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by Wendell Mayo

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Cleveland, Ohio

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ABSTRACT

A study of the effects of insertion of yttrium hydride into fast-spectrum reactors was conducted. Large, negative moderator temperature coefficients of reactivity that became more negative with increasing moderation were found. Partial or primary reactor control could be based on this temperature coefficient. An increase in the mean prompt-neutron lifetime and a decrease in the positive reactivity coefficients of volumetric compression were observed when moderator was added. Moderator addition, however, increases the core size and results in larger fast-neutron fluxes in the reflector, causing increased shield weight for compact nuclear spacepower systems.

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SUMMARY

This study was conducted to determine what significant beneficial effects accrue as a result of the insertion of yttrium hydride moderator into a nominally fast-spectrum reactor. Molybdenum is used as the structural material for the core and for the reflector. The fuel is uranium 233 dioxide and the coolant is lithium 7. The core volumes ranged from about 0.04 to 0.11 cubic meters. By varying the fuel loading and core volume, reactors with up to 40-volume-percent yttrium hydride were calculated which had multiplication factors of from about 1.10 to 1.14.

Calculations for cores containing yttrium hydride show a large, negative moderator temperature coefficient of reactivity. The Doppler temperature coefficient is also more negative in these partially moderated reactors.

A method of reactivity control is available in these partially moderated reactors by controlling the hydride temperature which, in turn, controls the hydrogen content. For a 0.06-cubic-meter core volume (about 20-volume-percent yttrium hydride), the moderator temperature coefficient can provide about 0.12 $\Delta k/k$ for a 500 K change in the yttrium hydride temperature. For 40 volume percent (0.096 m^3 core), the corresponding $\Delta k/k$ is 0.25.

A fast-spectrum reactor is computed as a base case with which to compare the effects of moderator insertion. This reactor has a calculated mean prompt-neutron lifetime of 0.08×10^{-6} second. This quantity increased to 0.59×10^{-6} second for the most moderated reactor.

The calculated reactivity coefficients due to core compression were all positive, but the coefficients decreased with increasing core volume. The range of values is from 5.6×10^{-6} to 1.8×10^{-6} $\Delta k/k$ per cubic centimeter. Hydrogen content in the core has little effect on these coefficients.

Finally, the increase in core size with moderator introduction would increase reflector fast fluxes and tend to increase shield weight, if these reactors were considered for compact nuclear space-power systems.

INTRODUCTION

In the development of reactors for space power the question arises as to whether a deliberate increase in core size due to the addition of a neutron moderator material might be advantageous. The possible benefits might include the availability of a negative moderator temperature coefficient, a more negative Doppler coefficient of reactivity, a longer neutron lifetime, and reduced positive reactivity coefficients due to core compression such as calculated in reference 1. Core compression may result from inadvertant movement of inadequately supported fuel toward the center of the core. Also, neutron absorbers, which might be used for reactivity control, should be worth more in the lower-energy spectrum of the partially moderated reactor. There is also the question of whether the added neutron moderator can reduce the fast neutron flux by an amount that would allow a smaller shield weight.

In this study yttrium hydride (YH_x) is used as the moderating material because of its moderately high-temperature capabilities. The hydrogen content in yttrium hydride remains constant to about 1170 K; it then decreases from a value of 5.5×10^{22} atoms per cubic centimeter to about 1.38×10^{22} atoms per cubic centimeter at 1670 K (ref. 2). The 1170 K temperature, at which the hydrogen density begins to decrease with increasing temperature, compares with 920 K for zirconium hydride which is the next most suitable material (ref. 2).

Materials used for core structure and fuel-element cladding for fast-spectrum reactors may differ markedly from those used for intermediate or thermal reactors. Fast-spectrum reactors for very high temperatures may use refractory metals such as tantalum, tungsten, molybdenum, or their alloys. The large resonance and thermal cross sections of tantalum and tungsten essentially preclude their use in thermal reactors though they may be considered for partially moderated reactors.

In order to reduce the parasitic absorptions in the clad and structure, molybdenum was used for this study. Its neutron capture cross section is small enough so that it can be used in well-moderated reactors. This allows the moderating effects of the hydrogen to appear with smaller amounts of hydrogen than would have to be used if tungsten or tantalum were assumed for the clad and structure. Molybdenum has a lower-temperature capability, but it is suitable for use within the temperature range of yttrium hydride. Molybdenum is also suitable for the reflector material for fast-spectrum reactors. Such a fast-spectrum reactor containing no hydrogen can serve as a base with which to compare the results calculated for reactors containing various amounts of hydrogen.

A simple reactor model is used for the calculations. The study is pursued only to the point where a judgement can be made as to the efficacy of the introduction of yttrium hydride into fast-spectrum reactors.

Core volumes range from about 0.04 to about 0.11 cubic meter. The lower limit is dependent on criticality considerations. The upper limit is arbitrary but near the maximum size that may be expected to have applications in space-power generation.

REACTOR GEOMETRY AND MATERIALS

The basic core is a right circular cylinder with a length-to-diameter ratio of 1. The fuel elements are uranium dioxide ($U^{233}O_2$) pins with diameter d of 1.905 centimeters arranged in a triangular lattice. The center-to-center pin spacing S is 2.057 centimeter. Molybdenum (Mo) is the cladding material. The coolant is lithium 7 (Li^7) which comprises 22.2 percent of core volume.

Variations in core composition, used in this analysis, as a function of core volume are given in figure 1. These compositions were based on stress calculations and represent the optimum-fuel composition which will limit creep in the cladding to 1 percent over the operating life of the reactor. The design lifetime τ is 50 000 hours at a power of 3 megawatts thermal (MW_t). An average coolant temperature T of 1670 K is assumed for the stress calculations, but for the purpose of this study it will be assumed that this temperature can be dropped to be compatible with yttrium hydride when it is added.

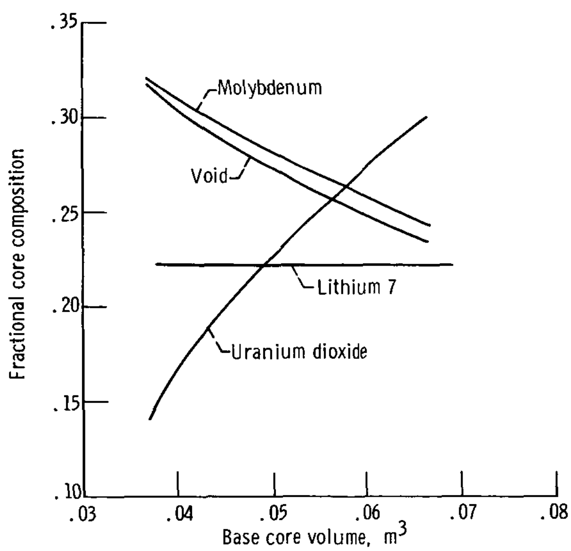

Figure 1. - Variation in core composition with core size. One-percent creep in molybdenum cladding. Reactor lifetime, 50 000 hours; reactor power, 3 megawatts thermal; reactor temperature, 1670 K; axial power factor, 1.25; radial power factor, 1.10; pin diameter, 1.905 centimeters; pin center-to-center spacing, 2.057 centimeters; pin spacing-to-diameter ratio, 1.08.

Axial and radial power factors (F_a and F_r) of 1.25 and 1.10, respectively, were assumed in the stress calculations.

The core compositions in figure 1 are referred to in this report as belonging to the base cores. Yttrium hydride is added to the base core in the form of pins clad with molybdenum. The coolant fraction of the additional core volume is maintained at 22.2 percent, while 5.8 percent is molybdenum cladding and the remaining 72 percent is yttrium hydride. The yttrium hydride occupies about 40 volume percent of the largest (0.113 m^3) core considered.

The entire core (base core plus the added hydride region) is then homogenized for computational purposes. The atom densities of the materials used are listed in table I.

TABLE I. - ATOM DENSITIES OF MATERIALS USED IN THE CALCULATIONS

Pure material	Atom density, at./cm^3	Temperature, K
Uranium 233 dioxide	2.433×10^{22}	(a)
Molybdenum	6.4	(a)
Lithium 7	3.57	1670
	3.87	1170
Yttrium	2.75	(a)
Hydrogen in yttrium hydride	1.38	1670
	5.5	1170

[a]Assumed to be temperature independent.

In order to simplify the calculations, the reactors are represented as spheres surrounded by thick (25 cm) reflectors; this is a reasonable representation of cylindrical reactors with length-to-diameter ratios of 1, if core volume is preserved.

ANALYTICAL METHODS

The analytical methods used in this survey are similar to those presented in reference 3. Ten neutron energy groups were used for all reactor calculations. The energy group structure is given in table II. Cross sections for groups 1 to 9 were obtained from the GAM-II program (ref. 4). The thermal-group cross sections (group 10) came from the GATHER-II program (ref. 5). Spectrum calculations with these two programs were

TABLE II. - NEUTRON ENERGY-GROUP STRUCTURE

Group	Lower energy,[a] eV
1	6.065×10^{6}
2	3.679×10^{6}
3	2.231×10^{6}
4	1.353×10^{6}
5	8.209×10^{5}
6	1.832×10^{5}
7	5.531×10^{3}
8	4.540×10^{2}
9	2.282
10	0

[a]Upper starting energy 14.918×10^{6} eV.

performed for each reactor calculated because the spectrum and resulting average cross section differed appreciably with different amounts of moderator in the core.

The reciprocal neutron velocity as a function of energy was also averaged over each spectrum for use in mean prompt-neutron lifetime calculations using the "1/v poison addition" method (ref. 6). In this method, two static multigroup spatial calculations are required. The reactivity change, due to the addition of the 1/v poison, between the two calculations is proportional to the mean prompt-neutron lifetime.

The reactivity coefficient due to core volumetric compression was also calculated by computing the reactivity change between two static multigroup calculations. In the perturbed calculation, which represents the core after having undergone compression, the core radius was reduced by 0.1 centimeter. The homogenized-core atom densities were recomputed to reflect this compression. The 0.1-centimeter gap between the core and molybdenum pressure vessel was allowed to fill with lithium. Thus the total core inventory was preserved. The reactivity coefficient is defined as the reactivity change per unit volume, $\Delta\rho/\Delta v$, between the unperturbed and perturbed calculations.

The spatial calculations are all performed with the TDSN (two-dimensional S_N) transport program (ref. 7). The S_4P_0 transport approximation, as described in reference 7, was used to account for scattering anisotropy.

RESULTS

Parameters examined in this study include multiplication factors, mean prompt-neutron lifetime, compressional reactivity coefficients, and moderator temperature coefficients as a function of the amount of YH_x in the reactor. Also considered are the effects on power distributions and shielding.

Multiplication Factors

Volume fractions of core materials as a function of unmoderated or fast core volume based on 3-MW_t power output for 50 000 hours are shown in figure 1. The data in figure 1 were generated independently of criticality considerations; constant reactor power, operating time, temperature, fission-gas release and internal pressure limits were assumed. Therefore, the first results are a determination of the effective multiplication factors k_{eff} as a function of base core volume, that is, before hydride is added. The next step is to determine how k_{eff} varies when hydride is added to the base cores.

Figure 2 shows k_{eff} as a function of core volume for all cases examined. A curve for the base cores (no hydride) is shown. The percent UO_2 in each base core calculated is marked (by the data points) on the curves. The core compositions were obtained from figure 1 for the corresponding core volumes.

The other curves in figure 2 are for cores containing yttrium hydride. The solid curves are for the reactors at 1670 K; the dashed curve is for 1170 K. The lower tem-

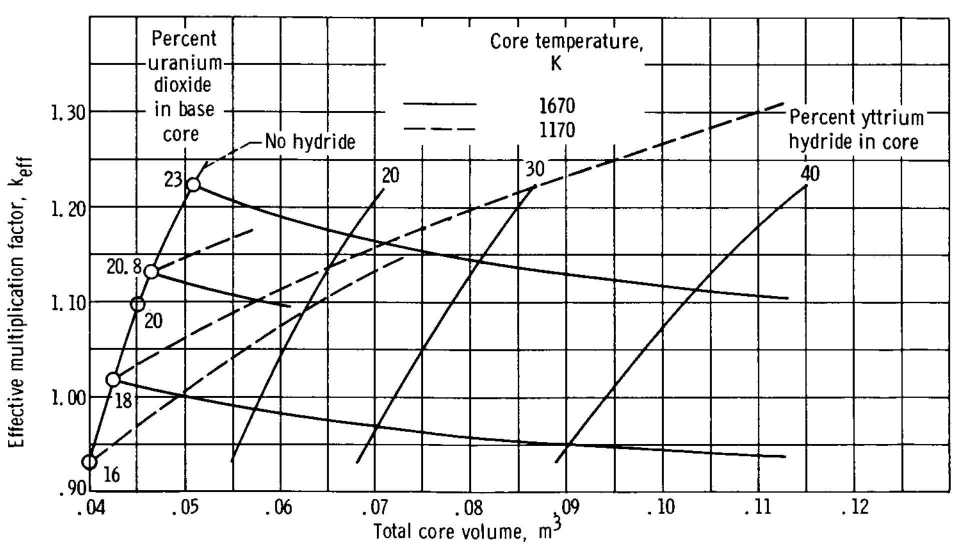

Figure 2. - Multiplication factor as function of core volume for cores with yttrium hydride moderation and molybdenum reflectors.

perature (1170 K) is a departure from the conditions used in figure 1 for determining core compositions within the 1-percent creep limitations. However, the calculations were done to show the effect on k_{eff} of increasing hydrogen content in the core at constant core volume, thus providing the moderator temperature coefficient also. Curves of constant percentage yttrium hydride in the core are also shown in figure 2 to relate the base core UO_2 loading of the base-core curve to core volumes of reactors containing hydride. For example, at 20-percent UO_2 and 0.078 cubic meter, yttrium hydride comprises 30 percent of the core volume.

For the 1670 K cases in figure 2, k_{eff} decreases with increasing core volume. The minimal benefits from the small amount of hydrogen at the higher temperature are more than offset by the parasitic absorption in the yttrium that is also being added. The thermal absorption cross section of yttrium is 1.36 barns. But k_{eff} increases with the addition of 1170 K hydride because of the increased effectiveness of the additional hydrogen.

Temperature Coefficients of Reactivity

The fact that, for a fixed UO_2 loading in a base core, the k_{eff} curves on figure 2 for the two temperatures diverge with invereasing core volume indicates a moderator temperature coefficient that becomes larger with increasing core volume. An increase in core volume at a constant fuel loading means a proportionate increase in the yttrium hydride volume fraction. Thus, the moderator temperature coefficient is related directly to the volume fraction of hydride in the core. Again referring to figure 2, the following average moderator temperature coefficients are obtained between 1170 and 1670 K for the 18-percent UO_2 case:

Yttrium hydride content, percent	Average moderator temperature coefficient, $(\Delta k/k)/K$
20	-2.4×10^{-4}
30	-3.6
40	-5.0

Even for very small amounts of hydride, a negative moderator temperature coefficient is evident. It should be pointed out that these calculations assume homogeneity which over emphasizes the effect of small amounts of hydrogen in the core. The same situation exists for larger amounts of hydrogen but to a lesser degree.

The moderator temperature coefficient is sufficiently negative for the larger core sizes so that it can be used for reactivity control. A method of reactor control using the reversible hydriding properties of a hydride is discussed in reference 8. A heterogeneous reactor using zirconium hydride is described. The temperature of the zirconium hydride is controlled, which, in turn, regulates the equilibrium hydrogen concentration, thereby controlling the reactor. A patent (ref. 9) has been issued on hydrogen difusion reactor control.

Even if primary reactor control by the reversible hydriding method is not chosen, shim control and long-term reactivity control to compensate for fuel depletion could be considered. With a moderator temperature coefficient of -2.4×10^{-4} $(\Delta k/k)/K$, a 100 K variation in the temperature provides 2.4 percent $\Delta k/k$.

Doppler temperature coefficients for these partially moderated reactors should be more negative because the spectrum is degraded toward and into the resonance energy range. The existence of positive reactivity coefficients for core volumetric compression is discussed in the next section. Large negative Doppler coefficients are required if the possibility of compressional fuel movement exists. The Doppler coefficient can be made more negative by the addition of absorbers with large resonance integrals, for example, tantalum, but the effectiveness of the hydrogen in terms of neutron multiplication and moderator coefficients will be diminished. The Doppler coefficient and moderator temperature coefficient in these partially moderated reactors, together with the negative coolant and core expansion temperature coefficients, assure an overall negative temperature coefficient.

Mean Prompt Neutron Lifetime and Reactivity Coefficients of Compression

Table III summarizes the results of mean prompt-neutron lifetime and reactivity coefficient calculations. Six cases were selected from figure 2 that had k_{eff} between about 1.10 and 1.14 for these calculations. Pertinent data for each case are given in the five columns under the heading Core Description. The effective multiplication factor, the mean prompt-neutron lifetime, and the reactivity coefficient due to core compression are then listed.

The compressional reactivity coefficient decreases with increasing core volume. There is about a factor of three reduction in the coefficient between the smallest core (case 1) and the largest core (case 6). For cases 3 and 4, at a core volume of 0.0595 cubic meter, the major difference in the reactor configurations is in the amount of hydrogen in the core, but there is only a small difference in the reactivity coefficient. Cases 1

TABLE III. - CALCULATED MEAN PROMPT NEUTRON LIFETIME

AND REACTIVITY COEFFICIENTS

Case	Core description					Effective multiplication factor, k_{eff}	Mean prompt-neutron lifetime, sec	Compressional reactivity coefficient, $\Delta\rho/\Delta V$, $(\Delta k/k)/cm^3$
	Uranium dioxide in base core, percent	Volume, m^3	Temperature, K	Volume fraction of yttrium hydride	Hydrogen atom density atom/cm^3			
1	20.0	0.0453	1670	0	0	1.098	0.08×10^{-6}	5.6×10^{-6}
2	20.8	.0468	1670	0	0	1.131	.08	4.3
3	20.8	.0595	1670	.155	$.21\times10^{22}$	1.098	.12	3.4
4	18.0	.0595	1170	.206	1.13	1.110	.28	3.2
5	16.0	.0708	1170	.317	1.74	1.137	.59	2.4
6	23.0	.1133	1670	.396	.55	1.105	.27	1.8

and 2 illustrate the dependence of the reactivity coefficient on core volume. Neither contain hydrogen but the reactivity coefficient for the smaller core (case 1) of 0.0453 cubic meter is 30 percent greater than for case 2 with a volume of 0.0468 cubic meter. Thus, it is found that the addition of moderator materials decreases the reactivity coefficient, not because of the added hydrogen, but primarily because of the increased core size.

Because the compressional reactivity coefficients are always positive, the core must be designed to minimize core compression. A large and prompt negative temperature coefficient, such as the Doppler coefficient, is the only control fast enough to counteract the reactivity insertion if the core undergoes compression.

The neutron lifetime is a more sensitive indicator of the effect of moderation than the compressional reactivity coefficients. The mean prompt-neutron lifetime can be interpreted as being proportional to the reactivity worth of a uniformly distributed, pure absorber material whose cross section varies as the reciprocal neutron speed. Thus, the more the spectrum is shifted by moderator insertion toward lower energies, the longer the mean prompt-neutron lifetime will be. The calculations in table III illustrate this trend.

The calculated values of 0.08×10^{-6} second for cases 1 and 2, neither of which contain hydrogen, show that a small variation in core size is not important in determining the mean prompt-neutron lifetime. Cases 3 and 4 (same size but different hydrogen content) show a strong dependence on hydrogen content. Cases 5 and 6 are consistent with these observations. Case 6 has slightly fewer atoms of hydrogen than case 4 and the neutron lifetime is shorter. However, the longest mean prompt-neutron lifetime of 0.59×10^{-6}

second calculated is not sufficiently longer than the smallest value calculated (0.08×10^{-6} sec) to make a positive statement about the difference in controlability of these reactors.

Spatial Power Distributions

The power factors ($F_a = 1.10$, $F_r = 1.25$) listed in figure 1 and used to determine core compositions were estimated as reasonable values obtainable for axially and radially separable cylindrical reactors. The neutronic calculations, however, were performed in spherical geometry. Thus, the computed maximum-to-average power ratios do not correspond directly to either F_a or F_r but more nearly to the product ($F_a \times F_r = 1.38$) which is the total power factor used for the creep calculations.

Table IV shows the computed maximum-to-average power ratios $P_{max}/\overline{P}$ computed

TABLE IV. - MAXIMUM-TO-AVERAGE POWER RATIO

Case	Core description				Maximum-to-average power ratio, $P_{max}/\overline{P}$
	Uranium dioxide in base core, percent	Temperature, K	Yttrium hydride volume fraction	Number of hydrogen atoms	
1	20.0	1670	0	0	1.39
2	20.8	1670	0	0	1.39
3	20.8	1670	.155	1.25×10^{26}	1.43
4	18.0	1170	.206	6.72	1.54
5	16.0	1170	.317	12.32	1.61
6	23.0	1670	.396	6.23	1.53

for each of the six cases as described previously. Also shown in table IV is the number of hydrogen atoms in each core. The $P_{max}/\overline{P}$ increase with increasing hydrogen content in the core, and all values exceed the value of $F_a \times F_r = 1.38$. Some type of power distribution tailoring to obtain acceptable values of $P_{max}/\overline{P}$ is required. Alternatively, the reactors could be made larger in order not to exceed structural or heat-transfer limitations and still produce the same power (3 MW_t).

In either case, more appropriate calculations using cylindrical geometry should be used for the purpose of determining the radial and axial power factors.

The power distributions for case 1 (smallest core), case 5 (most hydrogen) and case 6 (largest core) are plotted as a function of spherical core radius on figure 3. The addition of moderator has not only increased the radius of the reactor, but also increased the amount of power distribution tailoring required.

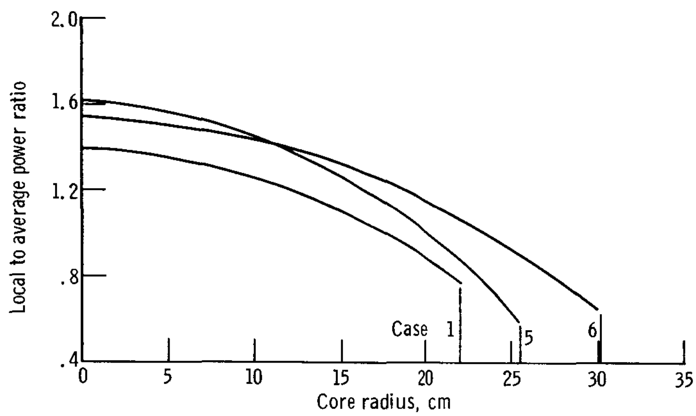

Figure 3. - Spatial power distributions for spherical cores with varying amounts of moderating materials.

Energy Distribution of Neutron Production

The effect of the moderator materials on the energy distribution of neutron production is illustrated in table V. The numerical entries in the table are the percentages of neutrons produced in each energy group for each of the six cases examined. The energy-group structure was given in table II. The reactor corresponding to each case was described in table III and again in table IV.

The most pronounced effect of hydrogen in the core is its effect in moderating neutrons from the higher energies into the resonant energy range (groups 8 and 9). Significant thermal neutron production (<2.4 eV) occurs only for case 5 with the greatest amount of hydrogen in the core. Although the thermal production for case 5 is 12.8 percent, the production in the resonant energy group 9 (2.4 to 454 eV) is 42.6 percent.

There is a direct correspondence between the percentage production in the lower-energy groups (8, 9, and 10) and the total hydrogen content in the core. For example, case 5 with the most hydrogen (atom density times volume) has the greatest production in

TABLE V. - PERCENTAGE OF NEUTRON PRODUCTION

BY ENERGY GROUP

Group	Case					
	1	2	3	4	5	6
	Yttrium hydride volume fraction					
	0	0	0.155	0.206	0.317	0.396
	Number of hydrogen atoms					
	0	0	1.25×10^{26}	6.72×10^{26}	12.32×10^{26}	6.23×10^{26}
	Neutron product ion, percent					
1	0.6	0.6	0.5	0.4	0.3	0.4
2	2.3	2.3	2.0	1.4	.9	1.4
3	5.4	5.6	4.7	3.2	2.1	3.4
4	7.4	7.5	6.5	4.4	2.8	4.8
5	8.9	8.9	7.6	4.7	3.0	5.8
6	38.9	38.9	29.9	14.5	8.2	19.1
7	36.4	36.1	38.0	22.3	13.1	29.2
8	.1	.1	8.0	18.0	14.2	17.5
9	0	0	2.4	28.0	42.6	17.4
10	0	0	.4	3.1	12.8	1.0

these groups (69.6 percent). Case 4 is next in both total hydrogen content and production; then case 6 and case 3 follow, in that order.

Note that there is, at most, only about a factor of three reduction in neutrons at high energies (groups 1 to 5) between the moderated reactor and the fast-spectrum reactors represented by case 1 and 2. The effect of this implied reduction in flux levels on shielding is considered in the following section.

Shielding

The magnitude of the high-energy neutron fluxes in the reflector at a fixed distance from the center of the core is a measure of the shielding requirements. Figure 4 shows relative flux distributions for energies greater than 0.82 MeV as a function of reactor radius for cases 1, 5, and 6 of table III. Case 1 is the base core with no hydrogen and is the smallest core. Case 5 is the core with the most hydrogen, and case 6 is the largest core. The flux levels at 35-centimeter radius are about 40 percent greater for case 5

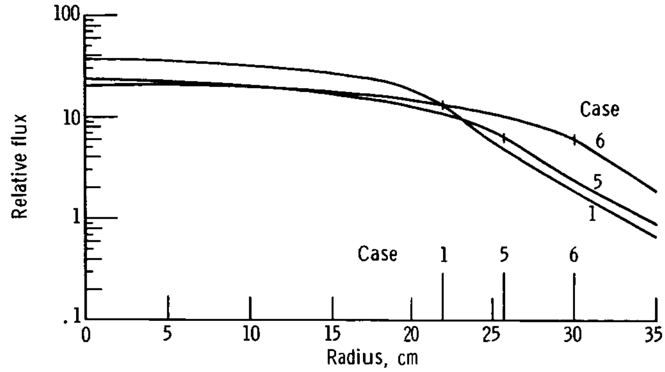

Figure 4. - High-energy flux distributions. Energy, >0.82 MeV.

than for case 1. Comparing case 6 with case 1 shows almost a factor of three greater fluxes for case 6 than for case 1. Consequently, the larger reactors, those containing moderating materials, will require greater amounts of shield materials.

CONCLUSIONS

A study concerning the desirability of introducing yttrium hydride into a nominally fast-spectrum reactor to degrade the neutron spectrum has been conducted. The major conclusions of this study are as follows:

1. A large, negative moderator temperature coefficient of reactivity is available in the partially moderated reactors. It becomes increasingly more negative as the amount of moderator increases. Shim control and reactivity loss due to fuel depletion could be compensated for by regulating the temperature of the yttrium hydride. Enough reactivity is available for the more moderated reactors to consider the reversible hydriding process for primary reactor control. Doppler coefficients should be more favorably negative in these partially moderated reactors because the spectrum is degraded into the resonance energy range.

2. The positive reactivity coefficients due to core compression decrease with increasing core size but are relatively insensitive to the amount of moderator in the core for the cases examined. The extreme values calculated are 5.6×10^{-6} and 1.8×10^{-6} $\Delta k/k$ per cubic centimeter.

3. The mean prompt-neutron lifetime increases with increasing amount of moderator in the core. The range of values are 0.08×10^{-6} to 0.59×10^{-6} second. Controlability of the reactors would probably not be affected much because of the small variation in these short neutron lifetimes.

4. The introduction of moderating materials into the core increases the critical size of the core and increases the fast-neutron fluxes in the reflector, which results in increased shield weight requirements. The minimal benefits due to degradation of the neutron spectrum are more than offset by the increased core size.

5. Maximum-to-average power ratios increase with increasing hydrogen content in the core. The increases are not large and power distribution tailoring could yield acceptable values.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 2, 1968,
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