experience because of the large C/E value for the worth of ^{239}Pu.

E. B_4C Rod Worths

The worth of a central B_4C control rod was measured in the undamaged and in the symmetric slump-in configurations and was calculated by the diffusion theory eigenvalue difference technique using infinitely dilute boron cross sections collapsed over the core spectrum. As shown in Table II, the rod worth in the slumped core decreased by 20% relative to the undamaged core, and the calculation predicted the change remarkably well.

F. Kinetics Parameters

The measurements of β/ℓ[9] and β_{eff}[10] were made in the undamaged and symmetric slump-in cores using noise analysis procedures and were computed based on ENDF/B-IV data and the diffusion theory RZ models. The 16% increase in β/ℓ induced by slumping was overpredicted, and the absolute value of the parameter was overpredicted in each case. The comparison of the calculated β_{eff} with a preliminary experimental value yields a preliminary C/E of 0.96 which is compatible with recent experience with ENDF/B-IV delayed neutron data in LMFBR cores.[10] It should be noted that the C/E values on eigenvalue displayed in Fig. 2 (which were based on a calculated β_{eff} value for the conversion of the experimental reactivity to k) would be little affected by a small (~5%) increase in β_{eff}.

CONCLUSIONS

The results of the present program provide a detailed benchmark characterization of the neutronics aspects of severely damaged LMFBR configurations and provide

means for validating nuclear data and neutronics methods used in accident analyses.

The experimental results show that large reactivity changes are induced by the material movements simulated in the experiment. The eigenvalue predictions of the reference and slumped configurations with diffusion theory lie within range of earlier experience with LMFBR assemblies. The reactivity worths of the material movements were mispredicted by diffusion theory and the mispredictions were in a non-conservative direction. Furthermore, for these experiments the results demonstrate an inability of present methods to ensure that the change in bias in the eigenvalue calculations between configurations is limited to a range less than β_{eff}.

In the reference core the central worth of ^{239}Pu was overpredicted by about 30% -- which is greater than earlier experience for lower enriched compositions (20%). For the full slump-in core the misprediction was much higher (C/E = 1.49). Generally the accuracies of worth predictions were poorer in the slumped configurations relative to the reference configuration. The axial shapes of the reactivity worths were mispredicted within the internal cavities. The shapes of the ^{238}U and stainless steel worths were more generally mispredicted.

The safety coefficients, ^{238}U Doppler, and B_4C central control rod worth, decreased considerably on fuel slumping-in, indicating a large degree of spectral hardening. The B_4C rod worths were predicted well by diffusion theory, but the ^{238}U Doppler effect was underpredicted. The preliminary results of the kinetics parameter determinations indicate a small underprediction of β and a large overprediction of β/ℓ, implying a large underprediction of the prompt neutron lifetime, ℓ. The underprediction is increased for the fuel slump configurations. For accident analyses, this underprediction is conservative.

The general conclusion from the results of the experiments and analyses is that diffusion theory based on ENDF/B-IV data miscalculates the parameters of interest to accident analyses. Efforts are underway to attempt to separate this miscalculation into a component attributable to the ENDF nuclear data alone and a remaining component due to the approximations inherent in the cross-section preparation and diffusion steps of the analyses.

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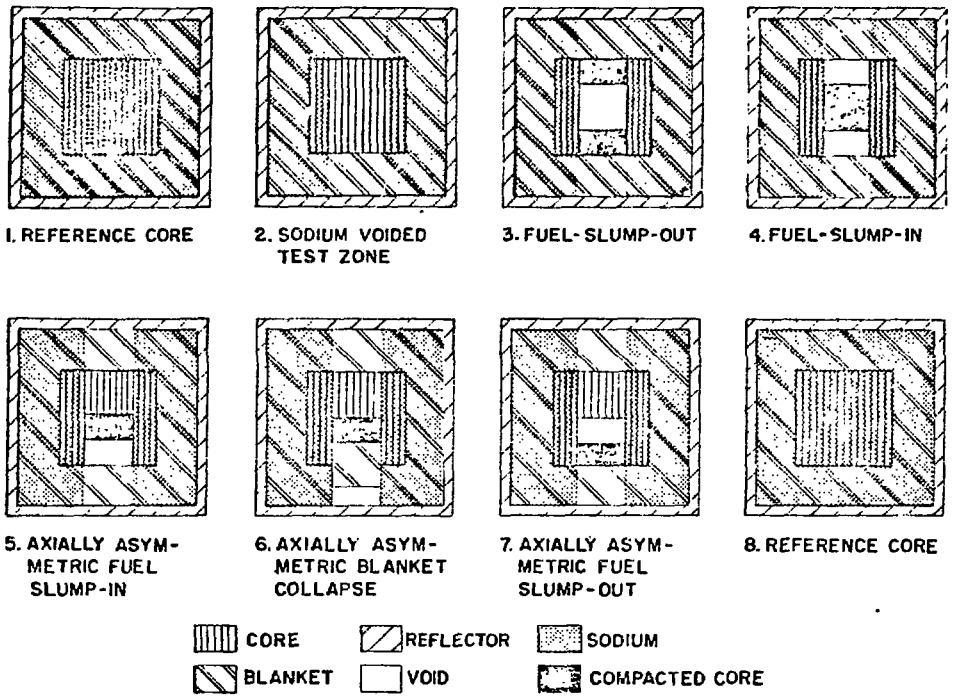

Fig. 1. Schematic Sketch of Configurations Studied in the LMFBR Meltdown Core Program.

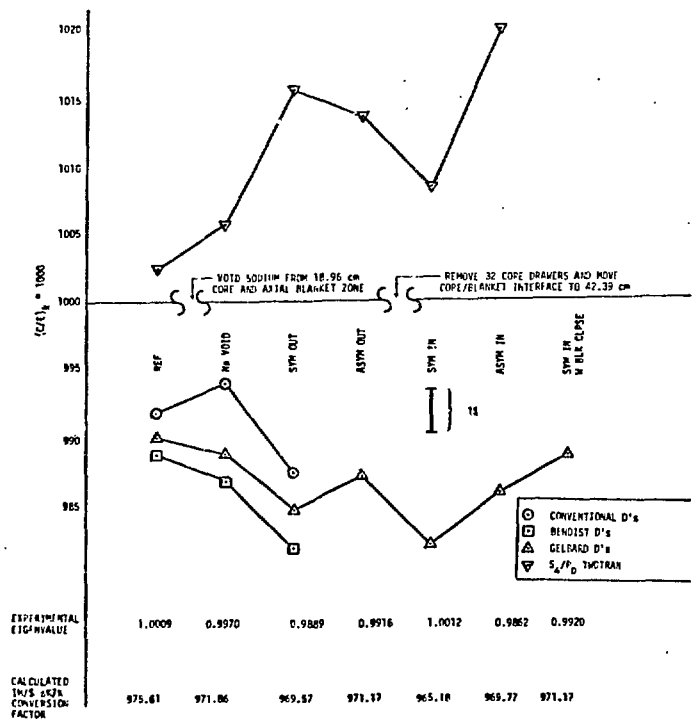

Fig. 2

Plot of C/E Ratio for Eigenvalues for the Configurations in the Experimental Program.

TABLE I. Reactivity Worths of Material Movement[a]

Configuration	Sodium Voided Zone	Symmetric Slump-Out	Asymmetric Slump-Out	Symmetric Slump-In	Asymmetric Slump-In	Asymmetric Slump-In With Blanket Collapse
Experimental Worth (Ih)	-386.3 ± 1.9	-731.1 ± 12.8	-518.8 ± 8.5	+2106.1 ± 57.2	+656.4 ± 59.8	+1221.4 ± 57.7
Calculated Worth[c]						
a. Isotropic D's	-159.3 (0.412)	-1427.1 (1.827)		+840.7 (0.399)		
b. Benoist D's	-576.8 (1.492)	-1231.5 (1.577)		+1056.1 (0.501)		
c. Gelbard D's	-498.1 (1.289)	-1149.6 (1.472)	-669.3 (1.290)	+1213.1 (0.576)	+142.8 (0.217)	+947.0 (0.775)
	← CORE RADIUS 44.2 cm[b] →			← CORE RADIUS 42.4 cm[b] →		

[a] The reactivity worth of the sodium voided test zone was determined relative to the reference configuration. The worths of all the slumped configurations were determined relative to the sodium voided test zone.

[b] For the determination of the reactivity worths of the configurations with the smaller core radius, an experimentally determined core/radial blanket edge drawer exchange worth was used. The experimental exchange worth was -53.08 ± 1.75 Ih and diffusion theory (Gelbard D's) calculations gave a C/E of 0.877.

[c] C/E value in parentheses.

TABLE II. Results of Measurements and Calculations of Integral Physics Parameters

	Integral Parameter	Reference Core		Fuel Slump-In Configuration[a]			Fuel Slump-Out Configuration[a]		
		Experimental Value	C/E	Experimental Value	C/E	Ratio of Experimental Value to that in Reference	Experimental Value	C/E	Ratio of Experimental Value to that in Reference
1.	Central Worth of ^{239}Pu [ρ^{49}, Ih/kg]	374.4 ± 3.6	1.28	609.4 ± 4.5	1.49	1.63	209.5 ± 2.1	1.26	0.56
2.	ρ^{28}/ρ^{49}	-0.0472	1.01	-0.0388	0.72	0.82	-0.0609	0.85	1.29
3.	ρ^{25}/ρ^{49}	0.6680	1.04	0.6163	1.04	0.92	0.6678	1.06	1.00
4.	ρ^{40}/ρ^{49}	0.1569	0.92	0.2097	1.09	1.34	0.1501	0.93	0.96
5.	ρ^{B-10}/ρ^{49}	-14.66	0.94	-10.57	0.92	0.72	-15.97	0.90	1.09
6.	ρ^{Na}/ρ^{49}	-0.0232	1.69	-0.0684	0.68	2.95	-0.0238	1.67	1.03
7.	ρ^{SST}/ρ^{49}	-0.0280	1.09	-0.0529	0.65	1.89	-0.0271	1.04	0.97
8.	$\rho(^{238}U$ Doppler$)/\rho^{49}$ [ΔT = 300-1100°K]	-3.286×10^{-3}	0.69[b]	-1.392×10^{-3}	-	0.42	-	-	-
9.	B_4C Control Rod Rod Worth	-705.2 ± 4.4	1.03	-567.3 ± 3.0	1.02	0.80	-	-	-
10.	β_{eff}	3.34×10^{-3} ± 5%[c]	0.96	-	-	-	-	-	-
11.	β_{eff}/ℓ (Sec^{-1})	7278 ± 60	1.17	8554 ± 60	1.24	1.16	-	-	-

lly symmetric configurations.

inary calculated value.

ber is preliminary in that the calculated Diven factor (D) needed for its determination has not been computed for . The value of D assumed is 0.93 (calculated for GCFR Phase I Assembly). The actual value of D is not expected ar from the assumed value, and the β_{eff} value reported can be assumed to be correct to within a few percent.

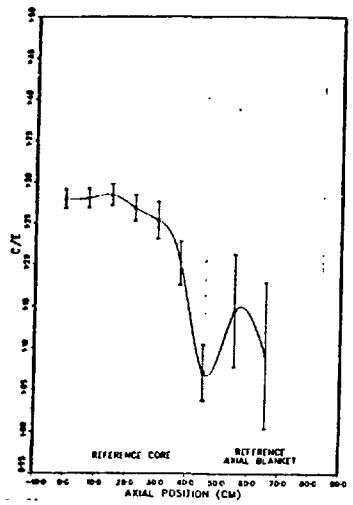

Fig. 3. Plot of C/E Ratio for ^{239}Pu Reactivity Worth as a Function of Axial Position for Reference Core.

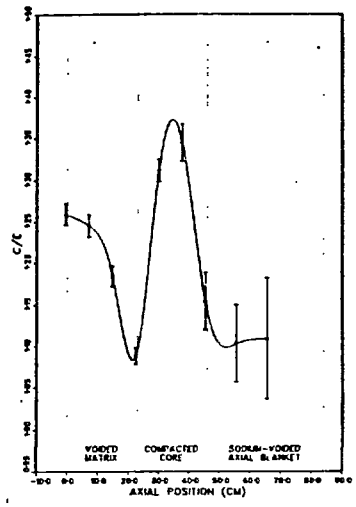

Fig. 4. Plot of C/E Ratio for ^{239}Pu Reactivity Worth as a Function of Axial Position for Fuel Slump-Out Core.

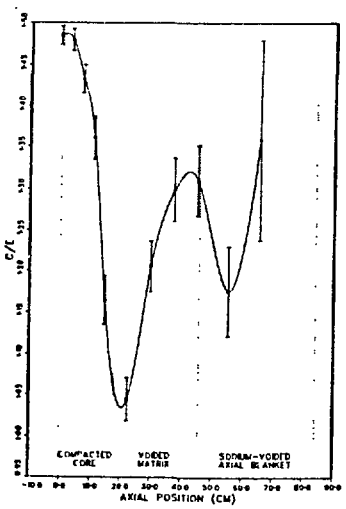

Fig. 5. Plot of C/E Ratio for ^{239}Pu Reactivity Worth as a Function of Axial Position for Fuel Slump-In Core.