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AN ESTIMATE OF THERMAL FLUX FROM THE JET OF A PROPOSED NUCLEAR ROCKET ENGINE

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ABSTRACT

Calculated here is an estimate of the thermal flux from the jet of a nuclear rocket engine developed at Los Alamos Scientific Laboratory and soon to be tested at full power. It is expected that radiant energy received on the ground near the test stand may be less than 0.04 cal/cm^2/sec, and certainly less than 1.5 cal/cm^2/sec.

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AN ESTIMATE OF THERMAL FLUX FROM THE JET OF A PROPOSED NUCLEAR ROCKET ENGINE

Introduction

At Los Alamos, a nuclear-powered rocket engine has been developed to the point where testing at full power appears to be feasible. The engine is to be mounted in a test stand so that the jet from the engine will flow off into air. The flame will consist of a relatively cold jet tooped by a plume of combustion products resulting from the burning of the propellant in air. It is now pertinent to know if the expected thermal radiation from the jet and plume will cause experimental difficulties on the ground near the test stand.

The proposed reactor will weigh about 1-1/2 tons. Its nuclear power rating will be 2700 megawatts, and it can be expected to run for 3 minutes. Internal gas temperature is expected to be about 3000°K, and internal pressure about 1600 psi. The nozzle will be about 1 foot in diameter and will expand the gas to nearly atmospheric pressure. The flow of propellant (ammonia) will be about 600 lb/sec. At full power, exhaust gases will be H_2 and N_2 in the ratio 3/14 by weight or 3/1 by volume.

In this paper is calculated thermal flux on the ground near the rocket stand originating with the jet which is directed vertically upward. It is believed that the jet, consisting of hot ammonia gas or its dissociated products, H_2 and N_2, rises to some altitude before it bursts into flame. The structure of this jet and plume is not understood as yet so the calculation will assume a model to which

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can be ascribed certain parameters that will be adjusted to fit the real case. For the model, the following assumptions are made:

1. The region of hot gas may be described by a geometric surface which is the actual thermal emitter.

2. This surface behaves as a black body.

3. The surface has cylindrical-symmetry about the vertical Z-axis (Fig. 1).

4. The temperature of the surface is a function of z only.

By analogy with other flames, it seems reasonable that this jet will burn at the surface all along its length until enough air can be entrained to permit complete burning. Roughly, then, one expects to see a hot plume atop a much cooler, rather well-defined column of gas. If the temperature of the gas in the engine is T_e and its pressure is P_e and if it expands adiabatically to ambient pressure P_o in going through the nozzle, then its temperature before any burning will be

$$T = T_e \, (P_e/P_o)^{\frac{\gamma-1}{\gamma}} \quad .$$

At present, estimated values for T_e, P_e, and P_o are 3050°K, 1900 psi, and 13 psi, respectively. The corresponding exterior jet temperature is about 730°K.

Effective temperature of the jet will almost certainly be greater than this due to the surface burning. It probably will increase with altitude until the main flame forms. To take some numbers, let us choose 800°K and 1000°K for the jet and let the temperature be constant from the nozzle to the base of the plume at altitude a. The altitude of the nozzle can be taken as zero without serious consequences.

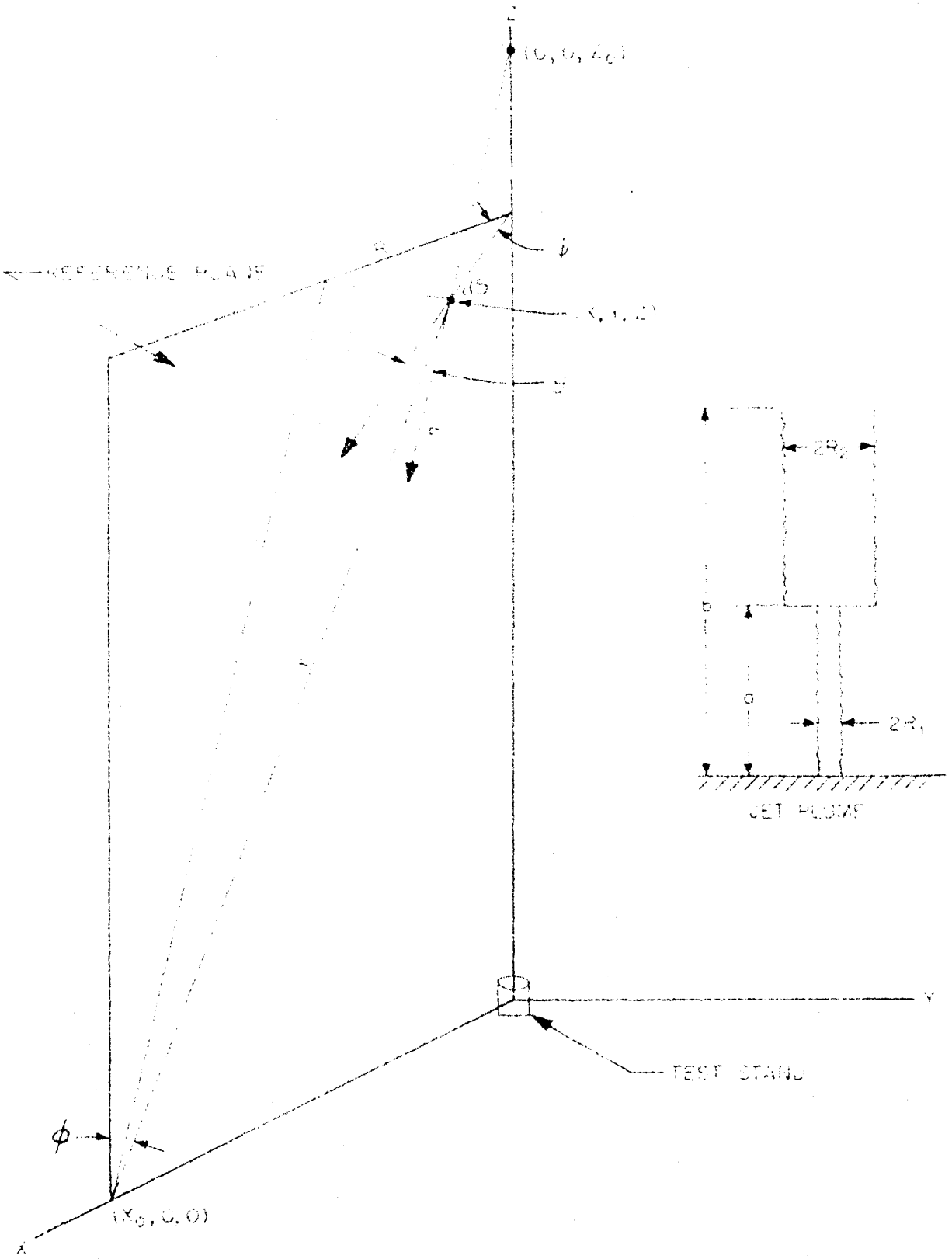

FIGURE 1 - ANALYTICAL SET-UP FOR CALCULATION

The plume will consist of burning ammonia or, if the reactor is running hot, of burning hydrogen and nitrogen in air. The temperature of an oxyhydrogen flame is about 2800°C. For our example, however, the oxygen as well as the hydrogen gas is diluted with nitrogen so that it is unlikely that the temperature increase could be much over 1000°C. It might be considerably less. We shall assume that the plume has a temperature of about 2000°K and will extend from a to its effective top b, Fig. 1.

The jet and plume have now been assigned temperatures and limited in altitude by values a and b. Upper limit b has been estimated to be about 400 feet. For an appropriate range of a, we choose 50 feet and 200 feet, the latter having been drawn from crude observation of chemical rocket operation. None of these values is considered very certain, but each seems reasonable enough for our present purpose.

Geometrical Consideration

Let dS be a differential element of area somewhere on the surface of the flame. Assuming that it emits as a black body, a point X_o on the ground (Fig. 1) will receive a flux contribution

$$dF(X_o) = \frac{\sigma T^4(Z) \cos\theta \cos\phi \, dS}{r^2}$$

where r is the distance from dS to X_o, θ is the angle between r and the normal to dS, and ϕ is the angle between r and the normal to the ground at X_o. From Fig. 1,

$$\cos\theta = \frac{(Z-0)(X_o-X) + (Y-0)(0-Y) + (Z-Z_o)(0-Z)}{\sqrt{X^2+Y^2+(Z-Z_o)^2}\ \sqrt{(X_o-X)^2+Y^2+Z^2}}$$

$$= \frac{X_c R \cos\Psi - R^2 + (Z-Z_c)(Q-Z)}{\sqrt{h^2+(Z_o-Z)^2}\,\sqrt{X_c^2-2X_c R\cos\Psi + h^2+Z^2}}$$

where $R^2 = X^2+Y^2$ is the radius of the circle through dS which forms the cross section of the flame. Also,

$$\cos\phi = \frac{Z}{\sqrt{(X-X_c)^2 + Y^2 + Z^2}} \quad .$$

The differential element is

$$dS = R\sqrt{1 + (dR/dZ)^2}\, d\Psi dZ$$

where $R = R(Z)$.

If all these quantities are substituted into the flux equation, we find that the normal flux at X_c is given by the integral over Ψ and Z of the product $\sigma T^4(Z)$ and a geometry factor $G(\Psi,Z)$

$$F(X_o) = \int_\Psi \int_Z \sigma T^4(Z)\, G(\Psi,Z)\, d\Psi dZ \quad .$$

Integration will not be possible analytically unless some simplifications are made in the integrand.

Simplified Model

Any number of arbitrary flame models can be devised, all of which can be made to yield the same flux by properly adjusting certain parameters. At this time, however, the flux is unknown. A model must be chosen which is sufficiently simple to permit integration and which is reasonable enough to lend some confidence to the calculated flux. We choose the following:

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$$T(Z) = T_1 \qquad 0 \leq Z \leq a$$

$$T(Z) = T_2 \qquad a \leq Z \leq b$$

and

$$R(Z) = R_1 \qquad 0 \leq Z \leq a$$

$$R(Z) = R_2 \qquad a \leq Z \leq b \quad .$$

Thus $dT/dZ = 0$, and $Z - Z_o = 0$. To facilitate integration, we make $R \ll X_o$ which means that, with $R = 2$ feet, for reasonable accuracy X_o may be as little as 20 feet. Also, the contribution of $2X_o R \cos \Psi$ relative to $X_o^2 + Z^2$ is small. With these simplifications, we arrive at a general integral

$$F(X_o) = \sigma T^4 X_o R \int_\Psi \int_Z \frac{Z \cos \Psi \, d\Psi \, dZ}{\left[X_o^2 + Z^2\right]^2} \quad .$$

Now with $R \ll X_o$, Ψ ranges essentially from $-\pi/2$ to $+\pi/2$ so that finally we integrate

$$F(X_o) = 2\sigma T^4 X_o R \int_{Z_1}^{Z_2} \frac{Z dZ}{\left[X_o^2 + Z^2\right]^2} \quad ,$$

or the flux is made up of two terms each of the form

$$F = \sigma T^4 X_o R \left[\frac{Z_2^2 - Z_1^2}{(X_o^2 + Z_1^2)(X_o^2 + Z_2^2)} \right] \quad .$$

Correction Term

The curve $R(Z)$ was discontinuous at $Z = a$ so there should be a contribution from the lower surface of the plume not yet accounted for which might be significant

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at close-in positions. We shall add this as a correction factor. Thus we expect to find the contribution

$$F'(X_o) = \sigma T_2^4 \int_0^S \frac{\cos^2 \theta \, dS}{r^2} \quad .$$

To a good approximation

$$\cos^2 \theta = a^2/r^2 \quad ,$$

and since r is essentially independent of the position of the element dS, we have for the correction factor, neglecting a small shadow zone,

$$F'(X_o) = \frac{\sigma T_2^4 a^2 \pi (R_2^2 - R_1^2)}{(X_o^2 + a^2)^2} \quad .$$

Calculations

Assembling all three terms, we now have

$$F(X_o) = \sigma T_1^4 X_o R_1 \left[\frac{a^2}{X_o^2(a^2+X_o^2)}\right] + \sigma T_2^4 X_o R_2 \left[\frac{b^2 - a^2}{(b^2+X_o^2)(a^2+X_o^2)}\right] + \frac{\pi \sigma T_2^4 a^2 (R_2^2 - R_1^2)}{(a^2 + X_o^2)^2} \quad .$$

Numerical values are:

$\sigma = 5.7 \times 10^{-5}$ erg/cm^2/deg^4/sec,

$T_1 = 800$ or 1000°K,

$T_2 = 2000^\circ$K,

$a = 50$ feet (1510 cm) or 200 feet (6070 cm),

$b = 400$ feet (12,140 cm),

$R_1 = 2$ feet = 61 cm, and

$R_2 = 6$ feet = 183 cm.

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Calculations for distances from 25 to 300 feet are shown in Table I. It makes very little difference whether or not jet temperature is 800°K or 1000°K. However, if the heavy burning occurs as low as 50 feet, radiation on the ground is increased by almost an order of magnitude over what it was when the heavy burning occurred at 200 feet.

TABLE I

a = 50 feet			a = 200 feet		
	$F(X_o)$ in cal/cm²/sec			$F(X_o)$ in cal/cm²/sec	
X_o	T_1 = 800°K	T_1 = 1000°K	X_o	T_1 = 800°K	T_1 = 1000°K
25	1.72	1.77	25	0.16	0.23
50	1.53	1.54	50	0.19	0.22
75	1.26	1.27	75	0.22	0.24
100	1.01	1.01	100	0.23	0.25
125	0.84	0.84	125	0.24	0.24
150	0.69	0.69	150	0.23	0.23
200	0.49	0.49	200	0.21	0.21
300	0.27	0.27	300	0.15	0.15
400	0.16	0.16	400	0.10	0.10

Discussion

It has been assumed that the hot gases of the jet and plume can be represented by luminous surfaces and that black body radiation theory can be applied. There is at least some evidence to the contrary. Banister* has ignited a hot jet of hydrogen

*John Banister, private communication.

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in air, and in sunlight it was not luminous to the eye. It is quite possible that most of the radiant energy in the rocket flame will be emitted in bands characteristic of the chemical reaction, i.e., that the gases will not be luminous in the ordinary sense of the word. Actual energy received on the ground would be less (and possibly very much less) than that estimated here. Arooste and Benton* have shown that for hydrogen gas at high temperatures the emissivity at any given frequency is not greater than that predicted by a black body at the same temperature, but that at many frequencies the emissivity is less. Total energy radiated in such a case is thereby reduced from black body.

More practically, the emissivity of water vapor has been studied by Hottel and is given in McAdams' Heat Transmission‡ in the form of a table with $P_g L$ as a parameter, where P_g is the partial pressure of H_2O, and L is a characteristic dimension of the emitter. Since L = 12 feet and P_g is less than 1/4 atmosphere, let us choose $P_g L = 2$. Then at 2000°K, the emissivity is 0.16. If we assume that the radiation is entirely from water vapor formed by burning hydrogen in air, the flux is very much reduced, as is plotted in Fig. 2.

A crude complementary calculation may be made by first estimating the chemical power in the jet. Then the flux at a distance r is given by

$$\frac{\text{Power (cal/sec)}}{4\pi r^2} = \text{flux} \quad .$$

Let us therefore make the following assumptions about the reaction:

$$2NH_3 \longrightarrow 3H_2 + N_2 \quad ,$$

*Arooste and Benton, JAP 27 117 (February 1956).
‡McAdams, William H., Heat Transmission, McGraw Hill, Third Ed, 1954.

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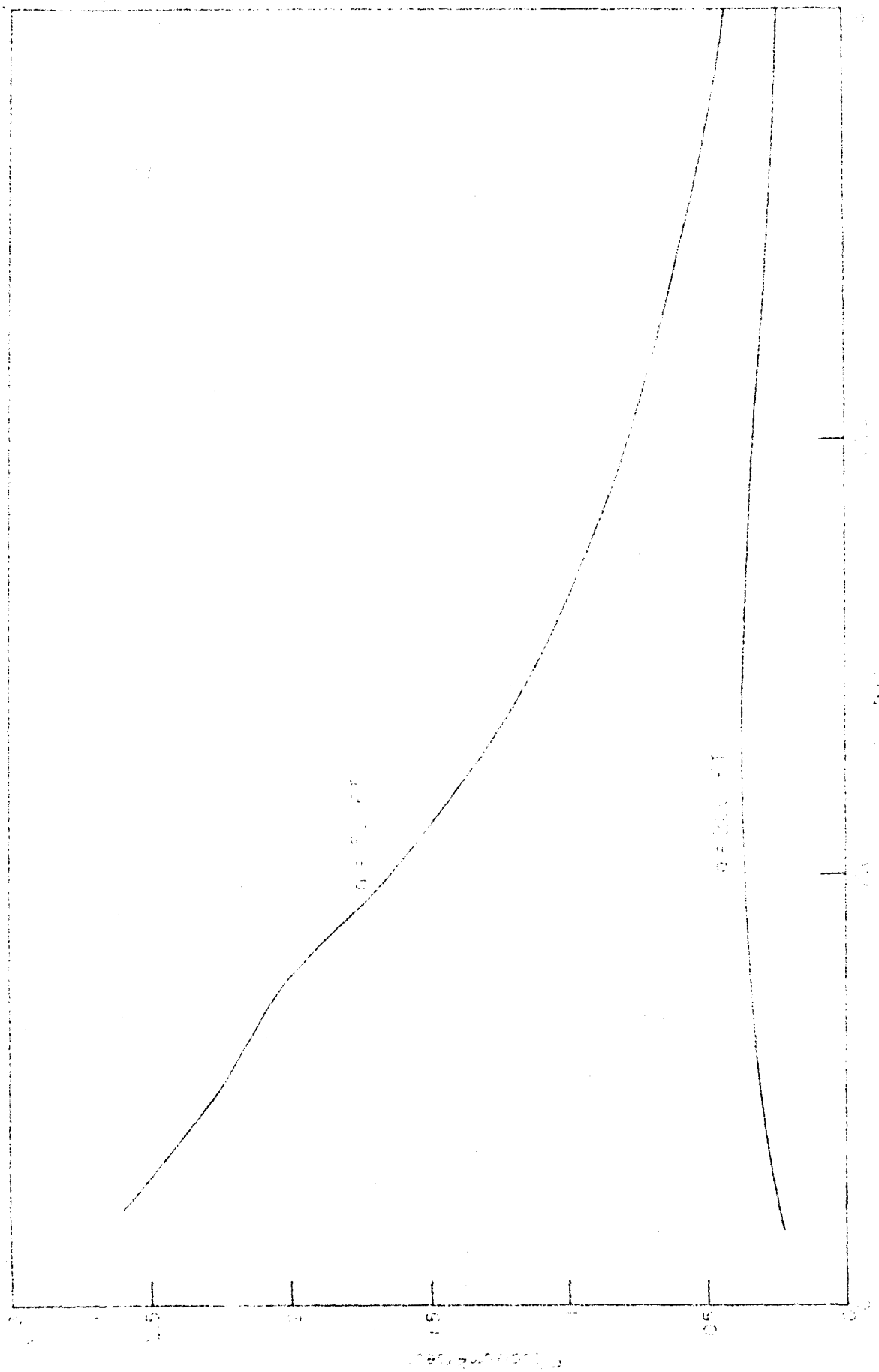

FIGURE [illegible] - CALCULATED FLUX [illegible] CAL/CM²/SEC VS THE GROUND VS DISTANCE FROM TEST STAND

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and the heat for this reaction is supplied by the engine. Then

$$2H_2 + O_2 \rightarrow 2H_2O \quad \Delta H = -57 \text{ kcal}$$

$$N_2 + 2O_2 \rightarrow 2NO_2 \quad \Delta H = +7 \text{ kcal} \quad .$$

Equilibrium is established only by the reactions going completely in the forward direction. No correction for temperature is made because we assume that all the reaction energy is radiated away.

Now every 4 moles of NH_3 yield 3x57 - 2x7 = 157 kcal exothermically. Thus 39,000 calories of thermal energy are assumed radiated per mole of NH_3 expelled from the motor. The number of moles expelled is obtained from the 600-pound-per-second flux.

$$\frac{600 \times 450}{10} = 27{,}000 \text{ moles } NH_3/\text{sec} \quad .$$

Thus the burning of NH_3 yields 10.5×10^8 cal/sec. At a height of 50 feet, this would give a flux of $10.5 \times 10^8 / 27 \times 10^6 = 39$ cal/cm^2/sec. At 200 feet, it becomes 2.4 cal/cm^2/sec.

By this calculation, the total chemical energy available during a five-minute run is $300 \times 1.05 \times 10^9 / 10^{12} = 0.3$ kt. Several comments are now pertinent:

1. The chemical reaction is undoubtedly oversimplified, yielding a much higher energy than probably will occur.

2. The burning is assumed to take place in a small volume.

3. It is assumed that all the chemical energy is available for thermal radiation without attenuation.

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In view of these several uncertainties, at the present time such a calculation cannot be taken very seriously.

Conclusion

On the basis of this calculation, it is expected that radiant energy received on the ground near the test stand will be less than 1.5 cal/cm^2/sec and very likely will be less than 0.04 cal/cm^2/sec, which is entirely negligible. Radiant energy received from the sun is 0.03 cal/cm^2/sec.

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