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SMALL PROPULSION REACTOR DESIGN BASED ON PARTICLE BED REACTOR CONCEPT†

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ABSTRACT

In this paper Particle Bed Reactor (PBR) designs are discussed which use ^{233}U and ^{242m}Am as fissile materials. A constant total power of 100MW is assumed for all reactors in this study. Three broad aspects of these reactors as discussed. First, possible reactor designs are developed, second physics calculations are outlined and discussed and third mass estimates of the various candidates reactors are made. It is concluded that reactors with a specific mass of 1 kg/MW can be envisioned if ^{233}U is used and approximately a quarter of this value can be achieved if ^{242m}Am is used. If this power level is increased by increasing the power density lower specific mass values are achievable. The limit will be determined by uncertainties in the thermal-hydraulic analysis.

1.0 INTRODUCTION

The Particle Bed Reactor (PBR) concept has been described elsewhere, (J.R. Powell, et al.). A single fuel element is illustrated in Figure 1. Coolant flows axially through the moderator, then enters the plenum surrounding the cold frit.

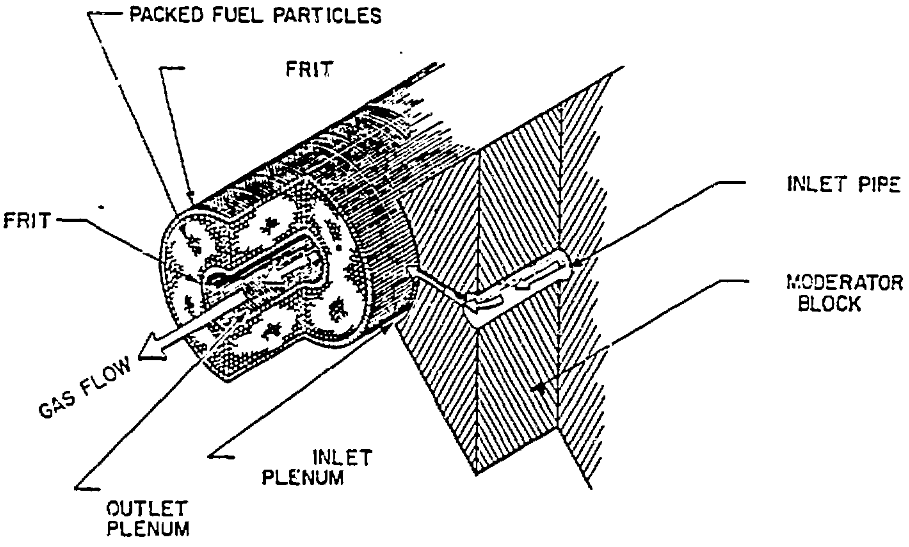

Figure 1 Baseline fuel element and moderator block.

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The flow through the cold frit, fuel bed and hot frit is radial. Finally, the hot coolant leaves the fuel element by flowing axially out through the element. A feature, unique to this reactor concept, which will be used in this study, is the possibility of keeping the entire moderator volume at the coolant inlet temperature. This feature makes it possible to pick a moderating material which will minimize reactor mass, rather than requiring it to operate at reactor outlet temperature. Furthermore, the use of fissionable materials other than ^{235}U will be investigated in this paper. The use of ^{233}U has been proposed2) as a method of reducing propulsion reactor mass, and thus the parasitic mass of a space craft. In addition, the possibility of using ^{242m}Am as a reactor fuel has been analyzed3) in other studies. The latter analysis confined itself to liquid cooled reactors, with the fuel arranged in rod bundles. In this paper the application of ^{233}U and ^{242m}Am to a PBR design will be investigated for a fixed reactor power level i.e. changes in reactor size to achieve criticality will imply vary the power density. Finally, it should be noted that extremely small critical masses have been calculated4) for idealized assemblies of various fissile nuclides including the two of interest here.

In the following sections physics analysis and reactor mass estimates will be discussed. These sections will be followed by a discussion of the possible implications of these results.

2.0 ALTERNATE FUELS

In this section, the nuclear properties of the most desirable fissile material for use in a PBR to be used as a propulsion reactor will be discussed. Several nuclides will be compared, however, only two will be used in the subsequent analysis.

The neutron multiplication factor for a propulsion PBR type reactor is given by

$$ke = \eta f p \epsilon P$$

where

$\eta = \dfrac{\nu\Sigma_f}{\Sigma_a^f}$ = average number of neutrons produced per neutron absorbed

$f = \dfrac{\Sigma_a^f}{\Sigma_a}$ = ratio of absorption in fuel to total absorptions

p = resonance escape probability

ϵ = fast fission factor

P = non leakage probability

In most PBR designs, the values of p and ϵ are close to unity. Since, the fuel is highly enriched and the structural material has very few resonances the value of p is essentially unity. Furthermore, since the bulk of the fission reactions takes place below 30.eV the fast fission factor is also essentially unity. The value of f, which is a measure of non-fissile material absorption is also close to unity. In most propulsion reactor analysis it is found that $.85 \leq f \leq .98$. Thus, it can be assumed that

$$k_\infty \approx \eta P$$

From this relationship it can be seen that for a critical system the value of η is inversely proportional to P. Thus, a increase in η implies a decrease in P, which implies a smaller/lighter reactor. For a propulsion PBR it is thus desirable to choose a fissile material with high value of η, in order to minimize the reactor/spacecraft parasitic mass. Although high values of η always lead to smaller critical masses, the improvement will not always be as dramatic as with a PBR. First, not all reactors have high values of f (parasitic absorption in structural materials is significant). Second, not all reactors have neutron spectra which peak in the thermal/epi thermal range where large increases in η occur.

Table 1 shows the values of η for ^{235}U, ^{233}U, ^{242m}Am, and ^{245}Cm. It is seen that ^{233}U has higher values of η than ^{235}U, except for the energy range 30ev - 550ev. Furthermore, the largest fractioned increases are seen to occur below 30eV. Comparing ^{235}U to the actinide nuclides ^{242m}Am and ^{245}Cm it is seen that the actinides have higher values over the entire energy range.

3.0 CONCEPT DESIGN

The major differences between the proposed reactors and other propulsion reactors based on the PBR concept are:

1) The use of ^{242m}Am and ^{233}U as the fissile material, and
2) The use of BeH_2/cryogenic high pressure hydrogen as the moderator/reflector.

A cross section of the reactors to be considered is shown in figure 2. Fuel elements as shown on figure 1 are arranged in a hexagonal lattice. In all cases 19 elements are used and a radial reflector with a minimum thickness of 5 cm surrounds the core. Axial reflector are simulated by 2 cm thick structures at either end. Finally the entire core and reflector is enclosed in a pressure vessel.

TABLE 1 ETA FOR FISSILE NUCLIDES

Energy Range Per Group (eV)	Nuclide U-235	 U-233	 Am-242m	 Cm-245
1.5(7) - 3.0(6)	2.86	2.96	4.08	4.49
3.0(6) - 1.4(6)	2.46	2.61	3.63	3.99
1.4(6) - 9.0(5)	2.38	2.50	3.44	3.76
9.0(5) - 4.0(5)	2.21	2.43	3.35	3.57
4.0(5) - 1.0(5)	2.12	2.37	3.22	3.21
1.0(5) - 1.7(4)	1.95	2.27	2.95	3.11
1.7(4) - 3.0(3)	1.87	2.20	2.82	3.18
3.0(3) - 5.5(2)	1.74	1.88	2.81	3.23
5.5(2) - 1.0(2)	1.68	1.49	2.81	3.23
1.0(2) - 3.0(1)	1.61	1.48	2.81	3.13
3.0(1) - 1.0(1)	1.5	2.1	2.81	3.09
1.0(1) - 3.0(0)	1.28	2.12	2.84	3.20
3.0(0) - 1.0(0)	1.88	1.93	2.97	3.11
1.0(0) - 4.0(-1)	2.14	2.26	2.78	3.33
4.0(-1) - 1.0(-1)	2.02	2.25	2.71	3.18
1.0(-1) -	2.07	2.28	2.71	3.1

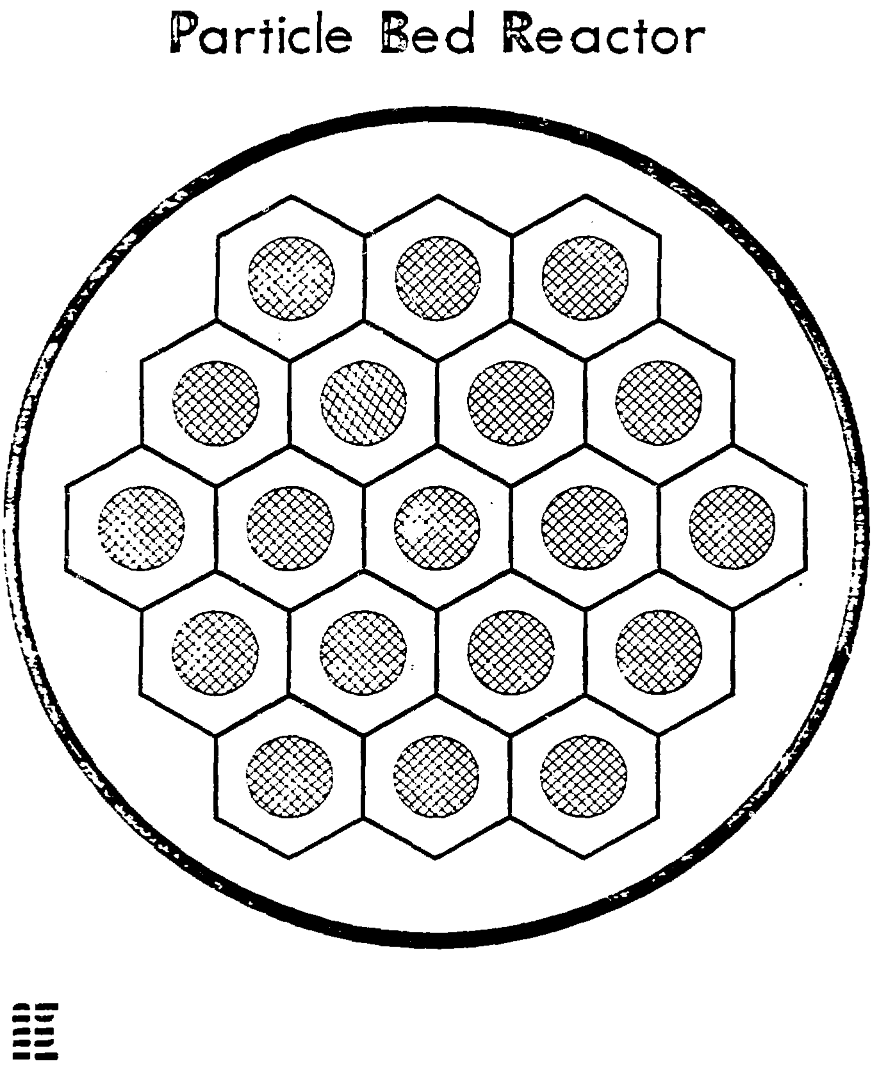

Figure 2 Particle Bed Reactor.

The BeH_2/cryogenic hydrogen used in the moderator/reflector is choosen in such a manner that the hydrogen number density is equal to that of water. This results in a density for these components of .6 gm/cc. The use of BeH_2 is made possible in a PBR by the fact that in a PBR the reflector/moderator operate at cryogenic temperatures. This is an important feature of the PBR since BeH_2 has a maximum operating temperature of approximately 150°C. It would thus be impossible for use in reactors where the moderator/reflector has to operate at coolant outlet temperatures. Furthermore, it should be pointed out that the ratio of BeH_2/cryogenic hydrogen can be varied depending on optimization refinements.

All reactors in this study will be limited to the following operating conditions

TABLE 2 REACTOR PARAMETER

Power (MW)	100
Power Density (MW/l)	variable
Outlet Temperature (K)	2500
System Pressure (MPa)	10
Thrust (kg)	2125
Number of elements	19
Outlet channel Mach number	.2
Pitch/Fuel bed OD	1.7
Hot frit thickness (mm)	2.0 (coated C/C)
Cold frit thickness (mm)	1.0 (Be)
Core H/D	1.0
Radial Reflector (cm)	5.0 (BeH_2/cryogenic H_2)
Axial Grid Plates/Reflector (cm)	2.0 (Be-C)

Fuel bed number densities are calculated based on 500 micron diameter fuel particle with a 234 micron diameter kernel composed of carbide ($XC_{1.7}$) and a 40 micron outside coat of ZrC. The density of the carbide kernel was assumed to be 11 gm/cc and the layers of pyrolytic graphitic between the kernel and the outside coat (low density and high density) was assumed to be 1.45 gm/cc.

TABLE 3 FUEL ELEMENT DIMENSIONS (CM)

Zone Description	1	2	3	4	5	6	7
Outlet Duct Radius	.772	.772	.772	.772	.772	.772	.772
Hot Frit Radius	.972	.972	.972	.972	.972	.972	.972
Fuel Bed Radius	2.35	1.932	1.736	1.616	1.533	1.471	1.423
Cold Frit Radius	2.45	2.032	1.836	1.716	1.633	1.571	1.523
Plenum Radius	2.55	2.132	1.936	1.816	1.733	1.671	1.623
Moderator Radius	4.196	3.448	3.098	2.884	2.736	2.626	2.540
Pitch	7.992	6.568	5.901	5.493	5.211	5.001	4.838
Core Radius	18.29	15.03	13.50	12.572	11.927	11.446	11.072
Mass of Fissile Carbide* (kg)	7.03	3.515	2.343	1.758	1.406	1.172	1.004

*Assuming density of 11.0 gm/cc.

4.0 REACTOR PHYSICS ANALYSIS

The physics analysis to be presented here will consist of determining the effective and infinite multiplication factors, absorption in the fuel and moderator zone and fuel element power shapes. Table 3 shows the fuel element dimensions which are consistent with the operating parameters shown on Table 2. It is seen that seven core designs of decreasing size are considered. These cores result in reactors of decreasing size and thus increasing leakage.

The variations of physics parameters for various unit cell (defined by a fuel element and surrounding moderator) sizes is shown on Table 4. It is seen that for all cases as the pitch decreases the value of the infinite multiplication factor (k_{oo}) increases. Furthermore, the absorption in the fuel region increases and the absorption in the moderator region decreases with decreasing cell size. The fractional absorption in ^{233}U is seen to be substantially lower than in ^{242m}Am for equivalent cell sizes. Table 5 shows the variation of effective multiplication factor k_e with core size.

TABLE 4 PHYSICS PARAMETERS FOR UNIT CELL CALCULATIONS

		U-233			Am-242m		
Case	Pitch	K_{oo}	Fuel Abs	Mod. Abs	K_{oo}	Fuel Abs	Mod. Abs
1	7.99	1.894	.856	.142	--	--	--
2	6.57	1.964	.887	.111	2.579	.934	.065
3	5.90	1.989	.897	.099	--	--	--
4	5.49	2.001	.902	.095	--	--	--
5	5.21	2.006	.903	.093	2.649	.959	.039
6	5.0	--	--	--	2.658	.963	.036
7	4.84	--	--	--	2.665	.966	.033

From these values and, noting that,

$$k_e = k_{oo} P$$

it is seen that approximately 40%-60% of the neutron leak from these cores.

TABLE 5 EFFECTIVE MULTIPLICATION FACTOR (k_e) AS FUNCTION OF RADIUS

Case	Effective Core Radius (cm)	U-233	Am-242m
1	18.29	1.125	--
2	15.03	1.018	1.342
3	13.50	.942	--
4	12.57	--	--
5	11.93	--	1.122
6	11.45	--	1.055
7	11.07	--	1.064

Furthermore, by noting that for these cores ($p \approx \epsilon \approx 1$)

$$k_{\infty} \approx \eta f,$$

and using values from Table 4 (k_{∞} and f (fuel absorption)) an average value for η ($\bar{\eta}$) for the cell can be obtained. It is found that:

$$\bar{\eta} = 2.217 \ ({}^{233}U)$$

$$\bar{\eta} = 2.760 \ ({}^{242m}Am)$$

This variation of k_{∞} and k_e for various values of the pitch is shown on Figure 3 for the case using ^{233}U as fissile material. It is seen that despite the fact that the k_{∞} is highest for the smallest pitches the leakage from the core overwhelms the neutron economy and the cases are subcritical. Large cores with lower leakage fractions are clearly required to remain critical despite the fact that they have lower values of k_{∞}.

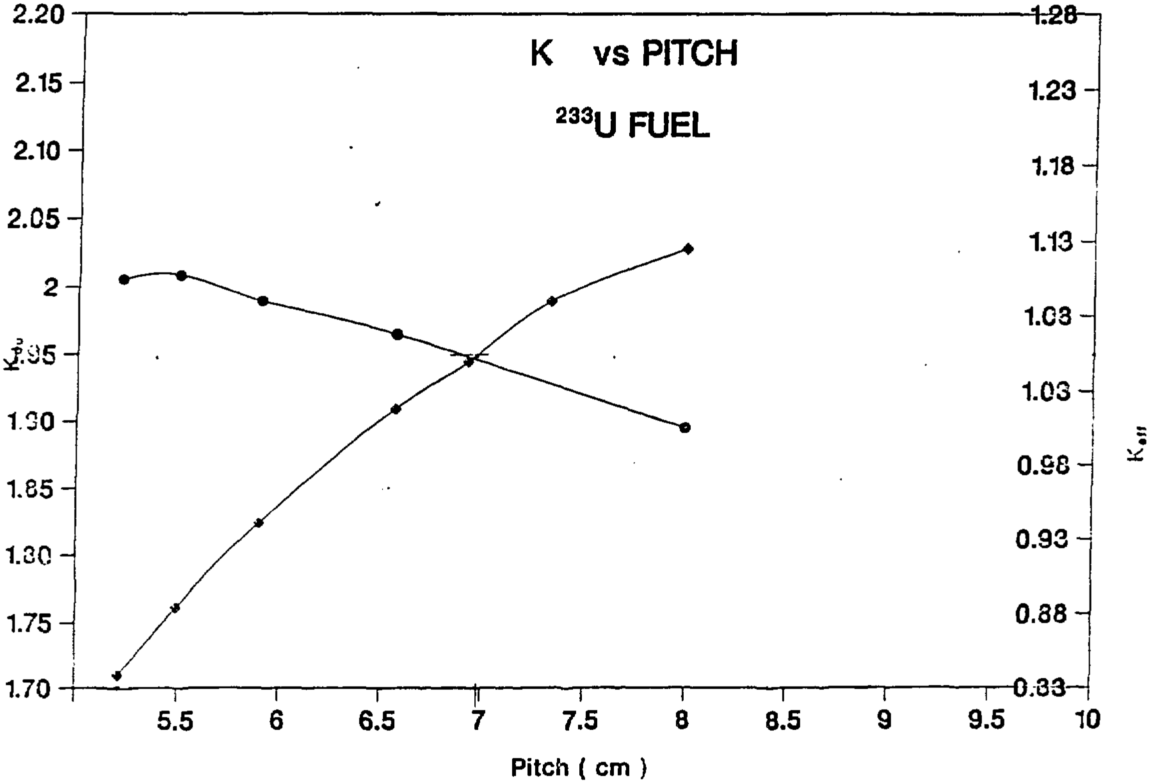

Figure 3 K vs. Pitch.

Figure 4 shows the neutron spectrum for case number 5, averaged over the fuel bed and the moderator respectively. From this figure it is seen that in the moderator the spectrum has a peak in the thermal region (high lethargy) and another peak at fission energies (low lethargy). However, in the fuel bed the fission peak is slightly enhanced and the thermal peak reduced quite substantially. The very strong shift in neutron spectrum between the moderator and the fuel is evident. Figure 5 show the radial power shape in the fuel bed. It is seen to have a minimum at the hot frit and at maximum at the cold frit. Since the ^{233m}Am has a high cross section the bed is black to thermal neutron and thus the bulk of the power is generated in the outer zone, closest to the moderator. This also explains the sharp drop-off at the low energy end in Figure 4.

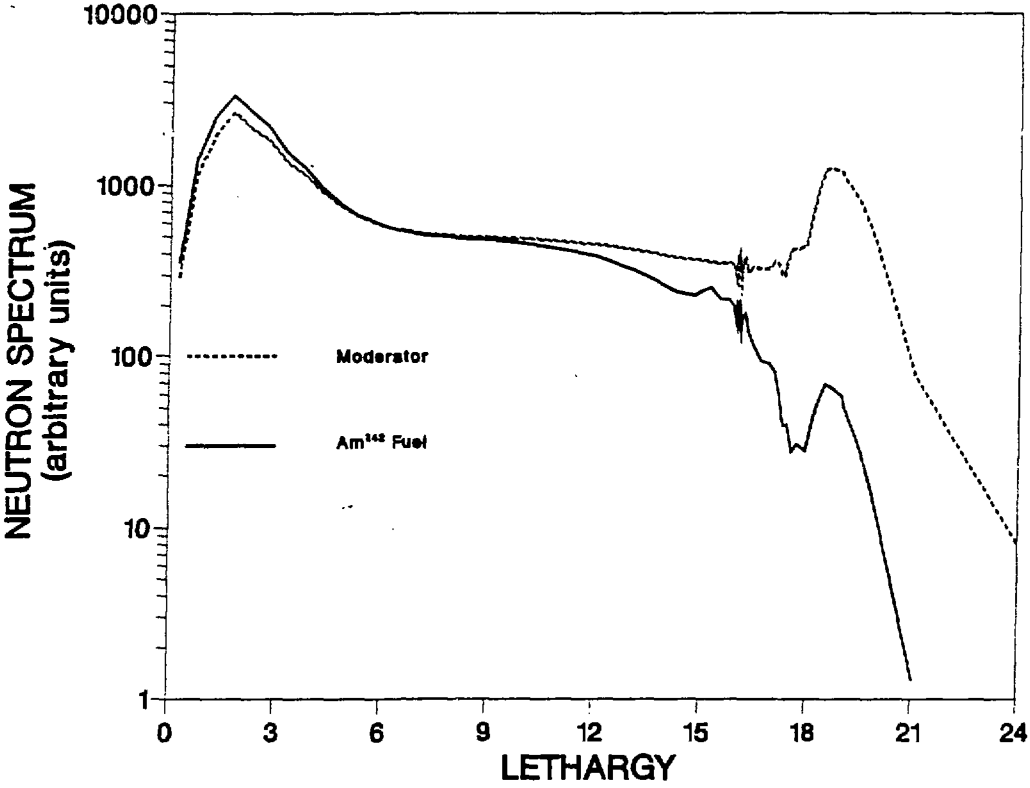

Figure 4 Neutron Spectrum.

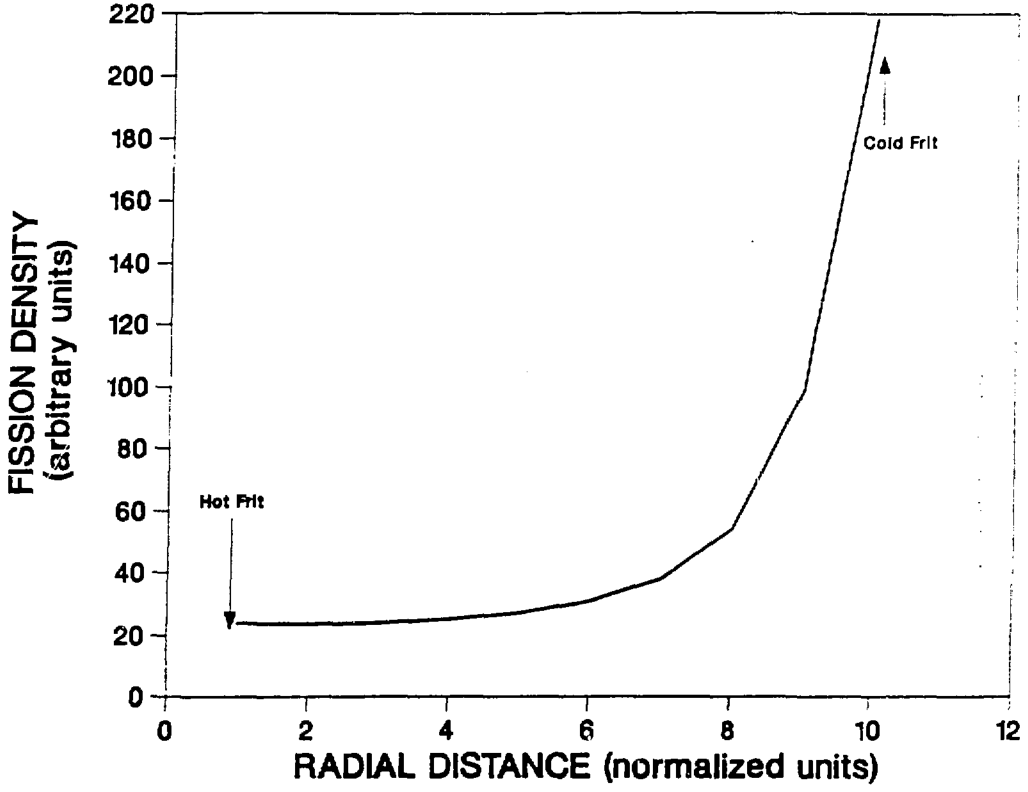

Figure 5 Fission Density.

Estimate of Reactor Mass

A reactor mass estimate can be made from the dimensions and material compositions determined in the above section. These estimates are approximate, since they include only those components included in the criticality calculations, and do not include any added mass from components which may be necessary for a complete mechanical design. However, the estimate should be accurate since all the major components are included and can be used in comparison studies.

The following components are included;

1) Fuel bed - It is assumed that the fuel particles are similar to those being manufactured for the PIPE experiment$^{5)}$. An average fuel bed density of 2.826 gm/cc is implied by this assumption. The fuel bed volume decreases, with decreasing reactor size.

2) Frits - The hot frit was assumed to be a coated (ZrC) carbon/carbon structure and the cold frit was assumed to be of beryllium. A density of 1.0 gm/cc was used in both cases to reflect the low effective density of these porous components.

3) Moderator/Radial Reflector - These components are assumed to be made of a beryllium hydride/cryogenic hydrogen mixture. The mixture was chosen to yield the same hydrogen number density as that of water. This assumption, for these materials implied a density of .6 gm/cc.

4) Grid plates/Axial Reflectors - These components are to be manufactured of beryllium at the cold end and coated carbon/carbon at the hot end. A density of 1.9 gm/cc was assumed in both costs.

5) Pressure Vessel - The pressure vessel was assumed to be manufactured of a material which has a working stress of 50,000 psi and a density of 2.0 gm/cc. A carbon fiber metal composite is a likely candidate material.

Table 6 shows the mass estimates and specific mass for each of the cases analyzed.

TABLE 6 MASS ESTIMATES

Case	Mass Estimates (ky)	Specific Mass (ky/mw)
1	96.9	.969
2	58.47	.585
3	44.66	.447
4	37.41	.374
5	32.88	.329
6	29.76	.298
7	27.47	.275

From the above table, it can be seen that it is possible to design a ^{233}U fueled reactor with a specific mass of approximately 1 kg/MW in this power range. If ^{242m}Am is used as a fuel a quarter of this value is possible. It should be noted that the power of these reactors can be increased and will be limited by the stochastic nature of the thermal-hydraulic uncertainties.

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