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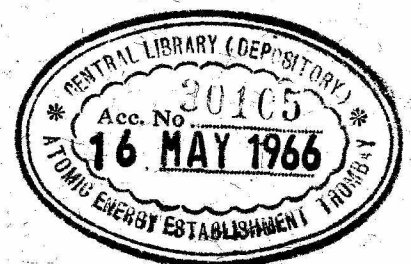
PHYSICS ASPECTS OF LARGE THORIUM FUELLED FAST REACTORS

by

R. Shankar Singh

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ABSTRACT

The feasibility of using U^{233} -Th as a fuel in a large fast breeder reactor has been studied from the point of view of the Doppler and sodium void coefficients. The composition and temperature dependent cross sections for thorium have been evaluated using the latest resonance parameters available. The parametric studies over a range of compositions and sizes of core for metal and oxide fuels indicate that the reactivity coefficients due to sodium loss and Doppler effects are negative even in a core volume as large as 15,000 liters. Based on these encouraging results, a performance characteristics study of a 15,000-liter, thorium- U^{233} -fueled, sodium cooled fast reactor of the type considered for desalination of sea water was made. The parameters like critical mass, breeding ratio and reactivity coefficients have been evaluated for the 'clean' core as well as for the core with equilibrium composition using metallic and carbide fuels.

The effect of interference interaction between the resonances of Pu^{239} and Th^{232} on the Doppler effect calculations and the sodium void coefficients in Th- Pu^{239} fueled fast reactors has been investigated. The temperature dependent effective cross sections for Pu^{239} and Th^{232} have been evaluated taking into account both types of interference interactions namely, the overlap of neighbouring resonances in one isotope and the interaction between the resonances of the two isotopes.

PHYSICS ASPECTS OF LARGE THORIUM FUELED FAST REACTORS*

INTRODUCTION

The selection of a suitable fuel for a very large fast breeder reactor of the type mentioned in connection with the desalination of sea-water depends very much on the nuclear properties of the fuel from the point of view of the reactivity coefficients. It has been observed that large sodium-cooled fast reactors based on Pu-U²³⁸ fuel are subject to positive sodium void reactivity effects. Thorium-U²³³ fueled reactors are much less subject to the undesirable positive sodium void effects because of their nuclear properties. The fission cross-section of U²³³ varies more rapidly with energy than does that of Pu²³⁹, and thorium has a much smaller fission cross-section and a higher threshold energy for fission than U²³⁸. As a consequence, the reactivity gain due to the spectral effect is much smaller with U²³³-Th as fuel compared to that with Pu-U²³⁸ as fuel. A parametric study of the reactivity coefficients due to sodium loss and Doppler effect was therefore undertaken and the latest nuclear parameters were collected for this purpose.

The importance of taking into account the interference interaction between the resonances of the fertile and fissile isotopes in the study of Doppler effect in fast reactors has been realised and extensive studies of this effect have been made for typical Pu²³⁹-U²³⁸ systems. A similar study for the Pu²³⁹-Th²³² system is of interest when plutonium is to be recycled with thorium, in fast reactors. This problem has been studied for some typical core sizes and compositions.

* Based on the work done by the author during his deputation to the Argonne National Laboratory, U.S.A. in collaboration with Dr. H. H. Hummel and Dr. D. Okrent.

CROSS SECTION PREPARATION

A 22 group cross section set⁽¹⁾ was prepared by using the first 13 groups of the YOM set⁽²⁾ and adding 9 groups for the lower energies. Below group 11 (25 kev), the capture and fission cross sections of heavy elements are composition dependent because of the resonance self-shielding effects.

Resolved resonance parameters for Th^{232} obtained upto 3 kev at Columbia University⁽³⁾ were used to evaluate the effective resonance integrals in the narrow resonance approximation using the RE-270 program of ANL. Temperature dependent effective group capture cross sections for thorium below group 11, covering the unresolved and resolved resonance regions and taking the s -wave contribution also into account in the unresolved resonance region, were obtained. These are discussed in greater detail and tabulated in reference no.4.

The experimental values of the capture and fission cross sections for U^{233} are available only in a limited range of energies. Detailed investigations to obtain shielded cross sections for U^{233} were not made in view of the absence of reliable resonance parameters for this element because of the problem of multilevel effects and also because its contribution to the Doppler effect is probably negligible. The 22 group cross section set was prepared using the same values as the YOM set⁽²⁾ for the first 13 groups and making some adjustments in the capture and fission cross sections to obtain reasonable values of σ_{eff} in the lower energy groups. The cross sections for U^{234} and fission products from U^{233} fissions were also prepared to study their effect on the reactivity coefficients. All these cross section sets are also given in reference 4.

For studies involving Pu-Th systems, the temperature dependent effective group cross-sections in the resonance region which are influenced by the interference and overlap effects were evaluated separately for thorium and Pu^{239} , over a number of combinations of the potential scattering cross sections per thorium atom σ_{p_2} , and those per plutonium atom σ_{p_9} to represent a range of Th to Pu

atom ratios and core compositions for metal and oxide fuels. A simplified method in which each type of interference interaction is treated separately in the calculation, developed by R.N. Hwang (5,6), was employed to evaluate the cross sections. The details of these calculations and the group cross-sections for Pu^{239} and Th^{232} in different cases have been tabulated in reference no.7.

U^{233} -THORIUM FUELED FAST REACTORS

The parametric studies of the reactivity coefficients were studied in large core volumes corresponding to 6,000; 8,000 and 15,000 liters. Both metal and oxide fuels were considered with core volume fractions of 70 percent sodium, 15 percent stainless steel and 15 percent fuel. For comparison purposes one case with volume fractions of 50 percent sodium, 20 percent stainless steel and 30 percent fuel was studied.

The spectral and capture components of the sodium void coefficient are calculated by the perturbation theory method using the cross sections derived from ELMOE code and the total sodium void coefficient is evaluated using the REX code. The methods of calculations are similar to those used in reference 8. The results are presented in Table I. It is seen that the spectral and capture components increase with decreasing enrichment and the addition of U^{234} and fission products makes them positive. Also they become more positive when evaluated at higher temperature. It is interesting to note that the total sodium void coefficient remains negative even in the 15,000-liter core under all conditions.

The Doppler effect which may provide the only reliable and prompt acting negative reactivity feedback towards the safety of a fast reactor, is due mostly to neutrons with energies below about 10 kev and therefore its effect is more pronounced in the systems with softer spectrum. The spectrum is softer in the U^{233} -Th metal fueled cores because of the lower density of the fuel and higher sodium volume fraction (70 percent) used in these calculations. The ELMOE program was used for these calculations and the results are given in Table II. It can be

seen from the table that the values of ρ/β obtained for metal fueled systems are large, comparable in magnitude to those that can be obtained in $\text{Pu}^{239}\text{-U}^{238}$ oxide fueled systems. It is also seen that this large Doppler coefficient drops down to a low value when the sodium is removed from the core. This can be attributed to the sharp decrease in the low energy spectrum in the core when sodium is expelled. The Doppler coefficients are larger for the oxide fueled cores. It appears therefore from the results of reactivity coefficients, $\text{U}^{233}\text{-Th}$ fueled fast reactors may not pose many safety problems even in very large cores.

Based on these encouraging results, a preliminary conceptual study was made on a 15,000 liter thorium- U^{233} fueled, sodium cooled fast reactor. The core was cylindrical with $L/D = 0.31$, having volume fractions as follows : 15 percent fuel (metal or carbide), 5 percent BeO , 65 percent sodium and 15 percent structural materials (8 percent SS + 5.6 percent V + 1.4 percent Ti). The radial blanket had the composition: 65 percent thorium, 15 percent stainless steel and 20 percent sodium and axial blanket was having the same composition as the core (with U^{233} absent). Both were having a thickness of 45 cms each. A reflector with stainless steel 60 percent and sodium 40 percent was also considered having a thickness of 30 cms. The 5 percent BeO was added to the core to overcome the decrease in Doppler coefficient in the absence of sodium. The parameters like critical mass, breeding ratio and reactivity coefficients were evaluated for 'clean' core as well as for the core with equilibrium composition. The same 22 group cross section set prepared for the preceding studies was employed and the multigroup diffusion theory code REX was used for the calculations. Part of the results are presented in Table III. More details about these studies are given in reference 9.

The breeding ratios are close to unity and the maximum value obtained is 1.259 for the core with equilibrium composition and without the presence of BeO which was replaced by the fuel. The sodium coefficients are negative in all cases and the Doppler coefficients are

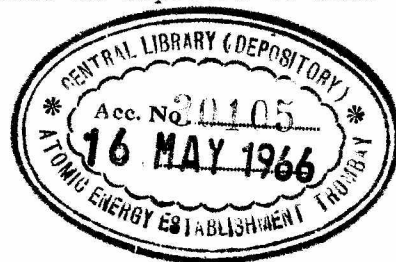
also highly negative. So, one can go to very large sizes of fast power reactors using U^{233} -Th as fuel and achieve the advantages of coupling such large power reactors to the desalination plants for obtaining not only power but also pure water from sea.

Pu^{239} -THORIUM FUELED FAST REACTORS

The effect of the interference interactions on the reactivity coefficients in Pu^{239} - Th^{232} fueled fast reactors was studied for three core volumes, namely, 1500, 4000 and 8000 liters. The cross sections of Pu^{239} and Th^{232} used for calculations were obtained for the different cases as discussed earlier.

The Doppler coefficient calculations were performed with the ELMOE code, using the cross sections with isolated resonance approximation and with the interference interaction effects included separately. The results of these calculations are given in Table IV. The interference effect makes the Doppler coefficients more negative. The percentage change in the overall δk due to interference interactions in Pu-Th systems seems to be small (4-10 percent) when compared to similar effects in U^{238} - Pu^{239} systems.

The spectral and capture components of the sodium void coefficient when half the sodium is removed from the core were evaluated using both the cross section sets for the 4000 liter core. The other cases were evaluated with the cross sections including the interference effects. The methods employed for calculations were the same as used for Th- U^{233} systems and the results are presented in Table IV. It is observed that the spectral plus capture components of sodium void coefficients become more positive when the interference effects are considered. The values tabulated are only the spectral plus capture components of the sodium void coefficient and do not include the leakage component which is negative. The effect of Pu^{240} addition to these systems has not been studied here, but its presence is expected to make



the coefficients less negative. This study reveals the importance of taking the interference effects of resonances into account in predicting the reactivity coefficients in Pu^{239} -Th fueled fast systems.

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REFERENCES

1. H.H.Hummel and A.L.Rago, 'Effect of Parametric Variations in Doppler Effect Calculations'; ANL-6792, page 747 (1963)
2. S. Yiftah, et al; 'Fast Reactor Cross Sections'; Pergamon Press, (1960).
3. J. Garg et al; AEC Nucl.Cross Sections Advisory Group Meeting; WASH - 1044 (August 1963).
4. R.S. Singh and H.H.Hummel, 'Preparation of Cross Sections and Parametric Studies of the Reactivity Coefficients for Large U-233-Th Fueled Fast Reactors'; ANL-6930 (to be published).
5. R.N. Hwang, 'Proceedings of Conference on Breeding Economics and Safety in Large Fast Reactors'; ANL - 6792 (1963) page 727.
6. R.N. Hwang, 'On the Doppler Effect Calculations with Interference Corrections' (To be published in Nuclear Science and Engineering)
7. R.S. Singh and H.H.Hummel, 'The Effect of Interference Interaction between the Resonances of Pu-239 and Th-232 on the Reactivity Coefficients in Pu-239-Th Fueled Fast Reactors. ANL report (to be published).

8. H.H.Hummel, et al, 'Calculations of Sodium Void Reactivity Effect for Large Fast Oxide Reactors in Spherical and Slab Geometry'; ANL-6792 page 65 (1965)
9. R.S. Singh, 'Performance Characteristics of a large U-233-Th-232 Fueled Fast Breeder Reactor'. A Memo to Dr. David Okrent, Laboratory Director's Office; ANL dated August 26, 1964.

TABLE - I - COMPONENTS OF SODIUM VOID EFFECT IN U²³³-Th FUELLED
SPHERICAL CORES

Fuel Type	% Na	Volume (litres)	Th-232+U- 234/ U-233 Ratio (approx.)	%δ k Full-Half			%δ k, Half - No		
				Total	Spectral and capture	Leak- age	Total	Spectral and capture	Leak- age
Metal	70	6,000	6.6		-2.1			-3.2	
Clean Core		8,000	7.1		-1.7			-2.9	
		15,000	8.9	-3.7	-0.6	3.1	-5.9	-1.4	-4.5
Oxide	70	6,000	5.5	-6.8	-3.0	-3.8	-8.3	-3.5	-4.8
Clean core		15,000	7.50	-6.0	-2.9	-3.1			
Metal	70	15,000	8.0		+0.2			+0.3	
+U-234+F.P.									
Oxide	70	15,000	8.0		+0.1			+0.4	
+U-234+F.P.									
Metal	50	15,000	11.8	-0.6	+1.1	-1.7	-0.9	+1.3	-2.2
Clean core									
Metal (F.P. + U-234) T = 1500°k	70	15,000	8.1	-1.3	+1.5	-2.8	-4.5	+0.8	-5.3
Metal (F.P.+U-234) T = 1500°k	50	15,000	11.7	+0.7	+1.8	-1.1			

For the cases in which total coefficient is evaluated, the blanket is 54 cm thick and has a composition: 20 vol percent Th²³², 15 vol percent S.S. and 65 vol percent sodium, and the reflector is 30 cms thick with composition: 40 vol percent sodium and 60 vol percent S.S. Wherever present, atoms of U²³⁴/atoms of U²³³=0.4 and fission products (F.P) correspond to 5 atom percent of Fuel.

TABLE - II. DOPPLER REACTIVITY COEFFICIENTS IN
U²³³-Th FUELLED CORES.

Fuel Type	Th/U-233	Sodium	300°-750°k	750°-1500°k	1500°-2500°k
			$-\frac{\Delta k}{\Delta T} \times 10^5$	$-\frac{\Delta k}{\Delta T} \times 10^5$	$-\frac{\Delta k}{\Delta T} \times 10^5$
Metal	6.0	Yes	1.22	0.51	0.25
		No	0.09	0.03	0.01
	6.8	Yes	1.56	0.78	0.32
		No	0.09	0.04	0.02
	8.0	Yes	2.04	0.84	0.42
		No	0.16	0.05	0.02
Oxide	4.4	Yes	2.178	0.98	0.52
		No	0.533	0.21	0.10
	5.5	Yes	2.956	1.31	0.71
		No	0.800	0.31	0.15
	6.5	Yes	3.822	1.72	0.92
		No	1.156	0.51	0.15

TABLE III - PERFORMANCE CHARACTERISTICS OF A
 ^{233}U -Th FUELED FAST REACTOR

Core Type	Th ^{233}U	Critical Mass Kg	Breeding IBR	Ratio TBR	Sodium void ef- fect -% Δk	Doppler Coeffici- ent. $\frac{\Delta k}{\Delta T} \times 10^5$	
						$300^\circ\text{K}-750^\circ$	$750^\circ\text{K}-1500^\circ\text{K}$
Clean core Metal fuel	8.29	1757	0.707	1.088	3.3	6.28	3.76
Clean core Carbide fuel	8.09	1531	0.660	1.022	3.75	6.86	4.15
$^{234}\text{U} + ^{235}\text{U}$ + F.P. added Metal fuel	7.68	1881	0.735	1.196	1.29	4.11	2.35
$^{234}\text{U} + ^{235}\text{U}$ + F.P. added Carbide fuel	7.16	1707	0.687	1.124	1.58	4.59	2.74
Clean core No BeO Carbide fuel	8.43	1967	0.734	1.136	2.87	4.41	
$^{234}\text{U} + ^{235}\text{U}$ + F.P. added No BeO Carbide fuel	8.00	2065	0.770	1.259	0.89		

Results are for an equivalent spherical core of volume 9000 liters. The blanket in all cases has the composition of the radial blanket. The sodium void effect is computed by removing 50 percent of the sodium originally present in the core.

TABLE IV - REACTIVITY COEFFICIENTS IN P_u^{239} -Th
FUELED FAST CORES

Core Description	Approximation	Th Pu	Doppler Coefficients		Sodium void Effect (Spectral plus Capture components) % δk Full-Half (1500°K)
			300-750°K	750-1500°K	
			$\frac{\Delta k_x}{\Delta T} 10^5$	$\frac{\Delta k_x}{\Delta T} 10^5$	
4000 liters metal fuel 70 vol % Na + 15 % fuel+15 % S.S.	Iso Res.	4	0.8891	0.3581	+ 0.8691
"	Interf. Interac.	4	0.9484	0.4001	+ 1.0674
4000 liters oxide fuel 70 vol % Na + 15 % Fuel+15 % SS	Iso Res.	3	1.8851	0.9148	
"	Interf. Interac.	3	2.0602	1.0476	
1500 liters metal fuel 50 vol % Na + 32 % Fuel+15 % SS	Iso Res.	6	0.3522	0.1290	
"	Interf. Interac.	6	0.3673	0.1350	+ 0.9219
1500 liters oxide fuel 50 vol % Na + 32 % Fuel+15 % SS	Interf.	4.5	1.7408	0.7193	+ 0.9816
8000 liters metal fuel 70 Vol % Na + 15 % Fuel+15 % SS	Iso Res.	5.8	1.9835	0.8132	
"	Interf. Interac.	5.8	2.1157	0.8674	+ 2.6605
8000 liters oxide fuel 70 vol % Na + 15 % Fuel+15 % SS	Interf. Interac.	4.4	3.663	1.625	+ 2.1848