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REACTIVITY INSERTIONS IN COMPACT REACTOR CORES DUE TO FUEL MOVEMENT

by Robert E. Sullivan

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

The reactivity effect of fuel movement in several compact reactor cores, highly fueled with uranium-233 dioxide ($U^{233}O_2$), has been calculated using a computer program to solve the Boltzmann transport equation.

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SUMMARY

The reactivity effect of fuel movement in several compact, highly fueled uranium-233 dioxide ($U^{233}O_2$) cores has been calculated using a computer program to solve the Boltzmann transport equation. The core configurations investigated were primarily intended to simulate the bowing of fuel rods due to radial temperature gradients. The large positive reactivities obtained indicate that design of a reactor core in which the fuel rods are firmly supported at both ends is not desirable. For cores in which the fuel rods are radially restrained by spacers and free to move in the axial direction, the reactivity change, while still positive, is smaller and of the order of the negative effects introduced by axial expansion and reduced coolant density.

INTRODUCTION

One of the important factors in the design of highly fueled, fast spectrum reactors is the amount of reactivity inserted by fuel movement in the core.

Movement of fuel within a core may result in several ways for core designs in which the fuel is distributed in rods supported at both ends by headers. The mechanisms of movement include expansion of the fuel rods, bowing of the fuel rods, and migration of fuel within the rods. Since the net effects of moving fuel in a given direction will be similar regardless of the mechanism, calculations of the reactivity induced by one mechanism may allow estimates to be made of other effects if linearly combinable. In general, fuel rod expansion per se may be expected to reduce reactivity. However, for the classical bowing case, in which the fuel rods are restrained at both ends (ref. 1), the fuel movement resulting from the radial temperature gradient across the rod can introduce a large positive reactivity during changes in power. If the reactivity increase is too large, the inability of the control system to compensate for it could result in a power excursion.

This report estimates the reactivity introduced by classical bowing of the fuel rods in compact reactors. Several reactors, fueled with $U^{233}O_2$ and having both tungsten and beryllium oxide reflectors, were considered. An idealized calculation of the effects of radially inward fuel movement, in which the core would tend to be compressed, is of interest because the results may be used to indicate the limits on the amount of fuel movement that will be permissible.

The calculated reactivities associated with fuel rod bowing are presented for different bowing models. In addition, the magnitudes of temperature dependent effects, such as core axial expansion and change in coolant density, which lead to negative reactivities, have been calculated and are compared with those due to the fuel rod bowing.

METHODS

General

The first quantity calculated is the effect of relatively large displacements of fuel. A cylindrical core (designated core I) is separated into several zones, and the magnitude and sign of the reactivity resulting from various degrees of core compression in each of the spatial regions are determined.

These results indicate the tolerances which would be required for the design of fuel rod clearances for stationary end supported reactor configurations. The effects of limiting the amount of core compression are calculated for several cores with different reflectors. A moderating beryllium oxide reflector and a nonmoderating tungsten reflector are considered. The reflector is 4 inches (10.16 cm) thick and is composed of either 95 volume percent tungsten (W) and 5 volume percent lithium-7 (Li^7) or 95 volume percent beryllium oxide (BeO) and 5 volume percent lithium-7.

Three different diameter reactor cores have been assumed to consist of the unit cells shown in figure 1. The fuel rods are natural tungsten and contain uranium-233 dioxide ($U^{233}O_2$) with lithium-7 between the fuel rods as coolant. The volume fraction of fuel in each core has been adjusted to make the effective multiplication factor the same for the various core sizes.

Calculational Method

Neutron transport calculations using the TDSN code (ref. 2) have been made in the S2, P0 approximation for the two-dimensional core and in the S4, P0 approximation for the one-dimensional spaced fuel rod problems.

The GAM II (ref. 3) and GATHER II (ref. 4) cross-section compilations and programs have been used for flux averaging the microscopic cross sections. The thermal neutron flux may be neglected for highly loaded compact cores with tungsten reflectors; seven high energy group cross sections were used for these cases. The lethargy and energy divisions are shown in table I. For the beryllia-reflected cores, in which the thermal neutron flux at the core-reflector interface is important, the 18-group set shown in table I has been used. The cross sections are averaged over the flux spectrum existing in an infinite medium of the same composition as the given region with the exception of the core microscopic cross sections for the thermal groups, which are averaged over the reflector spectrum for the beryllia-reflected cores.

Fuel Movement

The following assumptions are made for the fuel rod bowing study:

(1) The fuel rods are fixed at both ends permitting lateral movement only.

(2) The temperature gradient is a function of the power density gradient so that maximum lateral movement occurs where the gradient is a maximum and in the direction of increasing power density. (Oxide fuels have low thermal conductivities and the tungsten fuel tube is thin so that this assumption is reasonable.)

(3) The total number of atoms of all materials in the core is kept constant. To accomplish this the total number of atoms in each region, according to the spacing described previously, is calculated from the center of the core outward, and the nuclear densities in the outermost region are adjusted to conserve this total number.

(4) At the high operating temperatures under consideration, both fuel and fuel tube have low strength. Therefore, for closely spaced fuel rods, compressive stress will cause adjacent rods to bow and remain separated along their entire length only by the distance fixed by the spacer tolerance. It is also assumed that the circular-cross-sectional areas of the fuel rods are maintained.

ANALYSIS AND RESULTS

Zoned Two-Dimensional Cases

The first set of cases considers a two-dimensional reactor (designated core I) described in reference 5. The volume fractions for all reference cores are given in table II, and the unit cells are shown in figure 1. The core dimensions are fixed by the coolant volume fraction specified and the required reactivity conditions.

For these cases the initially straight fuel rods are caused to bow in varying degrees for different regions of the core. Such a physical change in the core could be caused by thermal stresses set up in the rods by the temperature gradient or by a rapid reduction in coolant temperature due to increased power demand. This increased demand could lower the inlet coolant temperature, cause a thermal contraction of the header plate, and set up axially compressive stresses in the fuel rods.

In order to allow for a different amount of fuel compaction in various regions of the core, the cylindrical reactor is separated into nine zones of equal dimension as shown in figure 2. As the fuel rods are fixed at the top and bottom of the core, radial displacement of the fuel rod will vary from zero at the ends to the fully compacted case at the midplane of the cylindrical core. For the present calculations, the change in fuel rod spacing is taken to be linearly proportional to the distance from the reactor midplane, with the condition that the fuel rods touch at the center only. For a better approximation, the axial power distribution should be used in conjunction with the radial power distribution to estimate the inward fuel rod movement as a function of core height. As no deformation of the circular shape of the fuel rods is considered, the most compacted case will be that in which the rods are mutually tangent as shown in figure 1. This fully compacted case is assumed to occur in the region of the core where the power density gradient is largest. The radial power density variation is shown in figure 3 for both reference cases. The maximum slopes are observed to be at the outer radii of the cores, and bowing should be most pronounced in this region.

From this model a series of calculations was made for various degrees of bowing of the core. Calculations were also made of the magnitude of two negative reactivity effects assumed to be independent and separable. The first involved a reduction of 20 percent in the coolant density, representing a temperature change of approximately 2000 K (ref. 6). The second allowed a 1-percent axial increase in the reactor core height, a change in dimension valid over the same temperature range (ref. 7) if the tungsten is assumed to control the expansion. These reactivity results, with the reactivity associated with bowing as represented by the zones shown in figure 2, are given in table III.

The results of table III indicate that a serious control problem can exist for highly loaded compact reactors with fuel rods fixed only at the ends. The net reactivities associated with the fuel rod bowing are positive and range from \$4.42, for the case in which the core is fully compacted at the midplane, to \$0.86, for the case in which the outer central one-third of the core is bowed inward by only 2 millimeters. These reactivities are prohibitive if the reactivity insertion is accomplished rapidly. The primary mechanism which might cause a rapid insertion of the reactivity predicted by this model would be a rapid axial loading of the fuel rods. To eliminate any axial loading requires designing the core so that the fuel rods are free to move in the axial direction; this requirement sets one condition on the design of a reactor of this type. If this condition is met, it seems probable that the reactivities calculated will be inserted as a slowly varying function of temperature. The large positive reactivity (\$3.13) associated with only a 2-millimeter decrease in the core radius (case 5, table III) exceeds the negative contributions of both the lithium density change and the axial expansion. Therefore, a design in which the fuel rods are free to move axially but are not otherwise constrained would still have a net positive reactivity effect. Therefore, gross lateral movement of the fuel rods must be further constrained.

One-Dimensional Spaced Cores

The results obtained in the previous section show that unrestrained fuel compaction could result in reactivity insertions which are large from a control design viewpoint, and that the gross radial movement of fuel rods must be limited in some manner. Therefore, in the second set of cases considered, a model is assumed in which the amount of bowing is controlled by a spacer. The term "spacer" is used to define any mechanical device which is inserted between, or forms an integral part of, the fuel rods and which serves to control their distance of closest approach.

If no additional constraint is used after assembly, or if the fuel rods are not force fitted during assembly, there must be some clearance permitted on the spacer dimensions. In order to determine the clearance which would result in acceptable reactivities on compaction, calculations were made for three cores of different sizes (cores I, II, and III), with both tungsten and beryllia reflectors, as illustrated in figure 4. Inasmuch as the bowing mechanism is difficult to specify, the most extreme case of compaction is used in which it is assumed that the rods are forced together, against the spacers, along their entire length. The effect of a spacer having clearances of 1, 3, and 5 mils (0.0254, 0.0762, and 0.1270 mm) was determined for each of these cores. The unit cell is again that shown in figure 1, but its size on each side is reduced by only 2, 6, and 10 mils (0.0508, 0.1524, and 0.2540 mm) when the spacers on adjacent rods are in contact.

The reference reactor configurations for both the tungsten- and beryllia-reflected cores are given in figure 4.

Tungsten-reflected cores. - As illustrated in figure 3, there is no point of inflection in the radial power density curve, and therefore, all bowing should be in the inward direction. The various clearances on the fuel rod spacers used to compute the new volume fractions in each case are shown in figure 4. Conservation of the total number of atoms in the core is then used to establish the compacted core atom densities. The increased annular gap at the outer radius of the core is filled with normal density lithium-7. The resulting reactivity changes for these configurations are presented in table IV and figure 5.

The introduction of a spacer to limit the radial movement of the fuel rods reduces the magnitude of the reactivity. The magnitude is not, however, a strong function of the core radius, since core III, which has a radius more than twice as large as core I, demonstrates only about a 10 percent smaller reactivity. It is evident from table IV that the restrictions imposed on the spacer clearances strongly affect possible reactivity insertions. The magnitudes of the reactivities exhibit an almost linear dependence on the spacer tolerance, the 5-mil (0.1270-mm) tolerance resulting in a reactivity greater, by a factor of approximately 5, than that of the 1-mil (0.0254-mm) case. While these results are for extreme cases of compaction, it is obvious from the magnitudes calculated that, even when the combined effects of axial expansion and reduced coolant density are considered, the spacer tolerances allowable on an individual pin must be of the order of 1 mil or less. This spacer tolerance is, of course, also dependent on the initial fuel pin size.

Beryllia-reflected cores. - As shown in figure 3, the thermal neutrons produced in the reflector result in a point of inflection in the power density curve. This reversal in gradient is located at a radial position which would cause an outward bowing effect in the outermost fuel rod array with the remaining arrays still contributing compactive fuel reactivity effects. The fuel rod spacers would limit the extent of this outward movement, but a small gap, filled with lithium-7, would be created between this array and the remainder of the core. In order to separate the effects of inward and outward bowing, the reactivity for both the single annulus and the fully bowed cases is determined.

The outward fuel movement, into a position of larger volume, requires that the nuclear densities of fuel and clad be reduced while that of the coolant is increased. The conservation of atoms in the annulus is used to determine the new volume fractions, and the remainder of the core is treated as in the tungsten-reflected case. Inasmuch as the reactivity insertions for the tungsten-reflected cores exhibited little variation with reactor size, the beryllia-reflected configurations described previously are studied only for core I. The results for each of these cases are presented in table IV and figure 5.

These results indicate that the power inflection caused by an oxide reflector would greatly reduce the net positive reactivity associated with fuel compaction. The primary reason for the reduction is the high importance of small changes in the active core radius. While the negative reactivity resulting from outward bowing of the annulus constitutes only a small fraction of that caused by full compression of the core, the outward bowing tends to increase the core size slightly and so reduce the total positive reactivity by a factor of about 3. The negative effect found here for the outward bowing differs in sign from that reported for a similar calculation done elsewhere (ref. 8). Although a different fuel was used in reference 8, the difference in calculated results tends to emphasize the importance of the specific calculational model used. The net positive result reported in reference 8 appears to have been due to reduction of fuel density in the interior of the core, but not at the outer edge as would be required if the fuel expanded into an annulus of greater cross-sectional area.

CONCLUSIONS

Fuel movement reactivity calculations for representative, compact, highly fueled cores have been made. Results indicate that fuel movement restraints are required for the design of compact cores composed of fuel pins to prevent large positive reactivity insertions.

For cores in which the fuel rod movement is limited to prescribed clearances by fuel rod spacers, inward fuel movement caused by bowing of fuel rods gives rise to acceptable positive reactivities. For cores with tungsten reflectors, spacer limited clearances of 1 mil (0.0254 mm) or less would be permissible. As the reactivity is not a strong function of core size, clearance tolerances of this magnitude would have to be held even for larger cores. For the same cores, but with beryllia reflectors, there is a power spike at the core-reflector interface due to the return of moderated neutrons. This power density gradient is the reverse of that obtained in a heavy-metal-reflected core and will tend to make the outer fuel elements bow outward instead of inward. The bowing out of these outer fuel elements leads to a negative reactivity component, but the net reactivity for the entire compacted core is still positive.

The calculations also indicate that the negative reactivity associated with axial expansion of the core is sufficient to override the positive component introduced by the compacted, beryllia-reflected cores. The reduction in lithium density with temperature also introduces a relatively large negative reactivity effect.

In summary, the design of a reactor core in which the fuel rods are firmly supported at both ends is not desirable. The fuel rods should be restrained from inward radial movement and should be free to expand in the axial direction. While a reactor using a moderating reflector would tend to reduce the positive reactivity component due to bowing, the associated power spike at the reflector-core interface would introduce other heat-transfer and metallurgical design problems.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 4, 1968,
120-27-06-18-22.

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TABLE I. - GROUP CROSS SECTION LETHARGY[a]

AND ENERGY DIVISIONS

Group	Lethargy		Eighteen group energies, eV
	Tungsten reflector	Beryllia reflector	
0	-0.4	-0.4	14.92×10^{6}
1	1.5	1.0	3.68
2	2.5	1.5	2.23
3	4.0	2.0	1.35
4	5.5	2.5	8.21×10^{5}
5	7.5	3.0	4.98
6	9.5	3.5	3.02
7	17.0	4.0	1.83
8	----	4.5	1.11
9	----	5.5	4.09×10^{4}
10	----	6.5	1.50×10^{4}
11	----	7.5	5.53×10^{3}
12	----	9.5	7.49×10^{2}
13	----	17.0	.413
14	----	17.504	.25
15	----	17.951	.16
16	----	18.644	.08
17	----	20.030	.02
18	----	------	0

[a]Lethargy is defined as $u = \ln(E_0/E)$, where E is energy, with E_0 taken to be 10 MeV.

TABLE II. - VOLUME FRACTIONS FOR

REFERENCE CORE CONFIGURATIONS

Material	Core I	Core II	Core III
	Volume fraction, %		
Li^7	19.3	19.3	19.3
W	12.4	42.5	52.5
UO_2	63.3	33.2	23.2
Void	5.0	5.0	5.0

TABLE III. - REACTIVITY CHANGES FOR TWO-DIMENSIONAL ZONED CORE I

[Tungsten reflector.]

Zones	Reactivity, ρ	
	%	$
[a]1 to 9	-0.216	-0.884
[b]1 to 9	-.394	-1.612
[c]1, 2	1.072	4.422
[c]2	.626	2.578
[d]3, 6, 9	.76	3.13
[d]3	.21	.86

[a]Coolant density in all zones of core is reduced by 20%.

[b]Core axial dimension is increased by 1%.

[c]Zones listed are fully compacted with fuel rods mutually tangent. Remaining zones are partially compacted as described in text.

[d]Zones listed are compressed by 2 mm and only volume fractions in those zones altered. Resulting gap was taken to be filled with lithium.

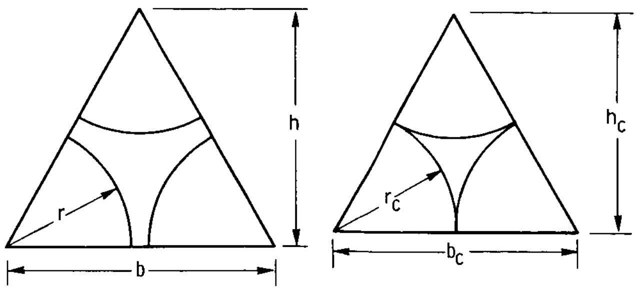
TABLE IV. - REACTIVITY FOR FULLY COMPACTED SPACED RODS

(a) Tungsten reflector

Spacer tolerance		Core I		Core II		Core III	
mils	mm	Reactivity, ρ					
		%	$	%	$	%	$
1	0.0254	0.216	0.85	0.178	0.70	0.179	0.70
3	.0762	.613	2.42	.563	2.21	.547	2.15
5	.1270	1.003	3.97	.949	3.74	.914	3.61

(b) Beryllia reflector; core I

Spacer tolerance		Outer annulus only		Fully compressed	
mils	mm	Reactivity, ρ			
		%	$	%	$
1	0.0254	-0.0088	-0.038	0.0551	0.240
3	.0762	-.0238	-.104	.1748	.763
5	.1270	-.0363	-.158	.3019	1.318



Core	Radius, r, cm	Height, h, cm	Base, b, cm	Radius, r_c, cm	Height, h_c, cm	Base, b_c, cm
I	0.635	1.1659	1.3462	0.635	1.100	1.270
II	.635	1.1703	1.3513	-----	-----	-----
III	.635	1.1711	1.3523	-----	-----	-----

Figure 1. - Core unit cells.

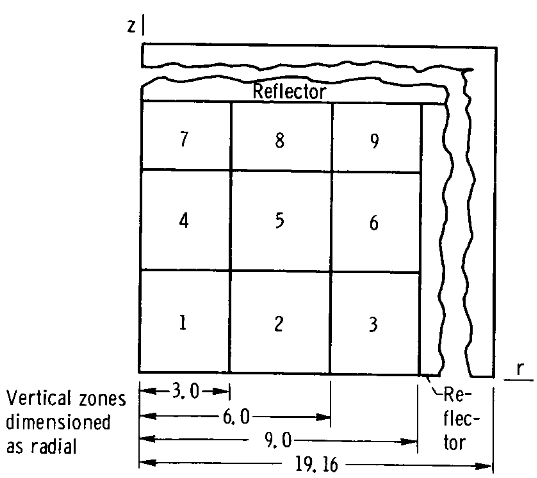
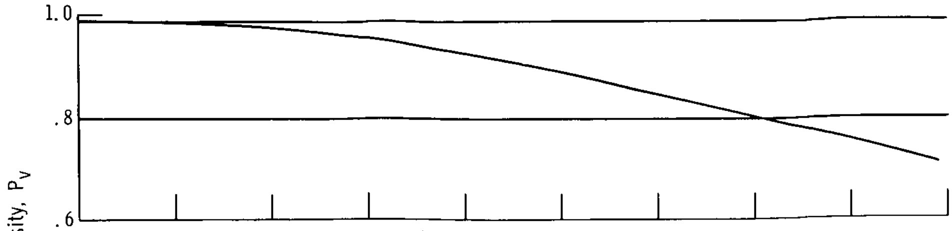
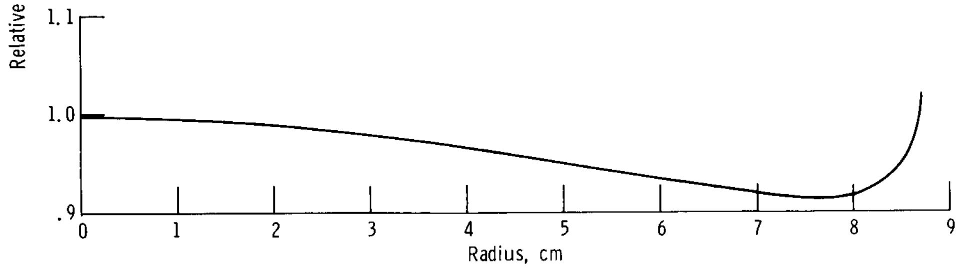


Figure 2. - Cross section of two-dimensional core I. (Dimensions in centimeters.)

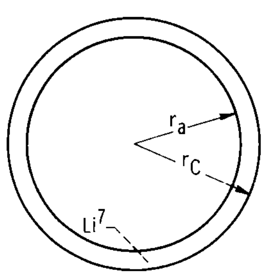


(a) Tungsten reflector.



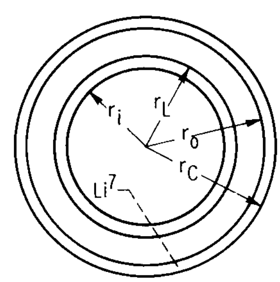
(b) Beryllia reflector.

Figure 3. - Power density as function of radius for core I.



Core	Spacer tolerance, mils	Spacer tolerance, mm	Active core radius, r_a	Core radius, r_c
I	Base	------	8.8605	9.0129
	1	0.0254	8.8270	↓
	3	.0762	8.7601	↓
	5	.1270	8.6933	↓
II	Base	------	14.9605	15.1129
	1	0.0254	14.9042	↓
	3	.0762	14.7917	↓
	5	.1270	14.6792	↓
III	Base	------	21.0803	21.2327
	1	0.0254	21.0012	↓
	3	.0762	20.8428	↓
	5	.1270	20.6845	↓

(a) Tungsten reflector.



Spacer tolerance, mils	Spacer tolerance, mm	Inner active core radius, r_i	Outer radius of Li^7 gap, r_L	Outer radius of bowed annulus, r_o
Base	------	7.5776	7.5776	8.8476
1	0.0254	7.5490	7.5801	8.8501
3	.0762	7.4918	7.5852	8.8552
5	.1270	7.4346	7.5903	8.8603

(b) Beryllia reflector; core I; core radius, 9.0.

Figure 4. - Spaced core dimensions.

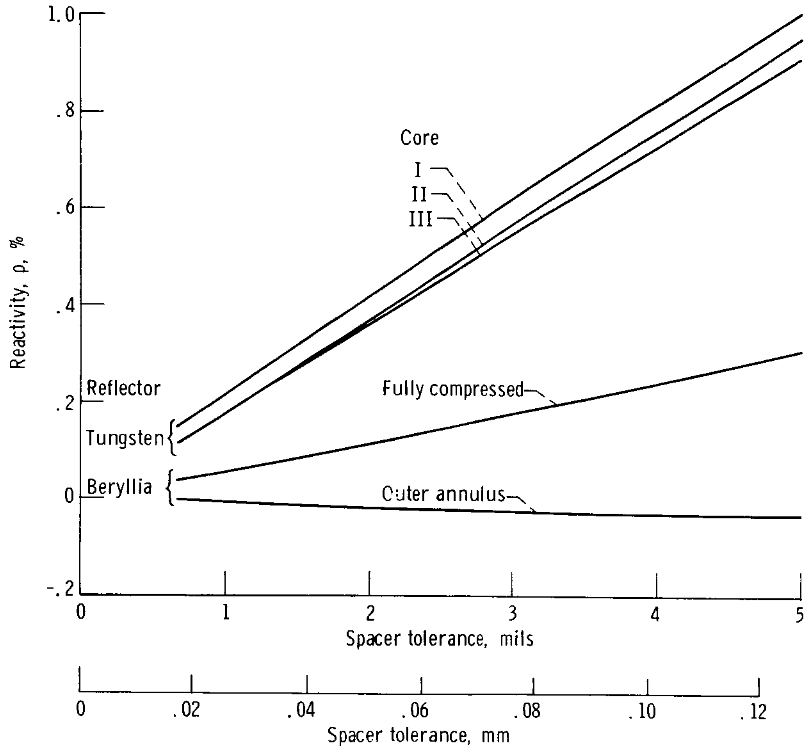


Figure 5. - Reactivity as function of spacer tolerance.