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CONSIDERATIONS PERTINENT TO THE DOPPLER EFFECT FOR SPACE REACTORS*

by

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INTRODUCTION

Because of the potential importance of the Doppler effect to the safety considerations of compact fast spectrum reactors for space applications, extensive investigations have been carried out. The purpose of this paper is two-fold. First, the magnitude of the Doppler reactivity of such reactors will be estimated. Secondly, some relevant questions concerning the fundamental nature of the problems will be addressed.

In general, the Doppler effect of a system is characterized by the resonance characteristics of various nuclides involved and the nature of the spectrum. A typical space reactor is usually highly enriched and consists of significant amounts of high-temperature resistant structural material such as tungsten, rhenium and molybdenum. The cross sections of all these structural materials exhibit sharp resonances. Because of the relatively small concentration of U^{238}, the structural material are expected to be the major contributors of the temperature coefficients. The combination of relatively high enrichment and the presence of Be reflector make the spectrum relatively hard near the center of the core but relatively soft in the outer core regions. Since the Doppler effect is extremely sensitive to the softness of the spectrum in the system, the Doppler reactivity for such systems must be strongly space dependent.

The distinct resonant as well as spectral properties of space reactors will clearly give rise to various problems that are not present in the more thoroughly studied Doppler effect of fast breeder reactors.

ANALYSIS

In the present study, a generic space reactor design having features of current designs is examined. In R-Z geometry, the reactor consists of 3 core regions which are made of UN with various enrichments mixed in with a W/Re matrix and coolant channels filled with Li^7 and surrounded by Mo-vessel and beryllium oxide reflector along with external control drums made of B_4C in the radial direction and accompanied by axial regions. The axial region above the core contains BeO with W/Re structure. The enrichment increases as a function of radius to provide an approximately constant power distribution in the core regions. Hence, the temperature distribution is also expected to be approximately constant in various core regions. In the following analysis, the Doppler reactivities will be given for various radial and axial regions.

All temperature-dependent cross sections were processed through MC^2-2/SDX packages which provide both resonance treatment and spatial treatment before they were collapsed into 27-broad groups (1,2,3). ENDF/B Version 5 data were used. In the preliminary studies, the NR-approximate was used and various regions were assumed to be homogeneous in the resonance calculations. A more rigorous analysis using the integral transport theory RABANL option is also under consideration (1). The subsequent Doppler reactivity calculations were carried out using DIF3D/VARI3D packages (4) to provide the group-wise as well as total reactivities for various material and regions. The values of dk/dT are assumed to follow the usual C/T^x distribution within a reasonable temperature range. The parameters C and x can be determined readily from the calculated δk values for two temperature steps in the following way:

$$\delta k = \frac{C}{1-x}\left[T_2^{\,1-x} - T_1^{\,1-x}\right] \qquad (1)$$

and, for convenience, if one chooses $\left(\frac{T2}{T1}\right) = \left(\frac{T3}{T2}\right) = R>1$

$$\frac{\delta k_{T1\rightarrow T2}}{\delta k_{T2\rightarrow T3}} = \left(\frac{1}{R}\right)^{1-x} \qquad (2)$$

The value of x, which usually assumes values between 0.5 and 1.5 corresponding to the low energy and high energy limits of $d\tilde{\sigma}_a/dT$, can serve as a useful index to measure the relative softness or hardness of the spectrum under consideration.

RESULTS AND DISCUSSIONS

Since the main Doppler contribution is expected to come from the outer core region close to the Be-reflector where the spectrum is the softest, the position of the external control drum will undoubtedly have a significant impact on its outcome. Hence, calculations have been made at a number of control drum positions. Table I shows some illustrative results of the Doppler reactivities (both in dk/dT and in δK) for all main contributors in various regions with the control drums turned inward from their extreme outward position to 63° and 106° respectively. As expected, the Doppler reactivities are dominated by the structural material in the outer core region and the molybdenum vessel. The strong spatial dependence of the Doppler effect indicates the spectral differences in various regions. It is interesting to note that the x values for the U^{238} component given in Table Ia becomes comparable to that expected for large breeder reactors in the outer core region. The hardening of the spectrum becomes quite evident when the external control drums turn inward. The magnitudes of dk/dT, in turn, are reduced significantly. One other striking consequence of the spectrum hardening is the increase of the relative Doppler contribution of the Mo vessel with respect to that of the W/Re matrix. The reason is that the contribution of the more dominant W/Re resonances in the lower energy region becomes less important. Table II shows the group-wise δK and the corresponding values in percent for the structural material in various regions. The results further illustrate the strong dependence of the Doppler contribution on the local spectrum of the region. The energy dependence of the Doppler contributions is also sensitive to the resonance characteristics of individual nuclides under consideration. The relative importance of the low energy resonances of the tungsten isotopes as compared to that of the molybdenum isotopes can be better illustrated in Table II when the spectrum is hardened by the inward position of the control drums.

It is important to realize that the reliability of the calculated values depends, to a great extent, on the reliability of the available nuclear data. For tungsten isotopes, the resonance data are relatively better known than those for Re and Mo isotopes. A significant portion of the Doppler contribution in the core 3 region is attributed to the resolved resonances of the tungsten isotopes as is readily shown in Table II. On the other hand, the contribution of the Mo isotopes relies heavily on the unresolved resonances estimated on a statistical basis. One necessary condition required for the validity of the statistical approach is that the average level spacing between resonances must be much less than the energy interval in question. Unlike the tungsten isotopes, the average spacings for the Mo isotopes given in ENDF/5 range from 300 eV to 2.4 keV. The required criterion clearly cannot be met in the low keV region where the contributions are most important. The resonance cross sections for the widely separated resonances must be estimated on a deterministic basis to be meaningful. Hence, the extension of the existing resolved resonance data to the higher energy region (low keV region) is clearly desirable especially for Mo.

CONCLUSION

In the presence of Be reflector, the Doppler effect of the space reactors is dominated by the structural isotopes in the outer core region and the Mo vessel. The overall reactivity feedback is sensitive to the locations of the external control drums. Since the control drum worth between the "open" and "closed" positions is only of the order of 10% in keff, the Doppler reactivities may become an important safety consideration. The accuracy of the estimated Doppler effect can be enhanced by using more rigorous computational models and through improvement of the basic data.

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TABLE I. Doppler Reactivities by Material and Region

a. $\frac{dk}{dT}$ - at operating temperatures

Heavy Nuclides at 1850°K
Structural (W/Re) at 1600°K
Vessel (Mo) at 1400°K

CONTROL DRUM LOCATIONS

	63° from 'open' position				106° from 'open' position			
Region	U238	x	U235	Structural	U238	x	U235	Structural
Core 1	-1.6968D-09	1.175	1.3967D-09	-1.8313D-08	-17054D-09	1.177	1.4145D-09	-1.8410D-08
Top 1	0.0		0.0	-3.9453D-09	0.0		0.0	-3.9456D-09
Core 2	-7.8836D-09	1.264	9.0090D-09	-1.0729D-07	-7.3974D-09	1.277	8.4540D-09	-1.0100D-07
Top 2	0.0		0.0	-2.0678D-08	0.0		0.0	-1.9774D-08
Core 3	-7.4638D-08	0.815	5.7916D-08	-1.0248D-06	-3.0129D-08	0.873	4.1308D-08	-4.6689D-07
Top 3	0.0		0.0	-3.6335D-08	0.0		0.0	-2.5647D-08
Vessel (Mo)	0.0		0.0	-5.6755D-07	0.0		0.0	-3.0749D-07
Top 4 (Mo)	0.0		0.0	-1.7054D-08	0.0		0.0	-1.0477D-08

b. δK

TEMPERATURE STEP FROM 1600→1000°K FOR STRUCTURAL & 1850→1156°K FOR HEAVY

	63° from 'open' position			106° from 'open' position		
Region	U238	U235	Structural	U238	U235	Structural
Core 1	1.5378D-06	-1.3933D-06	1.3952D-05	1.5465D-06	-1.4108D-06	1.4032D-05
Top 1	0.0	0.0	2.6359D-06	0.0	0.0	2.6388D-06
Core 2	7.2994D-06	-9.2111D-06	8.2023D-05	6.8700D-06	-8.6422D-06	7.7386D-05
Top 2	0.0	0.0	1.5087D-05	0.0	0.0	1.4435D-05
Core 3	6.2157D-05	-1.0312D-04	7.5624D-04	2.6261D-05	-5.1156D-05	3.4989D-04
Top 3	0.0	0.0	2.6646D-05	0.0	0.0	1.8925D-05
Vessel (Mo)	0.0	0.0	3.6669D-04	0.0	0.0	2.0109D-04
Top 4 (Mo)	0.0	0.0	1.1001D-05	0.0	0.0	6.8039D-06

TABLE II. Group-Wise wK for Structural Material in Various Radial Regions
(Control Drum at 63°)

Temperature Step - 1600°K T 1000°K

Eu KeV	Core 1		Core 2		Core 3		Vessel	
	Delta K	Percent	Delta K	Percent	Delta K	Percent	Delta K	Percent
111.09	4.9908D-07	3.5771D+00	2.4422D-06	2.9774D+00	2.8167D-06	3.7246D-01	7.2963D-06	1.9898D+00
67.38	1.0766D-06	7.7160D+00	5.4324D-06	6.6231D+00	7.0705D-06	9.3495D-01	1.4821D-05	4.0418D+00
40.86	1.6769D-06	1.2019D+01	8.6892D-06	1.0594D+01	1.2859D-05	1.7003D+00	2.0271D-05	5.5281D+00
24.78	1.8497D-06	1.3258D+01	9.9905D-06	1.2180D+01	1.8095D-05	2.3927D+00	2.6892D-05	7.3337D+00
15.03	1.9582D-06	1.4035D+01	1.1183D-05	1.3634D+01	2.6326D-05	3.4811D+00	3.3662D-05	9.1801D+00
9.11	1.7152D-06	1.2294D+01	1.0513D-05	1.2817D+01	3.4697D-05	4.5881D+00	3.8667D-05	1.0545D+01
5.53	1.3640D-06	9.7760D+00	8.7750D-06	1.0698D+01	4.3039D-05	5.6912D+00	4.2197D-05	1.1508D+01
3.35	1.0492D-06	7.5202D+00	7.3870D-06	9.0061D+00	5.7088D-05	7.5489D+00	4.1299D-05	1.1263D+01
2.03	6.5966D-07	4.7280D+00	3.7209D-06	4.5365D+00	5.4761D-05	7.2412D+00	3.8505D-05	1.0501D+01
1.23	6.6363D-07	4.7565D+00	4.2468D-06	5.1777D+00	7.7285D-05	1.0220D+01	2.6084D-05	7.1135D+00
0.748	5.5558D-07	3.9820D+00	3.2902D-06	4.0113D+00	8.0799D-05	1.0684D+01	2.1431D-05	5.8446D+00
0.454	4.8053D-07	3.4441D+00	2.7107D-06	3.3048D+00	8.4080D-05	1.1118D+01	2.2623D-05	6.1696D+00
0.275	2.2763D-07	1.6315D+00	2.4912D-06	3.0372D+00	1.4086D-04	1.8626D+01	1.2492D-05	3.4066D+00
0.101	1.3000D-07	9.3178D-01	8.1419D-07	9.9265D-01	5.5607D-05	7.3531D+00	7.3500D-06	2.0044D+00
0.372	7.3995D-09	5.3034D-02	3.9549D-08	4.8217D-02	1.2620D-05	1.6687D+00	9.1073D-08	2.4837D-02
0.013	2.9497D-09	2.1141D-02	1.9397D-08	2.3649D-02	1.1863D-05	1.5686D+00	1.1922D-05	3.2513D+00
0.0050	2.3851D-10	1.7095D-03	3.7191D-09	4.5343D-03	5.7537D-06	7.6083D-01	1.2745D-08	3.4758D-03
0.0018	1.7215D-09	1.2339D-02	4.3978D-08	5.3617D-02	3.0284D-05	4.0046D+00	9.3745D-07	2.5565D-01
SUM =	0.1395D-04		0.8202D-04		0.7562D-03		0.3667D-03	

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