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A MINI-CAVITY PROBE REACTOR

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Abstract

The mini-cavity reactor is a rocket engine concept which combines the high specific impulse from a central gaseous fueled cavity (0.6 m diam) and NERVA type fuel elements in a driver region that is external to a moderator-reflector zone to produce a compact light weight reactor. The overall dimension including a pressure vessel that is located outside of the spherical reactor is approximately 1.21 m in diameter.

Specific impulses up to 2000 sec are obtainable for 220 to 890 N of thrust with pressures less than 1000 atm. Powerplant weights including a radiator for disposing of the power in the driver region are between 4600 and 32 000 kg - less than payloads of the shuttle.

This reactor could also be used as a test reactor for gas-core, MHD, breeding and materials research.

Introduction

Lately, there has been a re-emphasis on unmanned space missions both for the near future and the distant future (i.e. Grand Tour). 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-power-plant-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 to approximately 900 sec I_{sp} (limited by materials temperature). Both electric[1,2] and gas-core rockets[3] have or are capable of providing impulses in the order of thousands of seconds. 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 impulse from the gas-core with the compactness and low weight of a NERVA type reactor. This concept, presently nicknamed 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 under the NERVA program because an inert gas[4] can be used 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.

Symbols

A_R	Rosseland mean absorption coefficient, m^{-1}
D_C	cavity diameter, m
D_F	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, cm
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, $W/m^2\text{-}K^4$
τ	optical depth

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. 6. 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 light weight, a diameter less than 200 cm was set as the goal. Experimental results,[7,8] indicate cavity diameters of 25 to 45 cm can produce

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relatively large, stable flow patterns for the low velocity, heavier central gas regions. Based on optimization studies,[6] and to keep within the goal of 200 cm diameter, a cavity diameter of 60.96 cm (2 ft) was selected for the analysis. The remaining reactor regions composed of reflector and driver (fuel) elements were variable but an overall diameter of 121.92 cm (4 ft) as shown in Fig. 1 was maintained.

The uranium fuel region in the cavity was held to a radius of 21 cm ($D_FD_C = 0.7$). 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) between the cavity and the driver fuel zone as shown in Fig. 2 was varied as reported in Ref. 6. An optimum thickness of 15 cm, based on maximum power fraction in the cavity was obtained.

The driver region was varied in several ways. The region was either considered as one region or was split into two equal thickness regions with moderator (BeO) between. The fuel density for the split regions was either uniform or was varied between each region. And the location with respect to the cavity was varied. The results of these variations as reported in Ref. 6 indicate that a single fuel zone with uniform fuel produced the highest ratio of power in cavity to power in 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.[9] The analysis used 19 energy groups, with 7 in the thermal range, and allowed for upscattering into 7 energy levels above and downscattering into 8 levels below. An S_4 angular approximation was used with a one-dimensional spherical analysis.

All modifications to the geometry or materials was done on the basis of increasing the power in the cavity relative to the power in the driver region. As reported in Ref. 6, the use of uranium isotope 233 greatly increased this ratio of power. 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 also 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 fraction, the specific impulse and thrust level can be obtained for various pressure levels. The thrust and impulse are the maximum combination without exceeding the limitation set by the wall temperature and hydrogen flow rate. The heat-transfer analysis used is discussed in detail.[10]

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

$$I_{sp} = \sqrt{1.497\times10^{-2}\ H}$$

This equation assumed an 85 percent 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 Eq. (1),[11] to obtain the amount of uranium fuel that would be contained in the cavity. 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.

$$M_F = 10.7\ \frac{D_C^{3.28} P^{0.723} V_F^{1.092}}{F^{0.277} I_{sp}^{0.277}} \qquad (1)$$

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. 10 and is dependent on the back radiation from the propellant. The equations used to obtain the edge temperatures involved the energy equation

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

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.

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

Where E_3 and E_4 are exponential integrals, σ is the Stefan-Boltzmann constant, A_R the Rosseland mean absorption coefficient and (τ) is the optical depth and defined as

$$\tau = \int_{r_1}^{r_2} A_R dr \qquad (4)$$

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 according to Ref. 12 results in excellent agreement when optical thicknesses are seven or more times the mean optical path. 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 a gas, the following vapor pressure equation (obtainable from the results of Ref. 13) was applied, where P the chamber pressure is in atmospheres.

$$\log(P) = 5.998 - \frac{25\ 742}{T} \qquad (5)$$

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 element occupies 75 percent of the volume of the driver region. Fuel elements can be in the form of plates or pins or inverted matrix (i.e. holes in matrix). Since the fuel loadings run around 200 mg/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. Since the reactor size was 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 a more detailed nuclear and weight analyses. The thickness, t, for this study was obtained from the relationship of pressure, P, and stress S.

$$t = \frac{PR}{2S} \qquad (6)$$

The value used for S, the allowable stress at 20° C, for the titanium alloy was 4.13×10^8 N/m^2 (60 000 psi). 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. 14 result in very low weights, less than 9 kg (20 lb) for low flow rates. Even a factor of 10 times 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. Work reported in Ref. 15 on fin-tube radiators was 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 meteroid 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 selected as a function of chamber pressure is presented in Fig. 3. The weight of the radiator includes the header, 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 and the discussion 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 directly with cavity power fraction for a given pressure and thrust level. The power produced in the cavity for this system is highly dependent on the thermal 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 total fuel loading possible (criticality) will result in the highest power split of the cavity to driver. As a result of the work of Ref. 6 the use of ^{233}U in the driver produced the highest power fractions for the cavity. In addition to the fuel in the driver, the thermal neutrons being returned to the cavity are a function of the moderator and its thickness. This was optimized at approximately 15 cm for the BeO.

A typical plot of neutron flux (normalized) is presented in Fig. 4. 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. 5(a) 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. 5(b). The curves indicate that by using uranium isotope 233 cavity, power fractions of 0.20 or better can be obtained.

It should be noted here that as reported in Ref. 6, 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. Values of only 0.06 were obtained in Ref. 5 where a pressure vessel was used between the cavity and moderator and ^{235}U with Zircaloy 4 as the clad and structural material.

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 this range of 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 a comparison case using ^{235}U as the fuel is presented. For the same amount of fuel in the cavity, an approximate 60 percent increase in power over that for U^{233} in the driver region is required. In addition the amount of fuel for criticality goes up from near 20 kg to 140 kg. This shows that the use of ^{233}U in the cavity as well as the 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[6] 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 U^{238} seed (more than required for radiation absorption). This increase is due to back radiation from the seeded hydrogen. A value of mass fraction of 0.25 was used to obtain the specific impulses presented in Fig. 6. 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. 10, a fuel temperature profile is obtained. The fuel edge temperatures (the lowest temperature of the fuel for the results in Fig. 6) 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). There do exist some conditions 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 lb_f) thrust values and some of the 200 atm pressure conditions.

Powerplant Weight and Characteristics

For the range of thrust 220 to 890 N (50 to 200 lb_f) and the levels of specific impulse obtained, the propellant flow rates are very low. In most cases they are less than 0.0455 kg/sec. At predicted mass flow ratios of propellant-to-fuel in the range of 100,[7] the loss rate for uranium is less than 4.5×10^{-4} kg/sec. At this rate the reactor could operate for over 10^5 sec before losing 45.0 kg of uranium.

The powerplant weight consists of the weights for the reactor, pressure shell, pumps and radiator. The reactor which is 121 cm (4 ft) in diameter weighs approximately 2180 kg (4800 lb), and the pumps are estimated at 91 kg (200 lb). Only the pressure shell and the radiator weights vary with pressure and power. As the pressure increases the specific impulse increases, and the allowable fuel in the cavity increases. With this the power split increases for the cavity requiring less power in the driver. This higher pressure requires an increase in pressure shell weight. The reduction of power in the driver results in a smaller radiator at higher pressures, but because the pressure is increased the weight per megawatt of power increases. The result is an increase in radiator weight, and therefore an increase in powerplant weight, as shown in Table 2.

The powerplant weights are plotted in Fig. 7 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 using ^{235}U is presented. Although there was a larger difference in the fuel required in the driver the engine weight penalty is only around 40 to 50 percent.

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, weights, 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. Wall materials, injectors (propellant and fuel), control devices, nozzles, seeding and various measuring devices could be experimented on, 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 would be useful in the development of efficient MHD devices.

Other applications could include new materials research and fission fuel breeding both in a blanket surrounding the reactor and as a hyproduct from the seeding.

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 respect 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 impulse 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 of 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 N 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; approximately 50 kg over a period of 10^5 sec of firing.

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.

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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Thrust lb_f (N)	Pressure, atmosphere	Propellant flow rate, lb/sec	Fuel (cavity) mass, kg	Cavity power, fraction	Cavity power, MW	Driver power, MW	Fuel (driver) mass, kg	Fuel (cavity) edge temperature,	Fuel vaporization temperature, °C at chamber pressure
50 (222)	200	0.045	0.97	0.156	1.67	9.0	23	5 000	6690
	500	.036	1.79	.214	1.97	7.2	18	6 400	7525
	1000	.031	2.80	.287	2.42	6.0	13	8 050	8325
100 (445)	200	.077	.76	.140	3.95	24.2	24	6 100	6690
	500	.062	1.42	.188	4.55	19.7	20	7 800	7525
	1000	.056	2.24	.246	5.46	16.7	15	9 150	8325
150 (668)	200	.103	.66	.133	6.64	43.4	25	6 400	6690
	500	.085	1.23	.175	7.64	36.0	21	8 300	7525
	1000	.077	1.96	.226	8.91	30.5	17	10 500	8325
200 (890)	200	.131	.60	.130	9.28	62.1	26	6 700	6690
	500	.108	1.11	.166	10.90	54.7	22	9 150	7525
	1000	.097	1.79	.214	12.50	45.9	18	11 675	8325
100 (445)	200	.077	.76*	.090	3.95	40.0	145*	6 100	6690
	500	.062	1.42*	.120	4.55	33.4	138*	7 800	7525
	1000	.056	2.24*	.175	5.46	25.7	130*	9 150	8325

*Fuel was ^{235}U, all others fuel was ^{233}U.

TABLE 1 REACTOR POWER SPLITS AND FUEL LOADING FOR MINI-CAVITY

Thrust lb_f (N)	Pressure, atmosphere	Specific impulse, sec	Propellant flow rate, lb/sec	Driver power, MW	Reactor weight, lb	Pressure shell weight, lb	Radiator weight, lb	Total power-plant weight	
								lb	kg
50 (222)	200	1100	0.045	9.0	4800	800	4 350	10 150	4 615
	500	1375	.036	7.2	4800	1860	5 780	12 640	5 750
	1000	1600	.031	6.0	4800	4000	7 880	16 880	7 670
100 (445)	200	1300	.077	24.2	4800	800	11 700	17 500	7 950
	500	1600	.062	19.7	4800	1860	15 820	22 680	10 300
	1000	1800	.056	16.7	4800	4000	22 200	31 200	14 200
150 (668)	200	1460	.103	43.4	4800	800	21 000	26 800	12 190
	500	1770	.085	36.0	4800	1860	28 900	35 760	16 250
	1000	1960	.077	30.5	4800	4000	40 590	49 590	22 520
200 (890)	200	1530	.131	62.1	4800	800	30 060	35 860	16 300
	500	1850	.108	54.7	4800	1860	43 900	50 760	23 060
	1000	2060	.097	45.9	4800	4000	61 100	70 100	31 860
100 (445)	200	1300	.099	40.0	5100	800	19 350	25 450	11 570
	500	1600	.062	33.4	5100	1860	26 820	33 980	15 450
	1000	1800	.056	25.7	5100	4000	34 200	43 500	19 770

TABLE 2 POWERPLANT CHARACTERISTICS AND WEIGHT

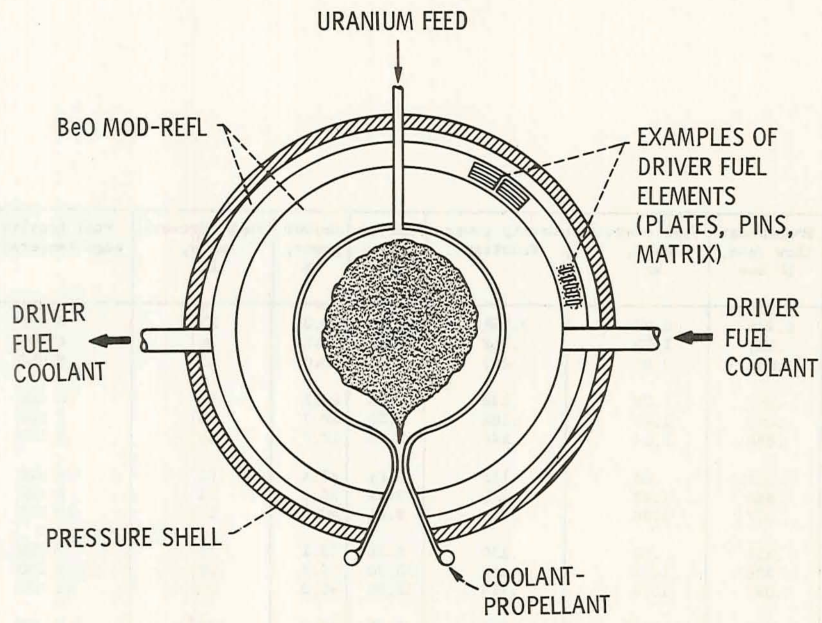

Figure 1. - Mini-cavity reactor concept for unmanned propulsion reactor diameter 1.22 meters; cavity diameter 0.61 meters.

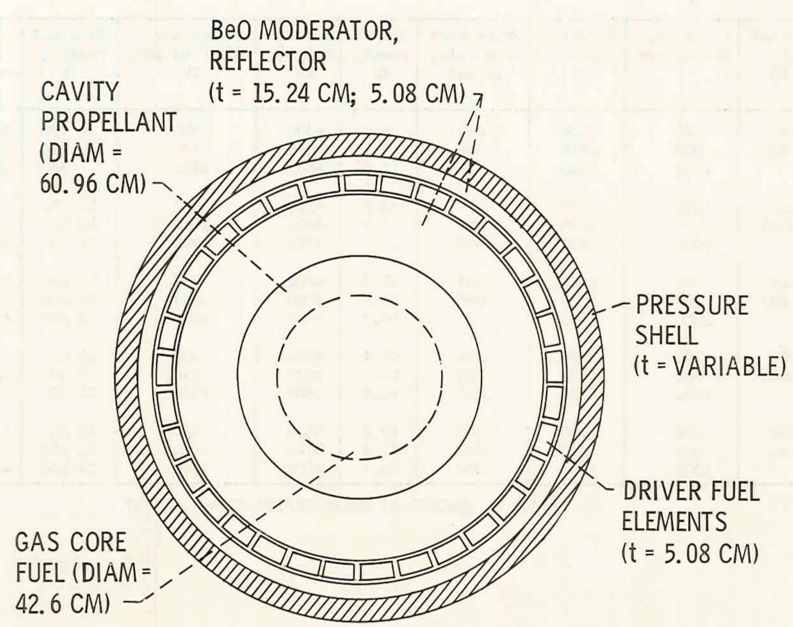

Figure 2. - Spherical calculation model of mini-cavity reactor.

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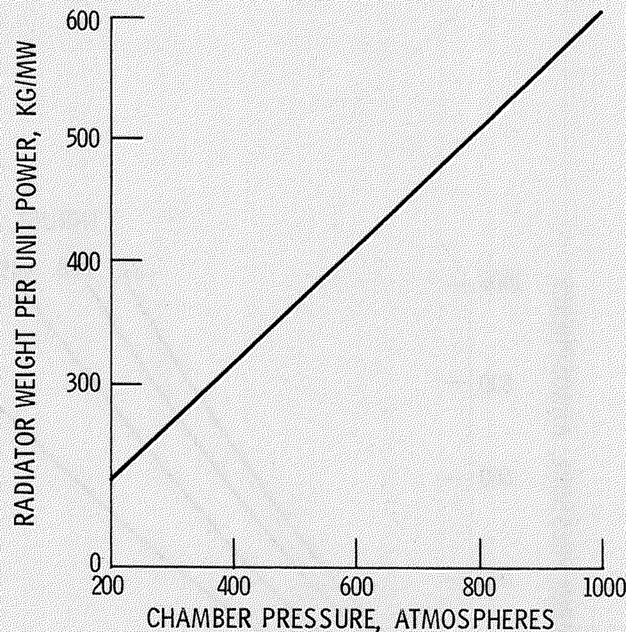


Figure 3. - Radiator weight for mini cavity - $T_{radiator}$ 1000° C, helium coolant.

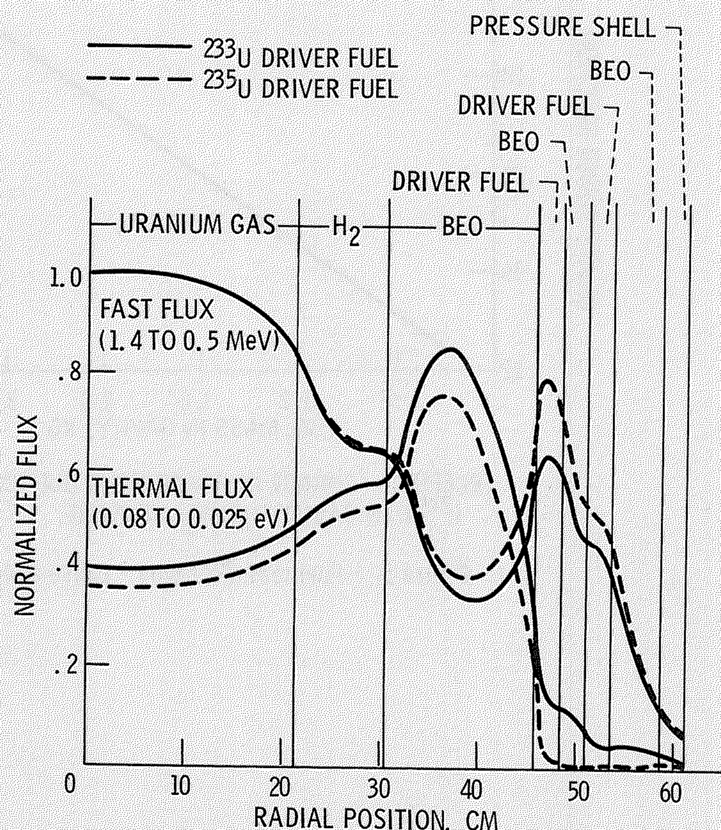
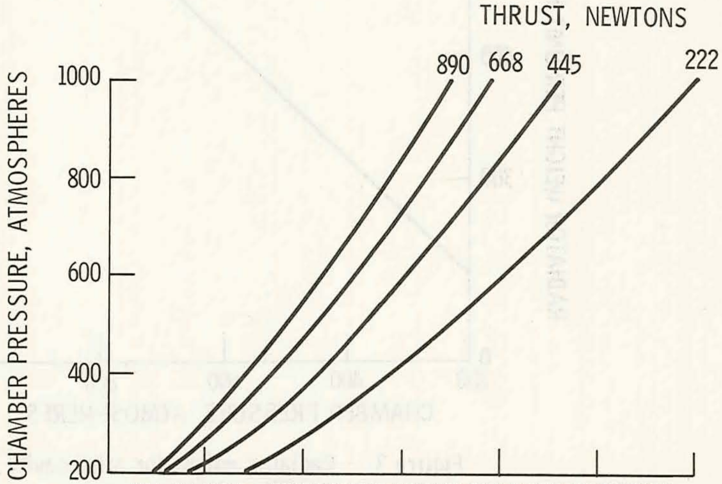
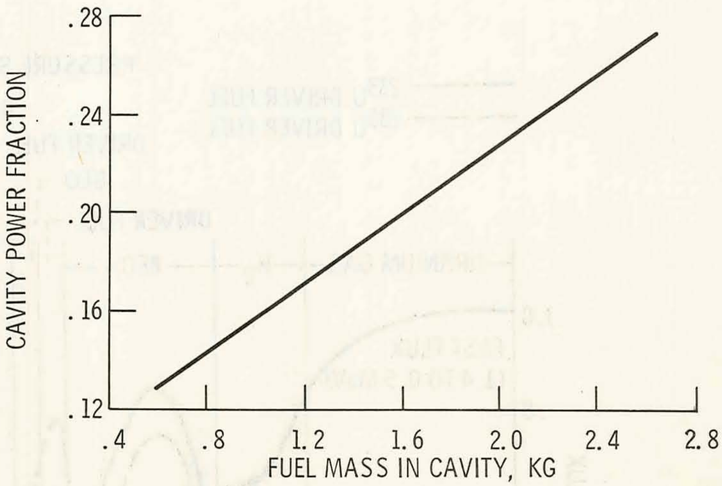


Figure 4. - Neutron flux for mini cavity reactor.



(A) CAUSE: PRESSURE AND FLOW RATE PRODUCE ALLOWABLE MASS.



(B) EFFECT: CHANGE IN POWER SPLIT DUE TO MASS (^{233}U) IN CAVITY THRUST, NEWTONS.

Figure 5. - Fuel mass in cavity - cause and effect.

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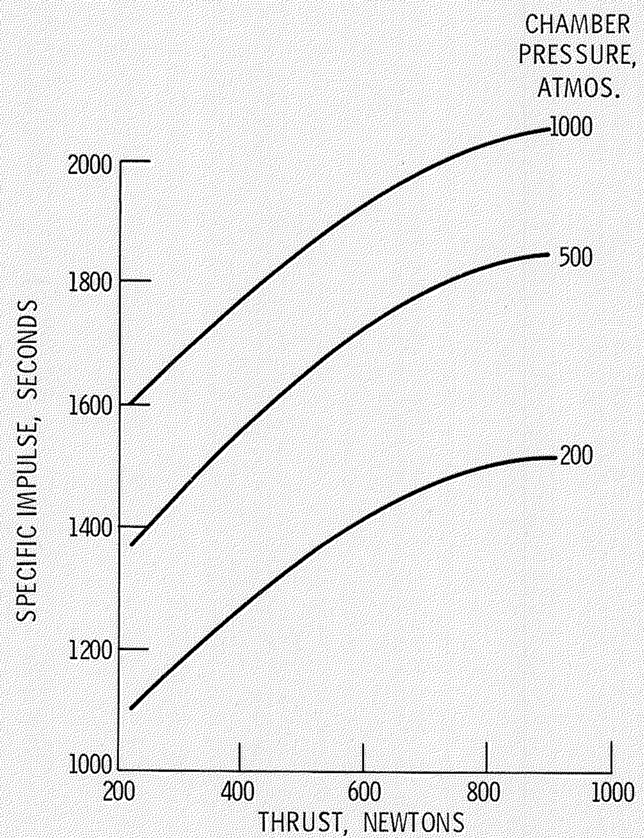

Figure 6. - Cavity specific impulse.

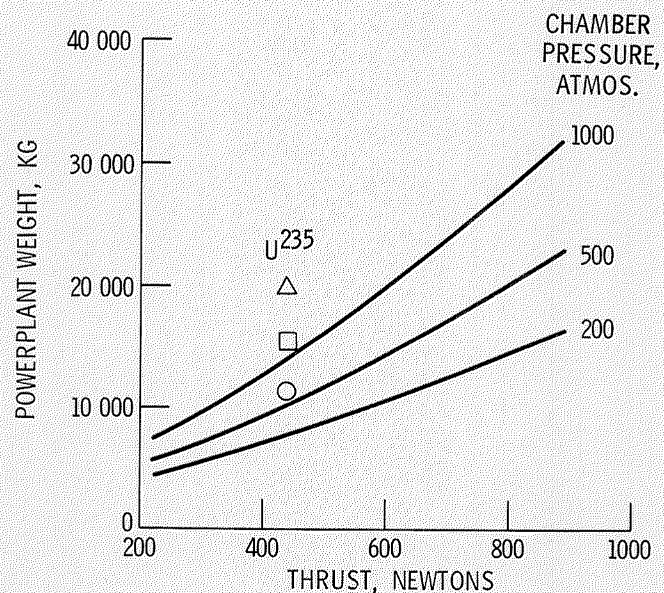

Figure 7. - Mini-cavity powerplant weights - (uranium-233 fuel).