Crew Radiation Dose from a High-Impulse Gas-Core Nuclear Rocket Plume

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Analytical calculations are performed to determine the radiation dose rate and total dose to the crew of a gas-core nuclear rocket from the fission fragments located throughout the plume volume. The mission chosen is a manned "courier" trip to the planet Mars. Four round trip times were picked in which the system was optimized so the initial vehicle mass in Earth orbit was minimized for each trip time. They are 80, 100, 150, and 200 days. For the most probable fission fragment retention time in the reactor of 100 sec, the unshielded radiation dose to a crew located 100 m from the nozzle exit varies from 170 rem for the 80 day round trip to 38 rem for the 200 day round trip. For the 80 day round trip the crew must be protected from the radiation dose. Five centimeters of lead shielding would reduce the radiation dose by two orders of magnitude thereby protecting the crew.

Nomenclature

A_0	= Avogadro's number
B	= defined by Eq. (3)
C	= source strength in Curies per unit volume
$C_F, C_{F\max}$	= thrust and maximum thrust coefficient, respectively
E	= photon energy in Mev
$F(t)$	= fission fragment energy release as a function of time after fission
$\vec{L}$	= vector distance from point $P_{r,\theta,\varphi}$ to the crew
M	= Mach number
m	= molecular weight
P_{FF}	= number fraction of fission fragments at point $P_{r,\theta,\varphi}$
R	= reactor power
r_e	= nozzle exit radius
r,θ,φ	= spherical coordinates
V	= mean velocity of particles in plume
$\dot{W}_{H2}$	= hydrogen mass flow rate
z	= distance from crew to nozzle exit
γ	= ratio of specific heats
λ	= defined by Eq. (4)
ρ	= mass density
Subscript	
e	= nozzle exit

Introduction

IN the open-cycle gas-core nuclear rocket concept, Fig. 1 (Refs. 1 and 2), the heat source is fissioning uranium gas. This released heat is radiated to and absorbed by the hydrogen propellant. The heated propellant is exhausted through a nozzle, producing thrust. Specific impulses of over 5000 sec are obtained by using a heat pipe space radiator to dispose of waste heat not regeneratively removed by the hydrogen propellant in the moderator. The fission fragments that are formed and the unfissioned uranium fuel are also exhausted into the vacuum of space. As the plume is formed, the crew is exposed to gamma radiation from the fission fragments in the plume.

The radiation dose to the crew from the fission fragments in the plume can be separated into two components. Component one results from the fact that there is a microscopic amount of plume material that has sufficient kinetic energy to flow back towards the vehicle. Some of this material will strike and stick to the vehicle. Since this material will contain fission fragments, these gamma radiation sources will stay with the crew throughout the entire trip and this dose could represent a significant source of radiation. Masser[3] has estimated this dose and has concluded it would be less than 10^{-3} rem for a typical manned Mars mission.

Component two of the dose results from the fission fragment distribution throughout the entire plume volume and is potentially much larger than component one. Since the plume contains over 99% of the exhausted material, 99% of the fission fragments will be in the plume. It is the purpose of this paper to estimate the radiation dose rate and total dose to the crew from the fission fragments in the plume for four specific missions to the planet Mars. The doses are calculated assuming that there is a vacuum in the space between the crew and plume.

Other sources of radiation include secondary fissioning due to delayed neutrons and direct radiation from the reactor core. These radiation sources, along with scattering from the space radiators and solar radiation, must be ultimately considered when total dose rates to the crew are evaluated. This study however, is concerned only with that part of the total radiation problem that arises from the fission fragments in the plume volume.

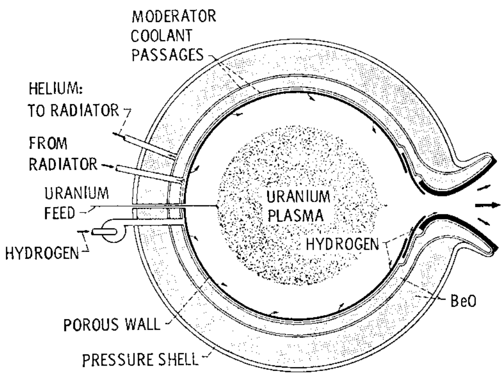

Fig. 1 Porous wall gas core engine concept.

Selected Mission Characteristics

The mission selected for the analysis of the plume radiation hazard is a manned "courier" trip to Mars.[4] The trip involves leaving a 600 km circular orbit around Earth with a trans-Mars injection maneuver, a high ellipse orbit insertion maneuver at the planet Mars, a Mars orbit time of approximately one day, a trans-Earth injection maneuver, and a circular orbit

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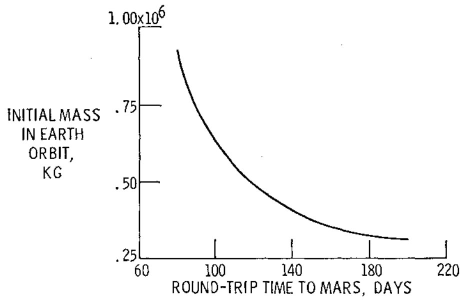

Fig. 2 Effect of round-trip time to Mars on the minimum initial mass in Earth orbit needed for the mission.

insertion maneuver upon return to Earth. The "courier" mission implies no payload will be sent to the planet's surface. It is possible with the radiatively cooled open-cycle gas core nuclear rocket to achieve this total trip in as little time as 75–80 days. Figure 2 shows the variation of this trip time with the initial mass in Earth orbit needed to accomplish the trip. Four trip times were selected on this curve to calculate the plume radiation dose associated with each trip. They were 80, 100, 150, and 200 days.

Rocket Engine Characteristics

For each mission time the system was optimized in order to minimize the initial vehicle mass in Earth orbit. Therefore for each mission there is a specific engine with its own characteristics. This results in a given thrust and specific impulse. Table 1 lists several characteristics of the engine for each of the chosen missions.

In the case of each engine, the hydrogen chamber exit enthalpy is diluted by cold hydrogen used to transpiration cool the nozzle; therefore one can calculate a specific impulse with nozzle cooling. The exit-to-chamber pressure ratio is assumed to be 10^{-5} and Patch[5] has calculated the exit parameters needed for the calculation of radiation from the plume. Table 1 also summarizes the exit parameters needed for the calculations for each of the missions.

Table 1 Mission characteristics for the four Mars round-trip times chosen for the analysis

	Mars round trip time, days			
	80	100	150	200
Thrust, lb	28900	19380	18200	17150
Thrust, N	128550	86200	80950	76280
Specific impulse, sec	5180	4840	4800	4750
Reactor power, Mw	4520	2830	2640	2460
I.M.E.O.,[a] kg	0.94×10^6	0.64×10^6	0.38×10^6	0.31×10^6
H_2 mass, kg	0.662×10^6	0.428×10^6	0.220×10^6	0.164×10^6
Engine running time, hr	72.7	65.4	35.9	27.8
Chamber temperature, °K	29760	27680	27430	27170
Chamber pressure, atm	1000	1000	1000	1000
Chamber pressure, N/m²	1.01×10^8	1.01×10^8	1.01×10^8	1.01×10^8
Exit temperature, °K	3310	3160	3150	3135
Exit Mach No.	10.03	9.96	9.93	9.90
Exit velocity, m/sec	5.52×10^4	5.15×10^4	5.11×10^4	5.06×10^4
Exit molecular weight	2.00	2.01	2.01	2.01
Ratio of specific heats	1.255	1.263	1.263	1.263

[a] Initial mass in Earth orbit.

Calculation of Fission Fragment Formation

The number of fission fragments formed is calculated using the following equation:

$$\text{reactor power (w)} = \text{fissions per sec}/3.1 \times 10^{10} \qquad (1)$$

Since the reactor powers and engine running times are known from Table 1, the number of fission fragments produced are known. It is also assumed the average molecular weight of the fission fragments is 117.5 or half of the molecular weight of the U_{235} fuel. In addition, it is assumed that the number fraction of fission fragments in any unit volume is constant throughout the plume.

Calculation of Plume Density

In order to calculate the number of fission fragments at any point within the plume volume, the density throughout the plume must be known. It has been shown in nozzle plume flows that far from the exit the mass flux, ρV, varies inversely as the square of the distance from the source point. From Grier[6] and Hill and Draper[7] it can be shown that the density in a plume can be closely approximated by

$$\rho = \frac{4\rho_e M_e B}{[1+(\gamma-1)/2M_e^2]^{1/2} 2/(\gamma+1)^{(\gamma+1)/2(\gamma-1)}} \left(\frac{r_e}{r}\right)^2 e^{-\lambda^2(1-\cos\theta)^2} \qquad (2)$$

Where the coordinates r and θ are shown in Fig. 3; ρ is the density at any point in the plume; r_e is exit radius; ρ_e is the exit density; M_e is exit Mach number; γ is the ratio of specific heats; and B and λ are constants.

Also from Hill and Draper[7] we have

$$B = [\lambda/4(\pi)^{1/2}][(\gamma-1)/(\gamma+1)]^{1/2})[2(\gamma+1)]^{1/(\gamma-1)} \qquad (3)$$

$$\lambda = \frac{1}{(\pi)^{1/2}(1 - C_F/C_{F_{\max}})} \qquad (4)$$

Where C_F and $C_{F_{\max}}$ are thrust coefficients and are evaluated Eqs. (4.33) and (4.34) of Shapiro.[8]

Radiation Dose to the Crew

The radiation dose to the crew is calculated using the basic equation from Glasstone and Sesonski,[9]

$$\text{radiation dose rate (rem/hr cm}^3) = 5.2 \times 10^3\ CE/(\vec{L} \cdot \vec{L}) \qquad (5)$$

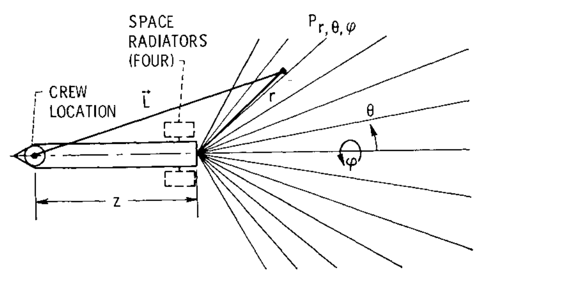

Fig. 3 Relationship between point $P_{r,\theta,\varphi}$, the distance to the crew $\vec{L}$, and the location of the crew from the nozzle exit z.

Where C is the source strength at the point $P_{r,\theta,\varphi}$ in the plume in curies per unit volume, E is the photon energy in Mev, and $\vec{L}$ is the vector distance in centimeters from the point $P_{r,\theta,\varphi}$ to the crew.

The energy release of U_{235} fission fragments $F(t)$ varies from approximately 0.07 Mev per fission/sec at 10 sec after fission to 0.00002 Mev at 10,000 sec after fission.[10] The number density of fission fragments at point $P_{r,\theta,\varphi}$ is given by

$$\text{number density of fissions fragments at } P_{r,\theta,\varphi} = \rho A_o P_{FF}/m \quad (6)$$

Where ρ is the density at point $P_{r,\theta,\varphi}$, A_o is Avogadro's number, P_{FF} is the number fraction of fission fragments at point $P_{r,\theta,\varphi}$ and m is the molecular weight of the nozzle exit gas.

The value of L as shown in Fig. 3 is given by

$$\vec{L}\cdot\vec{L} = z^2 + 2zr\cos\theta + r^2 \quad (7)$$

Where z is the distance from the crew to the exit plane of the nozzle. Combining the energy release of decay for the fission fragments and Eqs. (5) and (6), and using the identity that one curie equals 3.7×10^{10} disintegrations per second.

Radiation dose rate per unit volume from $P_{r,\theta,\varphi}$ in rem per hour per cm^3 is

radiation dose rate (rem/hr cm^3)

$$= \frac{5.2 \times 10^3 F(t)}{3.7 \times 10^{10}\vec{L}\cdot\vec{L}}\,\frac{1}{2}\left(\frac{\rho A_0 P_{FF}}{m}\right) \quad (8)$$

The number fraction of fission fragments (P_{FF}) at point $P_{r,\theta,\varphi}$ is given by

$$P_{FF} = (R)(m)6.2 \times 10^{13}/\dot{W}_{H_2}A_0 \quad (9)$$

Where the reactor power R, is given in megawatts, and the hydrogen flow, rate, $\dot{W}_{H_2}$, is given in kilograms per second. Combining Eqs. (7)–(9)

radiation dose rate (rem/hr cm^3)

$$= \frac{(5.2)[F(t)]10^6}{3.7(z^2 + 2zr\cos\theta + r^2)}\left[\frac{(R)(\rho)3.1}{\dot{W}_{H_2}}\right] \quad (10)$$

The total radiation dose in rem per hour is

$$\int_{r=r_e}^{r'}\int_{\theta=0}^{\pi/2}\int_{\varphi=0}^{2\pi} (\text{const})\,\frac{e^{-\lambda^2}(1-\cos\theta)^2}{(z^2 + 2zr\cos\theta + r^2)}\sin\theta\, d\varphi\, d\theta\, dr \quad (11)$$

Where the constant is equal to

$$\text{const} = \frac{F(t)(R)(5.2)(3.1)(10^6)(4)\rho_e M_e B r_e^{\,2}}{(\dot{W}_{H_2})(3.7)\{1 + [(\gamma-1)/2]M_e^{\,2}\}^{1/2}[2/(\gamma+1)]^{(\gamma+1)/2(\gamma-1)}} \quad (12)$$

After the integration on φ is performed one has

radiation dose rate (rem/hr)

$$= 2\pi\,(\text{const})\int_{r=r_e}^{r'}\int_{\theta=0}^{\pi/2}\frac{e^{-\lambda^2(1-\cos\theta)^2}}{(z^2 + 2zr\cos\theta + r^2)}\sin\theta\, d\theta\, dr \quad (13)$$

The integration of r is stopped at r' whenever an increase of r' by a factor of ten does not increase the radiation dose rate more than 1%. The resultant value of r' was 100 km. Since the plume expands at a rate of over 50 km/sec, the transient conditions at engine start up and shut down were ignored.

Discussion of Results

The radiation dose rate and total dose from the fission fragments in the plume to the crew is calculated for two crew locations—that of 100 m and 200 m from the nozzle exit.

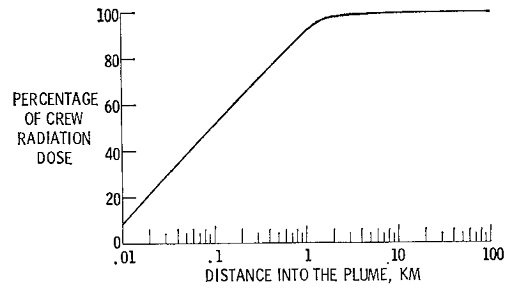

Fig. 4 Increase of crew radiation dose as a function of integrated distance into the plume.

In order to better understand the radiation hazard of the plume, one must analyze which part of the plume is most hazardous. Figure 4 shows the percentage of the radiation dose received by the crew as more of the plume is included in the dose calculation. If we include only the first 0.1 km of the plume, only 50% of the radiation dose is received from this volume. When one includes 1.0 km of the plume, over 90% of the radiation dose is included. At a distance of 10.0 km, 99% of the radiation dose is included. And at a distance of 100.0 km from the nozzle, essentially 100% of the gamma radiation dose to the crew is included.

Another variable of importance is the retention time of the fission fragments in the reactor core. The longer they stay in the reactor, the less of a radiation source they are to the crew. Retention times varied in the analysis from 10 sec to 10,000 sec. The large range used for the fission fragment retention times are based on the flow system itself. The average retention time of a uranium atom is calculated to be 1000 sec, and the average retention time of a hydrogen atom is 10 sec. From this and fluid dynamic considerations, 100 sec appears to be a reasonable retention time for the fission fragments.

The results of the radiation dose rate for the engine associated with each mission is shown on Fig. 5. One can see that the dose rate falls as retention time of the fission fragments increases from 10 sec to 10,000 sec. For the 80 day round trip, the dose rate falls from approximately 23 rem/hr for a

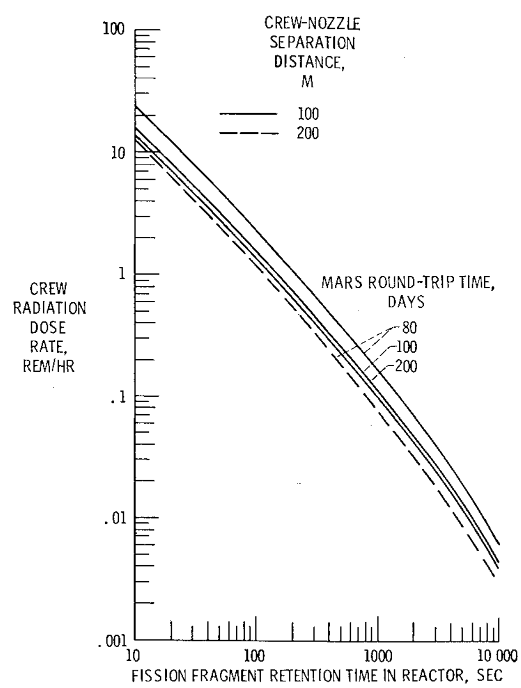

Fig. 5 Effect of fission fragment retention time in reactor on the crew radiation dose rate.

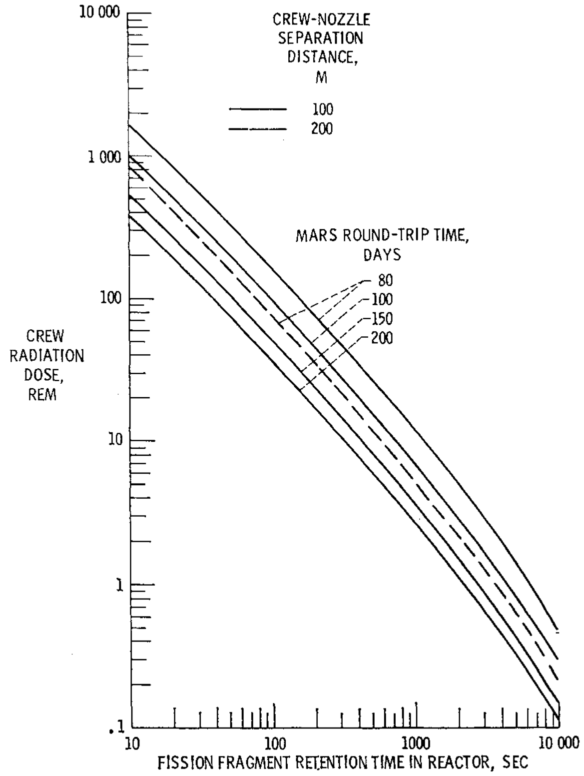

Fig. 6 Effect of fission fragment retention time in reactor on the total crew radiation dose.

fission fragment retention time of 10 sec, to less than 0.007 rem/hr for a retention time of 10,000 sec. Also as the trip time increases, the dose rate falls. However, there is almost no drop in dose rate between the 100 and 200 day round trip. This is because the engine powers are almost identical (see Table 1). Figure 5 also shows the effect of crew-nozzle separation distance on radiation dose rate for the 80 day round trip. The dose rates are just about half if the crew is 200 m forward of the nozzle exit instead of 100 m.

A more important factor than dose rate is the total dose. In Fig. 6, one can see the results of the total dose to the crew for the various round-trip times to Mars. Again it must be stressed that this is an unshielded case; no attenuation or scattering effect is taken into account. For the 80 day round-trip time, the radiation dose is as high as 1670 rem for a fission fragment retention time of 10 sec. The radiation dose, however, drops rapidly with increasing retention time; at 10,000 sec the radiation dose is only 0.5 rem. As the trip time increases, less energy is required and the crew dose decreases. For the 200 day round trip, the total dose for fission fragment retention times of 10 and 10,000 sec are only 380 and 0.1 rem, respectively.

At the most probable retention time of 100 sec, the radiation dose varies from 170 rem to 38 rem for the 80 and 200 day round-trip time, respectively. In this case the crew must be protected from the radiation dose. Five centimeters of lead shielding would reduce the radiation dose by two orders of magnitude thereby protecting the crew. The increase in vehicle weight would be insignificant. For example, a shadow shield of five centimeters thickness and four meters in diameter would add 7120 kg to the vehicle gross weight of 0.94 million kg. The equivalent attenuation of 5 cm of lead is also provided by 7.3 m of liquid hydrogen. The amount of liquid hydrogen that is necessary for the 80 day and 200 day trips is 9500 and 2300 m^3, respectively. This is equivalent to a tank that is 10 m in diameter and 121 m long for the 80 day trip, or one that is 10 m in diameter and 29.3 m long for the 200 day trip. Therefore, sufficient attenuation by this liquid hydro-

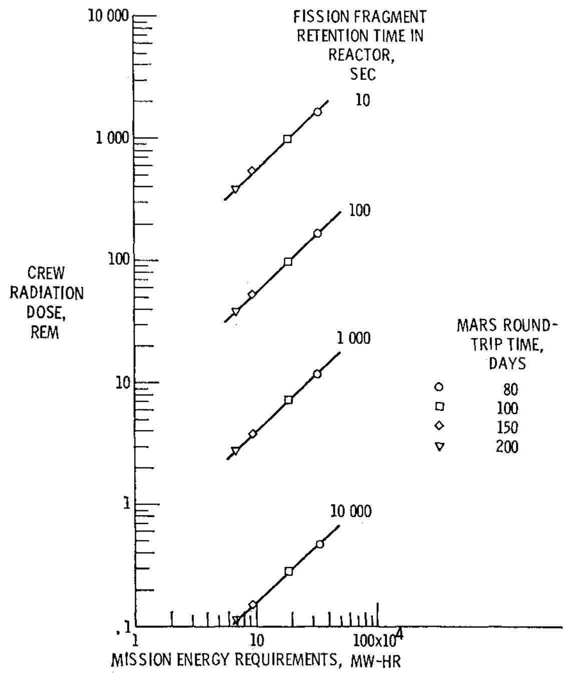

Fig. 7 Effect of mission energy requirements on the crew radiation dose. Crew nozzle separation is 100 m.

gen is possible during the initial portion of the trip. Also additional attenuation is available in the form of spacecraft structure, nuclear fuel, equipment, and stores.

Figure 6 also shows the effect of crew distance from the nozzle exit on total radiation dose. Again the total dose appears to be just about half if the crew is located 200 m from the nozzle instead of 100 m.

The energy required for this trip to Mars varies with trip time. Figure 7 shows the effect of total radiation dose received during the trip as a function of total energy needed for the trip. One can see as the energy needed for a particular trip time is increased, the crew dose increases. In fact, for the trip times included in this analysis the total radiation dose 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.

Summary of Results

Calculations were performed to determine the radiation dose rate and total dose to the crew of a gas-core nuclear rocket from the fission fragments located throughout the plume volume. Calculations were carried out for round-trip times to the planet Mars of 80, 100, 150, and 200 days. Crew distances from the nozzle exit were assumed to be either 100 or 200 m. Fission fragment retention times in the reactor were assumed to vary from 10 sec to 10,000 sec. The radiation dose from the plume was calculated assuming no shielding material existed between the crew and the total plume volume. The following results were obtained:

1) For the most probable fission fragment retention time of 100 sec, and crew nozzle separation of 100 m, the radiation dose varied from 170 rem to 38 rem for the 80 and 200 day round-trip time, respectively. Five centimeters of lead shielding would reduce the radiation dose by two orders of magnitude, thereby protecting the crew. The increase in vehicle weight would be insignificant. For example, a shield of 5 cm thickness and 4 m in diameter would add 7120 kg to the vehicle gross weight of 0.94 million kg. Also additional attenuation is available in the form of liquid hydrogen propellant, spacecraft structure, nuclear fuel, equipment, and stores.

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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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