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NASA PROGRAM APOLLO WORKING PAPER NO. 1181

ESTIMATION OF FIREBALL FROM SATURN VEHICLES FOLLOWING FAILURE ON LAUNCH PAD

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

AUGUST 3, 1965

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ESTIMATION OF FIREBALL FROM SATURN VEHICLES FOLLOWING FAILURE ON LAUNCH PAD

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SUMMARY

The design of an Apollo launch escape system requires that estimates be made of the hazards involved. One of the hazards is a failure of the Apollo launch vehicle resulting in an explosion and fire. Estimates of the fireball characteristics are presented in this report. Those parameters considered were: maximum fireball size, duration of the fireball, surface temperature, emissivity, thermal radiation, total radiant heat, atmospheric attenuation and fireball rise characteristics.

Data were collected and analyzed statistically where possible to provide an estimate of the parameters. Thermal radiation and atmospheric attenuation were treated mathematically since no data were available to treat these parameters empirically.

INTRODUCTION

An estimate of the characteristics of the fireball resulting from a failure of the Apollo launch vehicle (Saturn IB and Saturn V) was needed to determine the possibility of overheating the main parachutes in some escape modes. The results of the study initiated to provide the estimates needed to properly analyze this problem are presented in this report.

The study contains a collection of data used to evaluate the fireball parameters associated with a Saturn launch pad abort. Those parameters discussed in this report are: fireball size, duration, surface temperature, emissivity, thermal radiation, total radiant heat, atmospheric attenuation, and rise rate. The data representing the extent of the present knowledge of propellant fireballs are largely empirical and have been analyzed statistically where possible. The section on thermal radiation was treated mathematically since there was no empirical data available. This mathematical analysis was based on Lambert's Law for thermal radiation and the Stephan-Boltzmann law relating radiation intensity to the fourth power of the absolute temperature. Conclusions on atmospheric attenuation were also taken from a mathematical treatment of the subject.

Accurate theoretical analysis of the parameters necessary to describe the fireball would be desirable to more accurately define some of the phenomenon. Work in this area is anticipated, but it is felt that many of the parameters may defy an accurate theoretical treatment. The fireball parameters depend on such variables as failure mode, rate of propellant mixing, convective mixing of air and the combustion products, accurate chemical composition of the product gases, amount of fuel participating in the reaction, explosive yield, etc. The above variables can have a pronounced effect on the results, but variance resulting from these variables is generally unknown. Therefore, an accurate analysis by theoretical methods may not be possible and should be used principally to supplement the empirical data.

The fireball hazards associated with the Saturn V and Saturn IB vehicles were evaluated by assuming that all the propellant in the booster stages participate in the formation of the fireballs. This means that the propellant in the S-IC, S-II, and S-IVB stages would participate in the Saturn V fireball. For a Saturn IB Fireball, the propellants in the S-IB and S-IVB stages would be consumed. The amount of propellant participation is fairly realistic for this type of event. Large overpressures from detonations and the intense heat from both detonations and burning would cause failure of any propellant tanks not initially involved. This action would make all the fuel available during the formation of the fireball. During this period the fuel is burning, thus maintaining a pressure unbalance that usually results in an expansion of the fireball.

DISCUSSION

Maximum Fireball Size

The size of the fireball in a destruct or failure event is primarily a function of the amount of propellant involved. All the propellants in the booster stages of the Saturn vehicles were assumed to be consumed in the formation of the fireballs for this study. The fireball diameters for the Saturn V and Saturn IB were predicted from data on fireball sizes taken from references 1 and 2. These data from experimental tests and vehicle failures are the fireball diameters at maximum expansion. On figure 1 of this report can be found a plot of fireball size data. These data were analyzed statistically by a least squares regression analysis. Since the propellant weight is the principal variable, the statistical analysis produces an equation relating the weight of propellant to the fireball diameters. Using logarithms of the values, a linear equation was fitted which adequately represented the data. A linear or first degree equation is the most useful type of equation since it can be extrapolated to larger values.

Equation 1 — a product of the regression analysis — provides a means for predicting the diameters of large fireballs from the data available. The following is the curve fitted equation used:

$$\log Y = 0.992 + 0.320 \log X \tag{1}$$

where

Y = maximum diameter of fireball, feet

X = weight of propellants, pounds

S = standard error of values of log Y calculated with the above equation = 0.122

a = standard error of intercept = 0.036

b = standard error of slope = 0.012

In addition to the fireball size data, figure 1 contains the curve of equation 1. Although the data points exhibit considerable scatter about this curve, this scatter is not unreasonable since variations in propellant heats of combustion, volumes of gas formation, failure mode, and atmospheric pressure are inherent in the individual values. Also, measurement of diameter from film is not precise and in some cases — where the fireball is not symmetrical — the data represents a maximum or minimum dimension. The slope of the line, 0.320, lends additional support to the validity of equation 1 since the slope is not significantly different from the cube root scaling of weight used extensively in the field of explosives.

The fireball diameter from the Atlas-Centaur failure on March 2, 1965, is plotted on figure 1 but is not included in the curve fit. Since the fireball was irregularly shaped, the diameter plotted is that of the major axis of an oblate spheroid having the volume of the measured fireball. This dimension was chosen as being most representative of the horizonal diameter and compares with the data plotted on figure 1.

Using equation 1, the fireball diameters of Saturn IB and V were computed. Table I contains these results and the calculated 95 percent confidence values. The vehicle weights and the upper and lower 95 percent confidence limits are also shown in figure 1.

The acceptance of the 95 percent confidence limits from this statistical treatment of the data is not recommended. These limits are the result of the many variables mentioned earlier. There is a strong possibility that these 95 percent confidence values cannot be realized in an actual failure. There is, however, enough data in the collection to justify the use of the nominal or curve fitted diameters determined from equation 1. Therefore, the nominal or most probable diameters are recommended for use in accessing the fireball hazards.

Calculated Fireball Size

The gas volumes from propellant combustion were calculated to verify that the values from the curve fit are reasonable. Following the volume calculation, the effects of incomplete reaction and of mixing with atmospheric air were estimated. It was concluded that the volume decrease resulting from an incomplete reaction was small and could be neglected. An arbitrary estimate of 150 percent volume increase due to mixing of air resulted in a calculated diameter within 10 percent of the empirical diameter. The results of the calculation will be found in table II. A discussion of the calculations is found in the succeeding paragraphs. These calculations — used to predict nominal fireball size — are not intended to predict the theoretical maximum size of a fireball.

The ideal gas law was applied to determine the volume of a sphere of combustion gases. To determine the volume of gas using this relationship, the temperature, pressure, and moles of gas must be known. The temperature and pressure were assumed to be 3460° R (3000° F) and 1 atmosphere. These values were chosen from references 4 and 5 as being approximately those values expected at maximum expansion of the fireball. The total moles or volume of each chemical constituent was calculated from the amount of each propellant on board the vehicle assuming complete reaction of the propellants with no addition of atmospheric air. The results of these calculations are presented as item (a) in table II. The following general chemical reactions were used to determine the combustion products:

$$(1) \quad C_{10}H_{22} + O_2 \longrightarrow CO + H_2O + H_2 \quad \text{(RP-1/LOX)}$$

$$(2) \quad H_2 + O_2 \longrightarrow H_2O + H_2 \quad (LH_2/\text{LOX})$$

The above chemical reactions, if balanced, would reflect that there are more moles in the reaction products than in the original propellants. Therefore, the limiting effect on diameter would be to consider the propellants at the assumed temperature and pressure without reaction. This is, of course, a hypothetical condition, but one that results in a gas volume that is 77 percent of the volume of gases from a complete reaction. The effect on the diameter is the cube root of 77 percent or 91.7 percent. The actual condition is somewhere between the extremes of 91.7 percent and 100 percent. It is therefore concluded that incomplete reaction produced only a small error in the calculated diameter at the assumed temperature and pressure conditions.

The process of mixing atmospheric air with the combustion gases will tend to increase the size of fireball. This is a complex process combining cooling effects, reaction, etc., which will tend to stabilize the gas temperature. Therefore to calculate the diameter with mixed air, the same assumed temperature and pressure were used as in the gas sphere calculation.

The air that becomes part of the fireball by mixing has been estimated to increase the volume 50 percent. This estimate was made by the Martin Company in reference 11 for sea level events. Applying this factor, the diameters of mixed fireballs were calculated and are presented in item (c) of table II. These calculated diameters are within 10 percent of the diameters estimated from the empirical treatment in the previous section. The weights of the air included in the enlarged fireballs are shown in item (d). Item (e) contains the weight of air at ambient conditions in volumes equal to the volumes of the enlarged fireballs of item (c). It is interesting to note that the amount of air mixed with the fireball is about 5 percent of the amount present in the same volume before the event.

The assumed temperature and pressure were chosen for these computations as representative of the predicted conditions of the fireball at maximum expansion. Therefore, no change in the conditions was made when calculating the effects of the variables considered.

Duration of Fireball

Fireball duration has been studied and empirically determined from data of experimental tests and actual failures in a manner similar to that in the previous section. These data were derived from references 1 and 2. A plot of the data with a curve fitted by the least squares method is shown in figure 2. Scatter in the data is the result of wide variations in failure modes and the difficulty of visually estimating the duration of the events. Because of this wide scatter, the analysis determined that this mathematical curve fit was not significant. However, this fit does adequately describe the data and since the slope is approximately that of the cube root scaling of weight, this relationship was used to predict the duration of the fireballs from the Saturn vehicles. No attempt will be made to predict the reliability of these values. The following equation was used:

$$\text{Log duration} = -.634 + .320 \log \text{weight} \qquad (2)$$

Applying equation 2 to the weights of the Saturn vehicles, the following durations were determined:

Vehicle	Duration of Fireball
Saturn V	33.9 sec.
Saturn IB	20.1 sec.

Surface Temperature

An accurate estimation of the surface temperature (effective radiating temperature) of the fireball is quite difficult. The Martin Company (ref. 4) estimated the surface temperatures to be approximately 2500° F. This estimate was made from temperature measurements in some scale model Titan tests. Also, MSC's "Fireball and Blast Hazards Test Program" conducted by Aerojet-General Corporation (ref. 5) was examined to help determine this temperature. In this program, radiometer intensities were used to calculate the surface temperature of the fireball. For the RP-1/LOX tests, the maximum temperatures determined ranged between 1900° and 2670° F from black body radiation analysis. Since the higher temperatures were associated with explosive yields higher than those expected in booster explosions, the average temperature of 2325° F was calculated as more representative of the temperature to be used. Variations from black body radiation and attenuation by the atmosphere would tend to increase the average temperature computed by Aerojet-General Corporation. Therefore, the temperature recommended from this data is greater than 2325° F and approaches the 2500° F observed by Martin. For lack of more accurate data, the latter value of 2500° F is recommended to be used. Data will be collected on another contract similar to the above with Aerojet-General Corporation to further aid in the estimation of an effective radiating temperature. Also, part of the task of Project Pyro is the determination of radiation and surface temperature from destruct tests with rocket propellants.

Emissivity

The emissivity (e) of a surface relates the emissive power of an actual surface to that of a black body. Some knowledge of this parameter is needed to be able to determine an intensity of radiation from a source of known size and surface temperature. Accurate theoretical determination of the emissivity requires precise knowledge of a large number of variables including an accurate knowledge of the molecular species present. A small percentage of free carbon can greatly influence the emissivity and — because of the small amount present — it is difficult to accurately determine the amount.

The limits of the values of emissivity can be examined, however. A non-luminous gas with a large optical depth will have an emissivity approaching 0.45. This would represent a minimum value for large fireballs. Since all propellant fires and explosions will produce some carbon particles from incomplete combustion and thermal cracking of hydrocarbon molecules, a luminous gas is produced. This can be illustrated in a laboratory by adjusting a bunsen burner flame to a fuel-air ratio which gives a yellow, diffusion flame. A luminous gas greatly increases the radiation from a source because the emissivity is higher. The emissivity from luminous flames with large depths varies between .9 and 1.0 (see ref. 9). In other words, it approaches the radiation of a black body. Since no actual system can operate as a perfect radiator (black body), an emissivity value of 1.0 is too large. However, there is very little evidence available to permit determination of a more accurate value. The radiant heat hazard estimated from an emissivity value of 1.0 will be high enough to allow a small margin of safety. Therefore, a value of 1.0 will be used for the emissivity until more definitive information becomes available.

Thermal Radiation

The radiant heat flux densities at various distances from the fireballs of the Saturn vehicles are presented on the attached curves, Figures 3 and 4. These curves were prepared from information collected in an in-house study (refs. 6 and 13) concerned with the problem of radiation from a large sphere (object 1) to a perfect absorber (object 2).

In general, the radiant heat transferred from an opaque source of temperature T_1, area A_1, and total emissivity e_1, to a receiver at distance r and area A_2 is given by the following expression:

$$q_{1 \longrightarrow 2} = e \, \sigma \, A_2 \int_{A_1} T_1^{\,4} \, \frac{f(\gamma) dA_1}{r^2} \qquad (3)$$

For this expression it was assumed that object 2 is a small area and that it is a perfect absorber, i.e. it absorbs all radiant energy it receives independent of wave length and incidence angle. Object 1 is the fireball and is considered spherical with a radius R and the same surface temperature T_1 over the entire surface. The following definitions are used to simplify equation 3:

$$I = e \, \sigma \, T^4 \qquad (4)$$

And

$$F = \frac{q_{1 \rightarrow 2}}{A_2} \tag{5}$$

Equation 3 then becomes:

$$F = I \int_{A_1} \frac{f(\gamma)dA_1}{r^2} \tag{6}$$

Assuming that the gas sphere radiates according to Lambert's law, then $f(\gamma) = \text{Cos}\ \gamma$. The further development of equation 6 was the subject of the in-house study and will not be presented here, but the following expression (eq. 7) which relates the radiant heat transfer rate to the radius of the sphere and the distance between the receiver and the center of the sphere was the result of that development:

$$F = \pi I \left[\frac{R^2}{a^2} + \frac{R^4}{4a^4} + \text{------} \right] \tag{7}$$

This expression gives good results for radiation at distances beyond several radii. However, the assumptions made in the development of the equations result in deviations at distances near or less than 1 radius from the fireball surface. At these distances, a limiting value of $F = I$ should be used. Where the break in the curves are seen on figures 3 and 4, the heat flux shown is too large. This is the region where the deviations using equation 7 become significant.

Equation 4 gives the relationship to be used for emissivity. For figures 3 and 4, the emissivity value used was 1.0.

The following list contains the definitions of the symbols used in equations 3 through 7 and figures 3 and 4:

q = Radiant heat transfer rate

A_2 = Area of receiver

a = Distance from center of fireball sphere to receiver

a_o = Distance from surface of fireball sphere to receiver

R = Radius of fireball

e = emissivity

σ = Stefan-Boltzmann constant

T = absolute temperature

F = Radiant heat flux at the receiving surface

I = Radiation intensity of the source

γ = Angle of radiation from sphere

Atmospheric Attenuation

The thermal radiation reaching an object some distance from a radiating source in the atmosphere is subject to some attenuation that results from thermal absorption by the air. To complete the information, some estimate of the magnitude of this parameter is needed. In reference 8 it is found that atmospheric attenuation can be treated mathematically by a computer technique. It was concluded in this reference that the most effective compounds for absorption of radiation in the visible and infrared spectrums were carbon dioxide and water vapor. These materials are found in the fireball and influence many of the absorption and radiation effects. In the atmosphere surrounding the fireball these compounds are found in very low concentrations and therefore have only a small effect on the attenuation. It was estimated that atmospheric attenuation reduced the radiant energy approximately 20 percent beyond 5000 ft. For distance between 0 and 5000 feet, this attenuation is less than 20 percent. For lack of more precise values, it is assumed that 100 percent of the radiation produced reaches an object in the range up to 5000 ft.

Total Radiant Heat

The total heat received by an object is the product of the radiant heat flux and the duration of the radiating source. In a booster explosion, the fireball radiant heat flux is not a constant value, but varies with time forming a curve similar to that from a skewed probability density function. The initial rise of this curve is determined principally by the expansion rate of the fireball. Following maximum fireball expansion, the surface temperature of the fireball decreases. This temperature decrease is the determining factor in the descending portion of the curve. To evaluate the radiant heat hazard, some estimate of this curve must be made.

Thermal radiation from a fireball was determined to be approximately one-half the peak integrated value. This was estimated by plotting radiation measurements versus time from data collected during the fireball and blast tests of reference 5. The areas under these radiation intensity curves were integrated and compared with the areas derived by the product of the peak intensity and the duration time. It was found that for the smaller contact surfaces, the areas of the integrated curves were approximately 50 percent (average 48 percent) of the peak areas. This 50 percent value of peak total heat is considered the most reasonable value based on the present state of knowledge.

Rise Rate and Liftoff

A fireball will rise after it reaches pressure equilibrium. The temperature of the fireball gases at the time of pressure equilibrium is high. From the ideal gas law it can be readily seen that at high temperature and ambient pressure the gas density will be considerably lower than that of the surrounding atmosphere. This density difference produces a buoyant force which causes the fireball to rise. The rate of rise is not well known, but some representative rates are presented in figure 5. The slope of each of the curves in this figure is nearly the same. Therefore the curves for the Saturn vehicles are established with similar slopes. A similar rate of rise seems reasonable since there is little reason to believe that the size will significantly affect the rise rate.

The pressure is tending to relieve itself in all directions during fireball expansion. Therefore, the center of the fireball will remain in approximately the same location during the development of the fireball. Fireball lift has been observed to begin in the last quarter of the expansion period. The period of time required for expansion is dependent primarily on the amount of gas to be expanded. The volume of the gas produced is directly proportional to the mass of the propellants involved. Therefore, it can be concluded that the time of liftoff is a function of propellant weight.

The above conclusions about liftoff time must be qualified in considering various types of events. A high explosive yield from an event has a pronounced effect on the period of expansion and therefore the liftoff time. In missile destruct and failure events, however, the explosive yield is relatively small (less than 10 percent). The majority of the fuel is consumed by a burning process that follows. For events with small yields, the relationship of liftoff time to propellant weight is valid.

The liftoff times of several failure events are plotted on figure 6. The following approximate equation relating the liftoff time to the cube root of the propellant weight represents this data and was used to predict the liftoff times of the Saturn vehicles:

$$T_{(LO)} = \frac{W^{1/3}}{16} \qquad (8)$$

Where $T_{(LO)}$ = time to liftoff, sec.

W = Total propellant weight, lbs.

Residual Fire

In a failure event at very low altitude, it is generally accepted that there will be less than 100 percent fuel participation. Portions of the fuel will be spilled on the ground creating residual pools which will burn for relatively long periods of time following failure. It is particularly probable that the Saturn V will have spillage because fuel is held in the lower tank where it could spill without contacting liquid oxygen. Thus it is very likely that the residual fire and extreme heat from the fireball will prevent approach to the ground area enveloped by the fireball for an unknown period following vehicle failure.

EVALUATING THE FIREBALL HAZARD

The various parameters of fireballs are discussed in the previous sections of this report. This section is provided to aid in using these parameters to calculate the radiant heat hazard from the Saturn fireballs. The following example is provided as a guide in these calculations. The total radiant heating of a surface is the heat that will be absorbed by a perfect absorber. To apply this value to an actual material, the absorptivity and its function with respect to incidence angle must be known. These material properties are beyond the scope of this report.

Assume:

a) Saturn V vehicle.

b) Surface to be heated at 2,000 ft. from surface of fireball.

c) No change in distance due to rising of the fireball.

d) Negligible fuel spillage.

From report:

e) Nominal diameter = 1408 ft.

f) Fireball surface temperature = 2,500° F.

g) Emissivity = 1.0.

h) Fireball duration, t = 33.9 sec.

i) No atmospheric attenuation.

j) Radiant heat flux at 2,000' and 2500° F from figure 4.

$$F = .288 \times 10^5 \ \frac{Btu}{ft^2\text{-}hr}$$

Calculate:

k) Peak total heat = F × t

$$(.288 \times 10^5) \ \frac{33.9}{3600} = 271 \ \frac{Btu}{ft^2}$$

l) Actual total heating of surface = F × t × 0.5

$$= 271 \times .5 = 135.5 \ Btu/ft^2$$

CONCLUSIONS

The fireball will expand in a nearly fixed location. This expansion period is followed by the period in which the size is fairly stable and the hot gas fireball rises from the surface of the ground. The size, duration, and time to liftoff all appear to be a function of the cube root of the propellant weight.

The data compiled in this report are considered accurate enough to make some design concepts of launch escape systems. A theoretical study of fireballs would increase the confidence in the values presented. Additional data are needed to establish more definitive values.

Surface temperature is a parameter which needs further definition. It is hoped that the two programs mentioned will increase the knowledge of the effective radiating temperature and an insight to determining the integrated heat pulse.

The fireball expected from a Saturn booster failure can be described by the following parameters:

	Saturn V	Saturn IB
Nominal fireball diameter, ft.	1408	844
Duration of fireball, sec.	33.9	20.1
Effective peak surface temperature, °F	2500	2500
Emissivity	1.0	1.0
Thermal radiation intensity (flux)	See curve	See curve
Total radiant heat - $\frac{\text{Integrated}}{\text{Maximum}}$	50 percent	50 percent
Atmospheric attenuation	none to 5,000 feet	none to 5,000 feet
Rise rate	See curve	See curve

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TABLE I.- EMPIRICAL FIREBALL DIAMETERS

Vehicle	Saturn V	Saturn IB
Propellant wt., lbs.	5.492×10^6	1.110×10^6
Nominal diameter at maximum expansion, ft.	1408	844
95 percent confidence limits of diameter at maximum expansion, ft.		
Upper Limit	2570	1520
Lower Limit	771	470

TABLE II.- CALCULATED SIZE OF GAS SPHERES

Vehicle	Saturn V	Saturn IB
Wt. of propellants, lbs.	5.492×10^6	1.110×10^6
Temperature, °R	3460°	3460°
Pressure, atmos.	1	1
a. Calculated diameter of gas sphere, feet (complete R_x, no air)	1121	657
b. Unreacted diameter ÷ reacted diameter, percent	91.7	91.7
c. Calculated diameter of sphere with air added to increase volume to 150 percent	1283	752
d. Wt. of this additional 50 percent of air at chosen conditions	4.375×10^6	8.786×10^5
e. Wt. of air in this total volume at ambient conditions (60° F, 1 atmosphere)	8.733×10^7	1.754×10^7
f. percent of air included in fireball $\frac{d.}{e.}$ X 100	5.01 percent	5.01 percent
g. Diameter determined emirically, ft.	1408	844

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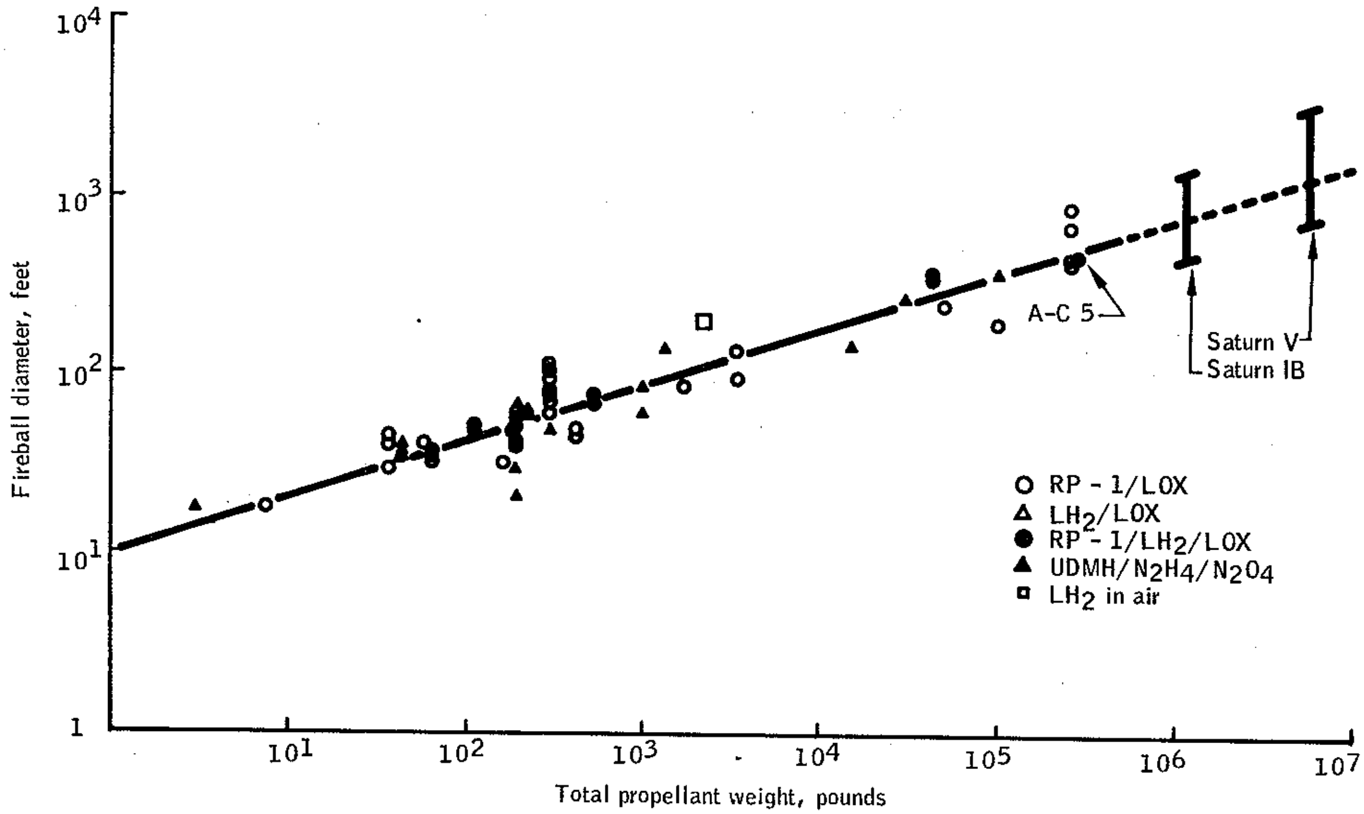

Figure 1.- Fireball diameters for various weights and types of propellants.

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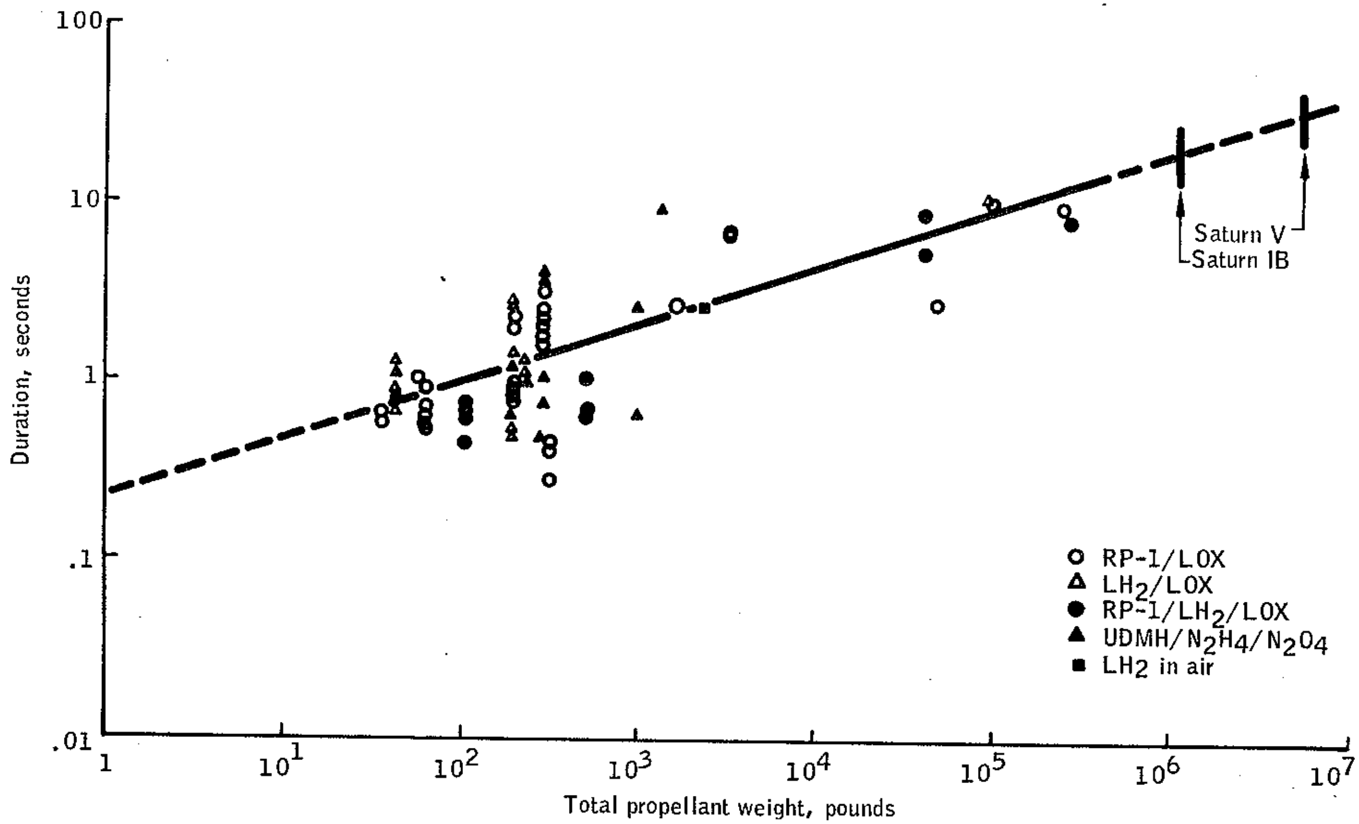

Figure 2.- Fireball duration for various weights and types of propellants.

NASA-S-65-6725 Saturn IB heat flux vs. distance

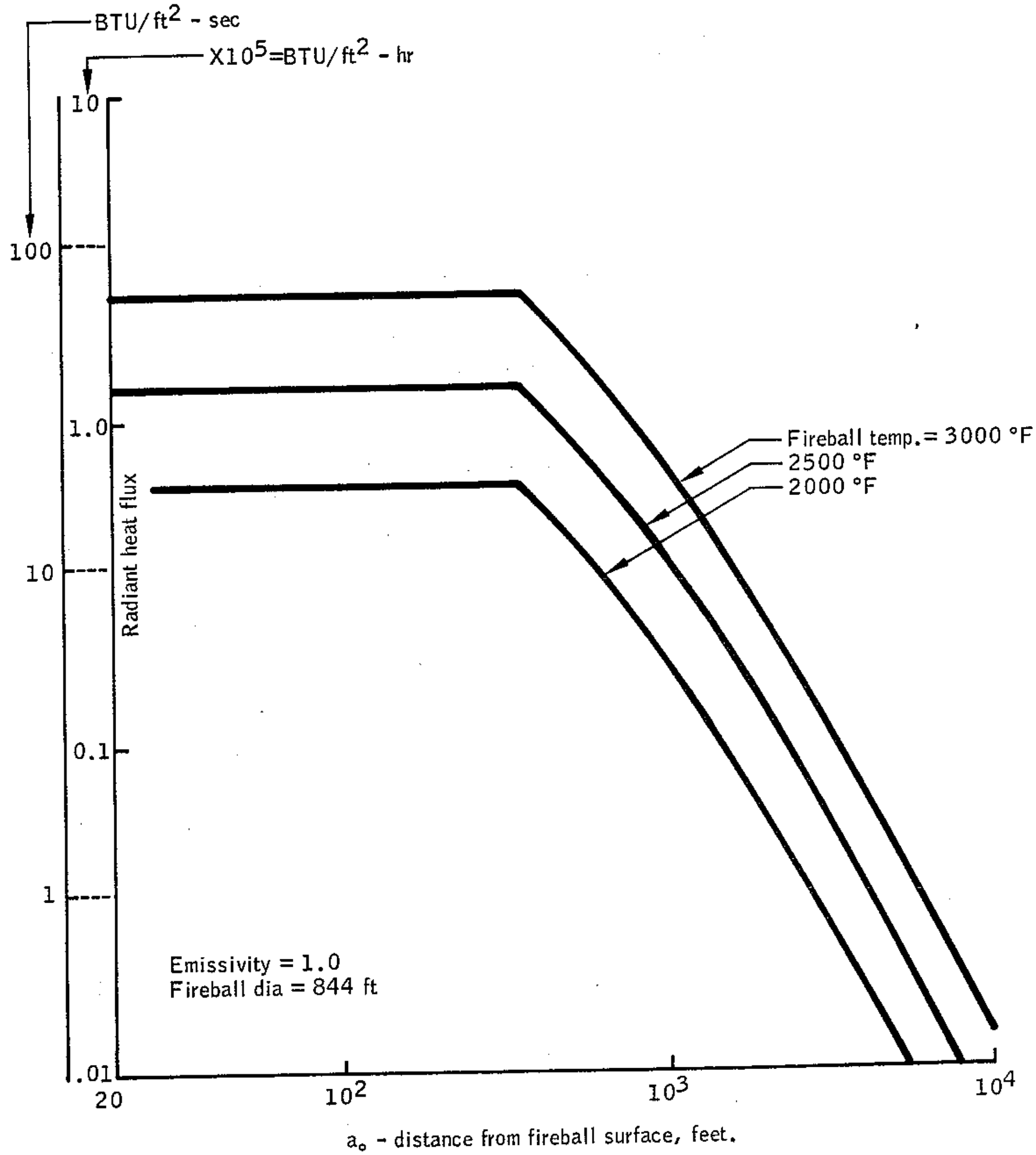

Figure 3.

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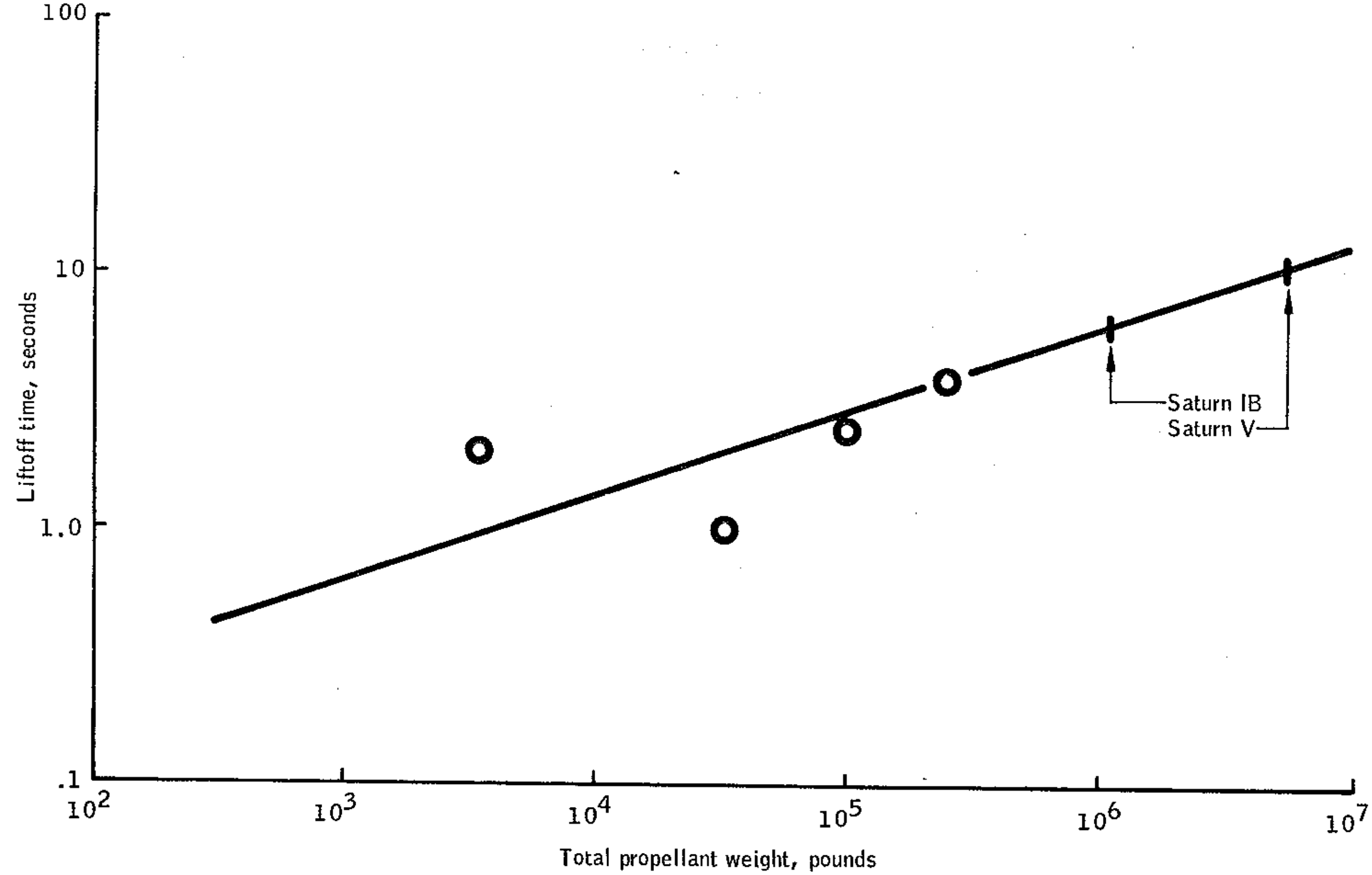

Figure 6.- Fireball liftoff time for various propellant weights