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SIZE AND DURATION OF FIREBALLS FROM PROPELLANT EXPLOSIONS

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ABSTRACT

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Data from tests and vehicle incidents have been compiled and analyzed with respect to fireball diameters and durations. Both variables were found to be dependent on the cube root of the weight of the combined propellants and independent of the particular propellant combination. Fireball diameters also appear to be roughly dependent on the cube root of the ambient pressures.

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SUMMARY

Literature data and photographic film for tests and incidents involving various propellant combinations and also high explosives have been analyzed with respect to fireball diameters and durations. The results indicated that fireball diameters are highly dependent on the cube root of propellant weight and independent of the particular propellant combination. Attempts to treat the problem theoretically indicated that fireball diameters probably are dependent also on the cube root of ambient pressure. The scatter of the data about a fitted curve corresponded to a standard error of approximately 30 percent. Data for fireball durations exhibited a much greater degree of scatter but also indicated a dependence on the cube root of propellant weight.

INTRODUCTION

The development of large launch vehicles, particularly those employing new high energy propellant combinations, has resulted in major problems in the siting of test stands and launch pads. A number of investigations are being made under the direction of the National Aeronautics and Space Administration/Marshall Space Flight Center (NASA/MSFC) to provide comprehensive information regarding the blast hazards of liquid propellants. Results of these investigations have indicated that for some incidents a significant proportion of the propellants may enter into detonation type reactions. In these cases, the greatest hazards to adjacent facilities and/or personnel are those associated with the blast waves and with flying debris. However, for other incidents, the propellants may undergo almost exclusively deflagration type reactions. In these cases, the greatest hazards to facilities and/or personnel are those associated with the fireballs. For the latter type of incidents, it is of particular importance to define the thermal environment for propellant explosions as closely as possible. To obtain quantitative information on this problem, sophisticated instrumentation is being used in connection with Project Pyro, which is a study of the blast hazards of liquid propellants being made by the United States Air Force Rocket Propulsion Laboratory under the direction of MSFC (Government Order H-61465). Thermal instrumentation also is being installed on some of the launch pads at Cape Kennedy. However, the results of these studies will not be available until some future date.

This report presents the results of a preliminary investigation that was undertaken to assemble and evaluate data which are currently available and which can be used for predicting the size and duration of fireballs resulting from catastrophes involving various liquid propellant combinations.

RESULTS

For the purposes of this investigation, fireball diameters and durations were obtained either from the literature or by reduction of photographic records of various tests and incidents. All data used for this study are included in the Appendix. In those instances where the fireballs were markedly assymetrical, attempts were made to estimate equivalent spherical diameters. However, the study was made difficult by the fact that the camera locations were not always precisely known; therefore, adequate reference points were not always available. Also, the results probably were influenced by variations in framing speed, type of film, and method of development.

RP-1/LOX

Data were obtained for 47 tests and incidents ranging from 10 to 250,000 pounds of combined propellants with fuel to oxidizer ratios ranging from 1:1.5 to 1:3.5. The data are plotted on logarithmic coordinates in FIG 1. Also included in the figure is a straight line fitted to the data by the method of least squares. The equation of this line is

$$D = 10.05W^{0.316} \qquad \text{(Equation 1)}$$

where D = fireball diameter (ft.) and W = total propellant weight (lbs.). The standard error of the exponent is 0.015. The standard error for fireball diameters calculated with Equation 1 is 0.1088 expressed in log units. This corresponds to a standard error of approximately 28 percent of the calculated fireball diameters.

LH_2/LOX

Data were obtained for 23 tests and one incident. For the tests, the combined propellant weights ranged from 3 to 225 pounds with a fuel to oxidizer ratio of 1:5. The single incident involved 100,000 pounds of LH_2/LOX with a fuel to oxidizer ratio of 1:5. The data are plotted in FIG 2. The equation of the straight line fitted to the data is

$$D = 11.05W^{0.306} \qquad \text{(Equation 2)}$$

The standard error of the exponent is 0.032, and the standard error for fireball diameters calculated with Equation 2 corresponds to approximately 33 percent.

RP-1/LH_2/LOX

Data for this ternary propellant combination were obtained for 12 tests ranging from 110 to 44,000 pounds. The data are plotted in FIG 3. The least squares equation is

$$D = 9.92W^{0.340} \qquad \text{(Equation 3)}$$

The standard error for the exponent is 0.009, and that for calculated fireball diameters is approximately seven percent.

The smaller scatter noted for this particular set of data is largely due to the use of similar configurations for all tests and to the small range of propellant weights tested.

N_2O_4/UDMH-Hydrazine

Data for 26 tests using this propellant combination are given in FIG 4. The equation of the straight line is

$$D = 8.86W^{0.328} \qquad \text{(Equation 4)}$$

The standard error for the exponent is 0.035, and that for calculated fireball diameters is approximately 25 percent.

High Explosives

Data obtained for 14 explosions involving TNT, composition C-4, and Pentolite are given in FIG 5. The equation of the line is

$$D = 8.50W^{0.341} \qquad \text{(Equation 5)}$$

The standard error of the exponent is 0.026, and that for calculated fireball diameter corresponds to approximately 50 percent.

DISCUSSION

Inspection of the equations for the individual propellant combinations and that for high explosives indicated that they do not differ significantly. Therefore, the data have been combined in FIG 6. The equation of the straight line is

$$D = 9.56W^{0.325} \qquad \text{(Equation 6)}$$

The standard error for the exponent is 0.010. The standard error for fireball diameters calculated with this equation amounts to approximately 30 percent.

Inspection of the data fails to indicate any marked tendency for results for any given propellant combination to fall consistently above or below the line. Thus, it appears that fireball diameters are substantially independent of the particular propellant combination used. Moreover, fireball diameters for propellant explosions do not differ significantly from those for high explosives. Because of the wide range of propellant types, test and incident configurations, and explosive yields represented by the data, it appears that fireball diameters are determined almost exclusively by the weight of the combined propellants. The extreme insensitivity to large variations in test conditions suggests that fireball diameters for multistage vehicles will be dependent on total propellant weight for all stages unless the explosions for the different stages occur at times which differ by amounts which are greater than the fireball duration for the first explosion, i.e., by more than a few seconds.

The exponent of the propellant weight term in Equation 6 differs from the value of 1/3 by less than one standard error. Therefore, it is evident that fireball diameters obey the cube root scaling law that is applicable to most other explosion parameters.

Attempts were made to predict fireball diameters theoretically by use of thermodynamic data, flammability limits, and adiabatic flame temperatures. Other temperature values also were assumed for the purposes of these computations. In view of the many assumptions which were necessary, the resulting model was a rough approximation and, therefore, has not been included in this report. However, comparison of the data with the results of the various calculations together with other considerations permitted the following inferences:

1. LH_2 is always completely consumed, utilizing oxygen from the air to react with any excess LH_2. In fact, approximately the same fireball diameter would be expected for a given weight of LH_2 tested

alone and with LOX present. This expectation was confirmed by the result for a single LH_2 test involving approximately 2350 pounds of LH_2.

2. RP-1 is consumed only partly within the fireball. In some tests, puddles of RP-1 remaining in partially destructed tankage have burned for relatively long periods, i.e., hours.

3. As a rough approximation, fireball diameters probably vary inversely with the cube root of the ambient pressure.

The scatter of data for fireball durations was appreciably more than for diameters. This would be expected since the results are much more sensitive to photographic variables such as framing speed, type of film, and method of developing. Also, it is difficult to define the end of the visible fireball in an unambiguous manner. For this reason, plots of the data for the individual propellant combinations have not been included. However, the combined results are given in FIG 7. The equation of the straight line is

$$d = 0.196W^{0.349} \qquad \text{(Equation 7)}$$

where d = duration, seconds. The standard error of the exponent is 0.055. The standard error for fireball durations calculated with Equation 7 amounts to approximately 84 percent. The data for high explosives indicated fireball durations appreciably shorter than those for propellant explosions and, therefore, have not been included.

Inspection of FIG 7 and Equation 7 indicates that fireball durations also are dependent on the cube root of the combined weight of propellants.

CONCLUSIONS

The results of this investigation indicate that fireball diameters are determined almost entirely by the cube root of the total propellant weight and by the cube root of the ambient pressure. Any dependence on such variables as propellant type, explosive yield, and test configuration is of secondary importance. Even high explosives yield fireballs with diameters approximately equal to those for explosions involving the same weights of propellants. Although some scatter of the data amounting to a standard error of approximately 30 percent about the best fitting equation is evident, the scatter does not appear excessive in view of the many sources of error, and it appears unlikely that the scatter can be reduced by further investigations of this type.

Fireball durations also are dependent on the cube root of propellant weight. However, the scatter of the data is appreciably greater, probably due to the influence of variations in photographic techniques used.

APPENDIX

Data for RP-1/LOX

Propellant Weight lbs	F:O	Fireball Diameter ft	Duration sec
300	1:3.5	67	1.90
300	1:3.5	80	1.99
300	1:3.5	82	2.55
300	1:2.5	73	1.70
300	1:2.5	60	2.25
300	1:2.5	68	1.99
300	1:1.5	80	2.50
300	1:1.5	82	2.49
300	1:1.5	72	2.07
300	1:2.5	75	3.22
300	1:2.5	87	3.25
300	1:2.5	78	2.00
300	1:2.5	79	2.46
200	1:2.5	56	0.89
200	1:2.5	53	0.86
200	1:2.5	51	0.93
200	1:2.5	40	0.88
200	1:2.5	41	0.89
200	1:2.5	43	2.29
200	1:2.5	41	2.26
200	1:2.5	39	2.07
200	1:2.5	62	1.01
58		42	1.04
64		36	0.74
64		35	0.59
64		37	-
64		33	0.66
64		34	0.57
64		33	0.91
321		47	0.41
321		50	0.47
321		48	0.29
38	1:2.25	30	0.65 ± 0.05
38	1:2.25	40	0.65 ± 0.05
38	1:2.25	46	0.65 ± 0.05
3,400	1:2.25	100	7
3,400	1:2.25	140	6.9
1,700	1:2.25	90	2.7
50,000	1:2.25	250	2.8
100,000	1:2.3	200	11
250,000	1:2.3	490	>5

Data for RP-1/LOX (Continued)

Propellant Weight lbs	F:O	Fireball Diameter ft	Duration sec
250,000	1:2.25	710	-
250,000	1:2.25	935	-
194	-	50	-
250,000	1:2.25	450	10
7.7		18	
170		33	

Data for LH_2/LOX

200	1:5	31	2.57
200	1:5	50	2.75
200	1:5	70	2.62
200	1:5	60	2.75
200	1:5	48	-
200	1:5	68	0.57
200	1:5	60	2.01
200	1:5	42	1.49
200	1:5	50	0.99
200	1:5	22	0.50
3		18	
100,000	1:5	380	0.50
44	1:5	39	1.35
44	1:5	35	1.31
45	1:5	40	1.05
45	1:5	40	1.11
45	1:5	38	0.96
45	1:5	35	0.90
45	1:5	35	1.13
45	1:5	40	1.05
44	1:5	38	0.70
224	1:5	61	1.37
225	1:5	63	1.12
225	1:5	65	1.20
2,350	1:0	210	2.6

Data for RP-1/LH_2/LOX

Propellant Weight lbs	F:O	Fireball Diameter ft	Duration sec
110	2.6:1:11	51	0.72
110	2.6:1:11	52	0.72
109	2.6:1:11	49	0.71
110	2.6:1:11	50	0.79
109	2.6:1:11	49	0.47
110	2.6:1:11	50	0.62
110	2.6:1:11	52	0.77
529	2.6:1:11	71	0.70
530	2.6:1:11	79	0.73
530	2.6:1:11	80	1.08
43,100	2.6:1:11	390	5.52
43,840	2.6:1:11	386	9.38

Data for N_2O_4/UDMH-Hydrazine

300	1:3	59	0.50
300	1:3	58	1.15
300	1:3	66	1.78
300	1:2	67	0.80
300	1:2	58	1.97
300	1:2	62	2.20
300	1:1	80	2.29
300	1:1	74	2.02
300	1:1	70	2.87
300	1:2	53	2.73
300	1:2	51	3.68
300	1:2	55	4.20
14,000		150	
30,000		280	
300		64	-
1,300		150	10
200		34	0.9
200		45	0.5
200		37	0.7
200		65	0.8
200		36	1.22
200		45	0.5
200		50	0.6
200		50	0.73
1,000		65	2.64
1,000		90	0.7

APPENDIX (Concluded)

Data for High Explosives

Propellant Weight lbs	Fireball Diameter ft	Duration sec
2.5	10	0.12
10	19	0.33
50	45	
50	47	
50	47	0.23
50	47	0.23
50	37	
100	50	
18	30	
105	40	
1,000,000	840	
1,000,000	870	
1	4	
8	8	
40,000	210	

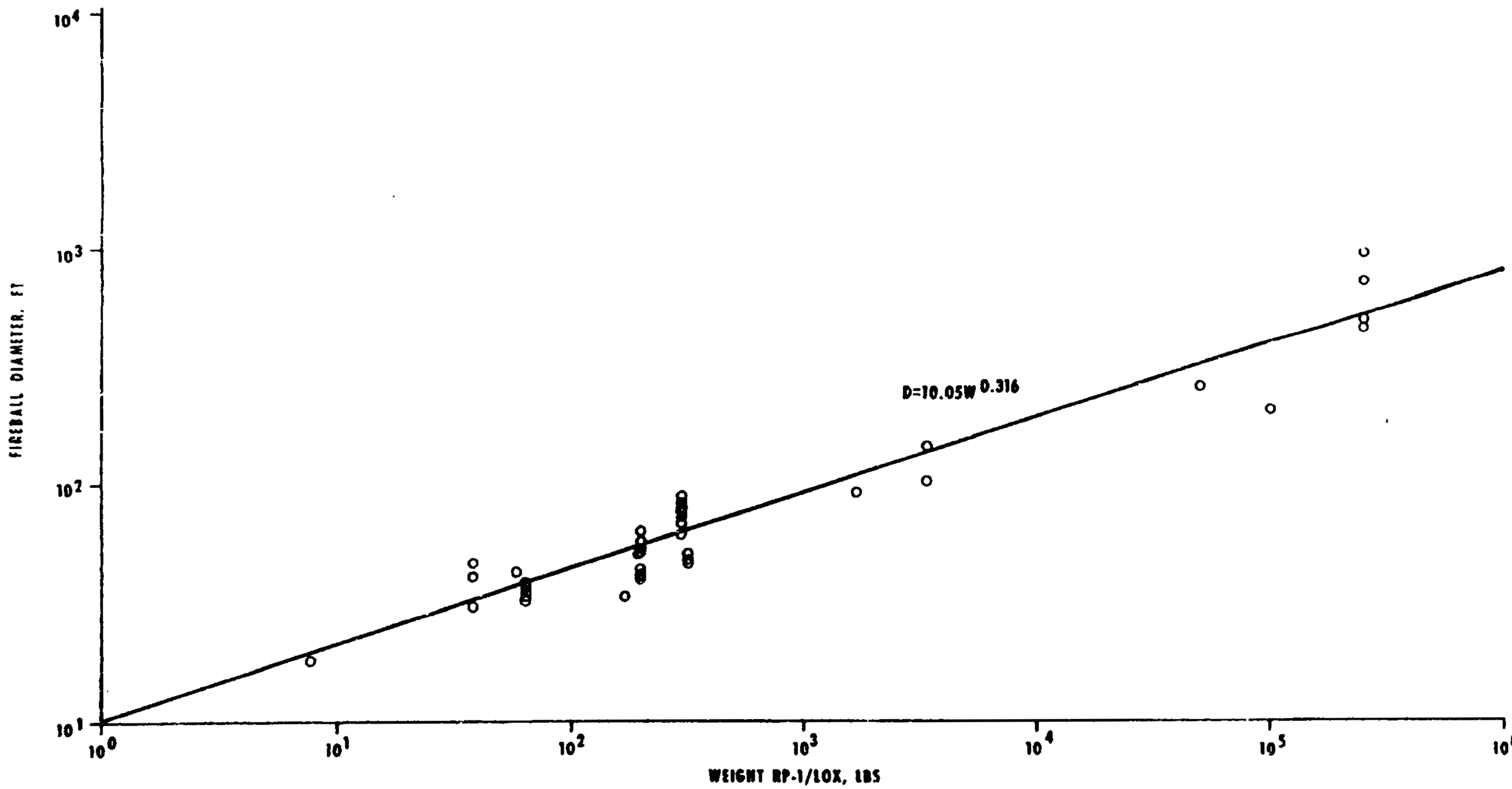

FIGURE 1. EFFECT OF PROPELLANT WEIGHT ON FIREBALL DIAMETERS FOR RP-1/LOX

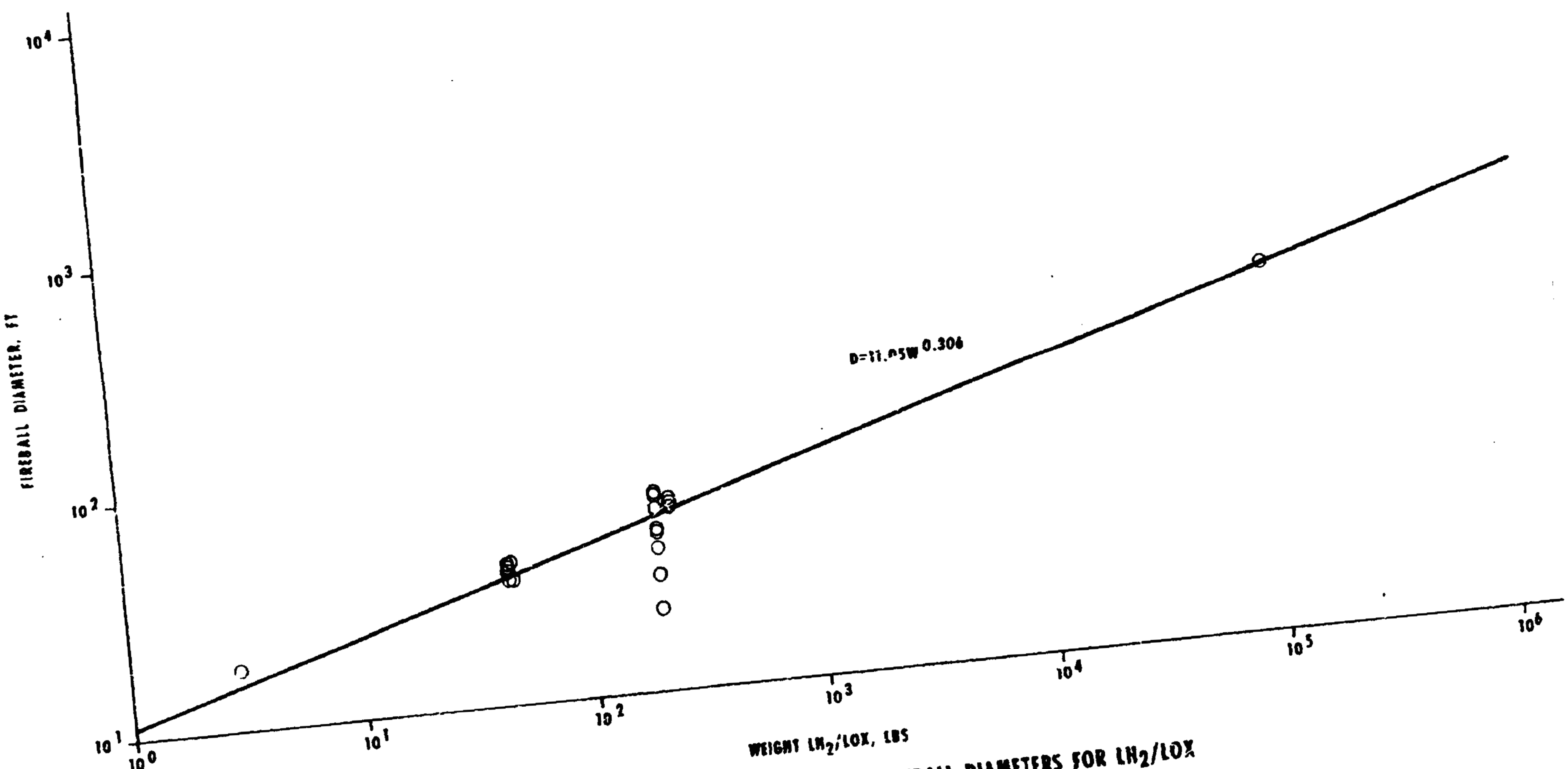

FIGURE 2.- EFFECT OF PROPELLANT WEIGHT ON FIREBALL DIAMETERS FOR LH_2/LOX

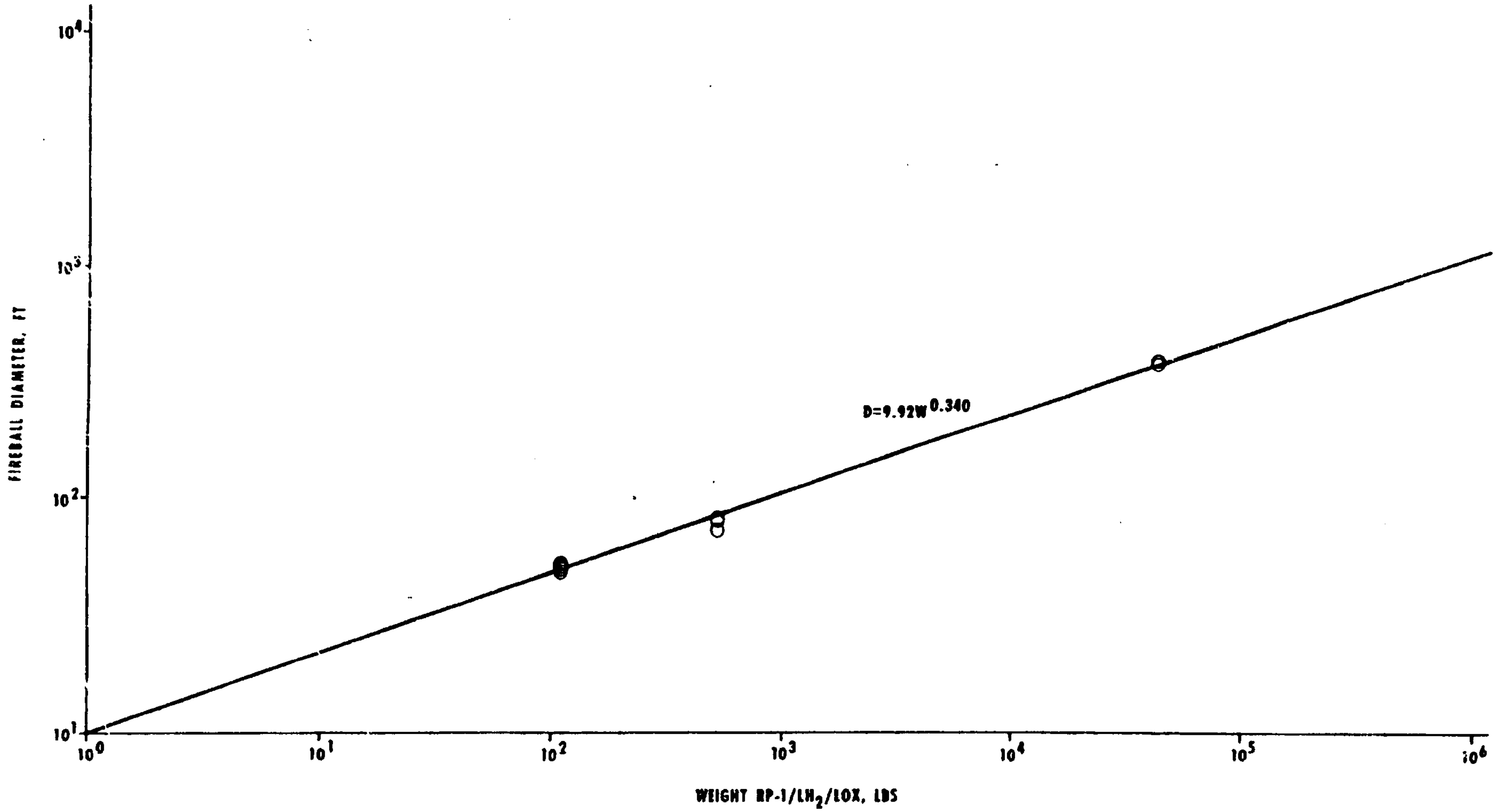

FIGURE 3.- EFFECT OF PROPELLANT WEIGHT ON FIREBALL DIAMETERS FOR RP-1/LH_2/LOX

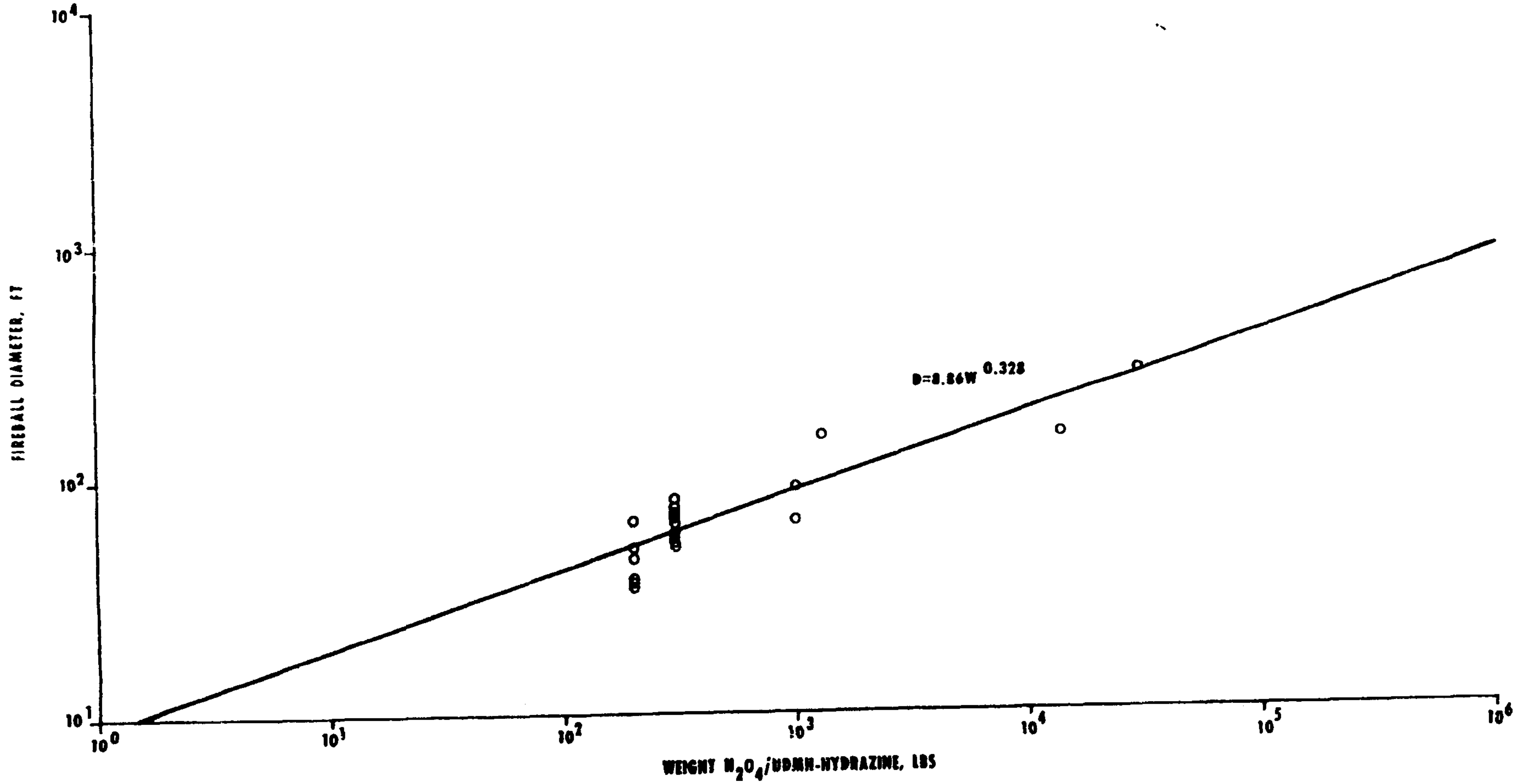

FIGURE 4.- EFFECT OF PROPELLANT WEIGHT ON FIREBALL DIAMETERS FOR N_2O_4/UDMH-HYDRAZINE

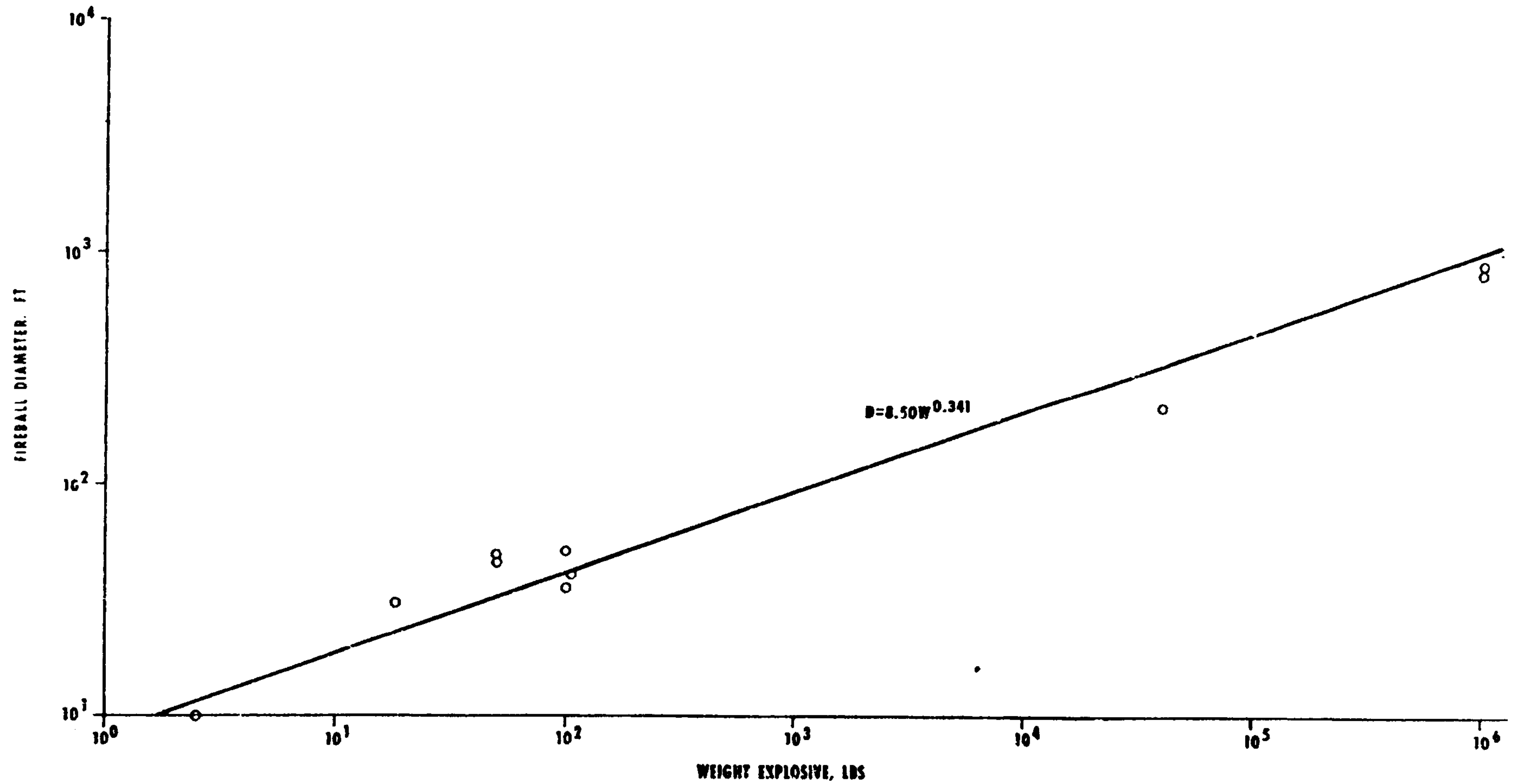

FIGURE 5.- EFFECT OF EXPLOSIVE WEIGHT ON FIREBALL DIAMETERS

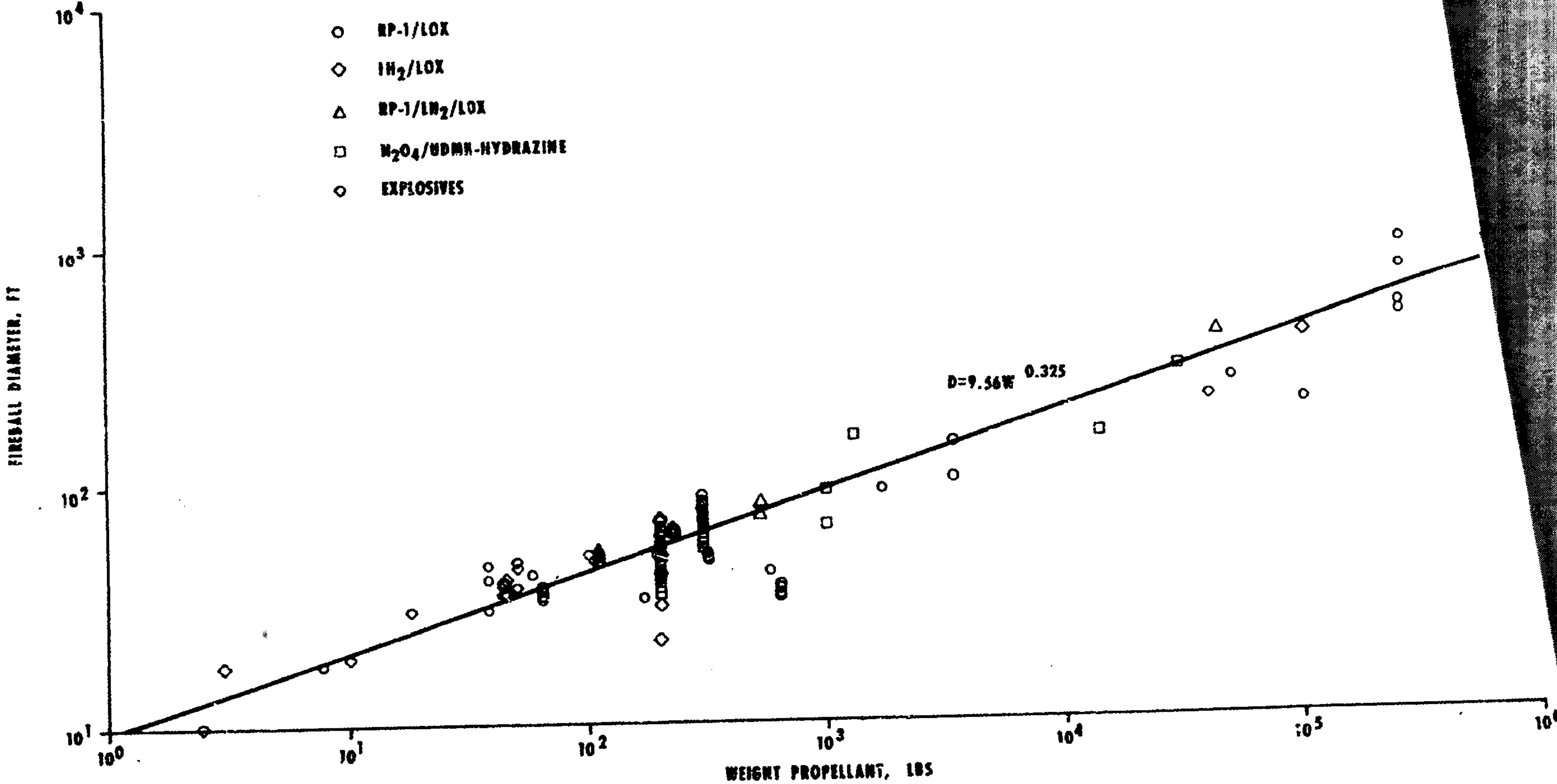

FIGURE 6.- EFFECT OF PROPELLANT WEIGHT ON FIREBALL DIAMETERS FOR ALL PROPELLANTS

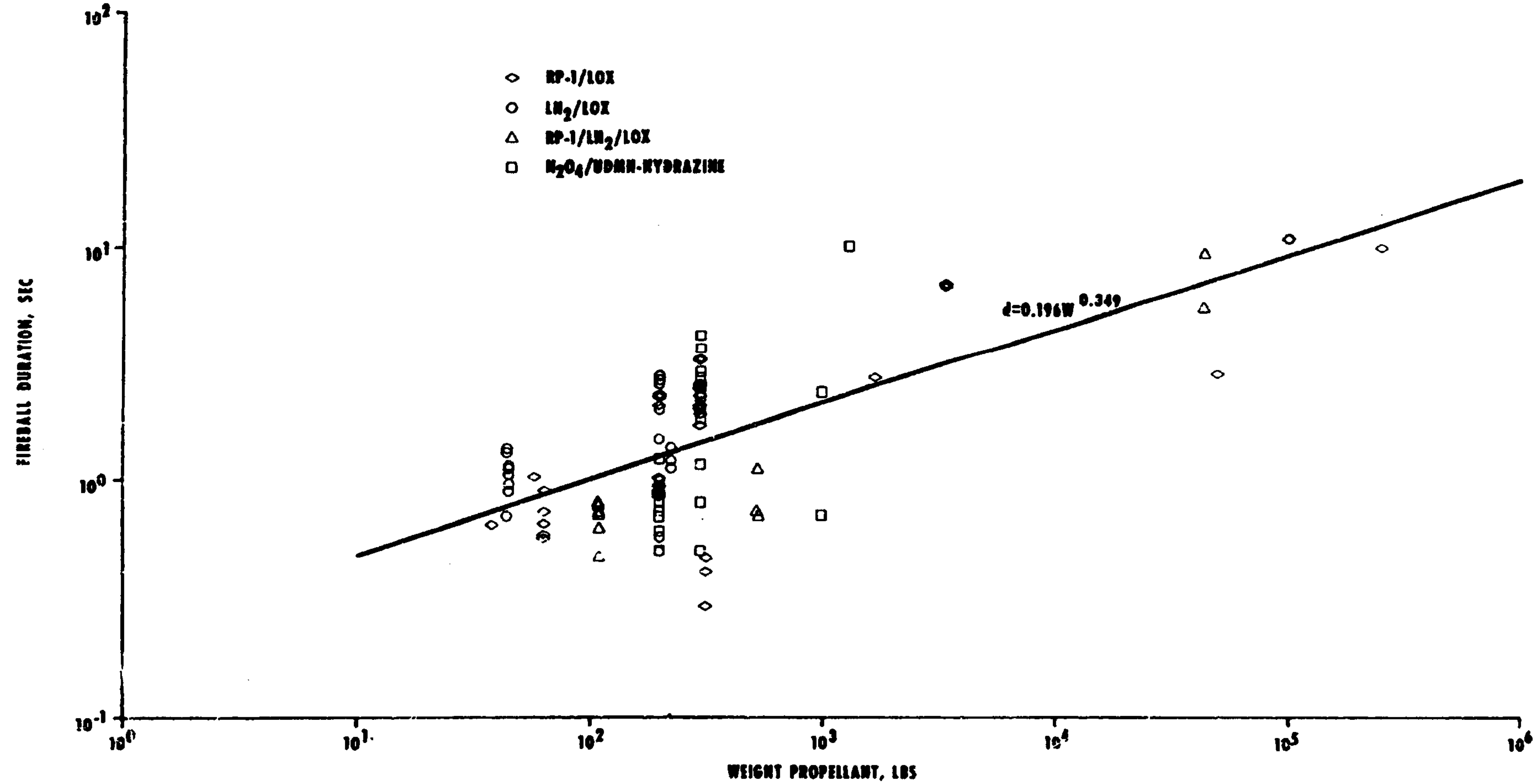

FIGURE 7.- EFFECT OF PROPELLANT WEIGHT ON FIREBALL DURATIONS FOR ALL PROPELLANTS