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CREW RADIATION DOSE FROM A GAS-CORE NUCLEAR ROCKET PLUME

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CREW RADIATION DOSE FROM A GAS-CORE

NUCLEAR ROCKET PLUME

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SUMMARY

Analytical calculations are performed to determine the radiation dose rate to the crew of a gas-core nuclear rocket from the fission fragments located throughout the plume volume. The rocket plume is generated by the products of the reactor and consists of hydrogen, uranium, and fission fragments.

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. The radiation dose rate from these fission fragments to two crew locations of 250 and 500 feet from the nozzle exit are calculated. The doses are calculated assuming that there is a vacuum in the space between the crew and the plume. For the fission fragment retention time in the reactor core of 0.01 second, the unshielded radiation dose to a crew located 250 feet from the nozzle exit was 2650 rads, while for a retention time of 10 seconds the dose to a crew 500 feet from the nozzle exit was 185 rads. For the most probable retention time of 0.1 second and a crew separation distance of 250 feet, the dose was 2200 rads. The equivalent attenuation of 3 inches of lead is needed for the most severe case to protect the crew from the rocket plume. This amount of attenuation would probably be provided by the vehicle structure, propellant, fuel, equipment, and stores.

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 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 problems. Problem one, there is a microscopic amount of plume material that has sufficient kinetic energy to flow back towards the rocket. Some of this material will strike and stick to the rocket. 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 (ref. 1) has estimated this dose and has concluded it would be less than 10^{-3} rads for a typical manned Mars mission.

However, a much larger potential dose source is the fission fragment distribution throughout the entire plume volume. Since the plume contains over 99 percent of the exhausted material, 99 percent of the fission fragments will be in the plume. It is the purpose of this paper to estimate the radiation dose to the crew from the fission fragments in the plume.

There is another radiation source associated with the gas-core reactor, that of the reactor core. This radiation source, along with 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.

ROCKET ENGINE CHARACTERISTICS

Certain exit nozzle conditions were selected in order to make a specific calculation of the radiation dose from fission fragments in the volume. Roback (ref. 2) calculated performance parameters for hydrogen at various stagnation pressures and temperature. Performance parameters were selected which produced a high flow rate of fission

fragments, thereby maximizing the radiation problems. A one million pound propellant storage capacity was selected which is typical of a manned Mars mission. The following table presents these selected values.

TABLE I. - PERFORMANCE PARAMETERS SELECTED FOR ANALYSIS

Thrust, lb	1,000,000
Specific impulse, sec	1,500
Chamber pressure, atm	1,000
Chamber temperature, ^{O}R	10,000
Reactor power, MW	41,900
Propellant storage, lb	1,000,000
Engine firing time, sec	1,500

For these performance parameters and from table 168 of Roback (ref. 2), nozzle exit properties were obtained for a nozzle exit to throat pressure ratio of 10^{-3} and are presented in the following table.

TABLE II. - NOZZLE EXIT GAS PROPERTIES USED IN ANALYSIS

Exit temperature, ^{O}R	3460
Exit density, lb/ft^3	7.978×10^{-4}
Exit velocity, ft/sec	48507
Exit Mach number	4.587
Exit molecular weight	2.015

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 FISSION FRAGMENT FORMATION

The number of fission fragments formed is calculated using equation (2.49) of Glasstone and Sesonski (ref. 3).

$$\text{Reactor Power}_{(watts)} = \frac{\text{fissions per second}}{3.1 \times 10^{10}} \tag{1}$$

Since reactor power and engine running time are known, the number of fission fragments produced 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.

TABLE III. - CONTENTS OF GAS-CORE PLUME

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

It is assumed that the fraction of fission fragments is constant throughout the entire plume volume and its value is

$$P_{FF} = \frac{3.896 \times 10^{24}}{1.36 \times 10^{32}} = 2.865 \times 10^{-8} \tag{2}$$

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 volume must be known. It has been shown in nozzle plume flows the mass flux ρV varies inversely as the square of the distance from the source point. Hill and Draper (ref. 4) have shown the density in a plume can be closely approximated by

$$\rho = \frac{4\rho_e M_e B}{\left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{1/2} \left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/2(\gamma-1)}} \left(\frac{r_e}{r}\right)^2 e^{-\lambda^2(1-\cos\theta)^2} \tag{3}$$

where the coordinates r and θ are shown in figure 2; ρ is the 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. 4) we have

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

$$\lambda = \frac{1}{\sqrt{\pi}\left(1 - \dfrac{C_F}{C_{F_{max}}}\right)} \tag{5}$$

where C_F and $C_{F_{max}}$ are thrust coefficients and are evaluated using equations (4.33) and (4.34) of Shapiro (ref. 5). Using these values and those of table II, B and λ are equal to 0.324 and 7.99, respectively.

RADIATION DOSE TO THE CREW

The radiation dose to the crew is calculated using the basic equation from Glasstone and Sesonski (ref. 3).

$$\text{Radiation Dose Rate (rad/hr)} = \frac{6CE_\gamma}{\vec{L} \cdot \vec{L}} \tag{6}$$

where C is the source strength at the point $P_{r, \theta, \varphi}$ in the plume in curies, E_γ is the photon energy in MeV, and $\vec{L}$ is the vector distance in feet from the point $P_{r, \theta, \varphi}$ to the crew. Figure 3 shows the relation between $\vec{L}$, $P_{r, \theta, \varphi}$ and the location of the crew.

The energy relase of U_{235} fission fragments ($F(t)$), is given in reference 5 and varies from approximately 0.6 MeV per fission per second at 0.01 seconds after fission to 0.08 MeV at 10.0 seconds after fission. The number of fission fragments at point $P_{r, \theta, \varphi}$ is given by

$$\text{Number of Fissions at } P_{r, \theta, \varphi} = \frac{1}{2} \frac{\rho A_o P_{FF}}{m} \tag{7}$$

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

6

The value of L as shown in figure 3 is given by

$$\vec{L} \cdot \vec{L} = z^2 + 2zr \cos \theta + r^2 \qquad (8)$$

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
equations (6), (7), and (8) and using the identity that one curie equals
3.7×10^{10} disintegrations per second.

Radiation Dose Rate from $P_{r,\theta,\varphi}$ in rads per hour is,

$$\text{Radiation Dose Rate}\left(\frac{\text{rads}}{\text{hr}}\right) = \frac{6F(t)}{3.7 \times 10^{10}}\left(\frac{1}{2} \frac{\rho A_o P_{FF}}{m}\right)\frac{1}{\vec{L} \cdot \vec{L}} \qquad (9)$$

Total Radiation Dose Rate in rads per hour is,

$$\int_{r=r_e}^{r'} \int_{\theta=0}^{\pi/2} \int_{\varphi=0}^{2\pi} \frac{3F(t)}{3.7 \times 10^{10}}\left(\frac{\rho A_o P_{FF}}{m}\right)\frac{(144)(2.54)^2}{\vec{L} \cdot \vec{L}} r^2 \sin\theta \, d\varphi \, d\theta \, dr \qquad (10)$$

This simplifies to

Total Radiation Dose Rate in rads per hour is

$$\int_{r=r_e}^{r'} \int_{\theta=0}^{\pi/2} (\text{Constant}) \frac{F(t)e^{-\lambda^2(1-\cos\theta)^2} \sin\theta}{r^2(z^2 + 2z + \cos\theta + r^2)} d\theta \, dr \qquad (11)$$

where the constant is equal to

$$\text{Constant} = 3.26 \times 10^{10} \frac{\rho_e M_e Br_e^2}{m\left(1 + \frac{\gamma-1}{2} M_e^2\right)^{1/2}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/2(\gamma-1)}} \qquad (12)$$

At any point in the plume the age of a fission fragment is

$$t = t_o + \frac{r}{V} \qquad (13)$$

where t is the age of the fission fragments in seconds, t_o is the re-
tention time of the fission fragments in the reactor core in seconds,
r is the distance from the nozzle exit to the fission fragment, and
V is the exit gas velocity. The exit gas velocity is assumed constant
throughout the plume volume. Therefore, the total radiation dose rate is

Total Radiation Dose Rate in rads per hour is,

$$\text{Constant} \int_{r=r_e}^{r'} \int_{\theta=0}^{\pi/2} F(t) \frac{e^{-\lambda^2(1-\cos\theta)^2} \sin\theta}{(z^2 + 2rz\cos\theta + r^2)} \, d\theta \, dr \qquad (14)$$

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 by more than
1 percent. The resultant value of r' was 71.4×10^5 centimeters which
is approximately 45 miles.

DISCUSSION OF RESULTS

The radiation dose rate from the fission fragments in the plume to the
crew was calculated for two crew positions, that of 500 feet and 250 feet from
the nozzle exit. For a storage capacity of one million pounds of hydrogen,
500 feet from the nozzle exit is a maximum distance; however, a value of
250 feet was also used to see how this shorter distance to the nozzle would
effect the radiation dose rate. Also, in these calculations the radiation
from the fission fragments that are in the portion of the plume which is
shielded from the crew by the reactor is not included. The diameter of
the reactor is 17 feet (ref. 6) and figure 4 illustrates the portion of the
plume which is shielded from the crew by the reactor.

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 were
varied from 0.01 to 10.0 seconds. The most probable retention time
in the core would be 0.1 second.

The results of the radiation dose against retention time for the two
crew distances are shown in figure 5. It can be seen that at 250 feet
from the nozzle exit the crew will receive a large radiation dose of
2650, rads if the fission fragment retention time is 0.01 second. A
retention time of 10 seconds and a crew distance from the nozzle exit
of 500 feet results in a radiation dose of 185, rads. For the most
probable retention time of 0.1 seconds and a crew separation distance of
250 feet, the crew dose is 2200, rads. This radiation dose occurs dur-
ing the firing time of 1500 seconds.

The radiation dose to the crew is not tolerable. If we assume 1 inch
of lead will reduce the radiation level by one order of magnitude then
3 inches of lead or its equivalent are needed to bring the radiation level
below 3 rads for the worst case. Part of that equivalent attenuation will
be the spacecraft structure, hydrogen propellant, uranium fuel, equip-
ment, and stores.

SUMMARY OF RESULTS

Analytical calculations are performed to determine the radiation
dose rate to the crew of a gas-core nuclear rocket from the fission frag-
ments located throughout the plume volume. 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 pro-
pellant consumption of one million pounds. The age of the fission frag-
ments was a function of retention time in the reactor and of location in
the plume. Calculations were carried out for crew compartments - nozzle
exit separation distances of 250 and 500 feet. The following results were
obtained.

1. For a crew-nozzle separation distance of 500 feet and a fission
fragment retention time of 0.1 second, the crew radiation dose would be
1180, rads, At 250 feet of separation, the dose would be 2200, rads.

2. The crew dose rate varies with the retention time of the fission fragments in the reactor core, so retention time is an important parameter.

3. The calculated radiation dose to the crew requires an equivalent attenuation of 3 inches of lead to protect the crew of a gas-core nuclear rocket from its plume. This attenuation will probably be provided by the spacecraft structure, propellant, uranium fuel, equipment and stores.

APPENDIX - SYMBOLS

A_o	Avogadro's number
B	defined by equation (4)
C	source strength in Curies
C_F	thrust coefficient
$C_{F_{max}}$	maximum thrust coefficient
E_γ	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}	fraction of fission fragments at point $P_{(r, \theta, \varphi)}$
R	gas constant
r, θ, φ	spherical coordinates
T	temperature
t	time
t_o	retention time of fission fragments in reactor core
V	mean velocity of particles in plume
z	distance from crew to nozzle exit
γ	ratio of specific heats
λ	defined by equation (5)
ρ	mass density

Subscript:

e	nozzle exit

11

REFERENCES

1. Masser, Charles C.: Radiation Hazard from Backflow of Fission Fragments from the Plume of a Gas-Core Nuclear Rocket. Presented at the Symposium on Research on Uranium Plasmas and Their Technological Applications. Gainesville, Florida, January 7-10, 1970. Available as NASA TM X-52743.

2. Roback, R.: Theoretical Performance of Rocket Engines Using Gaseous Hydrogen in the Ideal State at Stagnation Temperatures up to 200,000° R. NASA CR-696, 1967.

3. Glasstone, Samuel and Sesonske, Alexander: Nuclear Reactor Engineering. Third Edition, D. Van Nostrand Co., Inc., 1967.

4. Hill, Jacques F. F.; and Draper, James Stark: Analytical Approximations for the Flow from a Nozzle into a Vacuum. J. Spacecraft Rockets, Vol. 3, No. 10, October 1966, pp. 1552-1554.

5. Jaeger, R. G., Ed., Engineering Compendium on Radiation Shielding. Vol. I, Springer-Verlag New York Inc., 1968.

6. Ragsdale, Robert G.: Some Fuel Loss Rate and Weight Estimates of an Open Cycle Gas-Core Nuclear Rocket Engine. Presented at the AIAA Sixth Propulsion Joint Specialists Conference. San Diego, California, June 15-19, 1970. Available as NASA TM X-52775.
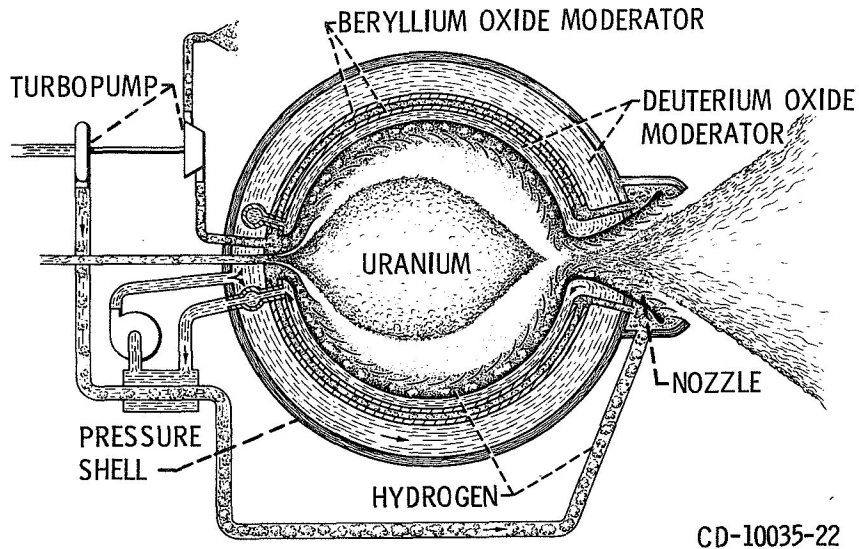
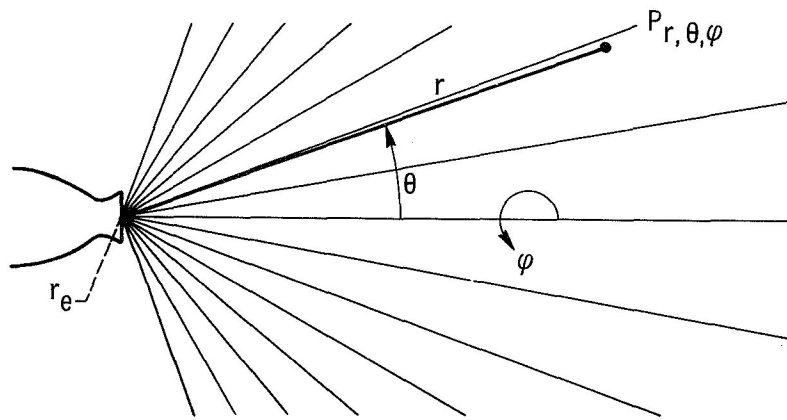Figure 1. - Conceptual gas-core nuclear rocket engine.

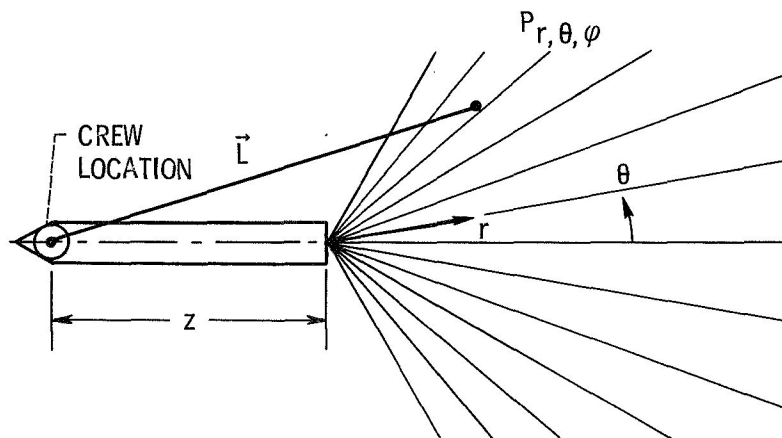Figure 2. - Spherical coordinate system used in analysis.

Figure 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.
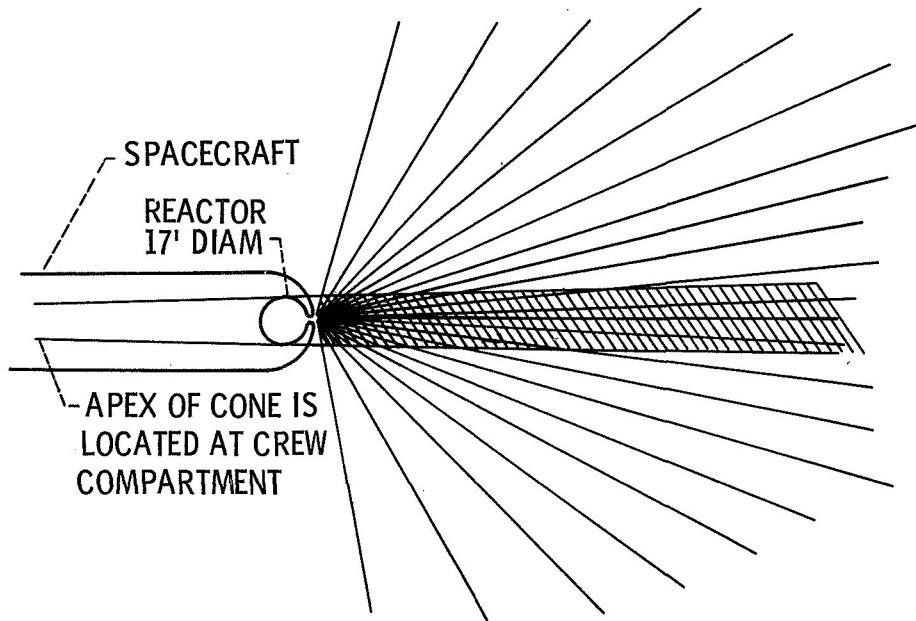
Figure 4. - Schematic drawing of the plume showing the portion which is included in the calculation of crew radiation dose.
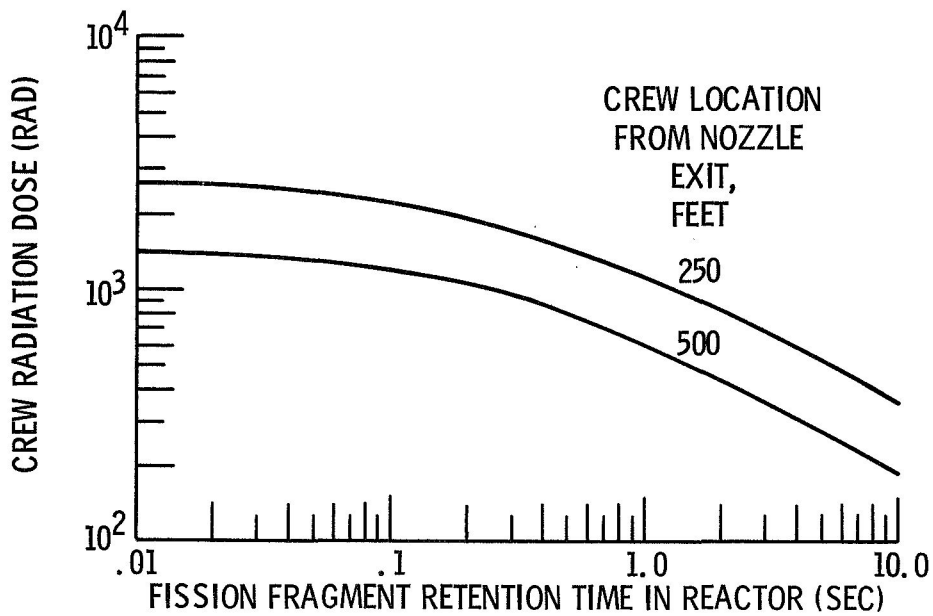

Figure 5. - Radiation dose to the crew from fission fragments in the plume.