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LIGHT WEIGHT SPACE POWER REACTORS FOR NUCLEAR ELECTRIC PROPULSION

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ABSTRACT

A Nuclear Electric Propulsion (NEP) unit capable of propelling a manned vehicle to MARS will be required to have a value of α (kg/kWe) which is less than five. In order to meet this goal the reactor mass, and thus its contribution to the value of α will have to be minimized. In this paper a candidate for such a reactor is described. It consists of a gas cooled Particle Bed Reactor (PBR), with specially chosen materials which allow it to operate at an exit temperature of approximately 2000 K. One of the unique features of a PBR is the direct cooling of particulate fuel by the working fluid. This feature allows for high power densities, highest possible gas exit temperatures, for a given fuel temperature and because of the thin particle bed a low pressure drop. The PBR's described in this paper will have a ceramic moderator (Be_2C), ZrC coated fuel particles and a carbon/carbon hot frit. All the reactors will be designed with sufficient fissile loading to operate at full power for seven years. The burn up possible with particulate fuel is approximately 30%-50%. These reactor designs achieve a value of α less than unity in the power range of interest (5 MWe).

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I. INTRODUCTION

It has been determined from mission studies that a nuclear electric propulsion (NEP) engine needs to have an overall value of α in the range 3-5 (α = kg/kw$_e$) to be a competitive candidate for a manned Mars journey. Included in the computation of engine mass are all the major components, i.e. reactor, shield, power conversion system, power conditioning system, thermal management system, and the thrusters. In order to meet the overall goal of $3 < \alpha < 5$, it is seen that any single component should not exceed a value of α equal to unity by a large amount. This paper will restrict itself to the reactor only, and thus any values of α quoted here apply to the reactor only.

The reactor to be considered in this paper is a helium cooled Particle Bed Reactor (PBR). In a NEP system, this reactor would be coupled to a Closed Brayton Cycle (CBC) power conversion system. The operating parameters would be chosen in such a manner that the thermal management system mass would be minimized. This latter condition might require a reduction of the overall thermal efficiency of the cycle in order to reject the waste heat at the highest practical temperature. Finally, the power conditioning system would have to be consistent with the alternator output and the thruster input requirements. These latter systems will not affect the design of the reactor and will thus not be discussed any further.

Reactor design will be impacted by the system operating pressure, reactor inlet and outlet temperatures, and the gas composition. The temperatures and pressures are set by operating limits of the turbine blades, compressor outlet temperature and radiator operating temperature range. Gas composition determines the molecular weight, (Helium/Xenon mixtures) which in turn determines the turbo-machinery size. It is thus seen that several system parameters impact the reactor design, and thus size and mass. This influence will be discussed in the next section. The third section will outline the analyses which have been carried out to date and the final section will outline the conclusions of this study.

II. DESCRIPTION OF PARTICLE BED REACTOR

The major components of a Particle Bed Reactor (PBR) are schematically shown on Figure 1. A PBR consists of particulate fuel packed in coaxial beds. These beds are held in place by porous cylinders (frits). The combination of fuel bed, frits and appropriately designed end-fitting form a fuel element. These fuel elements are arranged in a hexagonal pattern inside a moderator block to form the reactor core. Coolant enters the moderator first flowing through it axially, it then turns and enters a plenum region around each fuel element and flows radially inward through the frits and bed. As the coolant flows, through the bed, its enthalpy is increased, and it finally leaves the core by flowing axially down the duct formed by the inner (hot) frit. A larger plenum region attached to the end of the core collects the hot coolant for use in the power conversion system.

A PBR is to be used as the heat source in the proposed Closed Bryton Cycle (CBC) power source. In this application, the PBR has the following unique advantages:

1) Low pressure drop across the core minimizes the compressor effort;

2) Direct cooling of particulate fuel maximizes the possible reactor outlet temperature (ROT) while minimizing the fuel temperature. This is particularly important for reliable high temperature operation.

3) The possibility of using several neutron moderator types makes it possible to consider a variety of reactor designs. It is thus possible to consider a carbide-moderated system, which results in a comparatively heavy and large reactor and a light-weight balance of plant. Conversely, a hydride moderator can be considered which would result in a low mass small reactor, but would imply a large and heavy balance of plant; and

4) If the ROT and reactor inlet temperature (RIT) are appropriately chosen (ROT < 1700K, RIT < 600K), it is possible to use commercially available fuel (TRISO particles), moderator (ZrH_x) and structural materials to start a serious reactor design effort at the present time. No new materials or manufacturing development programs would be necessary.

SCHEMATIC REPRESENTATION OF A PARTICLE BED BASED POWER REACTOR

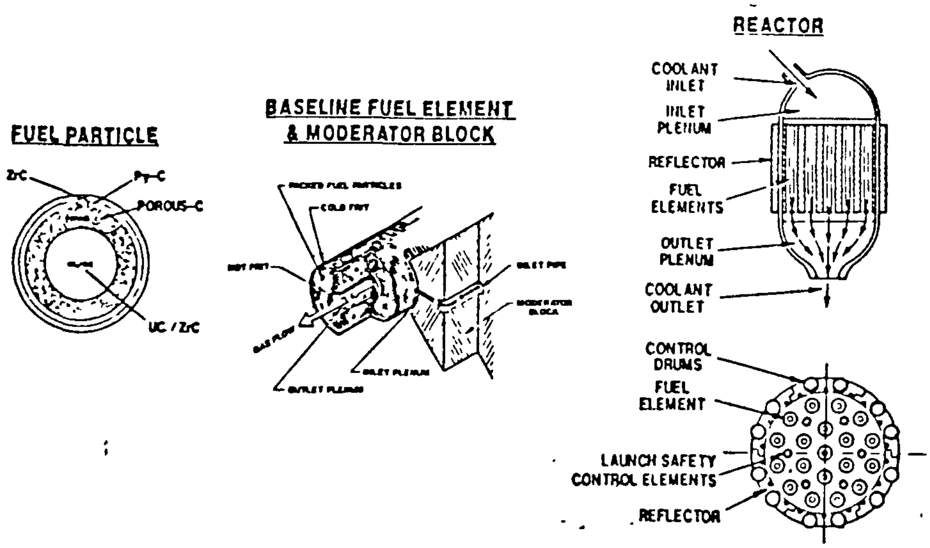

Figure 1

The power requirements of the proposed systems imposed the following requirements and assumptions on the reactor design.

TABLE 1 - REACTOR DESIGN REQUIREMENTS	
Power Range (MWt)	.3 - 21
Full Power Life (yrs.)	7.0
Fuel Burn up (%)	20.0 - 50.0
Core (Height/Diameter)	1.0
Fractional Core Pressure Drop (%)	3.0
Reactor Inlet Temperature (RIT) Range (K)	700 - 1900
Reactor Outlet Temperature (ROT) Range (K)	1700 - 2500
Coolant	He

The thermal power range is related to the desired electrical output by the thermal efficiency of the power conversion system. Improvements in the thermal efficiency would imply a reactor operating at a lower power level, either for a longer time or for the same time and with a lower fuel burn up.

The initial stages of designing a reactor involve estimates of its size, fissile loading and choice of materials. The latter choices are based on operating temperatures, estimated loads and moderating power. Following this stage, the possible designs are checked for criticality and depending on the outcome of this analysis, the core configurations are adjusted and rechecked for criticality. This iterative process continues until a satisfactory design is achieved. Such a design can only be viewed as an initial design, since in-depth mechanical design will change the configuration, which will change the neutron balance. The implication on reactor criticality of any change in design should be checked by a physics analysis. In the following discussion, the possible material choices and a sizing algorithm will be outlined. This discussion will be followed by the results of three reactor designs.

A. Reactor Size and Material Choices

The initial reactor size estimate is dependent on the following parameters:

1) Total fissile loading, and fuel particle design. This combination results in the determination of a total fuel bed volume;

2) Hot frit inner diameter. This parameter determines the inner diameter of the fuel bed, and together with the full bed volume can be used to determine the bed thickness and its outer diameter;

3) The moderating power of the moderator material. A highly efficient moderator allows the fuel elements to be closely spaced, i.e. small pitch. Less efficient moderators require a larger pitch which implies a larger reactor. This requirement is set by the pitch/diameter, where the diameter is the fuel bed outer diameter;

4) The reactor height/diameter ratio is required, since this impacts the bed thickness and thus its blackness to neutrons;

5) Finally, the number of fuel elements is required, since a larger number of elements results in thinner fuel beds, thus a more homogeneous reactor and for a given fuel loading a higher multiplication factor results. However, the larger the number of fuel elements the higher the cost since more parts (frits, end fittings, etc.) have to be

manufactured and assembled. Moderator and fuel choices available to the PBR design will be discussed below.

1. Moderator. The choice of moderator is determined entirely by the moderator operating temperature. This temperature is largely determined by the RIT and the conductivity of the moderator material. Values of RIT equal to or lower than 600K allow the use of a hydride moderator, i.e. ZrH_x. This choice results in the smallest size reactor, due to the high moderating power of the hydrogen.

In the range 600K < RIT < 1700K, a moderator must be chosen based on its ability to withstand extreme temperatures while still having an acceptable moderating power and a low density. The optimum choice in this case in Be_2C which satisfies all the desired criteria. However, due to its lower moderating power compared to a hydride moderated, the reactor size will increase.

Finally, in the range RIT > 1700K, an all-graphite moderator can be used. Graphite is a common reactor moderator (dating back to the first Chicago pile), and its behavior as a moderator is well understood. However, due to its poor moderating power, large reactors are implied, and thus, it will not be considered in this study.

2. Fuel. Mixed mean ROT values equal to or below 1700K allows the use of commercially available TRISO fuel particle. These particles have a uranium oxycarbide kernel, coated with two layers of pyrolytic graphite, a layer of silicon carbide and finally a high density pyrolytic graphite layer. Extensive manufacturing, testing and qualification of these particles has taken place, and they are well understood. Extremely high burn ups have been achieved[1-5] (in excess of 1000,000 MWD/ton or 50%) for these particles ROT values in excess of 1700K require new fuel particles to be designed, developed and a manufacturing technique to be perfected. A potential candidate design would consist of a modification of the traditional TRISO particle.

III. ANALYSIS AND RESULTS

In this section, four reactor designs will be discussed and the preliminary analyses presented. These designs are not optimized at this stage. However, they do form the basis for starting the optimization process.

TABLE 2 - REACTOR PARAMETERS AND RESULTS

REACTOR	1	2	3	4
Bed Volume (1)	131.0	50.0	35.0	10.0
Power Level (MWt)	21.0	4.3	3.0	.84
Life (yrs.)	7.0	7.0	7.0	7.0
U-235 Loading (kg)	136.0	72.0	50.0	14.0
Pitch	12.4	11.68	11.06	6.72
Number of Elements	61.0	37.0	37.0	37.0
Radial Reflector Thickness (cm)	5.0	5.0	5.0	5.0
Moderator	Be/ZrHx	Be_2C	Be_2C	ZrH_x
Reactor Height (cm)	111.0	89.0	85.0	55.0
Reactor Diameter (cm)	113.0	90.0	86.0	57.0
Estimated Reactor Mass (kg)	3000.0	1000.0	825.0	350.0

From this table, the large difference in size and mass between the beryllium carbide and zirconium hydride moderated reactors is evident. However, due to the high inlet temperature possible with a ceramic moderated reactor, the power conversion system and radiator should be appropriately reduced in size.

Furthermore, it can be seen that if a cycle efficiency of 20% is assumed for a CBC power conversion unit connected to these reactors, values of α for the reactor only are in the range $.72 < \alpha < 2.1$. This range for α corresponds to range in electrical output ranging from 4.2 MWe to 168 KWe. Clearly in the range of interest for the NEP application values of $\alpha = .75$ and lower can be expected with this concept. Finally, it should be pointed out that if the NEP mission is for 10,000 hrs (approximately 1.15 yrs) at 5 MWe, reactor number 1 should easily meet this requirement with extremely low burn up (since it is designed for 7 yrs). This would imply an $\alpha = .6$. Further optimization of this design could improve on this value.

All these reactors were analyzed using the Monte Carlo code MCNP and have a multiplication factor (k_e), which is sufficiently large to operate for 7 years.

Figures 2 and 3 show detailed sections of reactor number 1. The 62 fuel elements arranged in a hexagonal pattern are clearly visible in the horizontal section. In this fuel element detail the hot frit, fuel

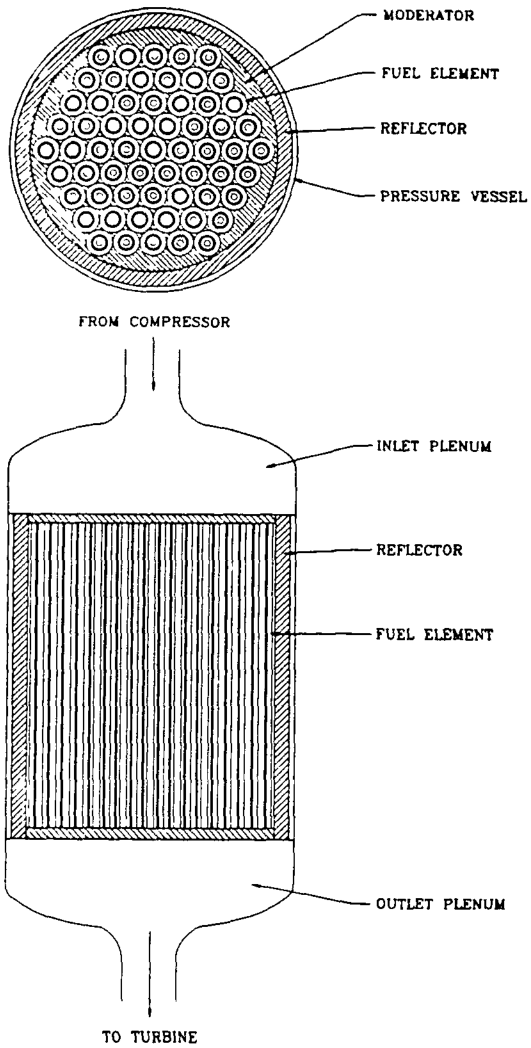

Figure 2 Reactor Cross Section (61 Element Core).

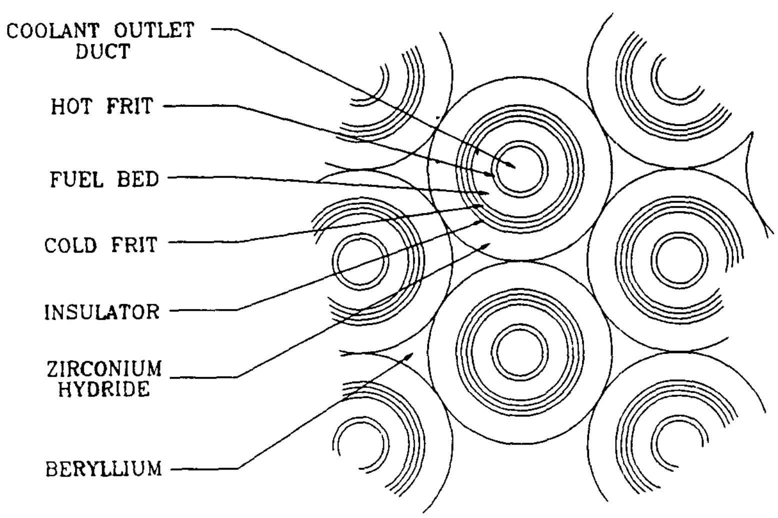

Figure 3 Detail of Fuel Element Arrangement.

bed, cold frit, fuel element plenum, and double moderator ($Be_2C/ZrHx$) is clearly illustrated. In an optimization process the arrangement (element pitch, pitch/diameter) and size of these components would be varied to minimize mass.

IV. TECHNOLOGY ISSUES

The following technology issues need to be addressed, and in most cases a development program will be necessary to bring the component part to a sufficient level of maturity.

1. Moderator. ZrH_x no issues currently used in reactors. Reactor inlet temperature limited to 600 K. Be_2C, manufacturing technique needs to be developed. No practical temperature limit.

2. Cold Frit. Zircaloy frit, mechanical properties at temperature need to be determined. Temperature limited to approximately 1500 K. Carbon/carbon, manufacturing, mechanical properties and elastic insert need to be developed. No temperature limit.

3. Fuel. TRISO, full qualified, commercially available. Temperature limited to 1700 K mixed mean outlet temperature. New particle needs to be qualified for long burn up for temperatures above 1700 K.

4. Hot Frit. Carbon/carbon only candidate material needs to be qualified in radiation environment. Mechanical properties needs to be developed.

5. Inlet Plenum Grid Plate Structure. $Be\text{-}Be_2C$ structure needs to be developed. Prototype structure needs to be tested at operating temperature. Temperatures limited to approximately 1000 K. $C/C\text{-}Be_2C$ structure needs to be developed. Prototype structure needs to be tested at operating temperatures. Temperature limited to approximately 2000 K.

6. Outlet Plenum Grid Plate Structure. Carbon/carbon structure needs to be developed, prototype structure needs to be tested at operating temperature. Temperature no practical limit.

7. Pressure Vessel. Needs to be mechanically and structurally strong at inlet temperatures and have low radiation heating. Development work on a suitable low Z material needs to be carried out. It must be able to operate at reactor inlet temperature and compressor outlet pressure.

8. Long-Term Fuel Integrated Element Test to Determine Material Compatibility and Mechanical Integrity. First tests using electrically heated element. Subsequent tests integrated into an appropriate test reactor.

9. Frit Clogging and Particle Erosion. An experimental program needs to be designed and carried out to ensure acceptable fuel stability and frit porosity. An initial experiment carried out at BNL using pyrolytic graphite-coated particles contained between commercially available steel frits in a Helium loop showed acceptable results. No clogging of either frit was observed in this experiment. If there is a concern regarding frit clogging a low pressure drop filter could be installed in line between the reactor inlet and the compressor outlet.

V. CONCLUSIONS

The following conclusions can be drawn from this preliminary study.

a. It is clear that an optimized PBR based design would result in a value of α (kg/KWe) of .6 or lower for the NEP mission profile.

b. The list of identified technology issues do not require a fundamental breakthrough to make the PBR a practical technology. All the issues are developmental in nature and a clearly defined path can be defined to their final resolution.

c. The issue regarding frit clogging has only been addressed partially, and a full scale experimental program is required to resolve it. However, to date no clogging has been observed. If a problem is uncovered in this area, low pressure drop, large area filters can be introduced in series ahead of the reactor.

d. The low mass and high temperature attributes of the PBR make it a competitive candidate for a NEP power source.

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