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USING LIGHT WATER STEAM AS A PROPELLANT

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NUCLEAR THERMAL PROPULSION ENGINE BASED ON PARTICLE BED REACTOR USING LIGHT WATER STEAM AS A PROPELLANT*

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Abstract

In this paper the possibility of configuring a water cooled Nuclear Thermal Propulsion (NTP) rocket, based on a Particle Bed Reactor (PBR) is investigated. This rocket will be used to operate on water obtained from near earth objects. The conclusions reached in this paper indicate that it is possible to configure a PBR based NTP rocket to operate on water and meet the mission requirements envisioned for it. No insurmountable technology issues have been identified.

INTRODUCTION

In a companion paper (Zuppero et al. 1993) the possibility of using water embedded in near earth objects (NEOs), has been explored. This water could be used in a variety of applications, such as, shielding, fuel for chemical rockets, or as propellant for a nuclear thermal propulsion (NTP) rocket. In addition, the solid material from NEOs can conceivably be processed into structural materials for building space habitats. It is the application to an NTP that will be explored in this paper. Although the specific impulse of water used in an NTP is lower than that due to the combustion of H_2 and O_2 (fuel rich) in a chemical system, it has the advantage that, besides filtration, no processing of the water is required. The elimination of a space based fuel factory to manufacture LH_2 and LO_2 makes an NTP based system more reliable and a lot more versatile.

In the following sections, the reactor concept will be described and mass and size estimates outlined. A section outlining the technical development issues will follow, which will be followed by a conclusion section.

REACTOR CONCEPT

The reactor concept to be used in this NTP application is the Particle Bed Reactor (PBR). This concept is illustrated in Figure 1. It is based on the direct cooling of particulate fuel. The fuel particles, shown on the left of Figure 1, is composed of a kernel of UC_2 and coated with the appropriate layers of pyrolytic graphite and an outside coat of SiC. These fuel particles are contained in the annular space formed by two porous tubes called frits (middle diagram). Coolant flow is radially across the bed from one frit to the other. The outer (larger) frit is known as the cold frit since it is exposed to the incoming coolant, and the inner (smaller) frit is known as the hot frit since it is exposed to high temperature exhausting coolant. The cold frit can be manufactured using a variety of materials, such as, stainless steel, aluminum or, Zircalloy. However, the hot frit can only be manufactured from a small selection of materials which are characterized by their resistance to steam erosion at the propellant exhaust temperatures: materials such as Si coated C/C and Inconel. This combination of fuel particles, frits, and the appropriate end fittings form a fuel element. These elements are arranged in a hexagonal pattern inside a pressure vessel and surrounded by a moderator (high-pressure water). The completed reactor assembly has top and bottom grid plates and inlet and outlet plena. A nozzle is attached to the outlet plenum.

In this study NTP reactors ranging in power from 6 MW to 500-MW will be considered. These cover the range of applications for the neofuel extraction missions as visualized by Zuppero and Redd (1993). In all cases it will be assumed that the water is above the super-critical pressure to avoid possible phase changes in the reactor and the implied mechanical load and reactivity feedback.

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The outlet temperature for the survey calculation presented here is assumed to be 1200° C in all cases. Finally, in the case of the 500 MW reactor two possible fuel bed power densities were assumed. The results of this analysis are summarized in Table 1.

TABLE 1. Reactor Parameters for Several Water NTP

Case	1	2	3	4
Power (MW)	500	500	25	6
Power Density (MW/ℓ)	20	5	1.25	.3
Fuel Bed Volume (ℓ)	25	100	20	20
Outlet Frit Mach Number	.25	.25	.1	.05
Hot Frit IR (cm)	1.46	1.05	.52	.36
Fuel Bed IR (cm)	1.76	1.35	.82	.66
Fuel Bed OR (cm)	3.37	3.62	2.90	2.87
Cold Frit OR (cm)	3.67	3.92	3.2	3.17
Fuel Element Length (cm)	50	76.0	43.5	43.1
Reactor Core OD/Height (cm)	50	76.0	43.5	43.1
Number of Elements	19	37	19	19
Nozzle Throat Diameter (cm)	6.35	6.35	1.42	.70
Element Pitch (cm)	10.11	10.86	8.7	8.6
Core Mass* (kg)	342	1080	260	260
Pressure Vessel (kg)	163	550	105	102
Nozzle (kg)	67	67	-	-
TPA+ (kg)	140	140	70	70
Total Mass (kg)	712	1837	435	432
Flow Rate (kg/s)	97.9	97.9	4.90	1.18
Thrust++ (N)	2.26(5)	2.26(5)	1.13(4)	2.71(3)
T/W	32	12	2.7	.6

*Includes Frits, Fuel, Moderator, Grid Plates.

+Space Shuttle Main Engine TPA mass assumed for 500 MW Unit.

Half of this mass is for 25 MW and 6 MW units.

++Based on assumed $I_{sp} = 235$ seconds.

A maximum bed power density of 3 MW/ℓ has been measured (2) for water cooled particle beds. This measurement was carried out at ambient pressure and fluid boiling limited the experiment. It is expected that at pressures in excess of the critical pressure (implying no phase change) the maximum assumed power density of 20 MW/ℓ should be achievable. A reduction in power density to 5 MW/ℓ implies a larger core and heavier components (compare Case 1 and 2). The TPA mass was assumed to be similar to that of the shuttle main engine since this pump is expected to raise the pressure of the hydrogen and oxygen to similarly high values. Accurate values for a steam driven TPA do not exist at this time. Furthermore, it should be pointed out that the

nozzles for Cases 3 and 4 are of negligible mass. This is particularly true for Case 4 since the nozzle has a throat diameter of only 0.7 cm and an overall length of 12.2 cm. Finally, the smaller reactor masses do not vary much, regardless of power level since a minimum critical fuel volume of approximately 20 l is required. Optimization studies could be carried out to minimize this mass if necessary.

TECHNOLOGY ISSUES

The following technology issues will need to be resolved before an NTP of the kind described above can be built and tested. In all cases the required technology can be obtained by developing currently available technical information.

Cold Frit

The cold frit will be manufactured of Zircalloy, which is a commonly used material in commercial light water reactors.

Fuel

The fuel can be based on the TRISO particle concept used in commercial high temperature gas cooled reactors.

Hot Frit

In the case of outlet temperatures in excess of 1000° C a silicon carbide coated carbon/carbon structure will need to be developed. This is not expected to be an insurmountable task. At lower temperatures a frit manufactured of Inconel can be used. This option will imply no particular development effort. In all cases material compatibility tests need to be carried out to determine the interaction of the fuel and frit in the presence of the hot coolant.

Grid Plate Structures

The internal structures need to be manufactured of materials which survive the mechanical loads and the oxidizing atmosphere. In addition the radiation induced heating should be minimized by choosing materials with low values of "Z".

Pressure Vessel

The pressure vessel will be constructed of aluminum alloy to minimize weight and radiation-induced heating. No technology issues are envisioned for the pressure vessel.

CONCLUSIONS

The following conclusions can be drawn from the preliminary study:

1. It is possible to develop an NTP using water as a propellant to meet the mission requirements stipulated by Zuppero and Redd (1993) to transport neofuel from NEOs to Earth's orbit.
2. 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 outlined to their final solution.
3. The low mass makes the PBR a competitive candidate for this NTP application.

SCHEMATIC REPRESENTATION OF A PARTICLE BED REACTOR BASED ROCKET CONCEPT .

FIGURE 1. Schematic Representation of a Particle Bed Reactor Based Rocket Concept.

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- Katscher, W. (1977) "Coated Particle Fuel Element For Pressurized Water Reactors," *Nuclear Technology*, 35, (2): 557-580.
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