# ENGINEERING PROGRESS AT THE UNIVERSITY OF FLORIDA

Vol. XXII, No. 7 July, 1968

Technical Paper Series

# CHARACTERISTICS OF LIQUID ROCKET PROPELLANT EXPLOSION PHENOMENA

No. 415A: Part VI. Explosive Yield Estimates for Liquid Propellant Rockets Based Upon a Mathematical Model

No. 415B: Part VII. Interpretation of Explosive Yield Values Obtained From Liquid Rocket Propellant Explosions

by

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(A Continuing Series of Research Reports on NASA Project NAS 10-1255. Parts VI and VII were presented to NASA, April 25, 1968, at Cape Kennedy)



PUBLISHED MONTHLY BY THE

FLORIDA ENGINEERING AND INDUSTRIAL EXPERIMENT STATION

COLLEGE OF ENGINEERING • UNIVERSITY OF FLORIDA • GAINESVILLE

ENTERED AS SECOND-CLASS MATTER AT THE POST OFFICE AT GAINESVILLE, FLORIDA

# CHARACTERISTICS OF LIQUID ROCKET PROPELLANT EXPLOSION PHENOMENA

A research project initiated in 1964 by Dr. Erich A. Farber, Research Professor of Mechanical Engineering, on liquid propellant rocket explosions, has resulted in the publication of five NASA reports and seven technical papers to date in this area. The research is under the sponsorship of the National Aeronautics and Space Administration. The seven papers listed below define and discuss the characteristics of liquid rocket propellant explosion phenomena. They are:

I: A Mathematical Model for Defining Explosive Yield and Mixing Probabilities of Liquid Propellants, by E. A. Farber.

II: A Systematic Approach for the Analytical Analysis and Prediction of the Yield from Liquid Propellant Explosions, by E. A. Farber and J. H. Deese.

III: Studies and Analyses of the Mixing Phenomena of Liquid Propellants Leading to a Yield-Time Function Relationship, by E. A. Farber and R. L. San Martin.

IV: Fireball Hypothesis Describing the Reaction Front and Shock Wave Behavior in Liquid Propellant Explosions, by E. A. Farber and J. S. Gilbert.

V: Thermocouple Grid Analysis of Two 25,000-lb LOX/RP Liquid Propellant Explosion Experiments, by E. A. Farber.

VI: Explosive Yield Estimates for Liquid Propellant Rockets Based Upon a Mathematical Model, by E. A. Farber.

VII: Interpretation of Explosive Yield Values Obtained From Liquid Rocket Propellant Explosions, by E. A. Farber.

Since research on this problem is continuous in nature, and considerable effort and time is expended thereon, more papers and reports in this series will be forthcoming.

CHARACTERISTICS OF LIQUID ROCKET PROPELLANT
EXPLOSION PHENOMENA

Part VI: Explosive Yield Estimates for Liquid Propellant Rockets
Based Upon a Mathematical Model

by

E. A. Farber*

## ABSTRACT

This paper demonstrates how the mathematical model,[1,2] developed earlier, can be used to estimate the expected explosive yields, as a result of liquid propellant rocket failures.

The best available data are incorporated and a comparison is made with results obtained from liquid propellant explosion experiments.

The mathematical model, programmed for an IBM-360 computer, used here is described briefly so as to eliminate the need for the references.

## INTRODUCTION

The yield from liquid propellant explosions, as a result of missile failures, is of extreme importance in assessing the hazards to astronauts, launch-support personnel, launch-support facilities and surrounding communities. Since explosive tests of large liquid propellant rockets are not practical because of the costs and hazards involved, prediction methods must be used in estimating the expected explosive yields.

A mathematical model was developed by the writer, a few years ago, for this specific purpose. At that time very limited information was available to evaluate the validity of the model. Considerable information has become available since that time. Data were obtained by the writer's University of Florida Group, by instrumenting two 25,000-lb LOX/RP explosive experiments[3] and one 200-lb LOX/RP cold flow and explosive experiment, carried out at the Air Force Rocket Propulsion Laboratory at Edwards Air Force Base, California, which established the yield function-spill function relationship. Only last week the Preliminary Final Report of Project PYRO became available, giving data which were used here to check the results predicted by the model.

This information, including the inert mixing experiments, increased the confidence in this model and established it as a very useful tool.

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## Yield Function

The yield function, as used for this paper, is defined as the fraction of the theoretically maximum yield which is actually obtained.

$$y = \frac{Y}{Y_{theor.\ max.}} \tag{1}$$

This yield can be expressed as TNT equivalent yield on an energy basis but care must be exercised in predicting damage, since the pressure-time trace for liquid propellants is different from that of TNT, especially in the near field.

## Spill Function

The spill function, as used in this paper, is defined as the fraction of the total volume of propellants mixed at any time t, multiplied by some modifying factors.

$$x = \frac{V_M}{V_P} F_T F_B F_F \tag{2}$$

$V_M$ Propellant Volume Mixed
$V_P$ Total Propellant Volume
$F_T$ Turbulence Factor
$F_B$ Boiling Factor
$F_F$ Freezing Factor

Inert laboratory experiments, utilizing such fluids as water and oil, hot wax and water, hot oil and water, $LN_2$ and water, $LN_2$ and kerosene, etc. established the factors $F_T$, $F_B$, and $F_F$.

It was shown that, in the early stages of mixing, these factors have a value near 1 and thus the spill function x is essentially the normalized mixing volume. This latter fact was also established by the explosive experiments of the 25,000-lb LOX/RP and the 200-lb LOX/RP.

## Yield Function - Spill Function Relationship

In the development of the mathematical model it was assumed that the relationship between y and x can be expressed as

$$y = \frac{b}{b + c} x^d \tag{3}$$

where b, c, and d are constants.

Again the explosive experiments of 25,000-lb LOX/RP and the 200-lb LOX/RP cold flow and explosive experiments proved the above relationship valid.

## MATHEMATICAL MODEL[1,2]

With the relationship between the yield function (y) and the spill function (x) established, the mathematical model can be formulated, resulting in a statistical function which is capable of incorporating the above y-x relationship, and is able to provide for valid estimating procedures of the parameters involved.[1,2]

The statistical function is a modified Dirichlet bivariate surface with four parameters a, b, c, and d. It is

$$f(x, y) = \frac{d\,\Gamma(a+b+c)}{\Gamma(a)\Gamma(b)\Gamma(c)}\, x^{d-1}(1-x^d)^{a-1} y^{b-1}(x^d-y)^{c-1} \qquad (4)$$

where $\Gamma$ is the gamma function. The only restrictions on this function are that

$$y > 0,\quad x > 0,\quad y \leq x^d,\quad d \neq 0$$

To fully define the above function it is necessary to evaluate the parameters a, b, c, and d on the basis of the particular y-x relationship describing the physical phenomena. This can be done by the following statistical estimating procedure.

Defining

$$u_i = 1 - x_i^d, \qquad v_i = \frac{y_i}{x_i^d} \qquad (5)$$

four simultaneous estimation equations can be written for the four parameters a, b, c, and d.[1]

$$\overline{\ln v} = \Psi(b) - \Psi(b + c) \qquad (6a)$$

$$\ln \bar{v} = \ln(b) - \ln(b + c) \qquad (6b)$$

$$\overline{\ln u} = \Psi(a) - \Psi(a + b + c) \qquad (6c)$$

$$\ln \bar{u} = \ln(a) - \ln(a + b + c) \qquad (6d)$$

where a bar over an expression indicates the average value of all available values

ln indicates the natural logarithm (base e)

$\Psi$ is Euler's Digamma Function

From this mathematical model, the modified Dirichlet bivariate surface, a wealth of information can be extracted. Some of these are

A. Probability Distribution of the Yield, $P_y$

$$P_y(y) = \int_{y^{\frac{1}{d}}}^{1} f(x, y)\, dx \qquad (7)$$

From this probability distribution, the average yield value can be found as well as confidence limits, indicating that a certain percentage of all yield values lies below the selected yield value.

B. Probability Distribution for the Spill Function, $P_x$

$$P_x(x) = \int_0^{x^d} f(x, y)\, dy \qquad (8)$$

This distribution can be analyzed the same way as the one under (A).

C. Confidence Regions for the Yield and Spill

The regions into which a certain percentage of all yield and spill values fall can be obtained by finding the normalized fractional volumes under the probability surface. This requires double integration of the function representing the mathematical model, necessitating the use of a large-scale computer. The integrals are of the form

$$V_{x, y} = \int_0^1 \int_0^{x^d} f(x, y)\, dy\, dx \qquad (9)$$

for the total volume and with the proper limits for the subvolumes. When plotting y versus x these regions can be seen looking like contour lines on a map.[2]

## EXPLOSIVE YIELD ESTIMATION

To use the mathematical model for the estimation and the prediction of expected yield values it is necessary to evaluate the parameters a, b, c, and d.

This was done and it was found that by taking the best available information that the parameters take on the following values:[2]

$b = 4.0, \quad c = 1.1, \quad d = 1.5$

a = function of the propellant quantity, (thus can be considered a scaling parameter)

The function for a is plotted in Figure 1 indicating that it is a distorted S curve. The circled points on the curve represent the best information available both in experiments for the smaller quantities and actual liquid propellant rocket failures for the larger quantities.[1,2,3]

The only experiments which were fully instrumented to obtain the yield-spill relationship were the two 25,000-lb LOX/RP explosion tests and the 200-lb LOX/RP cold flow and explosion experiment. The yield-spill relationship which was verified in those experiments was assumed to hold also true in the remainder of the experiments and failures.

The points not circled in this figure represent the a values based upon the PYRO data as presented in the Preliminary Final Report of Project PYRO which was received only one week ago.* It is seen that all a values calculated on the basis of the PYRO data are larger than the values used in the model, except for the 1000-lb LOX/RP CBGS V-V high velocity drop tests. These tests comprise only about 0.5 percent of the total number of tests reported and are not particularly representative of liquid propellant rocket failures.

Figure 1 can be used to predict the most probable parameter a for large-scale rockets such as the Saturn V.

From the figure, it is seen that the value of a increases beyond the last available point, so it can be concluded that it will be greater than 70 for the Saturn V. On the other hand, if the last two points are connected by a straight line its intersection with the Saturn V propellant weight will give an a value which is too large. Thus the actual value of a for the Saturn V must lie between 70 and 97.

Figure 2 shows that the effect of a on the yield is rather small in the range of these large propellant quantities. And so the predicted average yield value for the Saturn V based upon the mathematical model is between 3.5 and 4 percent.

Figure 3 presents the average yield values as predicted by the mathematical model as a function of the propellant weight involved and also gives the 95 percent confidence limit, indicating that 95 times out of 100 the explosive yield for the Saturn V would be less than 9 percent.

The mathematical model as used here included all types of propellants as well as all kinds of modes of failures or experiments.

It is clear that the mode of failure, as well as the propellant type, has a distinct influence upon the actual yield obtained.[5] If only a particular type of failures or a particular type of propellants is to be investigated then only that data can be used for analysis in the mathematical model, and the values of the parameters a, b, c, and d will change. The average explosive yield value should be better in such cases and the confidence limits will be found, in general, closer to the average values.

The last statement indicates that for large-scale liquid propellant rockets it may be desirable to control the mode of failure with a properly designed destruct

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*April 18, 1968

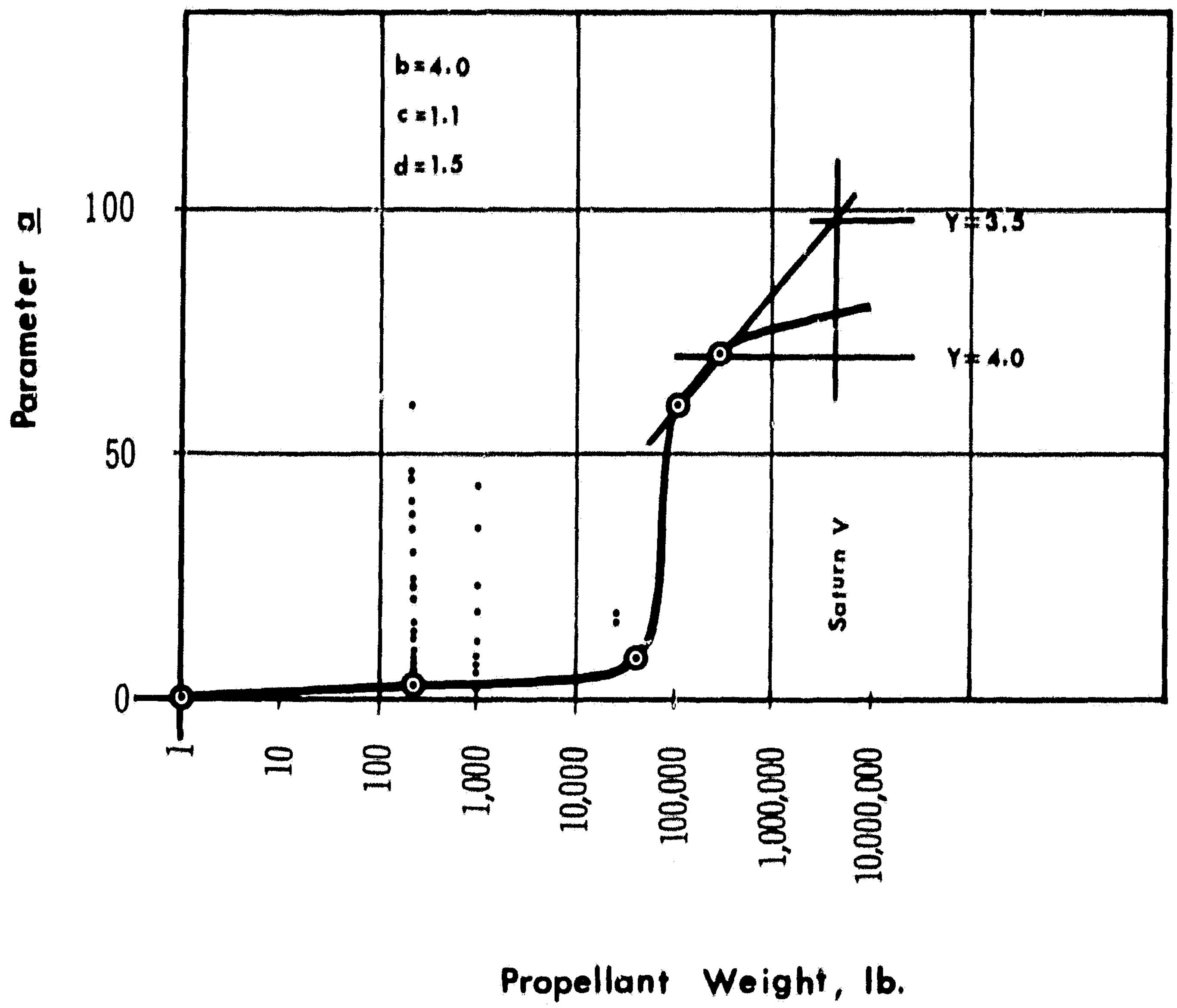


Fig. 1 Parameter a as a Function of Propellant Weight

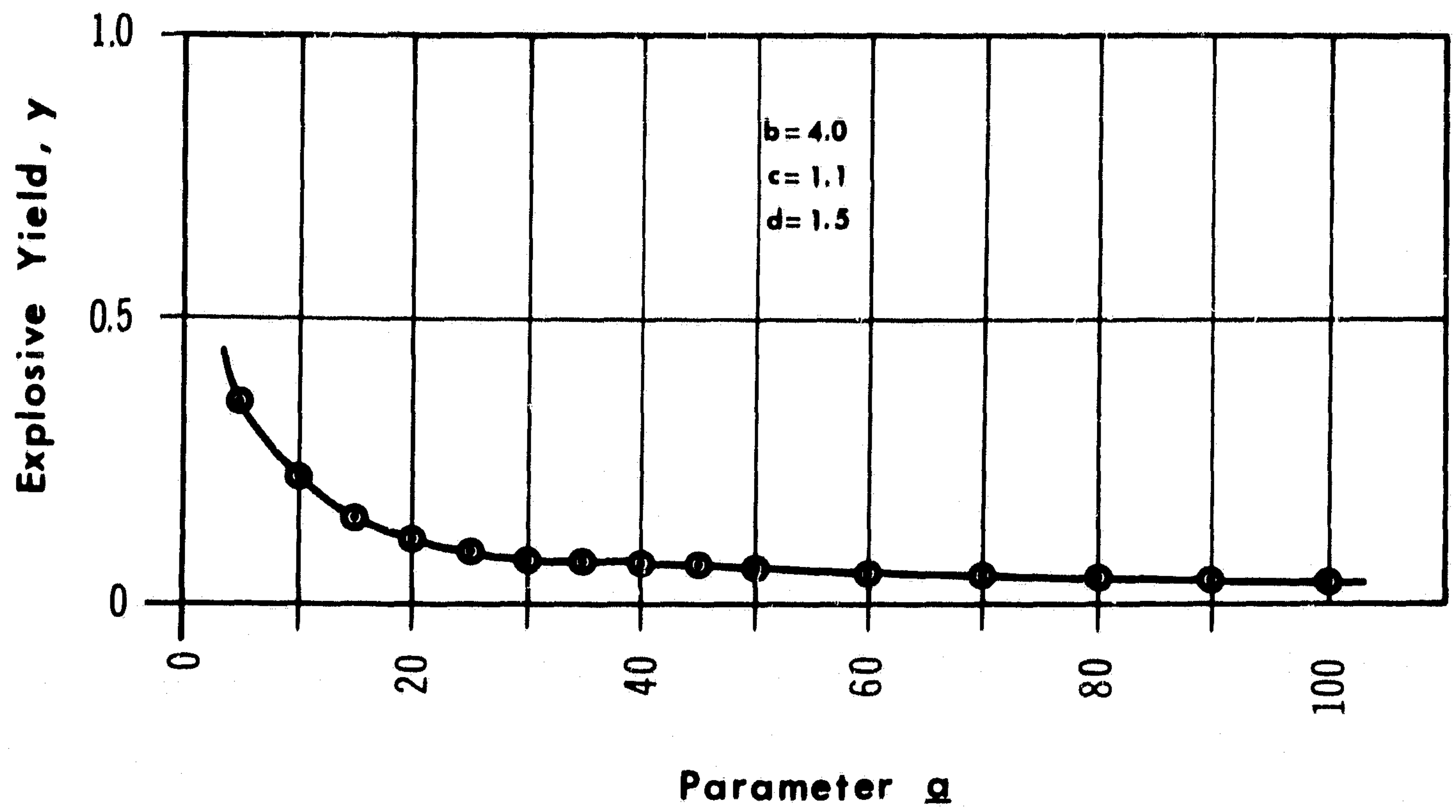


Fig. 2 Effect of Parameter a on Explosive Yield

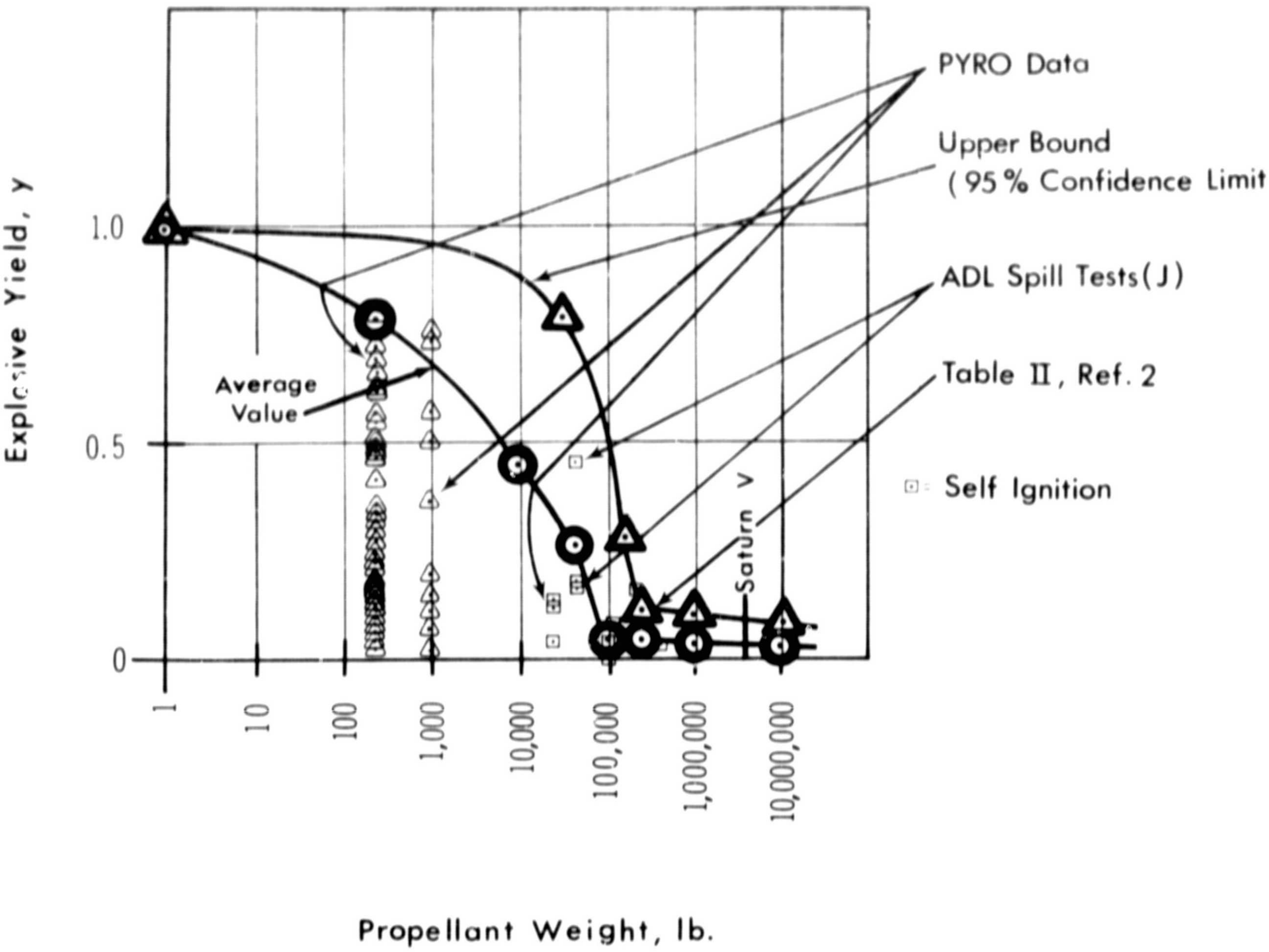


Fig. 3 Estimated Explosive Yield as a Function of Propellant Weight

system, in order to give a minimum explosive yield. With such a procedure the explosive yield value can be lowered and the explosion yield prediction reliability increased.

## CONCLUSIONS

1. Since the development of the mathematical model, several years ago, for the estimation and prediction of the expected yield from liquid propellant rocket explosions, much information has become available which increases the confidence in this model.

2. The yield function-spill function relationship was verified by instrumenting two 25,000-LOX/RP explosion experiments and one 200-lb LOX/RP cold flow and explosion experiment.

3. A check of the yields predicted by the model against the experimental results, reported in the Preliminary Final Report on Project PYRO, showed the mathematical model to be conservative in 99.5 percent of the cases and only underestimated a few of the high velocity impact experiments.

4. It seems that the mathematical model can set an upper limit on the expected yield of a large-size liquid propellant rocket for a chosen confidence limit and it can give the average value by conservative extrapolation.

5. All evidence indicates that the mathematical model developed for the prediction of expected yield values is conservative in its predictions.

## REFERENCES

1. "Feasibility Study to Explore the Explosive Effects of Liquid Propellants to Define the Mathematical Behavior of the Physical Processes Involved," by E. A. Farber et al, NASA Report, February, 1965.

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4. "Studies and Analyses of the Mixing Phenomena of Liquid Propellants Leading to a Yield-Time Function Relationship," E. A. Farber and R. L. San Martin, Proceedings of the New York Academy of Sciences Explosives Symposium, November, 1966.*

5. "Preliminary Final Report of Project PYRO." Received incomplete copy April 17, 1968.

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* copies also available from the Florida Engineering and Industrial Experiment Station as Technical Papers No. 346 and No. 386 respectively.

## CHARACTERISTICS OF LIQUID ROCKET PROPELLANT EXPLOSION PHENOMENA

### Part VII: Interpretation of Explosive Yield Values Obtained From Liquid Rocket Propellant Explosions

by

E. A. Farber*

It was mentioned previously that the results obtained by the writer and his associates are in terms of EXPLOSIVE YIELD defined as the fraction of the theoretical maximum (Normalized Yields). In this manner the difficulty of relating one propellant to another, or to other explosives is avoided.

The above difficulty comes from the observation that different propellants and explosives exhibit different pressure-time traces, or relationships, and not enough is known on how to properly correlate one of these traces with another. The most common correlation is made either on the bases of energy release, or over-pressure, or impulse with each of these correlations giving different results especially in the near field.

Since much of the work on liquid propellant explosions is reported in terms of "TNT Equivalent Yields," it was suggested that the writer provide some indication on how the yield values obtained by him could possibly be converted into equivalent TNT values.

Caution must be used when this is done because depending upon the method used different results can be obtained. This same fact is also born out in the yield estimation based upon actual field measurements. Yields obtained and based upon over-pressure measurements are different from those based upon impulse with the difference increasing the closer to ground zero the measurements are taken.

For the purpose of relating the "Normalized Yield" values to "TNT Equivalent" values, the writer used the method given in the "Summary Report on a Study of the Blast Effect of a Saturn Vehicle" by Arthur D. Little, Inc., dated February

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15, 1962. The results presented on page 70 of the above reference lead to the following correlation:

A. 1 lb of LOX/RP propellant in a 2.25/1 weight ratio is potentially equivalent to 1.23 lb of TNT.

B. 1 lb of LOX/$LH_2$ propellant in a 5/1 weight ratio is potentially equivalent to 1.52 lb of TNT.

C. 1 lb of LOX/RP/$LH_2$ propellant in a weight composition of 0.75/0.18/0.07 (Saturn C-2 Configuration) is potentially equivalent to 1.355 lb of TNT.

D. 1 lb of LOX/RP/$LH_2$ propellant in a weight composition of 0.721/0.244/0.035 (Saturn V Configuration) is potentially equivalent to 1.29 lb of TNT.

On the above bases the values of expected yields as predicted by the Mathematical Model for the Saturn V propellant quantities are:

<u>Saturn V</u>

| Normalized Yields | TNT Equivalent Yields |
|---|---|
| $y_{avg}$ = 3.8 | = 4.9 |
| $y_{0.95}$ = 9.6 | = 12.4 |

$y_{avg}$ average of all expected yields

$y_{0.95}$ 95% of all the expected yields fall below this value

A further word of caution should be added at this time in case a damage index is attached to these yield values expressed in terms of TNT equivalents. Again because of the difference in the pressure-time traces, a particular liquid propellant explosive yield can be expected to do a different amount and type of damage (especially in the near field) from the TNT explosive yield of the same value. In other words, care should be used in applying these results, taking cognizance of the explosive characteristics of the propellants under consideration.