2) For the trip times included in this analysis the total radiation dose to the crew is proportional to the energy required for the mission. Therefore, within the ranges used in this analysis one can estimate the crew radiation dose by knowing the energy needed for the mission.

3) For the crew-nozzle separation of 100 m, approximately 50% of the plume radiation is received from the first 0.1 km into the plume. This percentage is increased to 90% for 1 km and 100% for 100 km into the plume.

4) For an 80 day round trip to Mars, with crew-nozzle separation distance of 100 m, the radiation dose varied from about 0.5 rem to 1670 rem for fission fragment retention times of 10,000 and 10 sec, respectively.

5) For all cases, increasing the crew distance from 100 to 200m from the nozzle exit reduced the unshielded radiation dose by half.

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A Mini-Cavity Reactor for Low-Thrust High-Specific Impulse Propulsion

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The mini-cavity reactor is a concept which combines a driver region fueled with NERVA type fuel elements and a central gas core region to obtain high specific impulse (1000–2000 sec) for thrust levels in the 100–900 N range, which is applicable to probe type missions. The dimensions of the reactor, chosen as an example, are: an over-all diameter of 1.21 m including an external spherical pressure shell, and a central gas core cavity diameter of 0.61 m. The combined power level of the driver region and the cavity range from 8.5 Mw to approximately 70 Mw for various thrust levels and chamber pressures. Powerplant weights, including a radiator for disposing of low grade power in the driver, are between 4600 and 33 000 kg. These weights are within the payload capabilities of the space shuttle. It is apparent that this reactor could also be used as a possible test reactor for the gas-core reactor and for testing and coupling with MHD devices.

Nomenclature

A_R = Rosseland mean absorption coefficient, m^{-1}
$D_c D_F$ = cavity and fuel diameter, m
E = exponential integrals
F = thrust, N
H = enthalpy, J/kg
I_{sp} = specific impulse, sec
K = thermal conductivity, $W/m - K$
M_F = mass of fuel, kg
P = cavity pressure, atm
q = heat flux, W/m^2
R = radius of reactor, m
r = radial distance in cavity, cm
S = allowable stress, N/m^2
T = temperature, K
t = thickness of pressure vessel, cm
V_F = volume fraction of fuel, uranium to cavity
v = velocity, m/sec
ρ = density, gm/cc
σ = Stefan-Boltzmann constant, $W/m^2 - K^4$
τ = optical depth

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Index category: Nuclear Propulsion, Unmanned Lunar, and Interplanetary Systems.

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Introduction

LATELY, there has been a re-emphasis on unmanned space missions. Advanced propulsion concepts are the result of an attempt to obtain high-specific impulse (pound of thrust per pound of propellant flow per second) with high thrust-to-powerplant weight. These characteristics have the effect of reducing trip times and/or increasing payload capabilities. It is quite possible that reduction of trip times will become an important requirement of future deep space missions. If so, there will be a need for high impulse without overly sacrificing thrust-to-weight ratios.

Chemical rockets are limited to I_{sp} in the 400 sec range, and solid fueled nuclear rockets are limited by materials considerations to approximately 900 sec. Both electric[1,2] and gas core rockets[3] are capable of providing impulses of the order of thousands of seconds. However, electric thrusters suffer from low thrust-to-weight ratios, while the gas core suffers from large size and weight.

The purpose of this paper is to present a concept which combines the specific impulse from the gas core with the compactness and low weight of a NERVA type reactor. This concept, presently referred to as the mini-cavity, has a central cavity region used for propulsion power, surrounded by a moderator region which thermalizes neutrons from a driver region located outside of the moderator region but inside of a pressure vessel. The driver region can use fuel elements developed in the NERVA program and can be operated with an inert gas such as argon[4] in place of hydrogen for cooling. This combination has the potential of yielding a compact, easily controlled reactor, capable of several thousand seconds of I_{sp}. In addition, the concept may provide a method for developing the gas core reactor (both open and closed cycle) and also be capable of providing high outlet gas temperatures where MHD becomes very efficient.

Analysis

The analysis for this reactor concept is divided into three areas: nuclear, propulsion, and weight. A more detailed nuclear analysis is reported in Ref. 5. The propulsion and weight analysis are discussed in this report. The weight analysis includes weights of the reactor, pressure shell, pumps, and radiator.

Nuclear Analysis

The mini-cavity concept is a combination of two reactor types, a gas core surrounded by a solid fueled reactor. To keep this combination small and lightweight, a diameter less than 200 cm was set as the goal. Experimental results,[6,7] indicate cavity diameters of 0.25 to 0.45 m can produce relatively large, stable flow patterns for the low-velocity, high-density central gas regions. Based on optimization studies,[5] and to keep within the goal of 2.0 m diam, a cavity diameter of 0.61 m was selected for analysis. The remaining reactor regions for reflector and driver (fuel) elements were variable in thickness but an over-all diam of 1.22 m as shown in Fig. 1 was maintained.

The uranium fuel region in the cavity was held to a diameter of 0.42 m ($D_F/D_C = 0.7$). The uranium density was varied to obtain the effect on reactivity and obtain values over the range of chamber pressures (200 to 1000 atm). The reflector region (beryllium oxide) located between the cavity and the

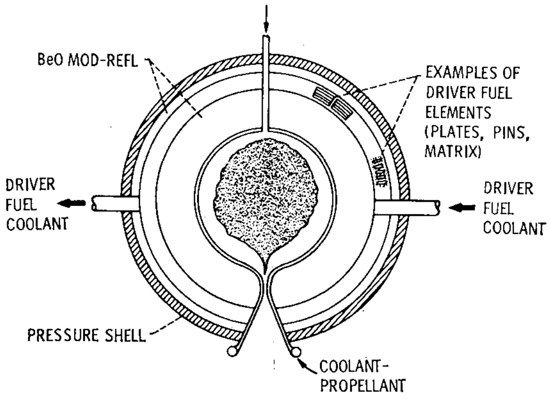

Fig. 1 Mini-cavity reactor concept for unmanned propulsion (reactor diameter 1.22 m; cavity diameter 0.61 m).

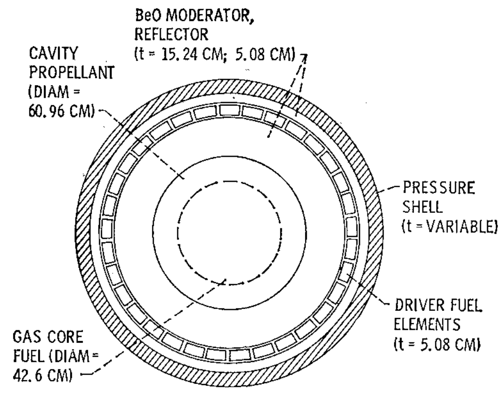

Fig. 2 Spherical calculation model of mini-cavity reactor.

driver fuel zone as shown in Fig. 2 was varied as reported in Ref. 5. An optimum thickness of 15 cm, based on maximum power fraction in the cavity was obtained.

The driver region was either considered as one integral section or was split into two equal thickness bands with moderator (BeO) between. Various fuel distributions were considered in the latter case, as well as their distance from the cavity. The results of these variations as reported in Ref. 5 indicate that a single fuel zone, with uniform fuel, produced the highest ratio of power in the cavity to power in the driver region.

The outermost region of the mini-cavity considered in the nuclear calculations was the pressure vessel. Because the driver region is located near the outer periphery of the reactor there is considerable fast neutron leakage. By adding a thick fast reflector such as the pressure vessel, the reactivity is enhanced by the reflection of the fast neutrons back into the reactor thus allowing a reduction of fuel density in the driver region.

The nuclear analysis performed on the calculational model shown in Fig. 2, was handled by transport theory using TDSN.[8] The analysis used 19 energy groups, with 7 in the thermal range, and allowed for upscattering into 7 higher energy levels and downscattering into 8 lower levels. An S_4 angular approximation was used with a one-dimensional spherical analysis.

All modifications to the geometry or materials were done for the purpose of increasing the power in the cavity relative to the power in the driver region. As reported in Ref. 5, the use of uranium isotope 233 greatly increased this power ratio. This increase in power was due to the decrease in uranium density in the driver region for a given amount of fuel in the cavity. The decrease in fuel density also allows the flux in the moderator to increase which adds to the relative power in the cavity fuel. The results presented in this report are predominately based on the use of ^{233}U as the fuel in both driver and cavity. A comparison with ^{235}U isotope is presented as part of the discussion.

Propulsion Analysis

The propulsion capability of the mini-cavity reactor is obtained by passing hydrogen through the cavity walls (predominantly tangent to wall), around a central fuel region where the hydrogen (seeded) picks up heat via radiation absorption, and out through a nozzle for expansion and thrust.

In the cavity, attainment of fuel temperatures sufficiently high to cause vaporization of solid uranium particles depends on back radiation from the surrounding seeded hydrogen. By assigning a limiting cavity wall temperature (1523° K), a hydrogen propellant mass flow rate along with a seed mass reaction, the specific impulse and thrust level can be obtained for various pressure levels. The thrust and impulse are the maximum combination obtainable without exceeding the limitation set by the wall temperature and hydrogen flow rate. The heat-transfer analysis is discussed in detail in Ref. 9.

The equation used in Ref. 10 to obtain the specific impulse from the hydrogen chamber enthalpy is

$$I_{sp} = (1.497 \times 10^{-2} H)^{1/2}$$

This equation assumed an 85% energy efficiency in the exhaust nozzle expansion. From the enthalpy, the power required for heating the propellant can be obtained. Assuming this to be equivalent to the power produced in the fuel, the power of the cavity region is obtained. Since the neutronics calculation relates the power in the cavity to the power in the driver region, the total power of the reactor can be obtained.

After the thrust and specific impulse are known for a given cavity pressure, these values can be used in the following equation[10] to obtain the amount of uranium fuel that would be contained in the cavity.

$$M_F = 10.7\ D_c^{3.28} P^{0.723} V_F^{1.092} / F^{0.277} I_{sp}^{0.277} \tag{1}$$

This amount of fuel is then used in a nuclear calculation to obtain the additional fuel necessary in the driver region for an overall critical configuration.

The remaining necessary information is the edge temperature of the fuel to determine whether or not the uranium will vaporize. The information is again obtained from the heat-transfer code used in Ref. 9 and is dependent on the back radiation from the propellant. The equations used to obtain the edge temperatures involved the energy equation

$$\rho v\ \partial H/\partial r + (1/r^2)\ \partial(r^2 q)/\partial r = 0 \tag{2}$$

where q is the heat flux for the seeded propellant and is obtained from the following equation involving the temperature distribution from the wall to the edge of the fuel

$$q = -2\sigma E_3(\tau)(T_W^4 - T_{\text{EDGE}}^4) - \left\{K + \frac{8\sigma T_{\text{EDGE}}}{A_R}\left[\frac{2}{3} - \tau E_3(\tau) + E_4(\tau)\right]\right\}\frac{dt}{dr} \tag{3}$$

where the optical depth (τ) is defined as

$$\tau = \int_{r1}^{r2} A_R dr \tag{4}$$

In this solution (referred to as the diffusion approximation), the results are more accurate with increasing optical depth. If the gas is optically thin, then the uranium "sees" the wall and the radiative heat transfer reverts to T^4 type solution. For spherical shapes, the diffusion approximation results in excellent agreement when optical thicknesses are seven or more times the mean optical path.[11] The optical depth for cases discussed in this report are much larger (i.e., many mean optical paths).

In order to determine if the uranium at the outer edge of the fuel in the cavity is at a temperature high enough to be vaporized, the following vapor pressure equation (obtainable from the results of Ref. 12) was applied, where the chamber pressure P is in atmospheres

$$\log(P) = 5.998 - 25\,742/T \tag{5}$$

If the temperature T is less than the edge temperature, not all of the fuel in that region is vaporized. The analysis to obtain the specific impulse considers both particle and gas species so the results are not changed if the uranium is not a gas.

Weight Analysis of Reactor, Pressure Shell and Radiator

The weight of the reactor is the sum of the weights of the moderator (BeO) and of the driver fuel elements. The main portion of the weight of the fuel elements is that of the graphite. The fuel elements, which occupy 75% of the volume of the driver region, can be in the form of plates or pins or inverted matrix (i.e., holes in matrix). Since the fuel loadings run around 0.2 gms/cc of graphite compared to 1.6 gms/cc for graphite, the weight of the fuel element is considered to be that of the graphite. With the reactor size fixed for the analysis, the only significant variable is the fuel loading in the driver region and the fuel in the cavity. These weights are less than 50 kg so the reactor weight for all practical purposes is a constant 2180 kg (4800 lb).

The pressure shell which also acts as a fast neutron reflector is considered a separate item in the weight analysis. The minimum thickness is a function of the pressure level required for the cavity. However, since the pressure shell can act neutronically as a fast neutron reflector, it has an effect on the relative power (i.e., the greater the thickness, the lower the power needed in the driver region).

For this series of calculations, an annealed titanium alloy (Ti, 6AL, 4V) was used because of its greater strength to weight ratio, high strength at high pressures, and established fabricability. An optimization study might provide a better or lower system weight but would involve more detailed nuclear and weight analyses. The thickness was obtained from

$$t = PR/2S \tag{6}$$

where the value used for S, the allowable stress at 20° C, was 4.13×10^8 N/m^2 (60 000 psi) for the titanium alloy. The density used for the material was 4.48 g/cc (280 lb/ft^3).

Since the power levels and coolant rates are low, the pump weights are relatively small. Equations such as those found in Ref. 13 result in very low weights, less than 9 kg (20 lb) for low-flow rates. Even a factor of 10, or a pump weight of 91 kg (200 lb), is an insignificant weight for this analysis.

In this concept the energy deposited in the driver region is rejected via a radiator using an inert gas rather than diluting the propulsion high-temperature gas from the cavity. Results reported in Ref. 14 on fin-tube radiators were used to establish the weight of the radiator per megawatt of power radiated, over the chamber pressure range used in this report. In that report meteoroid damage was not taken into consideration. The temperature for the radiator was taken as 1000° C. The radiator consisted of beryllium fins and TZM (molybdenum alloy) tubes with the fins between tubes on a center-to-center basis. The resulting weight per megawatt of radiated power W_R selected as a function of chamber pressure can be represented as

$$W_R = 125 + 0.475\ P \tag{7}$$

The weight of the radiator includes the headers, tube block, and fin chamber. The total weight of the powerplant consists of the reactor weight, the pressure shell weight, the pump weight, and the radiator weight.

Results and Discussions

The results presented will cover the power split between cavity and driver, specific impulse obtainable, fuel temperature in the cavity, powerplant weights, and possible applications or potential uses of the mini-cavity reactor.

Reactor Power Splits

The amount of power produced in the cavity relative to the driver region is very important in that total powerplant weight varies indirectly with cavity power fraction for a given pressure and thrust level. The power produced in the cavity for this system is dependent on the thermal neutron flux in the moderator region between the driver and the cavity. The ratio of power produced in the cavity to that of the driver is a function of both the amount of fuel in the cavity and the amount in the driver. For a given amount of fuel in the cavity, the lowest fuel loading possible (criticality) in the driver will result in the highest power split of the cavity to the driver. As a result of the work of Ref. 5, the use of ^{233}U in the driver produced the highest power fractions for the

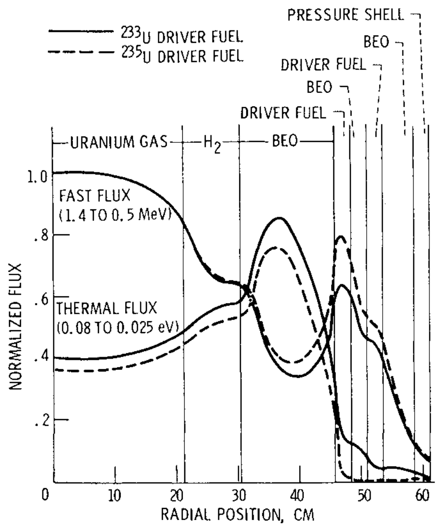

Fig. 3 Neutron flux for mini-cavity reactor.

cavity. In addition to the perturbation of the thermal neutron flux by the fuel in the driver region, the level of thermal neutrons being returned to the cavity is a function of the moderator material and thickness. For BeO moderator the optimized thickness was approximately 15 cm.

A typical plot of neutron flux (normalized) is presented in Fig. 3. The plot is for energy groups covering the high-energy neutrons (1.4 to 0.5 Mev) and the thermal energy neutrons (0.08 to 0.025 ev). This plot compares flux levels obtained with both ^{233}U and ^{235}U in the driver fuel. The mass of uranium gas in the cavity can be increased [see Eq. (1)] by the chamber pressure. This change in uranium mass in the cavity is plotted in Fig. 4a as a function of chamber pressure for various thrust levels. Associated with the chamber pressure and thrust level is the maximum I_{sp}. The amount of allowable fuel increases with pressure for any given thrust but also increases as the thrust level decreases (i.e., lower temperatures in the gas). This increase of fuel in the cavity increases the power in the cavity relative to that produced in the driver region. This effect is presented in Fig. 4b for various pressure shell thicknesses. The curves indicate that by using uranium isotope 233, cavity power fractions of 0.20 or more can be obtained. The curves also show that

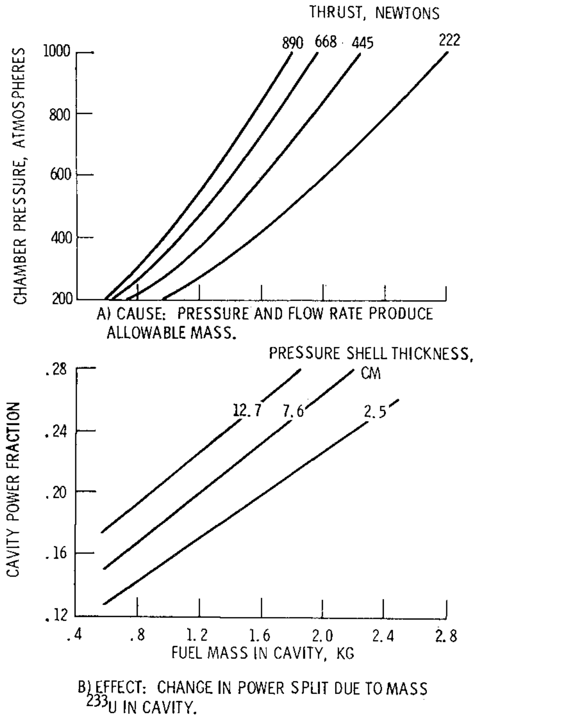

Fig. 4 Fuel mass in cavity—cause and effect: a) Cause: Pressure and flow rate produce allowable mass, b) Effect: Change in power split due to mass (^{233}U) in cavity.

thicker pressure shells increase the power fraction. This is due to the higher energy neutrons that are returned to the reactor that normally would have escaped.

It should be noted here that as reported in Ref. 5, any increases in absorption in the reflector-moderator or driver fuels will reduce these power fractions. These reductions in power fraction will cause increases in powerplant weight.

The power splits (cavity and driver) are presented in Table 1 for a range of thrust and pressure levels. Also presented in the table is the fuel mass required in the driver region for criticality. For thrust levels up to 890 N (200 lb) the power in the cavity was generally less than 10 Mw and the driver power less than 50 Mw. This indicates fairly low total power levels will be required for propulsion. At the bottom of the

Table 1 Reactor power splits and fuel loading for mini-cavity

Thrust, N (lbf)	Pressure, atmosphere	Propellant flow rate kg/sec	Fuel (cavity) mass, (kg)	Cavity power, fraction	Cavity power, MW	Driver power, MW	Fuel (driver) mass, kg	Fuel (cavity) edge temperature °C	Fuel vaporization temperature, °C at chamber pressure
222	200	0.020	0.97	0.156	1.67	9.0	23	5 000	6690
(50)	500	0.016	1.79	0.214	1.97	7.2	18	6 400	7525
	1000	0.014	2.80	0.287	2.42	6.0	13	8 050	8325
445	200	0.035	0.76	0.140	3.95	24.2	24	6 100	6690
(100)	500	0.028	1.42	0.188	4.55	19.7	20	7 800	7525
	1000	0.025	2.24	0.246	5.46	16.7	15	9 150	8325
668	200	0.047	0.66	0.133	6.64	43.4	25	6 400	6690
(150)	500	0.039	1.23	0.175	7.64	36.0	21	8 300	7525
	1000	0.035	1.96	0.226	8.91	30.5	17	10 500	8325
890	200	0.060	0.60	0.130	9.28	62.1	26	6 700	6690
(200)	500	0.049	1.11	0.166	10.90	54.7	22	9 150	7525
	1000	0.044	1.79	0.214	12.50	45.9	18	11 675	8325
445	200	0.045	0.76[a]	0.090	3.95	40.0	145[a]	6 100	6690
(100)	500	0.038	1.42[a]	0.120	4.55	33.4	138[a]	7 800	7525
	1000	0.025	2.24[a]	0.175	5.46	25.7	130[a]	9 150	8325

[a] Fuel was ^{235}U

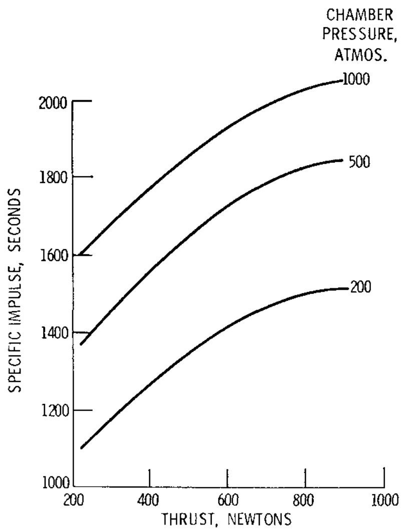

Fig. 5 Cavity specific impulse.

table a comparison case using ^{235}U as the fuel is presented. For the same amount of fuel in the cavity, an approximate 60% increase in power over that for ^{233}U in the driver region is required. In addition the amount of fuel for criticality increases from near 20 kg to 140 kg. This shows that the use of ^{233}U in both cavity and driver is highly effective in reducing the fuel loading in the driver and thereby increasing the relative power in the cavity.

A calculation was performed[5] in which only the cavity contained ^{233}U (1 kg). For this case the reactor was critical with 103 kg of ^{235}U in the driver region and the power split was 0.135.

Specific Impulse

As indicated in the section on analysis, the specific impulse is proportional to the square root of the enthalpy of the seeded hydrogen (seeded with ^{238}U). The enthalpy deposited in the gas (propellant) is a function of the pressure and temperature. In the calculations, the specific impulse for a given pressure could be increased slightly by the addition of ^{238}U seed (more than required for radiation absorption). This increase is due to a higher temperature caused by back radiation from the seeded hydrogen. A value of mass fraction of 0.25 was used to obtain the specific impulses presented in Fig. 5. For this concept as presented, a specific impulse of 2000 sec is obtainable at a pressure of 1000 atm for a thrust level of 730 N (164 lb). All of the cases presented produce specific impulses greater than 1000 sec.

In the heat-transfer calculations performed as per Ref. 9, a fuel temperature profile is obtained. The fuel edge temperatures (the lowest temperature of the fuel for the results in Fig. 5) are presented in Table 1. As discussed earlier, these high temperatures are obtainable because the propellant gas is optically thick and there is back radiation to the fuel (uranium). Conditions do exist in which a uranium particle would not evaporate. Without a complete analysis, it appears that all of the cases studied would produce a gaseous state, with the possible exception of the 222 N (50 lbf) thrust levels and some of the 200 atm pressure conditions.

Powerplant Weight and Characteristics

Because of the low thrust ranging from 220 to 890 N and the high specific impulse obtained, the propellant flow rates are very low and therefore the fuel loss rates will be low. For example a probe mission to Jupiter using simplified assumptions would result in the following losses. Selecting a thrust level of 445 N and an I_{sp} of 1600 sec a propellant mass flow rate of 0.03 kg/sec is obtained. An acceleration of 0.02 m/sec² is obtained assuming a gross weight of 25 000 kg. If a velocity of 10 km/sec is required for the mission, a firing time of approximately 5×10^5 sec is needed. The total propellant used would be 15 000 kg and the uranium loss would be 150 kg for a mass flow rate ratio of 100 to 1. The loss of uranium is therefore a relatively small amount.

The powerplant weight consists of weights for the reactor, the pressure shell, the pumps, and the radiator. The reactor which is 1.22 m in diameter weighs approximately 2180 kg. The weight of the pump is estimated at 91 kg. Only the pressure shell and the radiator weights vary with pressure and power. The allowable fuel in the cavity increases with increased pressure. With this increase in cavity fuel, the power split increases for the cavity, requiring less power in the driver region. With less power to radiate away the size of the radiator is decreased with increased pressure. However, the weight of radiator per Mw of power increases with pressure, Eq. (7), and the result is an increase in radiator weight. This increase coupled with an increase in pressure shell weight results in an over-all gain in powerplant weight as shown in Table 2.

Table 2 Powerplant characteristics and weight

Thrust, N (lbf)	Pressure atmosphere	Specific impulse sec	Propellant flow rate, kg/sec	Driver power, Mw	Reactor weight lb	Pressure shell weight lb	Radiator weight, lb	Total power-plant weight	
								lb	kg
222 (50)	200	1100	0.020	9.0	4800	800	4 350	10 150	5 614
	500	1375	0.016	7.2	4800	1860	5 780	12 640	5 750
	1000	1600	0.014	6.0	4800	4000	7 880	16 880	7 670
445 (100)	200	1300	0.035	24.2	4800	800	11 700	17 500	7 950
	500	1600	0.028	19.7	4800	1860	15 820	22 680	10 300
	1000	1800	0.125	16.7	4800	4000	22 200	31 200	14 200
668 (150)	200	1460	0.047	43.4	4800	800	21 000	26 800	12 190
	500	1770	0.039	36.0	4800	1860	28 900	35 760	16 250
	1000	1960	0.035	30.5	4800	4000	40 590	49 590	22 520
890 (200)	200	1530	0.060	62.1	4800	800	30 060	35 860	16 300
	500	1850	0.049	54.7	4800	1860	43 900	50 760	23 060
	1000	2060	0.044	45.9	4800	4000	61 100	70 100	31 860
445 (100)	200	1300	0.045	40.0	5100[a]	800	19 350	25 450	11 570
	500	1600	0.038	33.4	5100[a]	1860	26 820	33 980	15 450
	1000	1800	0.025	25.7	5100[a]	4000	34 200	43 500	19 770

[a] Fuel was ^{235}U.

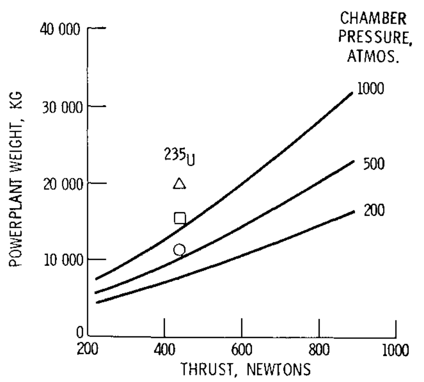

Fig. 6 Mini-cavity powerplant weights—^{233}U fuel.

For powerplant weights in the range shown in Table 2 and for low-thrust levels but high-specific impulses the specific powerplant mass commonly referred to as "α" in kg/kw of kinetic power in exhaust gas is about an order of magnitude (2 to 4 kg/kw) less than other systems proposed for low-thrust missions.

The powerplant weights are plotted in Fig. 6 as a function of thrust for three pressure levels. These plots are for reactors with ^{233}U as the fuel both in the cavity and driver regions. For 445 N (100 lb) of thrust, a comparison with ^{235}U is presented. Although there was a large difference in the fuel required in the driver the engine weight penalty is only 40 to 50%.

The powerplant weights obtained here (4500 to 32 000 kg) are less or comparable to the payloads considered in the shuttle program, so that a complete interplanetary rocket could be a payload for a shuttle rocket.

Potential Uses of Mini-Cavity Reactor

In reviewing the sizes, weight, temperatures, and power levels, it becomes apparent that a small sized cavity could have applications other than as a propulsion device. Because of the small size and low-power levels, a mini-core reactor could be used as a land-based test reactor for the gas core reactor concept. A larger system using a central test region for testing gas cores was suggested in Ref. 15. Wall materials, injectors (propellant and fuel), control devices, nozzles, seeding and various measuring devices could be studied under operating conditions.

The use of a gas core reactor with MHD has been suggested in Refs. 16 to 18. With a mini-cavity reactor, small MHD devices could be tested that could find direct application. Exhaust temperatures in the 4000° to 5000° C (7650° to 9500° R) range could be useful in the development of efficient MHD devices.

Conclusions

A spherical reactor containing a central gaseous fueled cavity (0.6 m diam), surrounded by a BeO moderator (15 cm), followed by a driver region supplying the majority of the neutrons through the BeO moderator was analyzed to determine its potential for providing rocket propulsion at a low-thrust level (<900 N) but high-specific impulse (>1000 sec). This concept, called the mini-cavity, results in specific impulses well above that of a NERVA type reactor, but less than that of a gas core reactor. The following results were obtained: 1) Cavity power levels less than 13 Mw coupled with driver power less than 60 Mw can produce thrust levels up to 890 N with specific impulse up to 2000 sec; 2) Powerplants, including a radiator for dumping the power produced in the driver reactor, weigh between 4600 and 32 000 kg for thrust levels between 220 and 890 N. These weights are less than payloads for the shuttle type rocket; 3) Because of the low-propellant flow rates, the loss of uranium would be extremely low; 4) In addition to having possibilities as a propulsion device, the mini-cavity could be used as a test reactor for the complete gas core, as a source for high-temperature gas for testing MHD devices, and for use in materials research; and 5) Using ^{233}U as the fuel in both the cavity and the driver regions resulted in a substantial increase in relative power produced in the cavity compared to the use of ^{235}U.

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