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# CREW RADIATION DOSE FROM A GAS-CORE NUCLEAR ROCKET PLUME

by Charles C. Masser
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TECHNICAL PAPER proposed for presentation at Sixteenth Annual Meeting of the American Nuclear Society
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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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, $lb/ft^3$ | $7.978\times10^{-4}$ |
| 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).

$$\text{Reactor Power}_{\text{(watts)}} = \frac{\text{fissions per second}}{3.1\times10^{10}} \tag{1}$$

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 | $3.896\times10^{24}$ | 1.68 lb |
| Hydrogen propellant | $1.36\times10^{32}$ | $10^6$ lb |
| Unfissioned uranium | $1.163\times10^{28}$ | $10^4$ lb |

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

$$P_{FF} = \frac{3.896\times10^{24}}{1.36\times10^{32}} = 2.865\times10^{-8} \tag{2}$$

## 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 $\rho V$ 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 $\theta$ are shown in figure 2; $\rho$ is the density at any point in the plume; $\rho_e$ is exit density; $M_e$ is exit Mach number; $\gamma$ is the ratio of specific heats; and B and $\lambda$ 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 $\lambda$ 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, $E_\gamma$ 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 $\rho$ 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.

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

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

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 $3.7\times10^{10}$ disintegrations per second.

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

$$\text{Radiation Dose Rate}\left(\frac{\text{rads}}{\text{hr}}\right) = \frac{6F(t)}{3.7\times10^{10}}\left(\frac{1}{2}\frac{\rho A_o P_{FF}}{m}\right)\frac{1}{\vec{L}\vec{L}} \tag{9}$$

Total Radiation Dose Rate in rads per hour is,

$$\int_{r=r_e}^{r'}\int_{\theta=0}^{\pi/2}\int_{\varphi=0}^{2\pi} \frac{3F(t)}{3.7\times10^{10}}\left(\frac{\rho A_o P_{FF}}{m}\right)\frac{(144)(2.54)^2}{\vec{L}\cdot\vec{L}} r^2 \sin\theta \, d\varphi \, d\theta \, dr \tag{10}$$

This simplifies to

Total Radiation Dose Rate in rads per hour is

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

where the constant is equal to

$$\text{Constant} = 3.26\times10^{10} \frac{\rho_e M_e B r_e^2}{m\left(1 + \frac{\gamma - 1}{2}M_e^2\right)^{1/2}\left(\frac{2}{\gamma + 1}\right)^{\gamma+1/2(\gamma-1)}} \tag{12}$$

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

$$t = t_o + \frac{r}{V} \tag{13}$$

where $t$ is the age of the fission fragments in seconds, $t_o$ is the retention 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,

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

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 $71.4\times10^5$ 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 during 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, equipment, 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 fragments 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 propellant consumption of one million pounds. The age of the fission fragments 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 |
| $E_\gamma$ | 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 |
| $r, \theta, \varphi$ | 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 |
| $\gamma$ | ratio of specific heats |
| $\lambda$ | defined by equation (5) |
| $\rho$ | mass density |

Subscript:

| | |
|---|---|
| e | nozzle exit |

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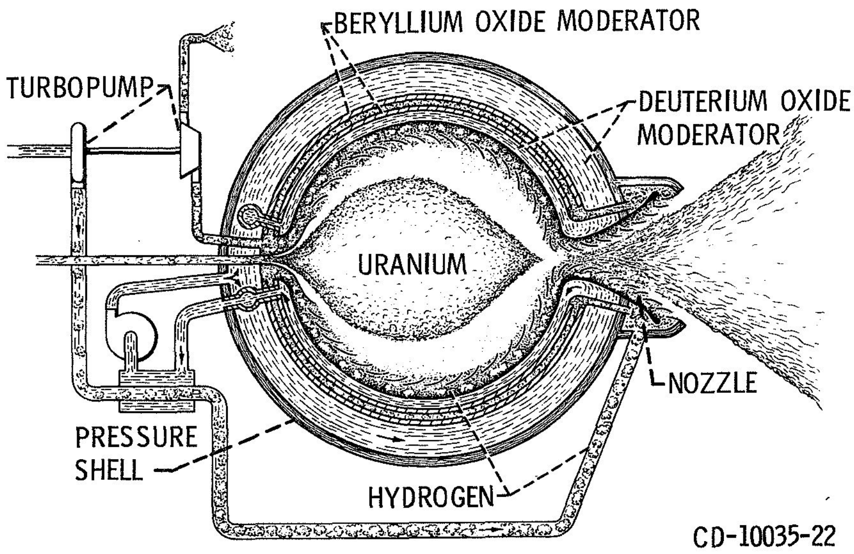


Figure 1. - Conceptual gas-core nuclear rocket engine.

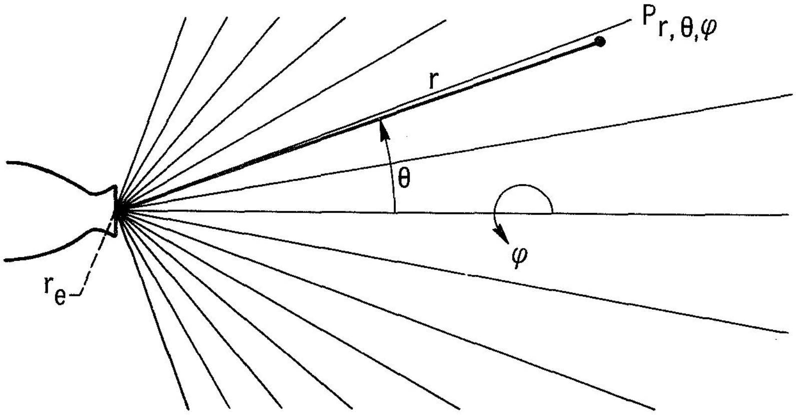


Figure 2. - Spherical coordinate system used in analysis.

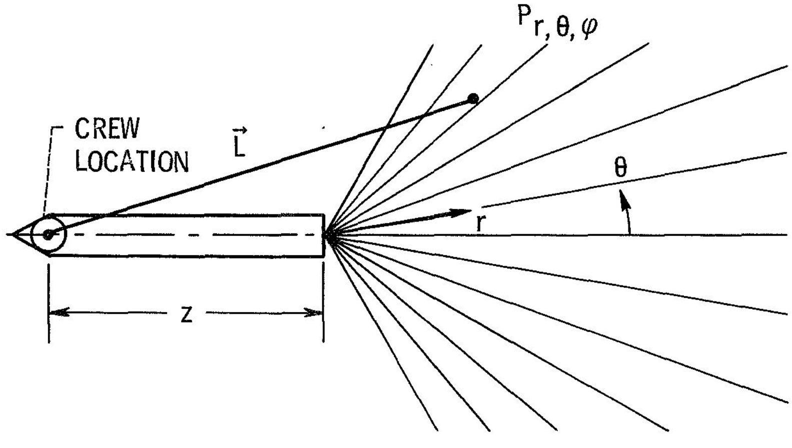


Figure 3. - Relationship between point $P_{r,\theta,\varphi}$, the distance to the crew, $\vec{L}$, and the location of the crew from the nozzle exit, z.

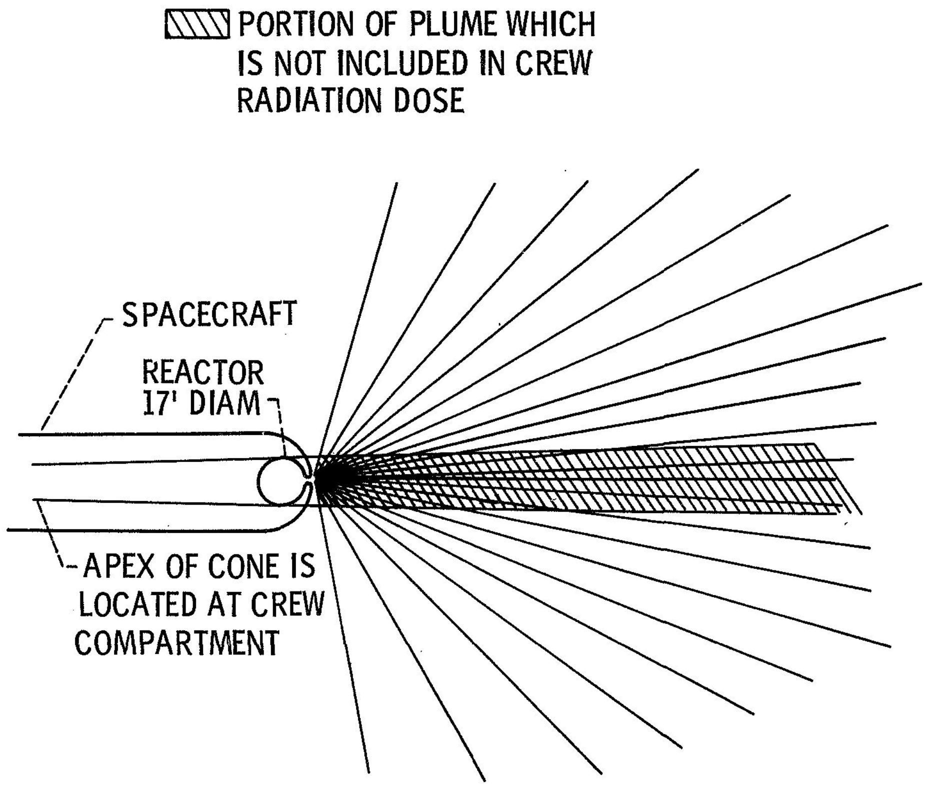


Figure 4. - Schematic drawing of the plume showing the portion which is included in the calculation of crew radiation dose.

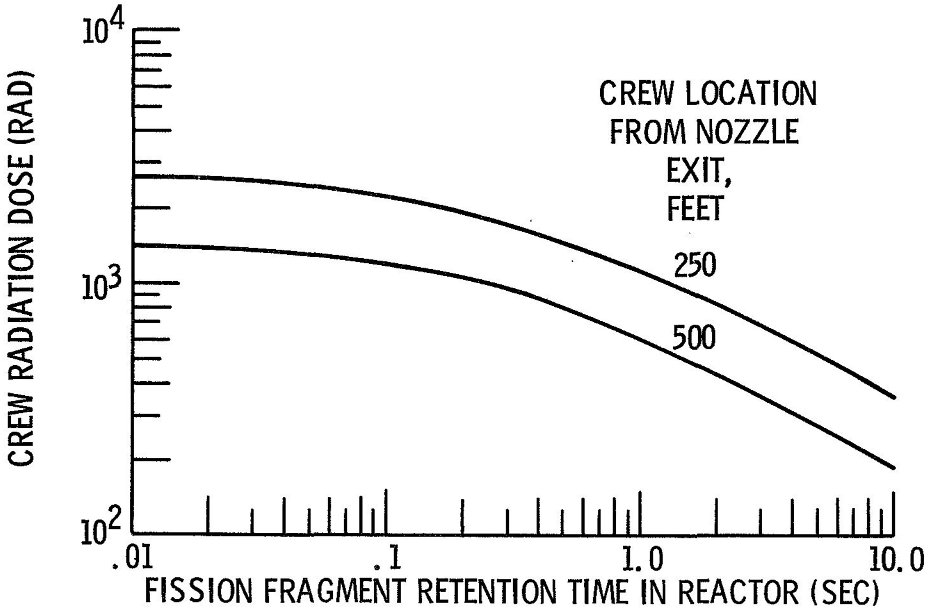


Figure 5. - Radiation dose to the crew from fission fragments in the plume.