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PARTICLE BED REACTOR SCALING RELATIONSHIPS

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ABSTRACT

Scaling relationships for Particle Bed Reactors (PBR's) are discussed. The particular applications are short duration systems, i.e., for propulsion or burst power. Particle Bed Reactors can use a wide selection of different moderators and reflectors and be designed for such a wide range of power and bed power densities. Additional design considerations include the effect of varying the number of fuel elements, outlet Mach number in hot gas channel, etc. All of these variables and options result in a wide range of reactor weights and performance. Extremely light weight reactors (approximately 1 kg/MW) are possible with the appropriate choice of moderator/reflector and power density. Such systems are very attractive for propulsion systems where parasitic weight has to be minimized.

INTRODUCTION

The Particle Bed Reactor (PBR) has been proposed for the generation of electrical power and direct propulsion.[1-4] Optimization studies of such systems require scaling relationships that relate reactor design parameters (power density, pressure drop, etc.) to overall reactor parameters important to the overall system (weight, size, etc.). This paper examines scaling relationships for PBR propulsion reactors. The results are also applicable to burst power PBR's.

The PBR consists of a hexagonal array of fuel elements embedded in a moderator matrix. The fuel elements consist of annular packed beds of fuel particles. These particles are typically 500 to 700 μm in diameter. They have a kernal of uranium carbide surrounded by pyrolytic graphite and coated with zirconium carbide. The bed of particles is held between two porous cylindrical walls (frits) to form the fuel element. Coolant flow is radially inward from the outer cold frit, through the packed bed and inner hot frit, and axially out along the channel formed by the hot frit.

The arrangement is shown schematically in Figure 1. The coolant is hydrogen, which enters the fuel bed at 300 K and leaves at 3000 K. The PBR is controlled by rotatable control drums in the reflector. The drums combine reflector material with partial (e.g. 120°) absorber sector (e.g. B4C). They act as reflectors when the absorbing material faces out and as absorbers when the absorbing material faces in.

The porous outlet frit operates at outlet coolant temperature, and its material must withstand the coolant at these conditions. A carbon-carbon frit coated with zirconium carbide is proposed. This should be capable of operating at 3000 K in the hydrogen environment. Figure 1 shows that only the small volume immediately around the hot frit experiences very high temperatures. This results from the radial flow path in the design. The moderator operates at coolant inlet temperature. This is an advantage over propulsion reactor concepts with an axial flow path, where the outlet reactor temperature affects a much larger fraction of the core. This design approach allows the exploration of a wide range of moderator options, with choice being based on parameters other than the ability to withstand outlet coolant temperature.

METHOD OF ANALYSIS

The reactors considered here have a very short duration at power. Fuel burn up is not important and the fissile loading is primarily determined by clean criticality considerations. In general, fissile loading is small and reactor size is controlled by thermal-hydraulics. For a given reactor fissile loading mass can be adjusted by appropriate variations of the fuel volume fraction in each particle, by adjusting the fuel enrichment, or by diluting the packed bed with inert particles. The outer diameter of the particle is assumed to be constant. An additional constraint on the analysis requires that the Mach number in the outlet channel not exceed 0.2. For a given power, this constraint determines the diameter of the hot fit.

The scaling calculation starts with a thermal-hydraulic analysis of the element shown in Figure 1, which determines fuel element size. Based on previous studies, the particle bed volume fraction is chosen as 0.3, a reasonable value for thermal reactors of the type considered here. The pitch between fuel elements is then determined, yielding the reactor size. Reactor cores are assumed to have a length/diameter ratio of unity. After sizing the reactor, appropriate algorithms determine overall reactor weight.

A detailed description of the thermal-hydraulic model is given in a companion paper.[5] Briefly, the pressure drop in the inlet channels, inlet frit, fuel particle bed, hot frit and outlet channel are determined. The inlet frit porosity is varied to control the axial flow rate in such a manner that an axially constant outlet coolant temperature results. The pressure drop across the frit and particle bed are determined by well known correlations.[6] By energy conservation, the local temperature distribution in the coolant can be determined from flow rate and bed power density. Coolant temperature and particle surface temperature is related by a well known correlation.[6] Central fuel particle temperatures can be determined by solving the heat conduction equation in spherical geometry.[7] The above results allow the determination of the fuel temperature distributions for a given bed power density and coolant flow rate. Configurations meeting the thermal-hydraulic criteria are considered viable, since fissile loading can be adjusted to whatever value is necessary as described above.

The mass algorithms are based on strength requirements and from scaled point designs. The first set determine required material thickness based on allowed working stress. The second set use data developed for orbital transfer vehicle designs[8] and scale by volume. Examples are given on Table 1. Results are for a reactor with Li^7H moderator/ reflector, 10 megawatts/liter bed power density and a total reactor power of 50 MW.

The following parameters were varied:

Moderator/Reflector:	Li^{7}H, TiH, VH	
Bed Power Density (MW/L)	10–50	
Power level (MW)	50–350	
Number of fuel elements	7 and 19	
Inlet coolant pressure (MPa)	6.0	} all cases
Coolant temperature In/Out (K)	300/3000	

RESULTS

Results are shown in Figures 2–7. Figure 2 shows how core diameter varies with reactor power for different bed power densities. There is significant gain from 10 MW/L to 20 MW/L; however, reduction in core size is less dramatic above 20 MW/L. Figure 3 shows how total pressure drop varies with reactor power. Except for low reactor power levels, nineteen rather than seven elements should be used. Figures 4–6 show how reactor weight varies with power level for the three moderator/reflector options. The variations are almost linear with bed power density. The lowest weight system use Li^{7}H moderator and the heaviest VH. Figure 7 shows how reactor weight varies with total power for the three moderators/reflectors at a constant bed power density of 20 MW/L. The advantage of Li^{7}H moderated and reflected systems is clearly evident.

The above results show that for a bed power density of 10 MW/L, specific weights as low as 2.5 kg/MW are possible with Li^{7}H. Use of TiH doubles this value, while VH increases it to approximately 6.5 kg/MW. Point designs[8] for an orbital transfer vehicle with beryllium moderator/reflector result in a similar specific weight.

CONCLUSION

The following conclusions can be drawn:

1) Reactors with nineteen elements are desirable since they minimize the pressure drop across the core and are necessary for the high power portions of the range studied.

2) Very light weight PBR reactors are possible since the moderators/reflectors can operate at low temperature. Specifically, use of Li^7H is practical, resulting in reactor masses close to 2.5 kg/MW.

3) The above result is based on a bed power density of 10 MW/L. This value is conservative; 8 MW/L has been measured for helium cooled beds at an outlet temperature of 1200 K. Power densities in hydrogen cooled beds could easily be double this value. With higher bed power densities even lighter systems are possible. Such ultra-light-weight reactors are particularly attractive for propulsion reactors where it is desired to minimize parasitic weight.

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DISCLAIMER

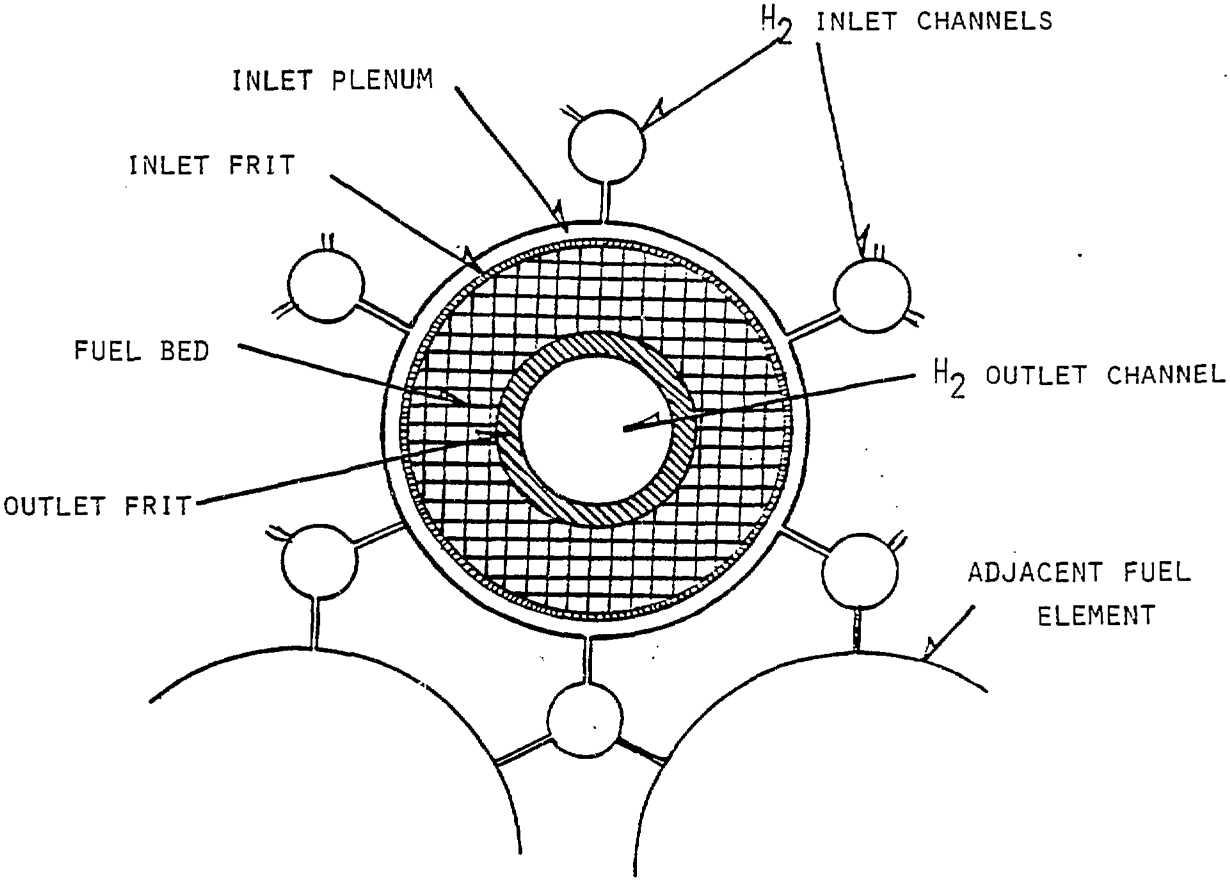
Table 1 - Weight breakdown (kg)

Fuel Elements	22.5
Moderator (Li^7H)	11.7
Reactor Vessel (AL)	45.6
Radial Reflector (Li^7H)	8.6
Central ______ and Drive	20.0
	164.1

Reactor Power (MW)	50
Fuel Bed Power Density (MW/L)	10
Number of Fuel Elements	10
Specific Reactor Wt. (kg/MW)	3.28

Figure 1

BASELINE FUEL ELEMENT CROSS-SECTION FOR PARTICLE BED REACTOR



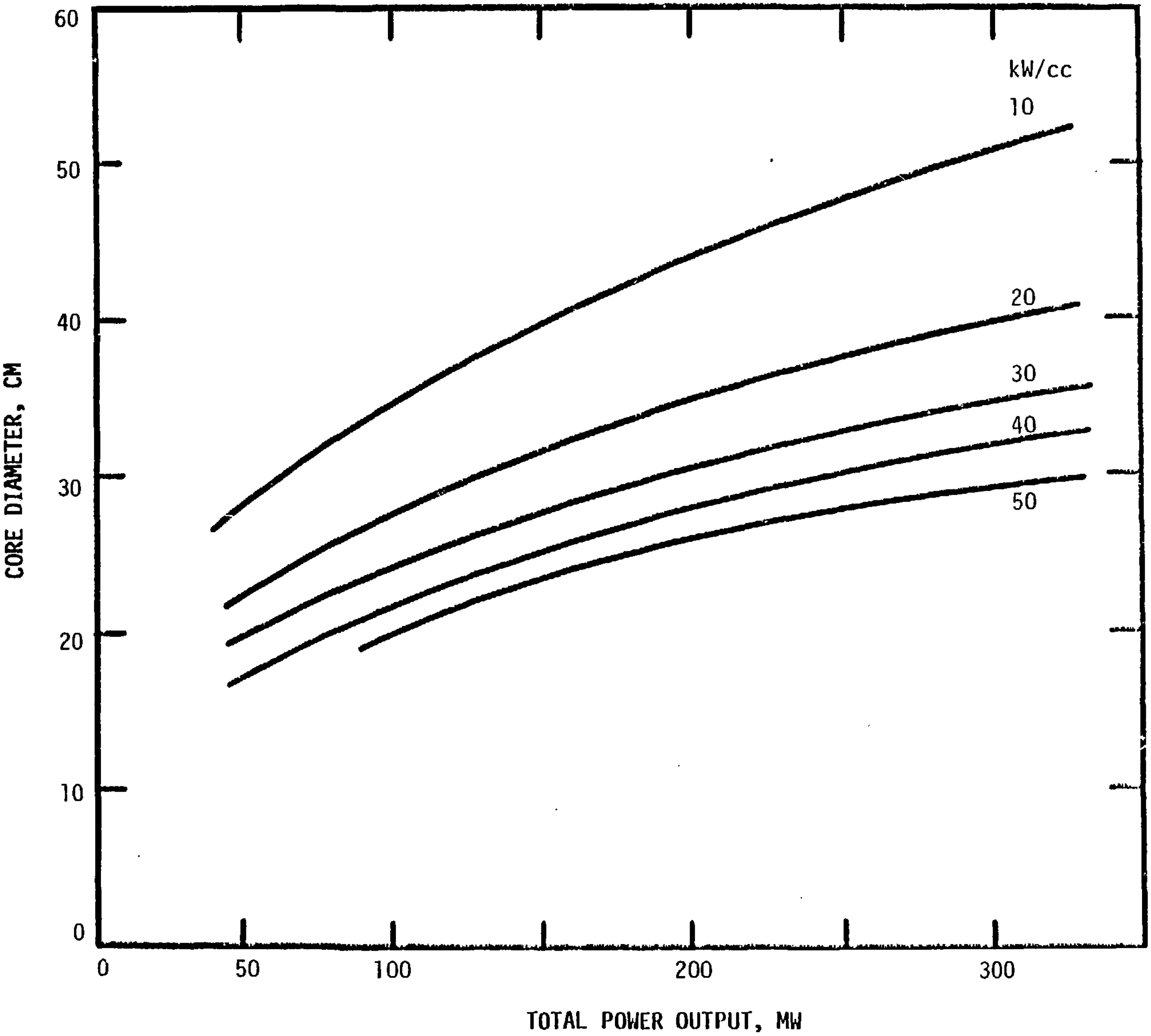


Figure 2 Core diameter as a function of power output

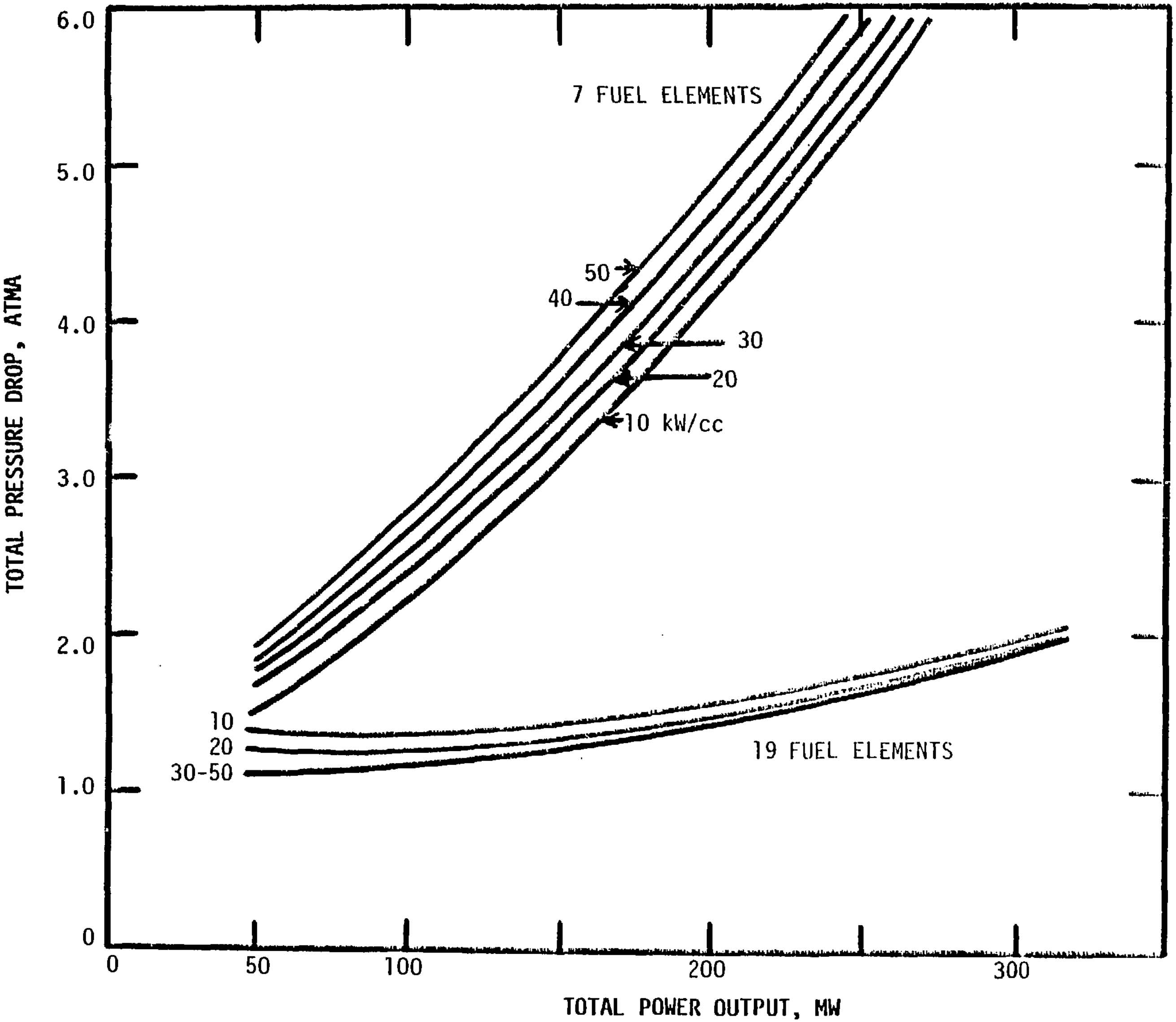


Figure 3 Total pressure drop as a function of power output

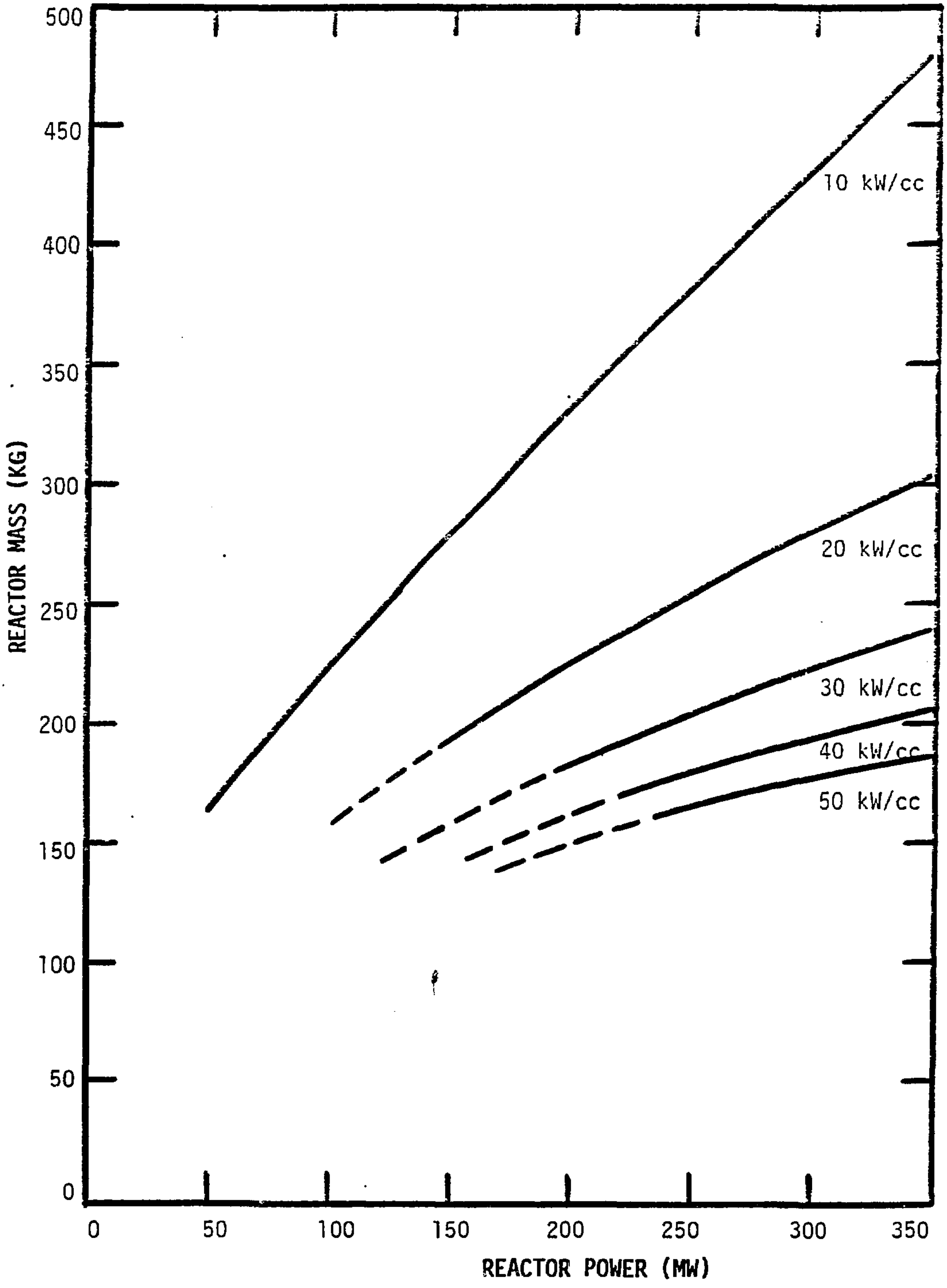


Figure 4 Mass as a function of power (Li^7H moderator)

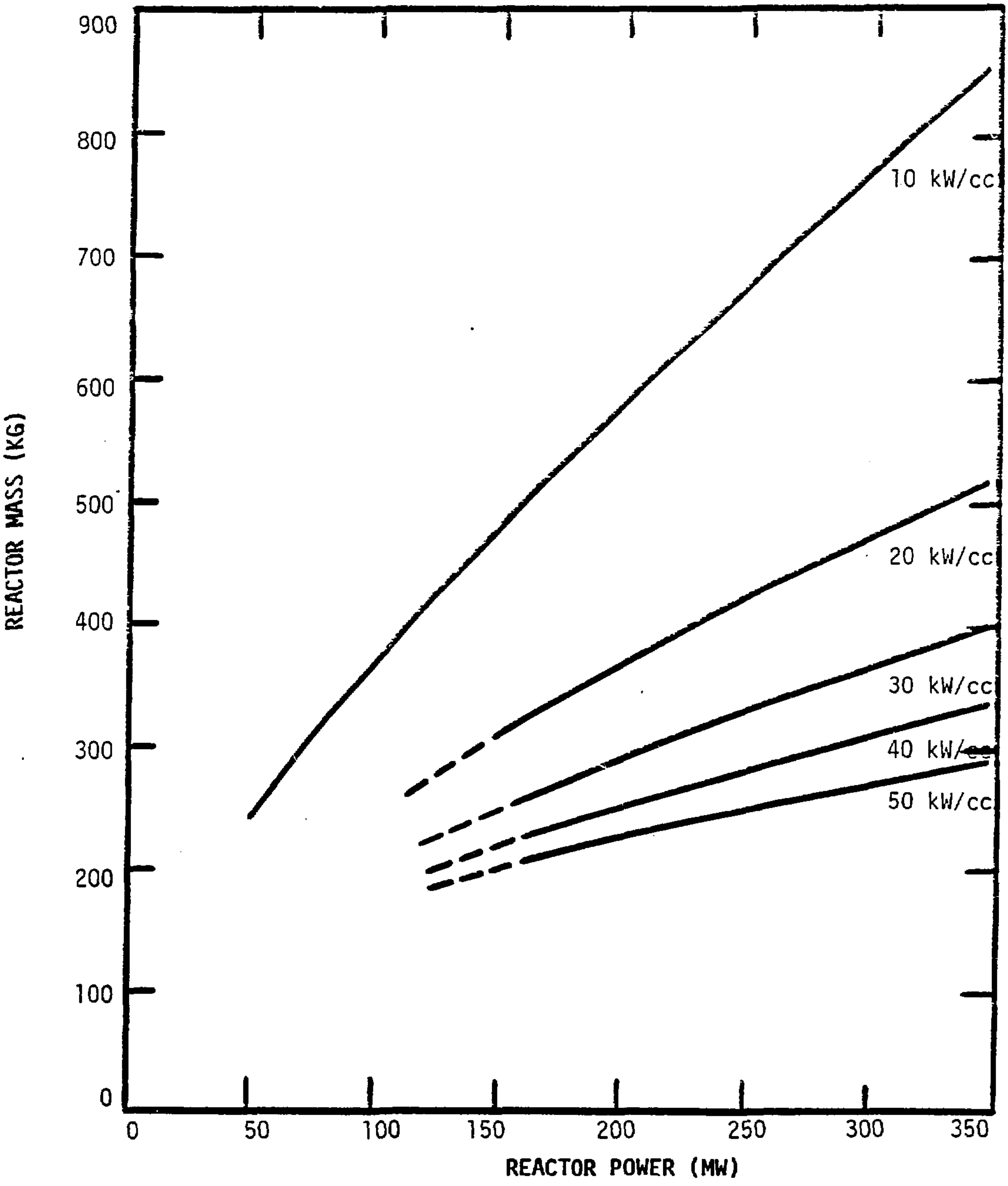


Figure 5 Mass as a function of power (titanium hydride moderator)

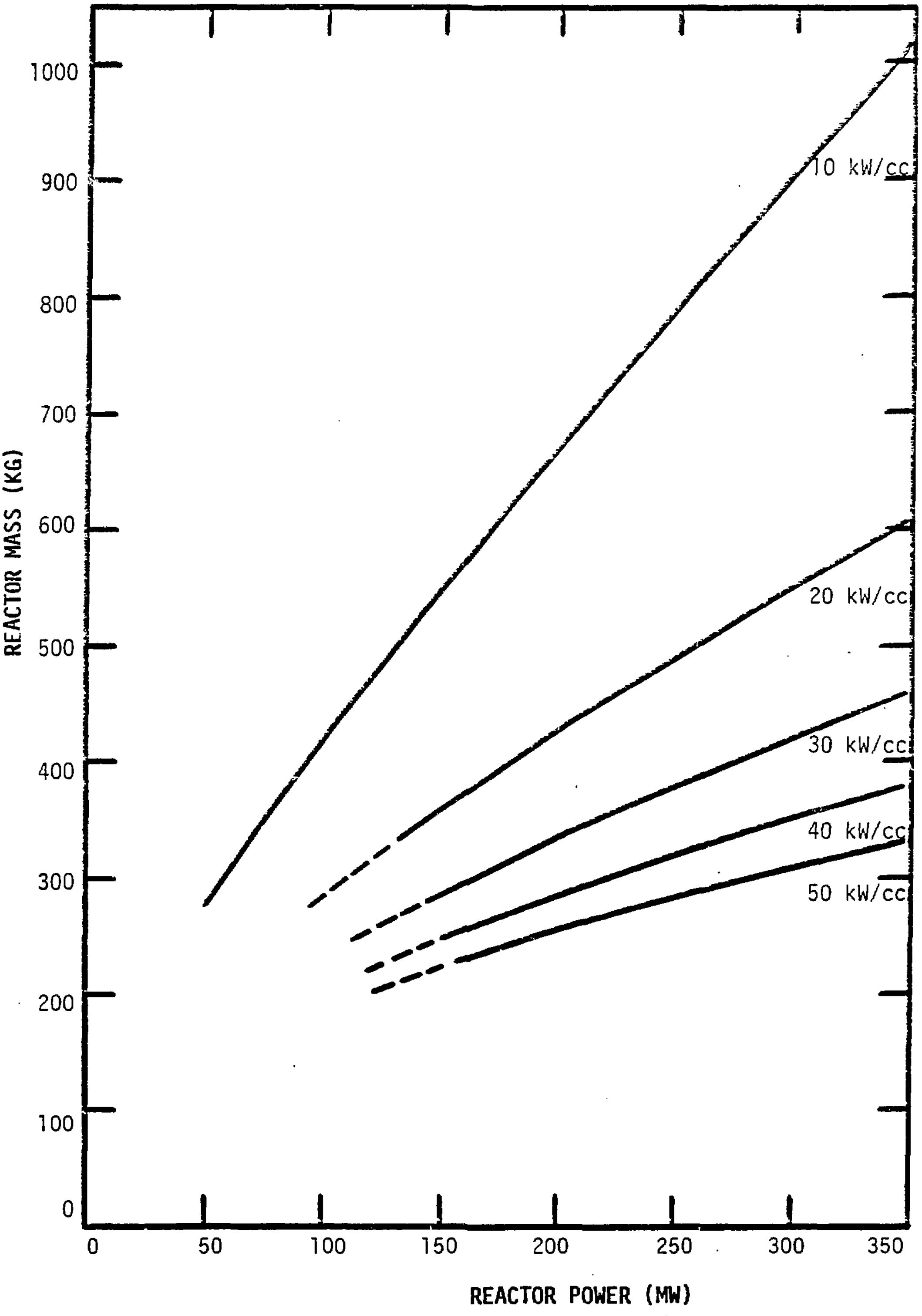


Figure 6 Mass as a function of power (vanadium hydride moderator)

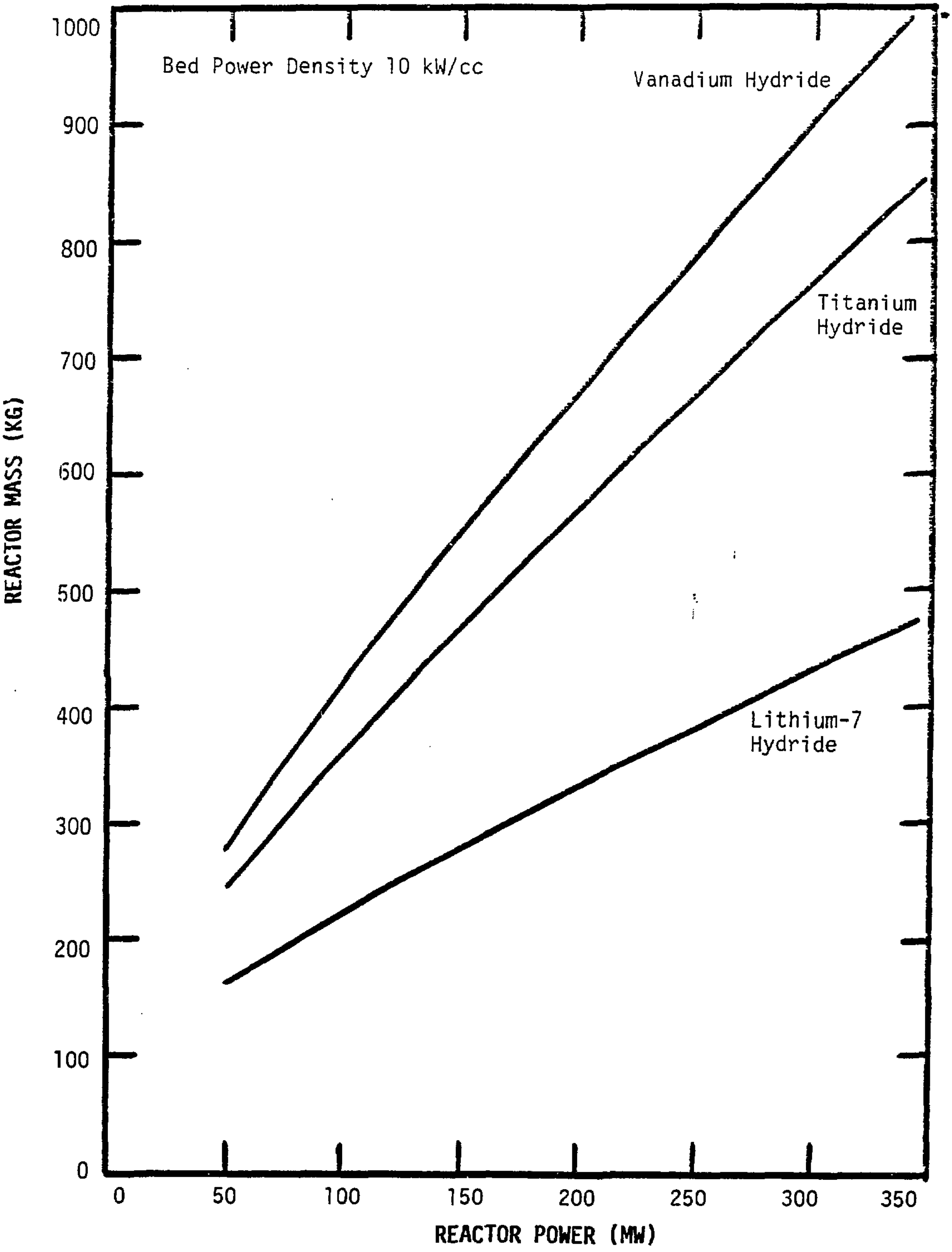


Figure 7 Mass as a function of power for various moderator types