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RADIATION HAZARD FROM BACKFLOW OF FISSION FRAGMENTS FROM THE PLUME OF A GAS-CORE NUCLEAR ROCKET

by Charles C. Masser
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TECHNICAL PAPER proposed for presentation at Symposium on Research on Uranium Plasmas and their Technological Applications sponsored by the National Aeronautics and Space Administration Gainesville, Florida, January 7-10, 1970

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SUMMARY

Analytical calculations are performed to determine the particle flux that leaves a rocket plume in a vacuum and strikes the rocket forward of the nozzle. The rocket plume is generated by the products of a gas-core nuclear reactor and consists of hydrogen, uranium, and fission fragments. The backflow flux is determined by the number of particles that leave the continuum of the plume and strike the rocket without experiencing any particle collisions. A percentage of these particles that strike the rocket are fission fragments and the radiation dose to the crew is calculated.

A total of 1.68 pounds of fission fragments are formed from a gas-core rocket that produces one million pounds of thrust at a specific impulse of 1500 seconds for a propellant consumption of one million pounds. Of the 1.68 pounds of fission fragments only 0.42×10^{-8} pound flow back from the plume. And only 0.66×10^{-10} pound of fission fragments strike the rocket. This weight of fission fragments causes a total integrated dose of less than 1.3×10^{-4} rad to the crew, which is well below acceptable levels.

INTRODUCTION

In the open cycle gas-core nuclear rocket concept (Fig. 1) 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. In an open cycle gas-core rocket the fission fragments that are formed and the unfissioned uranium fuel are also exhausted into the vacuum of space. As the exhaust plume is formed, a small percentage of the plume products have a sufficient velocity and the proper direction to leave the plume and flow back towards the rocket. It is the purpose of this paper to evaluate the radiation hazard to the crew associated with a backflow of fission fragments that strike the rocket. It is assumed that the fission fragments striking the rocket stick to it.

There are other radiation sources associated with the gas-core reactor such as radiation from the reactor core and radiation from inside the plume itself. These radiation sources along with solar radiation must be ultimately considered. This study, however, is concerned only with that part of the total radiation problem that arises from fission fragments leaving the plume and striking the rocket.

ROCKET ENGINE CHARACTERISTICS

Certain exit nozzle conditions are selected in order to make a specific calculation of the backflow of fission fragments from the plume. Roback (Ref. 1) calculated performance parameters for hydrogen at various stagnation pressures and temperatures. The selection was made to pick performance parameters which produced a high flow of fission fragments, thereby maximizing the radiation problems. A one million pound propellant storage capacity was picked, which is typical of a manned Mars mission.

Thrust, lb	1 000 000
Specific impulse, sec	1500
Chamber pressure, atm	1000
Chamber temperature, ^{o}R	10 000
Reactor power, MW	41 900

From table 168 of Roback (Ref. 1) for a

$$\frac{\text{Pressure nozzle exit}}{\text{Pressure nozzle throat}} = 10^{-3}:$$

Exit temperature, ^{o}R	3460
Exit density, lb/ft^3	7.978×10^{-4}
Exit velocity, ft/sec	48 507
Exit Mach number	4.587
Exit molecular weight	2.015
Molecular diameter, cm	2.75×10^{-8}

For the given thrust of one million pounds and a specific impulse of 1500 seconds, the propellant flow rate is 667 pounds per second. Therefore, if the propellant storage for the mission is one million pounds, the total firing time is 1500 seconds.

CALCULATION OF PLUME DENSITY

It has been shown that in nozzle plume flows the mass flux ρV varies inversely as the square of the distance from the source point. Hill and Draper (Ref. 2) have shown that the density in the plume can be closely approximated by

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

where the coordinates of r and θ are shown in Fig. 2; ρ is density at any point in the plume; ρ_e is 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 (Ref. 2) we have

$$B = \frac{\lambda}{4\sqrt{\pi}} \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2} \left(\frac{2}{\gamma + 1}\right)^{1/(\gamma-1)} \tag{2}$$

$$\lambda = \frac{1}{\sqrt{\pi}\left(1 - \frac{C_F}{C_{F_{max}}}\right)} \qquad (3)$$

Where C_F and $C_{F_{max}}$ are thrust coefficients and are evaluated using Eqs. (4.33) and (4.34) of Shapiro (Ref. 3).

DEFINITION OF PLUME BOUNDARY

The gas inside the plume is considered to be a continuum. As the plume expands, the density decreases to a point where free molecular flow can be assumed. At this point we can define our plume boundary. From Grier (Ref. 4), the plume boundary is defined by a surface on which the Knudsen number is constant. The Knudsen number, K, is defined as

$$K \equiv \frac{l}{r} \qquad (4)$$

where r is the distance from the plume source point to the plume boundary, and l is the mean free path of the particle and is given by Santeler et al. (Ref. 5) as

$$l = 3.736\times10^{-25} \frac{m}{\rho\delta^2} \qquad (5)$$

where m is molecular weight and δ is molecular diameter.

Solving Eq. (5) for density and substituting in Eq. (4) we have

$$\rho = 3.736\times10^{-25} \frac{m}{K\delta^2 r} \qquad (6)$$

Combining Eq. (6) and Eq. (1) we have the equation of a constant Knudsen surface, which defines the boundary of the plume.

$$\frac{r}{r_e} = \frac{1.07\times10^{25}\,\rho_e M_e B K \delta^2 r_e}{m\left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{1/2} \left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/2(\gamma-1)}}\, e^{-\lambda^2(1-\cos\theta)^2} \tag{7}$$

In this equation the maximum θ was taken to be the maximum Prandtl-Meyer expansion angle for a Mach number of 4.87. The backflow of flux is determined by the number of particles that leave this defined boundary and strike a particular point $P(x, y, z)$. A model of this is shown in Figs. 2 and 3.

CALCULATION OF BACKFLOW FLUX

Nöller (Ref. 6) has calculated the density at a point $P(x, y, z)$ due to the molecules leaving an elemental volume $d\tau$ adjacent to a constant Knudsen surface. Noller's result was:

$$\frac{dn_p}{n_\tau} = \pi^{-3/2} e^{-U^2} \left\{\frac{1}{2} U \cos\psi + \left(\frac{1}{2} + U^2 \cos^2\psi\right) \times e^{U^2 \cos^2\psi} \left(\frac{\sqrt{\pi}}{2}\right) [1 + \mathrm{erf}(U\cos\psi)]\right\} d\Omega \tag{8}$$

where n_τ is the number density of molecules in $d\tau$, ψ is the angle between the direction of $\vec{V}$ and the direction of flight of the molecules contributing to the density at $P(x,y,z)$, $U = \vec{V}/(2RT/m)$, R is the gas constant, T is the temperature, and $d\Omega$ is the differential solid angle of $d\tau$ as seen from $P(x,y,z)$. Figure 3 shows the coordinate system used.

Equation (8) was recalculated in this study to express mass flux (F) instead of density. The following equation resulted:

$$\frac{dF}{n_\tau} = \frac{\pi^{-2/3}}{2} e^{-U^2} \Bigg\{ (1 + U^2 \cos^2\psi) + \sqrt{\pi}\, U \cos \psi$$

$$\times \left(\frac{3}{2} + U^2 \cos^2\psi\right) [1 + \mathrm{erf}(1 + \cos \psi)] e^{U^2 \cos^2\psi} \Bigg\} d\Omega \qquad (9)$$

From Grier (Ref. 4), $d\Omega$ is given by

$$d\Omega = \left[\frac{y}{r_e} \sin \theta \cos \varphi (1 + 2\lambda^2 \cos \theta - 2\lambda^2 \cos^2\theta)\right] - \frac{r}{r_e}$$

$$+ \frac{z}{r_e} (\cos \theta - 2\lambda^2 \sin^2\theta + 2\lambda^2 \sin^2\theta \cos \theta) \left(\frac{r}{r_e}\right)^2 \left(\frac{r_e}{L}\right)^3 \sin \theta \, d\theta \, d\varphi$$

$$(10)$$

Where $\vec{L}$ is the vector from $d\tau$ to the point $P(x, y, z)$. Also, from Grier (Ref. 4) $|\vec{L}|$ is given by

$$\frac{|\vec{L}|}{r_e} = \hat{r} \left(\frac{y}{r_e} \sin \theta \cos \varphi - \frac{r}{r_e} + \frac{z}{r_e} \cos \theta\right)$$

$$+ \hat{\theta} \left(\frac{y}{r_e} \cos \theta \cos \varphi - \frac{z}{r_e} \sin \theta\right) - \hat{\varphi} \frac{y}{r_e} \sin \varphi \qquad (11)$$

The particle mass flux at any point upstream of the nozzle face is

$$F = \frac{\pi^{-3/2}}{2} e^{-U^2} \int_{\theta=0}^{\theta=\theta_{max}} \int_{\varphi=-(\pi/2)}^{\varphi=(\pi/2)} n_\tau \Bigg\{ (1 + U^2 \cos^2\psi) + \sqrt{\pi}\, U \cos \psi$$

$$\times \left(\frac{3}{2} + U^2 \cos^2\psi\right) [1 + \mathrm{erf}(U \cos \psi)] e^{U^2 \cos^2\theta} \Bigg\} d\Omega \qquad (12)$$

CALCULATION OF FISSION FRAGMENT FORMATION

The total engine running time is calculated by dividing the mass flow of propellant by the total mass of propellant carried. This results in a total engine running time of 1500 seconds. The number of fission fragments formed is calculated using Eq. (2.49) of Glasstone and Sesonski (Ref. 7)

$$\text{Reactor power}_{(\text{watts})} = \frac{\text{Fissions per second}}{3.1\times10^{10}} \tag{13}$$

Since reactor power and engine running time are known, the number of fission fragments are known. It is also assumed the average molecular weight of the fission fragments is 117.5. Therefore we have the values shown in the following table.

	Number of particles	Weight of particles, lb
Fission fragments	3.896×10^{24}	1.68
Hydrogen propellant	1.36×10^{32}	10^{6}
Unfissioned uranium	1.163×10^{28}	10^{4}

It is assumed the fission fragments are uniformly distributed throughout the plume which is composed chiefly of hydrogen, and that the number of fission fragments flowing from the plume is of the same relative concentration as the plume. This assumption should give an overestimate of the number of fission fragments leaving the plume because of the higher mobility of the hydrogen molecules.

MASS FLUX TO ROCKET

In order to calculate the number of fission fragments that strike and stick to the rocket, a particular shape was picked. The configuration picked was a cylinder 33 feet in diameter and 400 feet long. This size is sufficient for a tankage volume needed to store one million pounds of hydrogen which is typical of a manned Mars mission. The crew is assumed to be located at the front of the rocket 400 feet from the nozzle.

The distribution of fission fragments over the rocket is computed so the distance from the fission fragments to the crew is known. In Fig. 4 we have an enlarged view of the rocket nozzle area. The plume boundary is for the case of Knudsen number equal to 1. For this case the total number of fission fragments formed is 1.68 pounds. Of this amount only 0.42×10^{-8} pound flow back across the plane $z = 0$. Of this 0.42×10^{-8} pound, 0.66×10^{-10} pound deposits on the end surface of the rocket. It can easily be seen that only a small percentage of the total backflow ever strikes the rocket.

RADIATION DOSE TO THE CREW

The radiation dose to the crew is calculated in two parts: the radiation from the fission fragments that strike the end surface and the radiation from the fission fragments that strike the side of the rocket. In all cases studied the radiation dose level to the crew from the fission fragments striking the side of the rocket is at least six orders of magnitude less than the dose from the fission fragments striking the end of the rocket. Therefore the radiation from the fission fragments striking the end of the rocket are only discussed.

In calculating the radiation dose several assumptions are used in order to determine the highest dose that one could expect from the backflow. First, the gamma radiation from the fission fragments is released after they flow back and strike the rocket. Second, the fission fragments of the uranium atom release their total 6 MeV of energy (Glasstone and Sesonske, Ref. 7) in decay in 1 second. Third, an unshielded point kernel calculation was used to calculate the dose to the crew.

The total radiation dose to the crew for these extremely conservative assumptions in the case where the Knudsen number $K = 1$ is 1.3×10^{-4} rad. For a Knudsen number of 1.0 the mean free path of the particles is equal to the distance from nozzle. This is shown on Fig. 4. This level of radiation is small so no hazard to the crew is expected. Since the amount of fission fragments that strike the rocket may depend on the definition of the plume boundary, a variation of this definition is shown on Fig. 5. The plume boundaries represent the cases where the Knudsen number K is equal to 0.01, 0.1, and 1.0. The total radiation doses for these three cases are 8.3×10^{-4}, 3.6×10^{-4}, and 1.3×10^{-4} rad, respectively. However, even for the case where $K = 0.01$ the radiation level to the crew is small. Therefore, from the cases studied the radiation dose to the crew from fission fragments that flow back from the plume is considered not to be hazardous.

APPENDIX - SYMBOLS

B	defined by Eq. (2)
C_F	thrust coefficient
$C_{F_{max}}$	maximum thrust coefficient
F	mass flux
K	Knudsen number
$\bar{L}$	vector distance from $d\tau$ on constant Knudsen surface to point $P(x, y, z)$
l	mean free path of gas molecules
M	Mach number
m	molecular weight
n_p	particle density at point $P(x, y, z)$
n_τ	particle density in volume element
R	gas constant
r, θ, φ	spherical coordinates
T	temperature

U	dimensionless velocity $\lvert\vec{V}\rvert/(2RT/m)^{1/2}$
$\vec{V}$	mean velocity of particles in plume
x, y, z	Cartesian coordinates
γ	ratio of specific heats
δ	molecular diameter of molecules
λ	defined by Eq. (3)
ρ	mass density
ψ	angle between direction of $\vec{V}$ and direction of $\vec{L}$

Subscript:

e	nozzle exit

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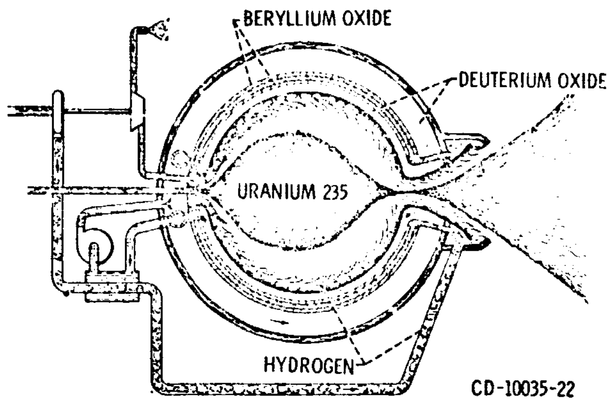

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Figure 1. - Lewis gas core nuclear rocket concept.

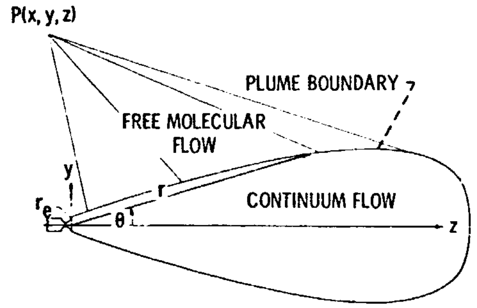

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Figure 2. - Model used for calculations.

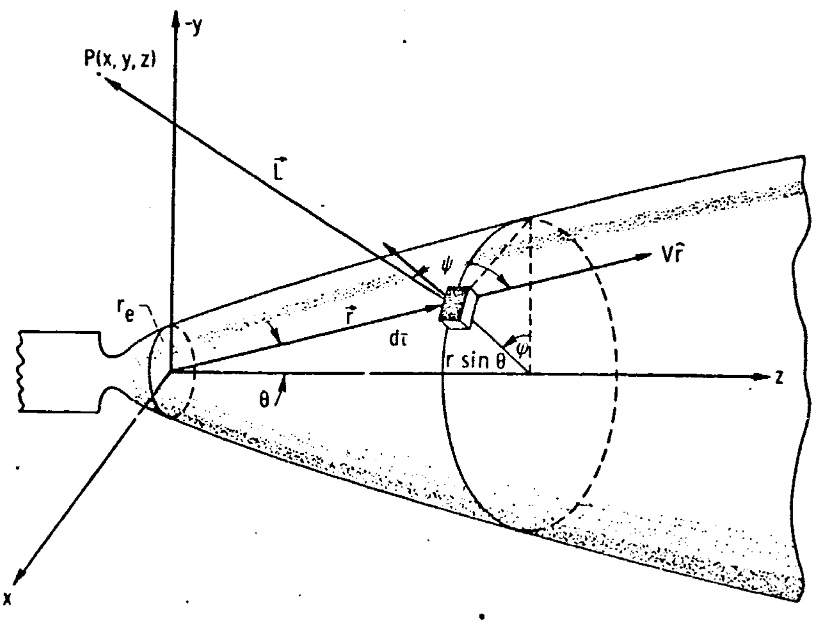


Figure 3. - Coordinate system used in calculations. (Note that $\hat{n}$ is normal to surface at $d\tau$ and $\hat{r} = \vec{r}/|r|$.)

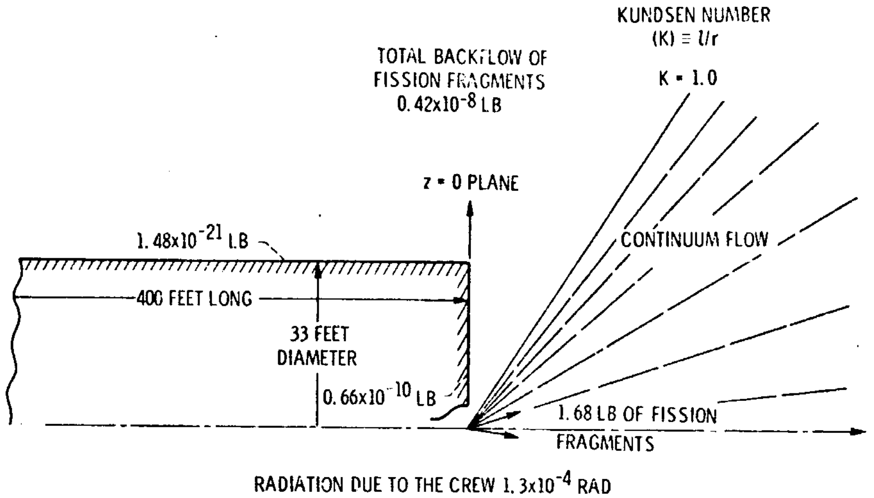
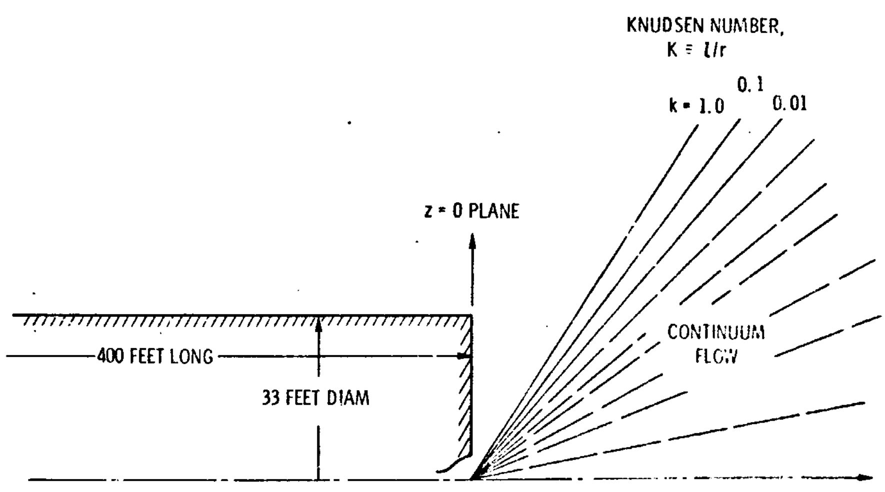


Figure 4. - Distribution of fission fragments for a plume Knudsen number of 1.0.



KNUDSEN NUMBER	TOTAL BACKFLOW OF FISSION FRAGMENTS	FISSION FRAGMENTS ON ROCKET	RADIATION DOSE TO CREW
1.0	0.42x10^{-8} LB	0.66x10^{-10} LB	1.3x10^{-4} RAD
0.1	1.16x10^{-8} LB	1.83x10^{-10} LB	3.6x10^{-4} RAD
0.01	2.69x10^{-8} LB	4.22x10^{-10} LB	8.3x10^{-4} RAD

Figure 5. - Distribution of fission fragments for a plume Knudsen number of 1.0, 0.1, and 0.01.