TEMPERATURE AND DOPPLER COEFFICIENTS OF VARIOUS SPACE NUCLEAR REACTORS

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Abstract

Temperature and Doppler feedback effects for a Particle Bed Reactor (PBR) designed to operate as a propulsion reactor are investigated.

Several moderator types and compositions fuel enrichments and reactor sizes are considered in this study. From this study it could be concluded that a PBR can be configured which has a negative prompt feedback, zero coolant worth, and a small positive to zero moderator worth. This reactor would put the lowest demands on the control system.

INTRODUCTION

The design of Nuclear Thermal Propulsion (NTP) reactors has as one of its goals the maximization of the thrust/weight ratio. This goal can only be achieved by making the reactor core as light as possible, within the constraints of a prudent mechanical and safe design. In a Particle Bed reactor (PBR) the moderator occupies approximately 50%-75% of the core volume. Thus, in order to minimize the core mass, it is important to reduce the moderator mass to its lowest possible value. In view of this requirement it is desirable to use the lowest density moderator, consistent with the moderating performance required. In addition the uranium enrichment plays a role in reducing the size and thus the reactor mass. Generally, the highest enrichment corresponds to the smallest possible reactors. However, this reduces the fertile fraction in the fuel and thus impacts the Doppler feedback.

Based on the general guide lines outlined above, it was decided to consider the following moderator types:

1. Al/Pe - This moderator consists of aluminum foam with polyethylene. The aluminum is added to enhance the heat transfer. This moderator is limited to comparatively low operating temperatures, and the aluminum acts as a diluent, since it is a relatively poor moderator.

2. Be/Pe - This moderator is similar to the one described in 1, except it uses beryllium instead of aluminum. Its primary advantage is that beryllium aids in the moderation process. In addition, this moderator could potentially be lighter than the aluminum based moderator, since beryllium is a lower density material.

3. Be/Li-7/H - This moderator is similar to the one described in 2, with the polyethylene replaced by lithium-7 hydride. This moderator allows for a higher operating temperature, without compromising the moderating performance of the moderator. It should also be lighter than the moderators described in 1 and 2, for the same moderating power.

The Doppler effect in PBR's is due to a combination of resonance broadening in the fertile material (U-238) and the hot frit coating material (Ta). Since the resonance integral for tantalum is much larger than for uranium-238, a thin coating on the hot frit has a significant effect. The uranium enrichment can still be varied to enhance the Doppler effect, ensuring a negative prompt coefficient.

Reactor Description

A brief description of a PBR will be given. More detailed descriptions are given in other papers presented at this meeting. The reactor consists of particles (500 microns OD) contained between two co-axial porous tubes (frits). These assemblies are referred to as a fuel elements, and are embedded in moderating material. The fuel elements are arranged in a hexagonal pattern within the moderator. Coolant (hydrogen) flows into the core from one end, cooling the moderator first and then flows radially through the fuel element, and out the core through the duct formed by the inner frit (hot frit). The core is contained in a pressure vessel, and has inlet and outlet plena attached at the ends. An exhaust nozzle is integrated into the outlet plenum.

The reactors to be discussed in this study will consider all of the above mentioned moderators and a variety of uranium enrichments. Both 37 and 61 element reactors will be considered. Finally, two thrust levels will be considered; the first consistent with 1000 MW, and the second consistent with 2000 MW. The overall reactor geometric parameters are given below:

Reactor Power	1000 MW	2000 MW	
Case	1	2	3
Number of Elements	37	37	61
Fuel Bed Volume (liters)	25	50	50

The method of analysis used in this paper is based on the Monte Carlo method. This method was deemed necessary since PBR's are characterized by high leakage and are very heterogeneous. In addition it is important to conserve both volume of material and neutron leakage area. This requirement cannot be simultaneously satisfied using a method which does not model all the components explicitly. The MCNP code was used, which is based on a combinatorial geometric representation and a continuous energy cross section description. This makes it unnecessary to create approximate geometric representations of the core and special position dependent group cross sections.

Results

In this section the feedback effects due to the change in the moderator temperature, and thus changes in its scattering kernel will be discussed. In addition the Doppler feedback and coolant worth as a function of moderator volume will be outlined.

Moderator Worth

The variation of moderator worth with temperature has been presented in detail in a previous publication (Mughabghab, 1993). Here we will discuss the dependence of the feedback on moderator volume. Table 1 shows the dependence of a moderator composed of beryllium/hydrogenous material on moderator volume for Case 1.

TABLE 1. Dependence of Moderator Worth by Component on Volume.

	(Worth in cents/K)					
	Beryllium			Hydrogenous Material		
Volume (cc)	150(K)	250(K)	350(K)	150(K)	250(K)	350(K)
2.36(5)*	-0.06	0.08	0.5	2.05	1.04	1.08
2.86(5)	0.15	0.49	0.87	2.89	1.75	1.35
6.89(5)	0.87	1.28	3.79	6.69	3.74	3.14

*2.36 (5) = 2.36×10^5

These results show that the component of worth due to beryllium increases with increasing moderator volume, and beryllium temperature. The increase with moderator volume is approximately proportional to V^n, where n = 1.6. In the case of the hydrogenous component, the worth also increases with increasing moderator volume, but it decreases with increasing hydrogenous material temperature. Thus it is important to determine the component temperatures when determining the moderator worth for any given average temperature. In general the metal component will respond faster (due to better heat conduction) to changes in coolant conditions, particularly during start-up transients. The hydrogenous component (hydride or polyethylene) will not respond as rapidly and thus is expected to operate at higher temperatures during start-up transient conditions in which the moderator cooling depends on both conduction and convection. Finally, it is clear that the design details of the moderator configuration are important, since long conduction paths in the beryllium will lead to a more responsive moderator temperature than long paths in the hydrogenous material.

Doppler Worth

The Doppler worth has been determined for several cores of the larger reactor (Cases 2 and 3). Table 2 shows the variation of Doppler worth with number of elements and moderator volume.

TABLE 2. Doppler Worth Variation with Number of Elements and Moderator Volume.

	(Worth in Delta k)		
Volume (cc)	37 Elements	Volume (cc)	61 Elements
2.40 (5)	-0.026	2.52 (5)	-0.024
4.02 (5)	-0.009	4.27 (5)	-0.015
6.12 (5)	-0.016	6.50 (5)	-0.011

The above results show that the Doppler worth drops off with increasing moderator volume. This effect is due to the softening of the neutron spectrum and the lower fraction of neutrons in the resonance energy band. The difference between the two reactor configurations is small, despite the thicker fuel beds, and thus larger disadvantage factor in the case of the 37 element core.

Hydrogen Worth

Hydrogen is the coolant used in propulsion reactors, and thus the effect of introducing such a good moderator into the core needs to be studied, particularly for start-up transients. The magnitude of the hydrogen worth depends on whether the core is over- or under-moderated. Furthermore, the moderator volume determines whether a core is over- or under-moderated. Thus, there is a strong correlation between the hydrogen worth of a core and its moderator volume. Table 3 shows the hydrogen worth for Case 2.

TABLE 3. Hydrogen Worth as a Function of Moderator Volume.

Moderator Volume (cc)	Hydrogen Worth (delta k)
2.40 (5)	+0.029
4.02 (5)	-0.011
6.12 (5)	-0.027

The results show that the hydrogen worth is a monotonically reducing function of moderator volume. The volume at which the introduction of hydrogen has zero worth, generally corresponds to a core which is neither under- or over-moderated, and would thus pose the smallest control requirements.

Conclusions

The following conclusions can be drawn from this study:

1. The moderator feedback due to scattering kernel effects is always positive, although it becomes exceedingly small for some designs, and may be over-ridden in certain temperature ranges by the other effects i.e. expansion and dissociation (hydrides).

2. In the case where the moderator is composed of metal/hydrogenous material combination, their individual temperature responses needs to be determined in order to estimate the overall feedback effect. This is necessary since the metal and hydrogenous material feedback worths vary in opposing directions.

3. For a given fuel volume, the magnitude of the Doppler effect is not sensitive to the number of elements.

4. The magnitude of the Doppler effect decreases with increasing moderator volume.

5. A moderator size can be defined at which the introduction of hydrogen coolant has no effect on the multiplication factor. This implies a neutrally moderated system.

6. A PBR can be configured which has a negative prompt feedback coefficient, zero coolant worth, and a small to zero moderator worth. This reactor would put the lowest demands on the control system.

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References

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