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CHARACTERISTICS OF LIQUID ROCKET PROPELLANT EXPLOSION PHENOMENA

No. 448. Part VIII. Prediction of Explosive Yield and Other Characteristics of Liquid Propellant Rocket Explosions

by

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27

PREDICTION OF EXPLOSIVE YIELD AND OTHER CHARACTERISTICS OF LIQUID PROPELLANT ROCKET EXPLOSIONS

By

Dr. E. A. Farber*

Abstract

This paper describes the work carried out by Dr. Farber and his group at the University of Florida on the characteristics of liquid propellants.

Three independent methods were developed describing the phenomena and are useful in the prediction of explosive yield.

I. THE MATHEMATICAL MODEL[1,2,3,4]

II. THE SEVEN CHART APPROACH[4,5,6,7,8,9]

III. THE CRITICAL MASS METHOD[4]

These methods will be described briefly in this paper and references given where the detail can be found.

In addition to the above work, original in nature, giving much insight into the time sequenced phenomena from the mode of failure of a particular missile, through mixing of the propellants, ignition, formation of the shock and reaction fronts, their propagation and separation, their interaction with missile tankage, their emergence into the atmosphere, formation of the fireball, the fireball growth and cooling with finally the resulting combustion products cloud with its composition. These phenomena will be described in

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I . Fireball Hypothesis and Experimental Verification, Describing the Reaction Front and Shockwave Behavior of Liquid Propellant Explosions.[4,10,11,12,13]

V. Fireball and Post-Fireball Combustion[4,14] Products Cloud History and Composition.

The measurements taken inside the exploding tank configurations are believed to be the first of their kind furnishing new information.

The methods described above, which were developed with regard to liquid propellants, are now being used in the analysis of the Saturn V destruct system, making predictions as to the expected explosive yield from our largest liquid propellant rocket. This work or the early phases of it are briefly discussed in

VI. Saturn V Destruct System Analysis

A great wealth of information is condensed into this paper and for further information a number of reports and papers are listed as references for those who wish to delve deeper into this subject.

Introduction

In the early days of the liquid rocket development the hazards could be reduced to negligible values through distance from the rockets. This was possible because the rockets were small and the quantities of liquid rocket propellants involved were not large.

With the increased size of today's liquid propellant rockets, now in the range of several hundred of thousands of pounds to millions of pounds in the case of our moon rocket the Saturn V, the hazards take on major proportions.

For this reason it becomes of utmost importance to be able to predict the explosive behavior of such large quantities of liquid propellants so that adequate measures can be taken to protect the astronauts, the launch and support personnel, the neighboring communities, and in some measure the launch and support facilities.

This paper presents three independent methods

I. THE MATHEMATICAL MODEL

II. THE SEVEN CHART APPROACH

III. THE CRITICAL MASS METHOD

which can be used in predicting the explosive yield of liquid propellant rockets.

The three independent methods, requiring different input information, lead to essentially the same results.

The second method mentioned above requires more input information than the other two, but in return it gives more detail about the processes involved. This becomes especially valuable when the processes are to be controlled to give minimum explosive yield.

In connection with this work, as the various natural phenomena were studied, a Fireball Hypothesis was developed, describing in detail the time sequenced phenomena leading to the explosion. After the explosion it gives information about the shock and reaction fronts and their behavior, the generation of the fireball, the combustion products cloud and its composition. This is described in

IV. Fireball Hypothesis and Experimental Verification, Describing the Reaction Front and Shockwave Behavior of Liquid Propellent Explosions.

V. Fireball and Post-Fireball Combustion Products Cloud History and Composition.

Through the above work, methods were developed by which the explosive yield of liquid rocket propellant explosions can be described and predicted. The methods were applied to field experiments for comparison of predictions with actual measurements, then with a minimum number of assumptions to actual rocket explosions for which yield estimates were available, and finally to the destruct system of the Saturn V, our largest liquid propellant rocket.

The analysis of the Saturn V will be briefly described and some preliminary results given in

VI. Saturn V Destruct System Analysis

I. THE MATHEMATICAL MODEL

In the early stages of the investigation to describe the physical phenomena in liquid propellant explosions it was assumed that a relationship exists between the mixing characteristics of the liquid propellants and the explosive yield obtained.

The very sparse data available indicated the possible functional relationship and so a MATHEMATICAL MODEL was developed. It had to satisfy the data, available at the time, and be flexible enough to incorporate future data if modification of the functional relationship seemed desirable. In addition the model had to satisfy requirements for statistical analysis so that probability averages, confidence limits and confidence regions can be determined.

The MATHEMATICAL MODEL developed was a rather complicated function forming a probability surface controlled by four parameters. Three of these parameters were needed to describe the data of possibly considerable range. The fourth parameter allowed the description of an average characteristic of all the data or, if the data was grouped, the characteristic of the grouping criteria.

In this work it was used to express the effect of quantity of propellants upon explosive yield.

The expected explosive yield can be obtained from the MATHEMATICAL MODEL, a bivariate function, carrying out the indicated mathematical operation

$$E(y/x) = \int_0^1 y \frac{f(x,y)}{\left[\int_0^{x^d} f(x,y)dy\right]} dy$$

where the function is

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

The probability of a certain yield to occur can be found from

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

The probability of a certain degree of mixing to occur can be found from

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

If the confidence regions into which a certain percentage of all values fall is desired it can be found from

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

Even though the MATHEMATICAL MODEL was originally developed for the purpose of describing the overall behavior of liquid propellant explosions it has since been employed to predict explosive yields.

The results from the analysis of the MATHEMATICAL MODEL with parameters b = 4.0, c = 1.1, d = 1.5, which satisfy the available information and parameter a = 70, a value which satisfies all the information, are presented in Figure 1.

Figure I-1A presents the probability with which each of the various explosive yields can be expected to occur.

Figure I-1B presents the probability with which each of the various degrees of mixing can be expected to occur.

Figure I-1C presents the probability regions which contain the explosive yield and the spill (mixing) values. The triangular area slightly smaller than half of the square contains all yield and spill values. The small oval area contains 80 percent of all yield spill values.

If the data is grouped as to quantity of propellants involved the parameter a becomes a function. Figure I-2 presents the functional relationship, an "S" curve. The last data point available is for about 282,000 lbs of propellants and so the value for the Saturn V is shown, bracketed by the two limiting values.

Figure I-3 indicates that the yield is not sensitive with respect to the parameter a at large values of a. So rather large variations or uncertainties in a, for large liquid propellant rockets has very little effect on the predicted explosive yield value.

Figure I-4 presents the final results, the average explosive yield as predicted by the MATHEMATICAL MODEL, the upper bound (95% Confidence limit) and experimental results.

The behavior of the small quantities of liquid propellants is quite different from the large ones, observed as a step in the value of parameter a.

The Mathematical Model, a = 70, b = 4.0, c = 1.1, d = 1.5

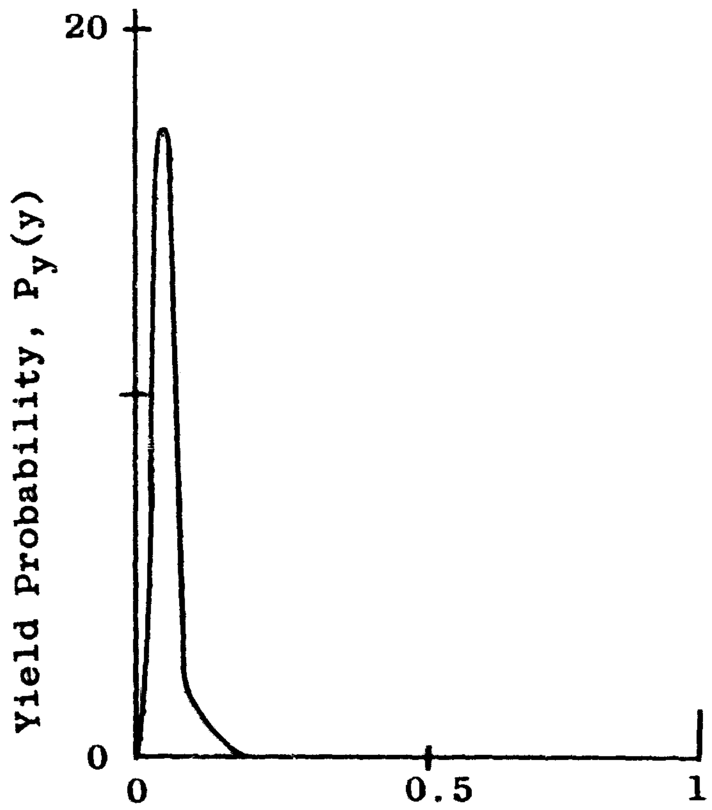


Figure I-1A Probability Distribution for the Yield Function (Missile Failures)

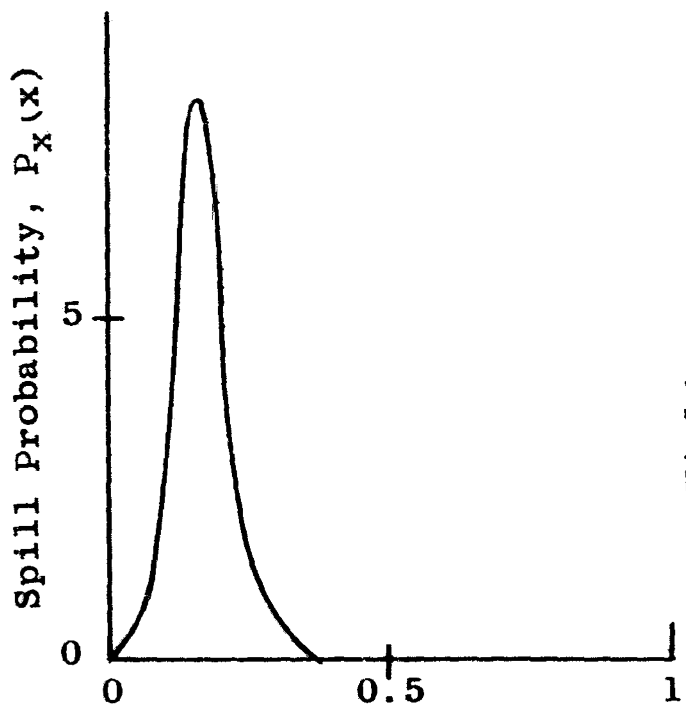


Figure I-1B Probability Distribution for the Spill Function (Missile Failures)

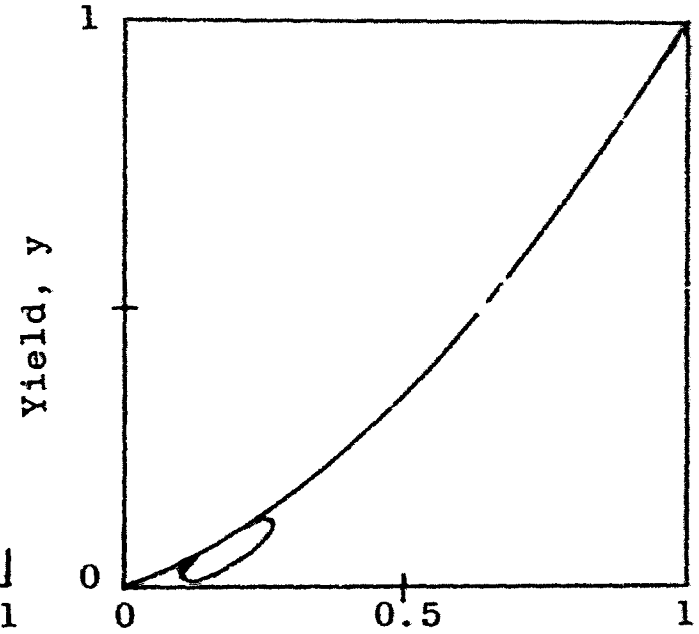


Figure I-1C Yield-Spill Probability Regions (Missile Failures)

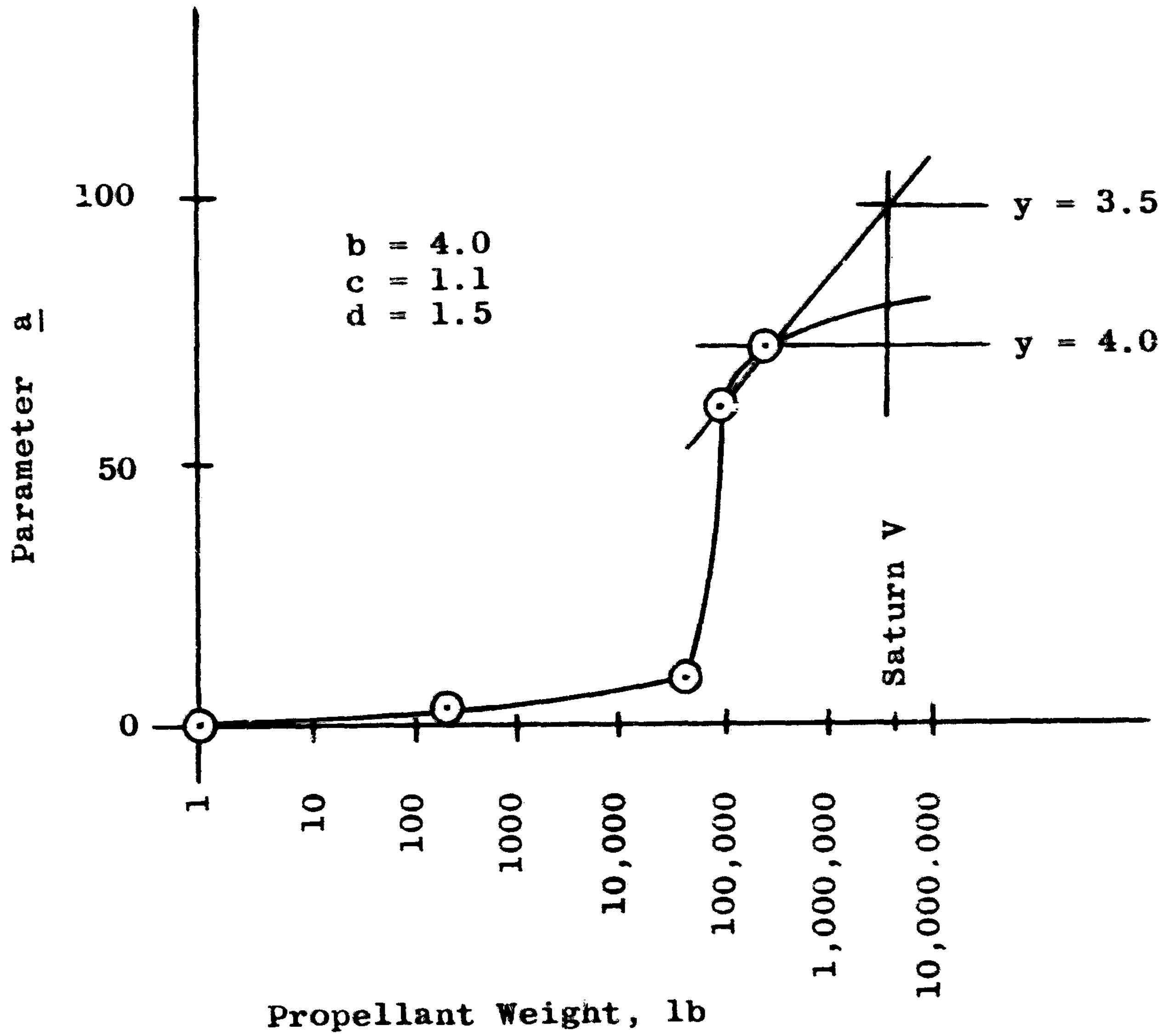


Figure I-2 Scaling Parameter a as a Function of Propellant Weight

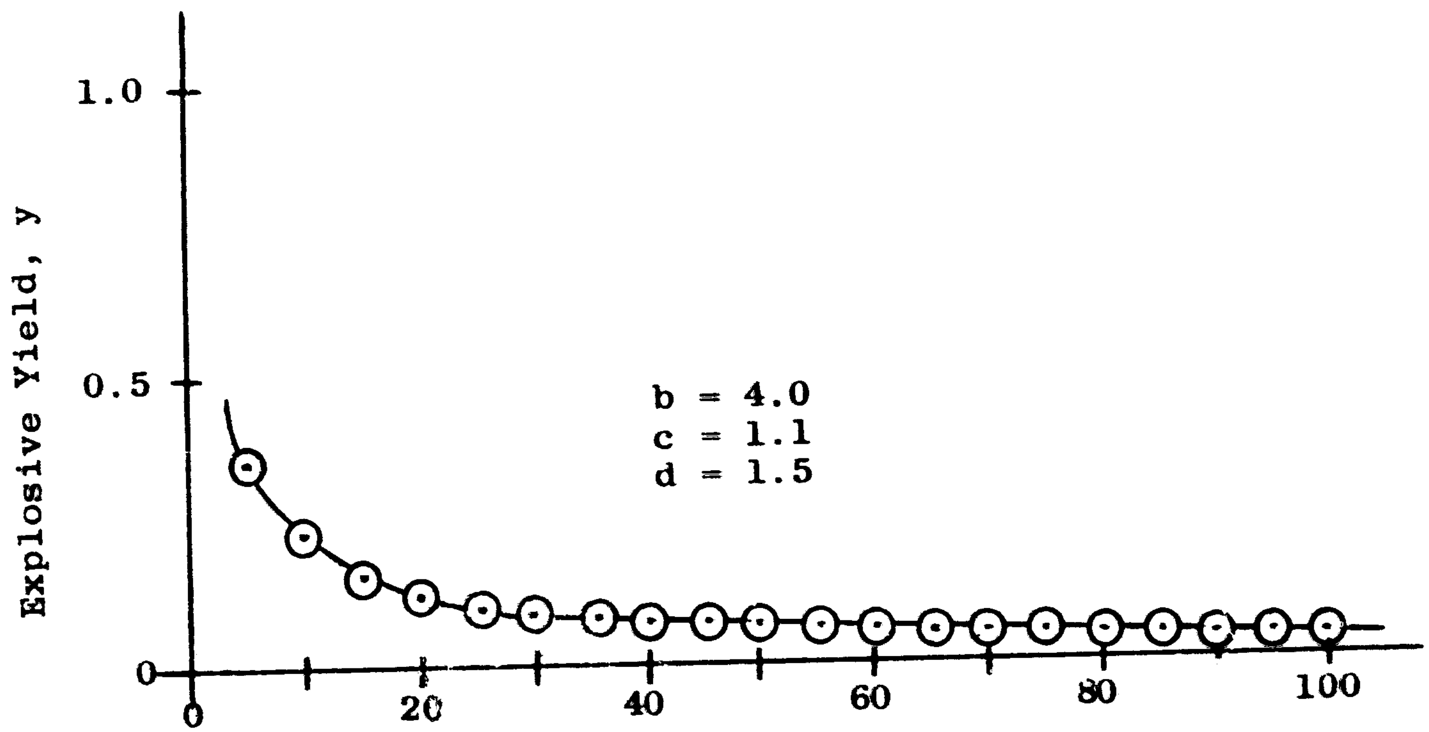


Figure I-3 Effect of Scaling Parameter a on Explosive Yield

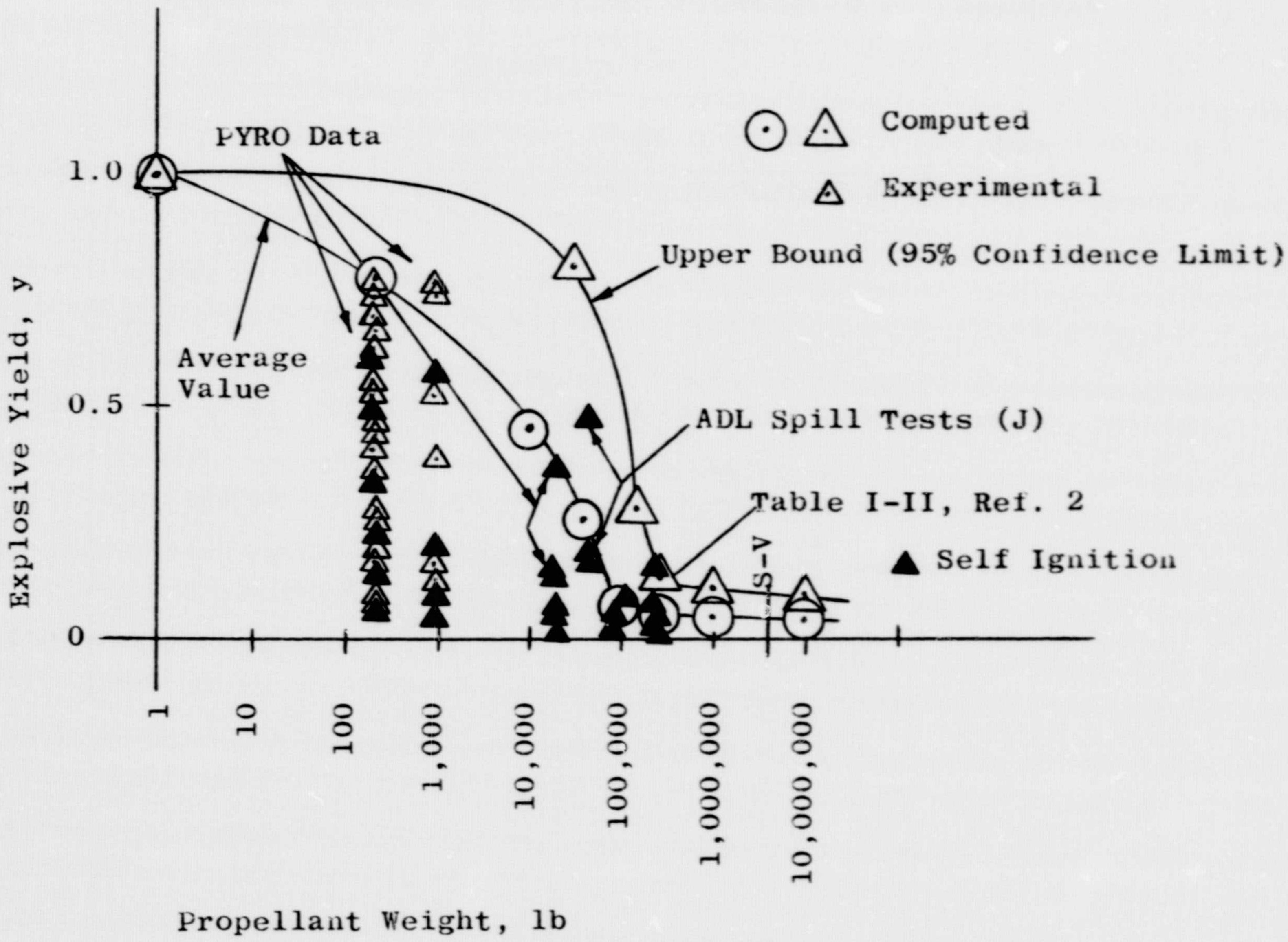


Figure I-4 Estimated Explosive Yield as a Function of Propellant Weight

Large explosive yields could be obtained by the small liquid propellant quantities since they could be ignited at will at a pre-selected time. This was not possible with the large quantities of liquid propellants since they auto-ignited relatively early during the mixing process.

The large circles and triangles represent computed values the small triangles experimental results and actual missile failures.

From Figure I-4 it can be seen that the predicted explosive yield values are high for small quantities of propellants and relatively small for the large liquid propellant quantities.

It might again be mentioned that the values presented here as predicted by the MATHEMATICAL MODEL are fractions of the theoretical maximum so as not to bring in the very questionable relationships of different propellants. If however a comparison is desired such as a TNT equivalent one of the references allows, with reservation, this process.

II. <u>THE SEVEN CHART APPROACH</u>

The SEVEN CHART APPROACH is a systematic procedure to arrive at a prediction of the explosive yield from liquid propellants.

This method essentially divides the problem of determination of the explosive yield from liquid propellant explosions into three basic phenomena.

1. The Yield Potential Function
2. The Mixing Function
3. The Ignition and Detonation Time

Each of these three basic phenomena can be studied separately and then the results of each study combined for the explosive yield prediction.

<u>Yield Potential Function</u>. The Yield Potential Function can be calculated from the knowledge of the propellants involved and the knowledge of the mode of failure.

In this manner, by the principles of chemical kinetics and heat transfer, the maximum yield which can be obtained theoretically at any time after failure can be calculated. This value is naturally greatest at time zero when all the propellants are still present.

Figure II-1 and Figure II-2 give this relationship for a three propellant, LOX/LH_2/RP-1, mixture, when dumped into a splash area.

Mixing Function. Even though the explosive yield potential, as defined above, is greatest at time zero, none of the propellants have come together or are mixed so that an explosion is impossible. At any time later if ignition should occur, only the propellants which are mixed at that time can take part in producing the explosive yield.

The fraction of the total propellants available at any time and actually mixed is referred to as the Mixing Function. The Mixing Function for the above case is shown in Figure II-3. This function is typical of mixing functions since they start at zero at some time after failure, reach a maximum and decrease again.

The Mixing Function can be determined from hydrodynamic calculations including heat transfer or from experiments both full scale and modeling. Four methods

a. The Vibration Mixing Analysis

b. The Wax Cas Analysis

c. The High Speed Photographic Analysis

d. The Thermocouple Grid Analysis

were developed by Dr. Farber's group to do this and after checking them against each other were employed.

Figure II-4 presents the Mixing Function for the S-IVB experiment carried out under project PYRO.

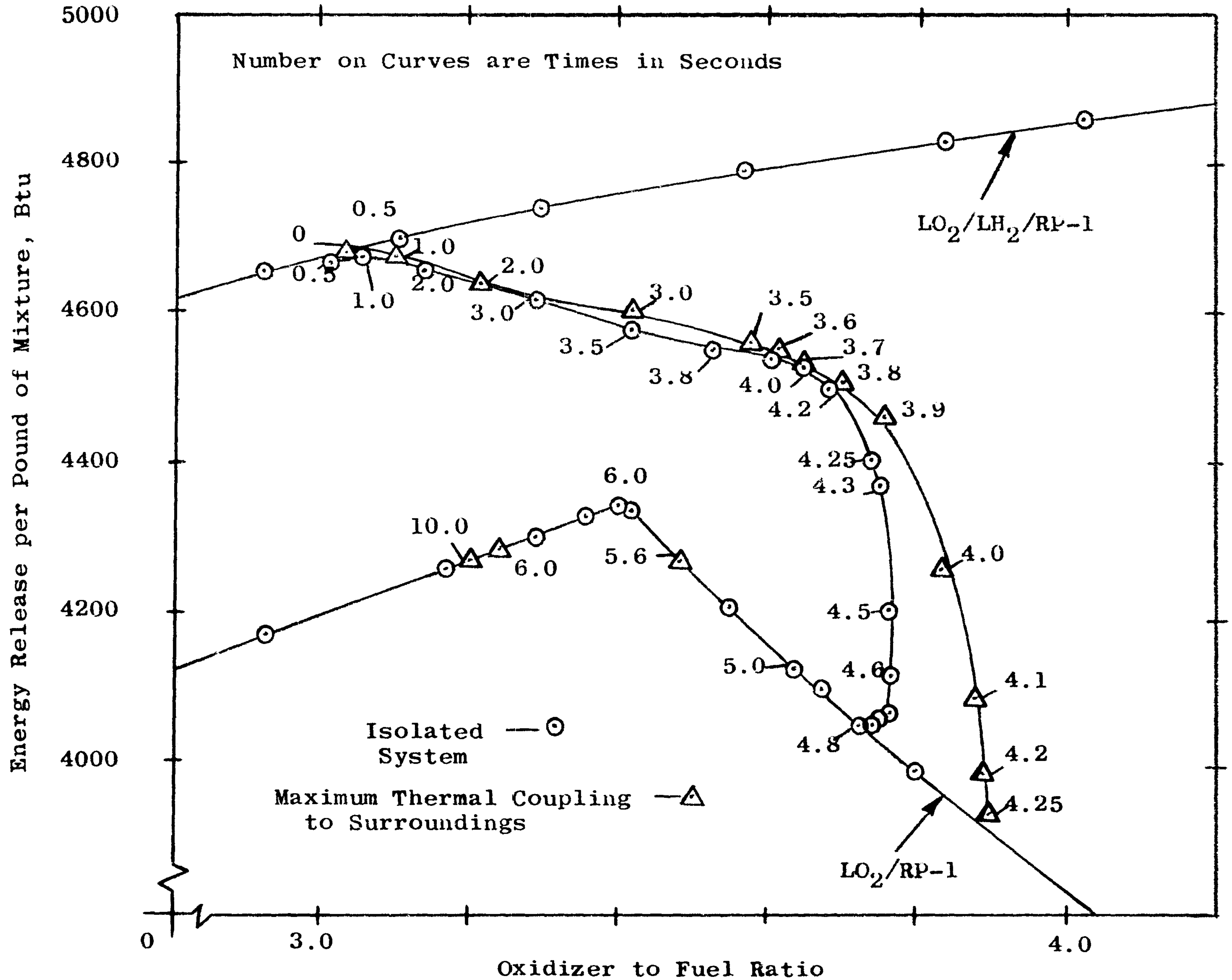


Figure II-1 Maximum Amount of Energy Release for a Three Component Liquid Propellant Mixture

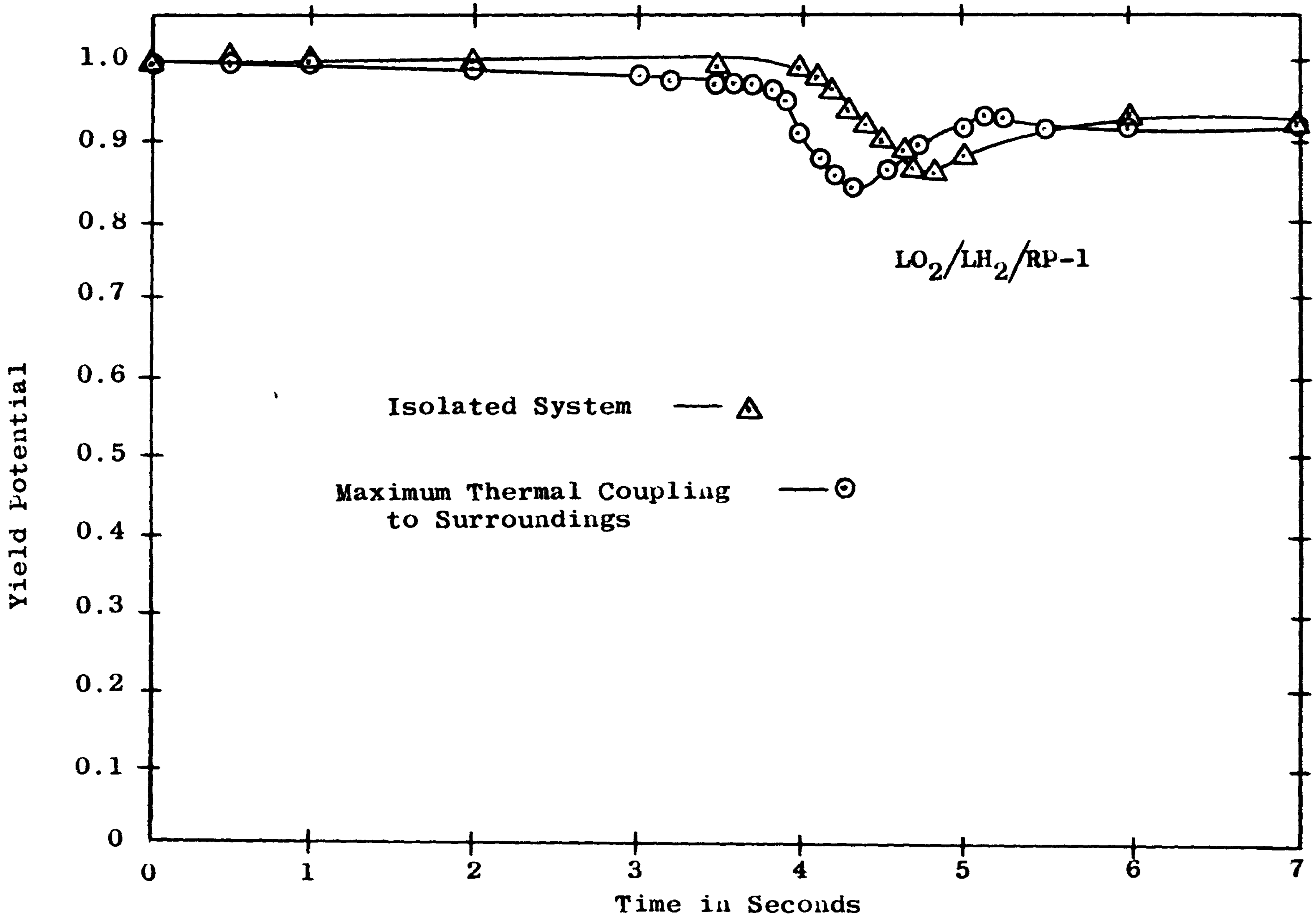


Figure II-2 Yield Potential as Time Function

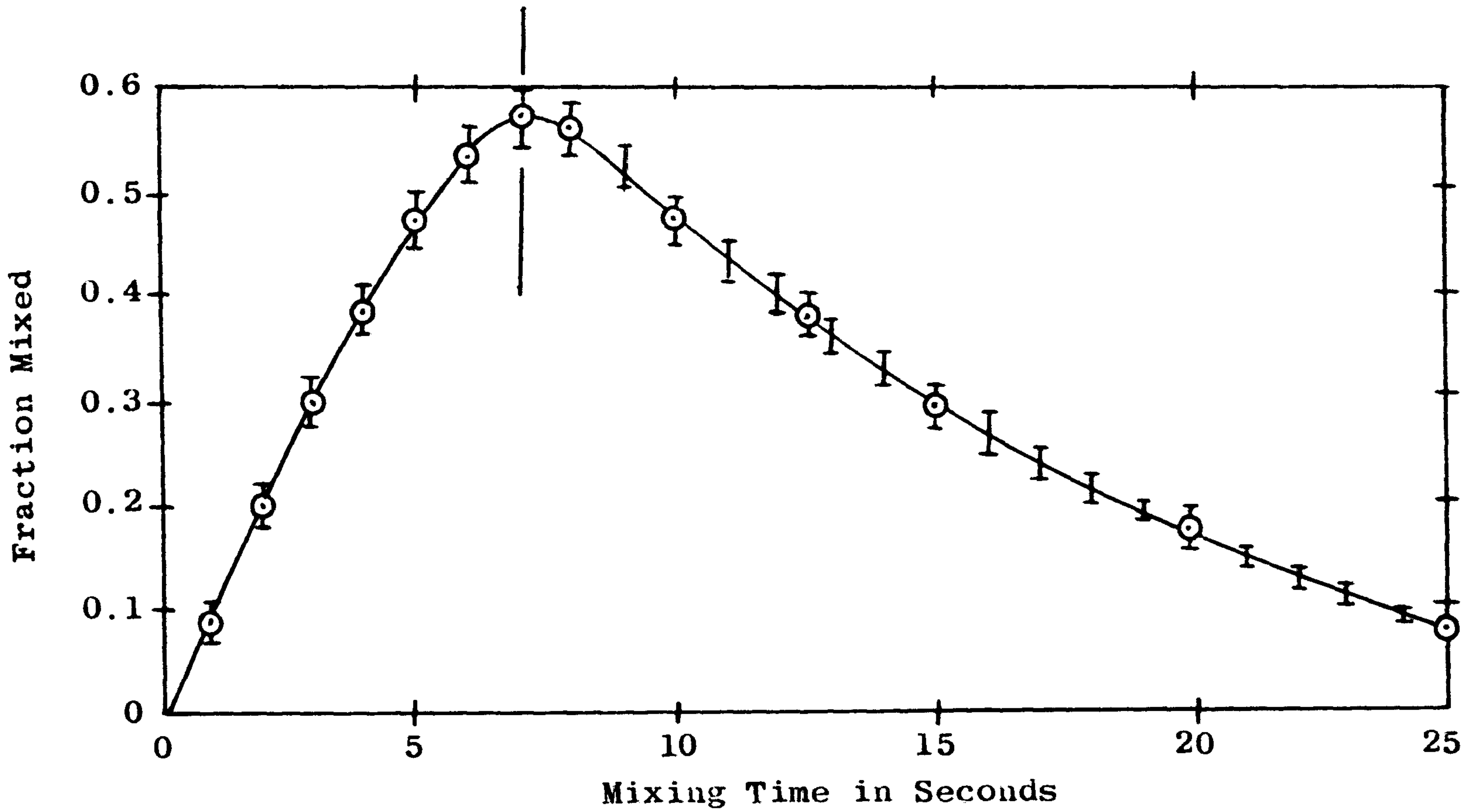
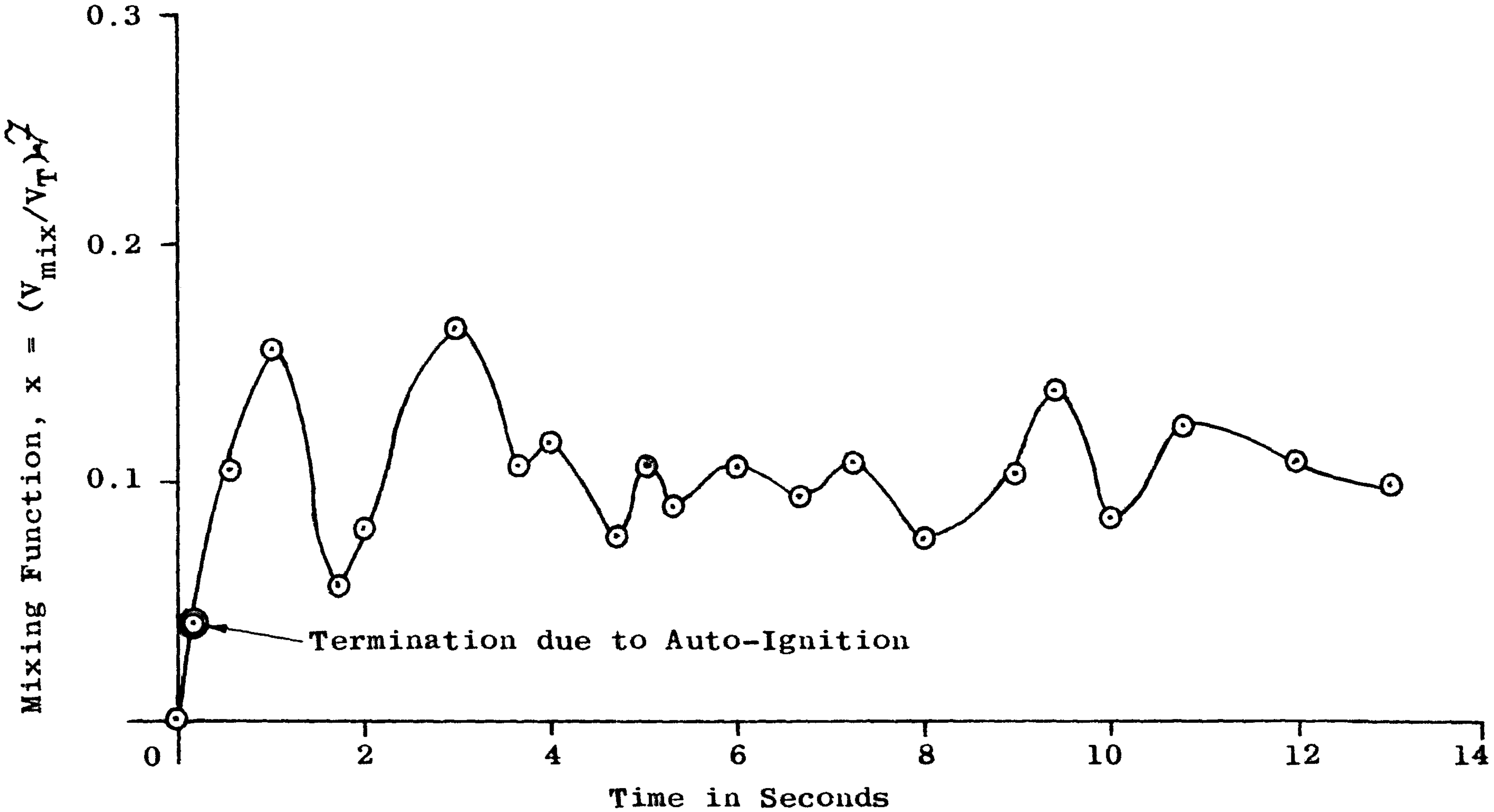


Figure II-3 Mixing Function or Spill Function for Three Component Liquid Propellant Spill Tests



<u>Figure II-4</u> Mixing Function, S-IV LO_2/LH_2 (Based upon 3" Diameter Simulated Experiment)

Figure II-5 presents the Mixing Function for the 25,000 lbs LOX/RP bulk head type failure mode experiments.

Figure II-6 presents the Mixing Function for the 200 lb Cold Flow and Explosive Experiment.

Expected Explosive Yield. Multiplying the explosive yield potential at any time t by the Mixing Function at the same time t, the Expected Explosive Yield is obtained at that time. Doing this for all t the Expected Explosive Yield, as a function of time, is obtained. In other words if ignition occurs at any time t the Explosive Yield Expected is the value of the expected yield curve at that time t.

Figure II-7 and Figure II-8 present explosive yield prediction curves corresponding to the Mixing Function curves Figure II-3 and Figure II-6.

The experimental results are marked on the first curve as J_1, J_2 and J_3 involving approximately 44,000 lb of propellants and the second curve marks the point of ignition and yield value for the 200 lb Cold Flow and Explosive Experiment. The agreement between the measured explosive yield values and the predicted values was in all cases excellent.

Ignition and Detonation Time. The ignition time for prediction purposes, can be a controlled value, a known value based upon the characteristics of the propellants, a statistical value with confidence limits, or it can be a value determined by the CRITICAL MASS METHOD as described in the next section.

It was shown that if the propellant characteristics, the mode of failure, and the ignition time are known, the explosive yield can be predicted for liquid propellants by the SEVEN CHART APPROACH.

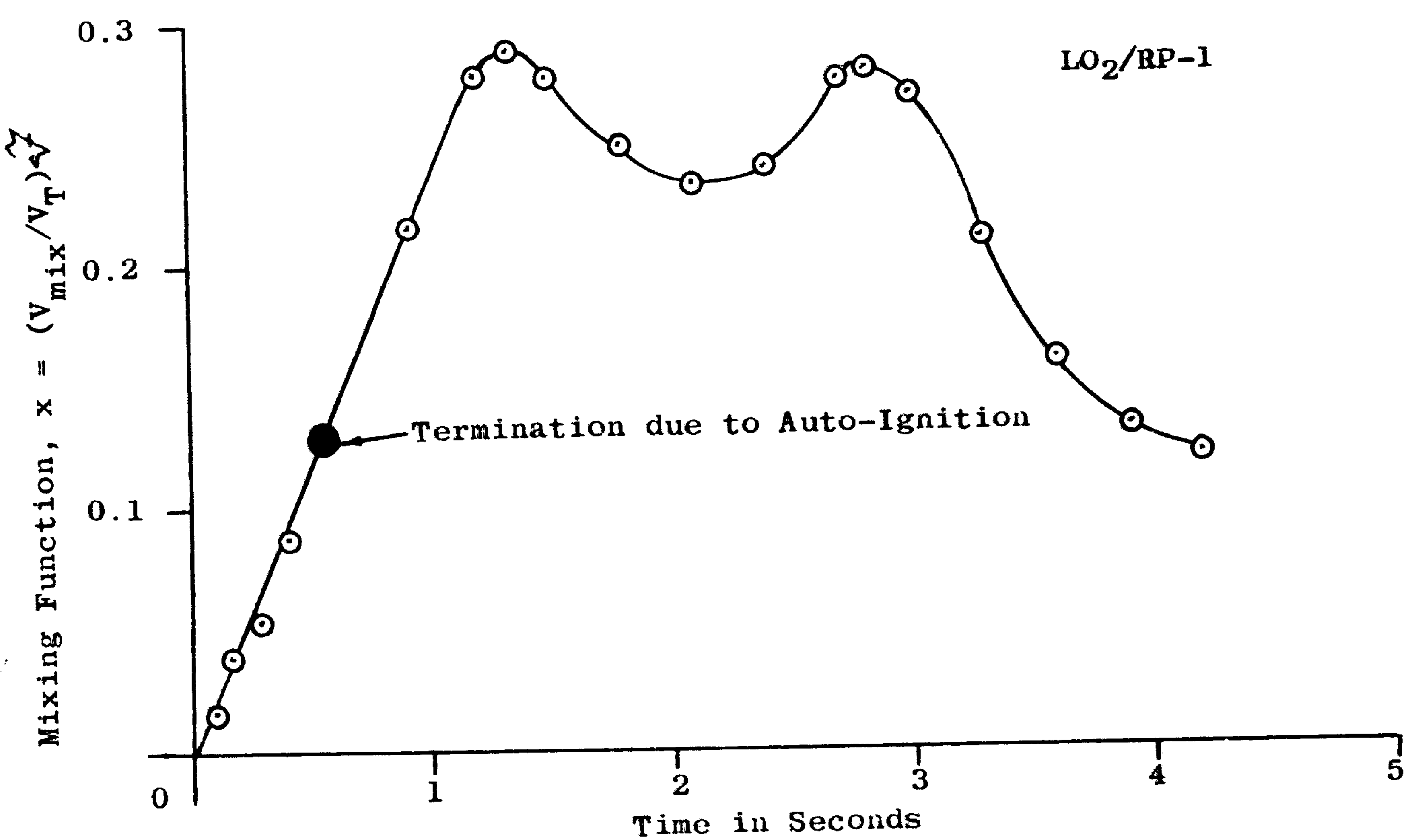


Figure II-5 Mixing Function, 25,000 lb Explosion Experiment (Based Upon 3" Diameter Simulated Experiment)

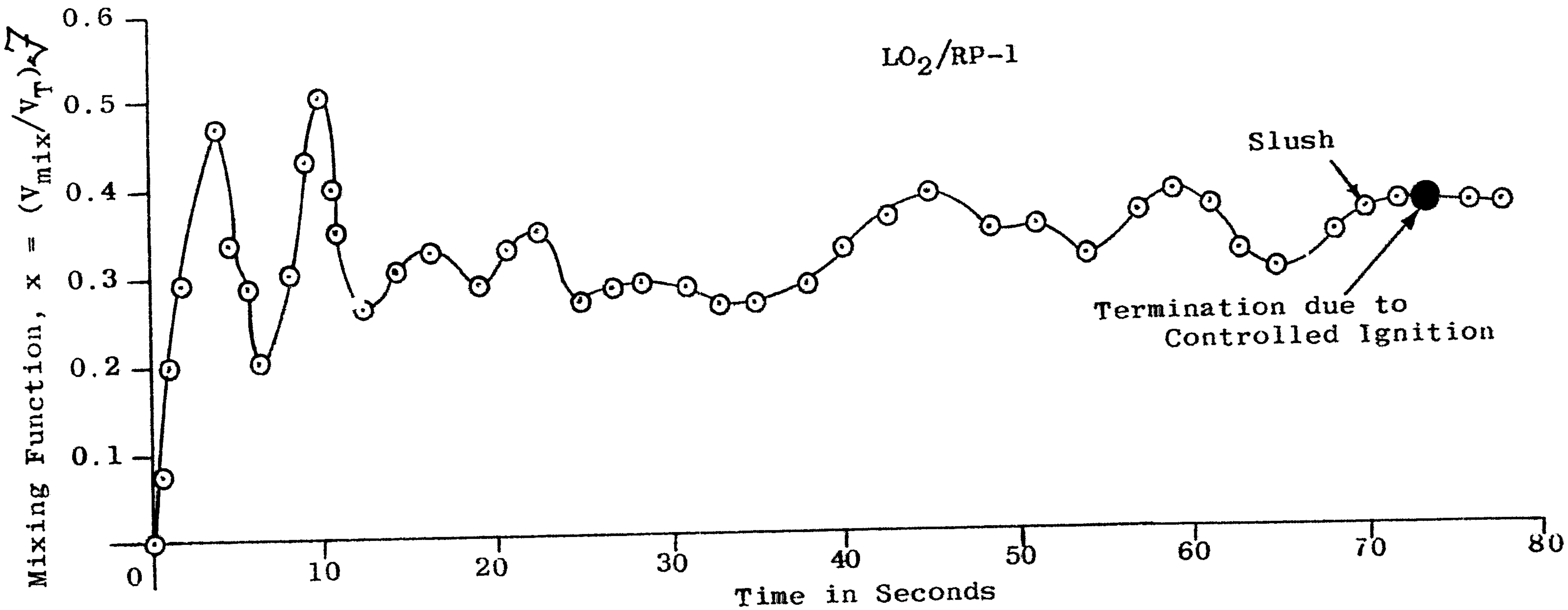


Figure II-6 Mixing Function, 200 lb Cold Flow Experiment (Based Upon 3" Diameter Simulated Experiment)

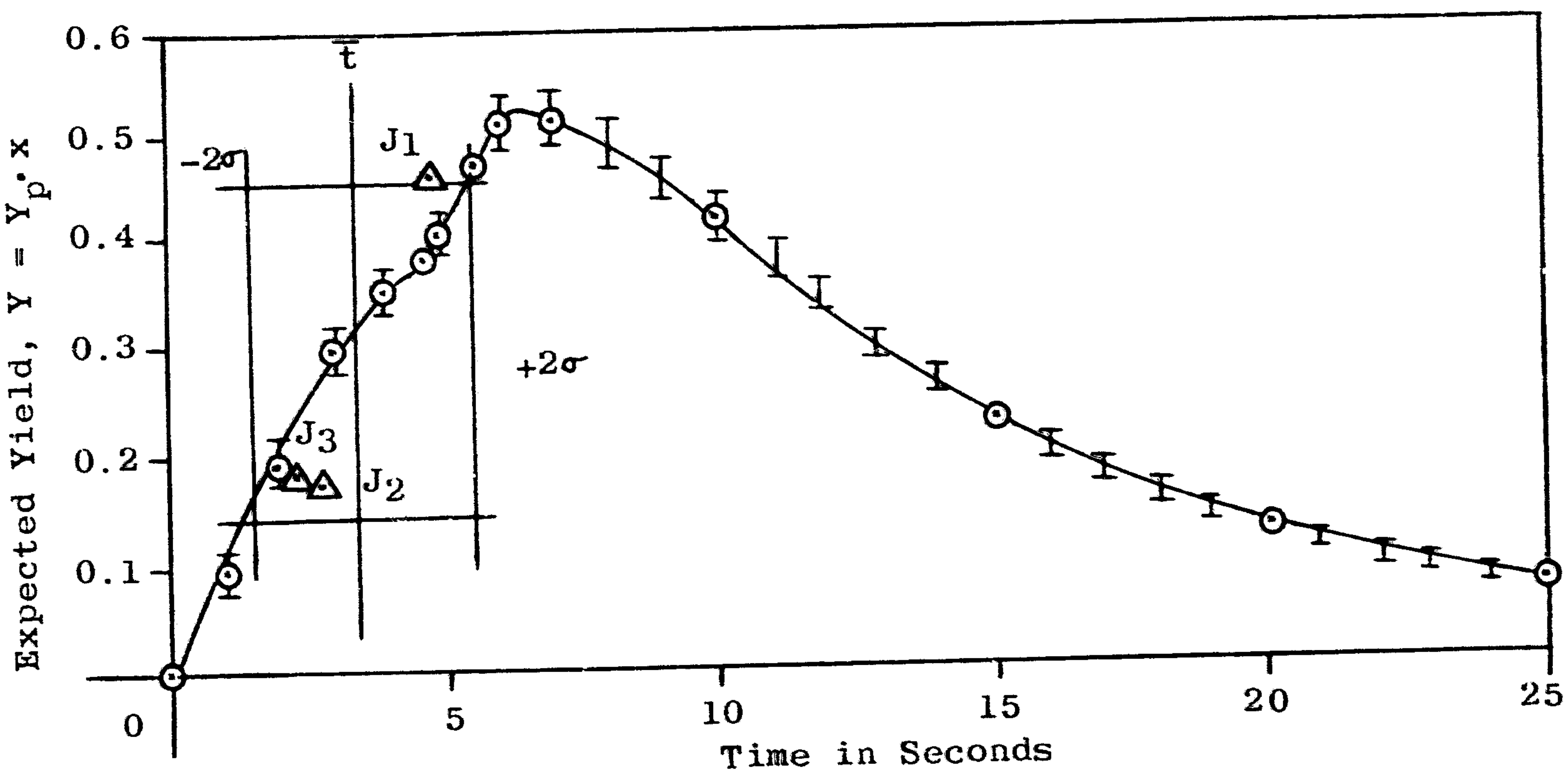


Figure II-7 Actual Yield for Random Ignition and Detonation Showing the Upper and Lower Limits of the Statistical Confidence Regions for Liquid Propellant Spill Tests

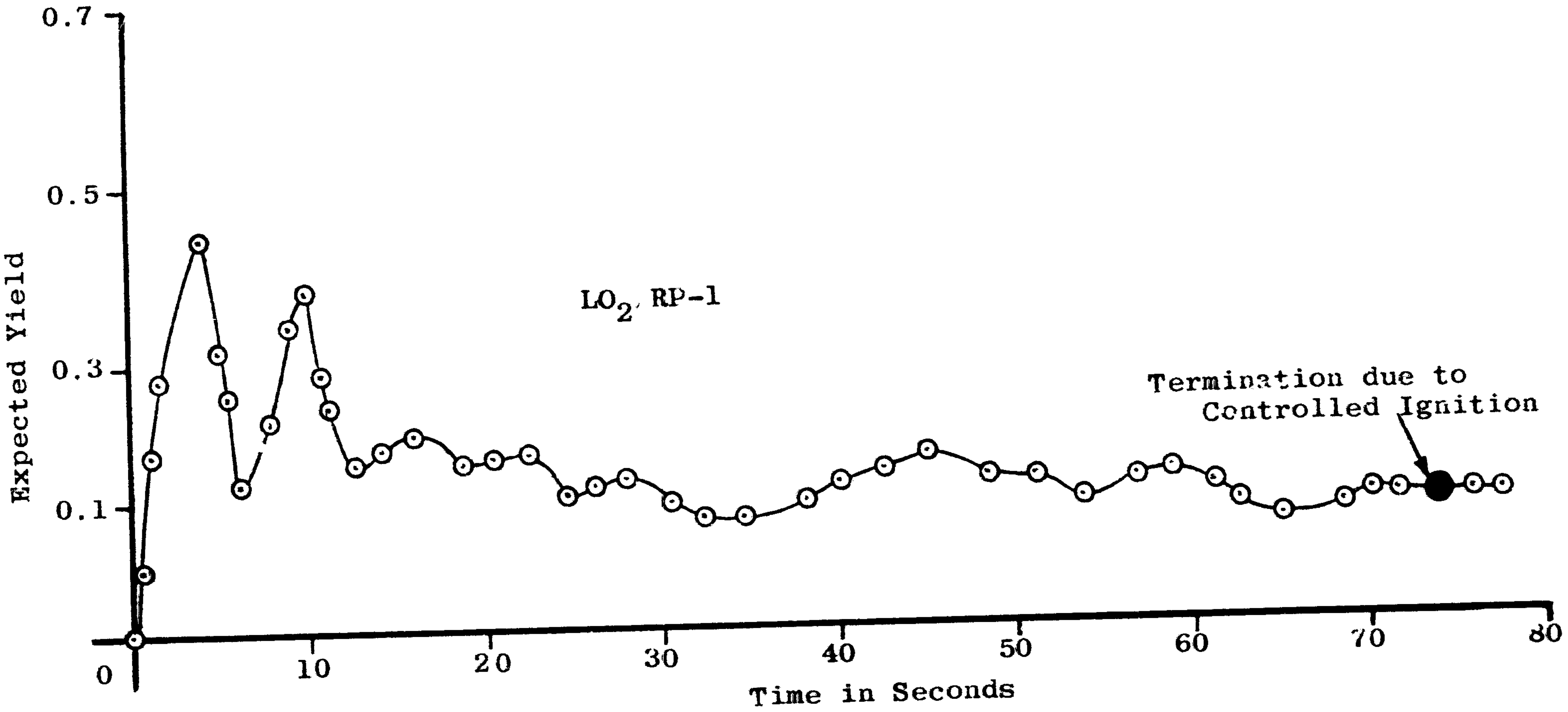


Figure II-8 Expected Yield as a Time Function
(200 lb Cold Flow and Explosion Experiment)

III. THE CRITICAL MASS METHOD

It was observed that auto-ignition occurred with large liquid propellant quantities. Many sources of ignition are available during a missile failure, such things as hot surfaces, flames or fires, the energy of falling structural members, striking of sparks, crystal fracture, silent glow, phase change mixing, electrostatic charge generation, etc.

In this work it was assumed that if no external ignition sources are available, the mixing processes themselves produce the ignition through electrostatic charge generation and discharge across one of the vapor bubbles.

For the purpose of studying these phenomena many combinations, including LN_2 and RP were mixed and their electrostatic charge and voltage buildup determined. The experiments showed that an average voltage of 4 volts was produced for every 200 ml of LN_2. Projecting this to mixtures of LOX and RP and LOX and LH_2, corresponding values not much different were obtained.

Using the observation that the smallest most prevalent bubbles were 1/4 inch in diameter and combining it with the literature information that it takes an electric field strength of 76,000 volts/inch before sparking can occur a CRITICAL MASS of about 2300 lb LOX/LH_2 and about 2800 lb for LOX/RP are obtained.

Ignition can occur earlier and especially with LOX/LH_2, masses of as small as 13 lb have on occasion been observed to auto-ignite.

Figure III-1 presents the voltage buildup for LN_2/RP and Figure III-2 the charge buildup.

When the CRITICAL MASS METHOD is applied to the field experiment it would indicate that at values below the critical auto-ignition may occur but is not normally expected. Above the critical value it is statistically a certainty that auto-ignition will occur.

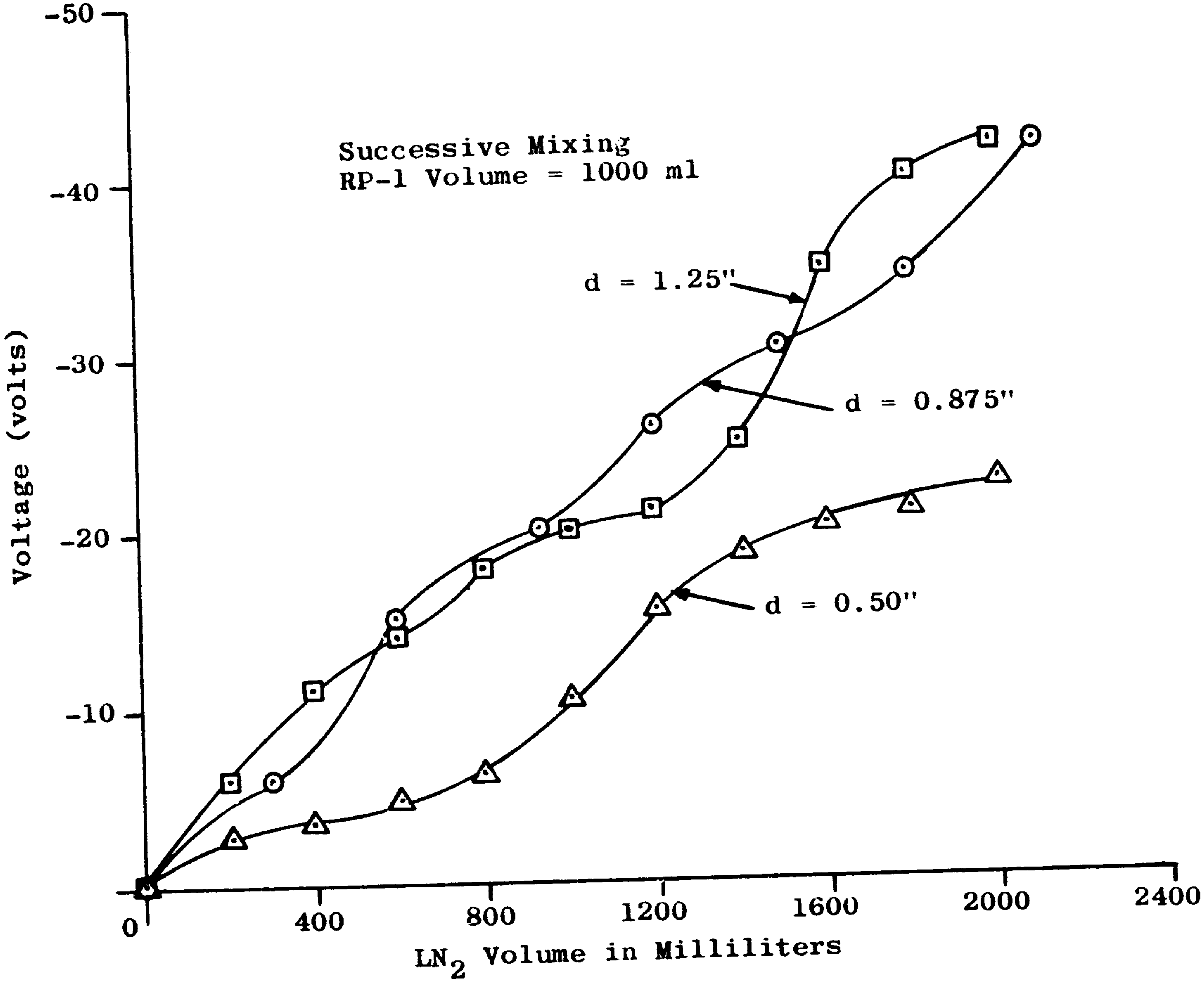


Figure III-1 Typical Voltage-Volume Relationship as a Function of Electrode Spacing

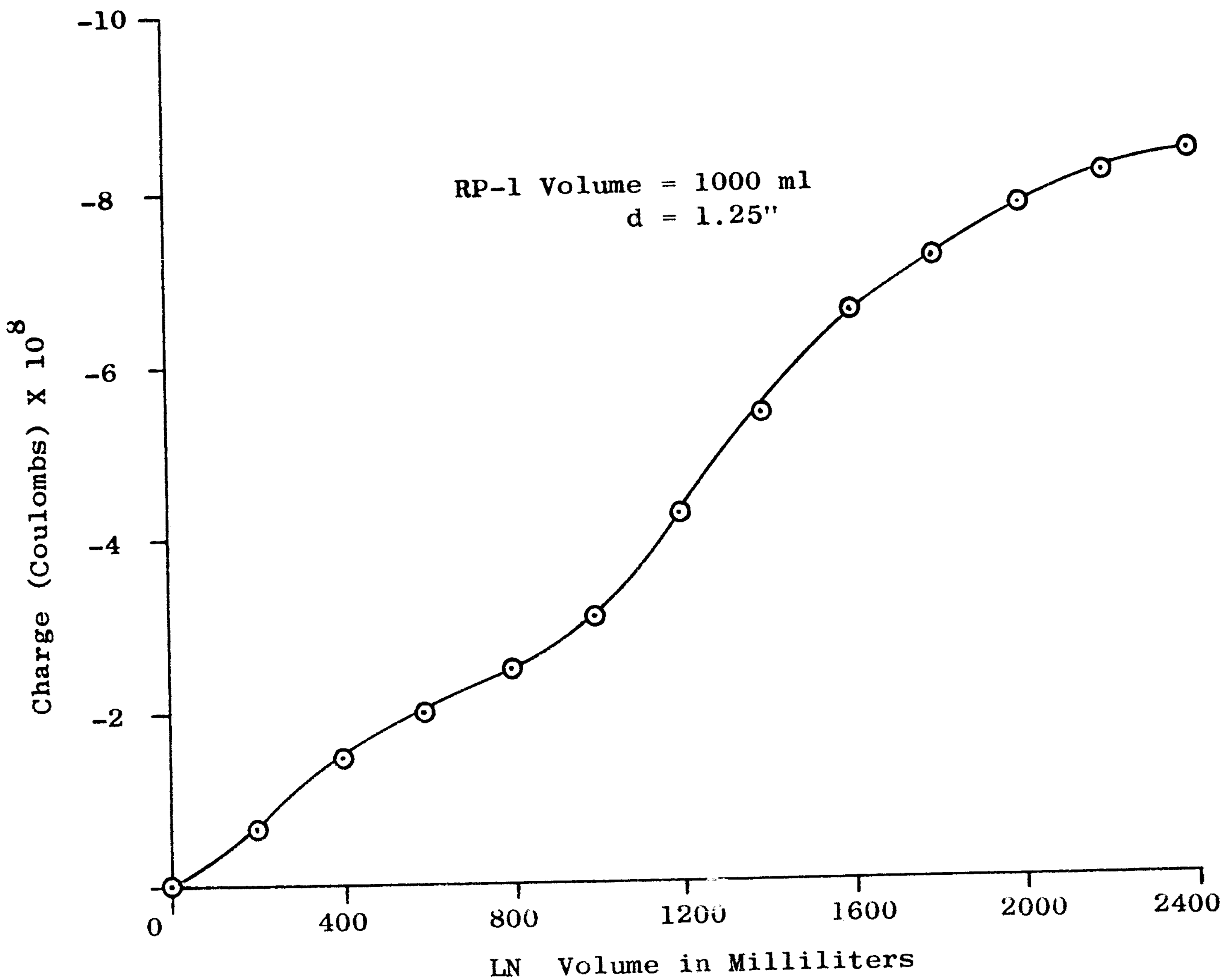


Figure III-2 Typical Charge-Volume Relationship

For the 25,000 lb experiments the CRITICAL MASS METHOD predicts an explosive yield value of 2800/25,000 = 0.113 while the actual measurements were 0.12 and 0.12.

For the S-IVB the predicted value is 2300/92,400 = 0.025 and observed values were 0.036, 0.01, 0.01.

The CRITICAL MASS as determined here was due to mixing primarily through boiling of the propellants. If they are brought together more violently, since it takes a definite but small time to build up the voltage, more of the propellants can be mixed before detonation is induced thus increasing the CRITICAL MASS value. The same is true if liquids at the same temperature are mixed very gently, greater quantities can be mixed than those quoted here. The above values are however typical if the boiling process is the primary factor in the mixing.

From the CRITICAL MASS an ignition time can also be obtained when the mixing function is taken and the time determined at which the CRITICAL MASS is reached. This ignition time can be used as the input to the previous section.

IV. Fireball Hypothesis and Experimental Verification, Describing the Reaction Front and Shock Wave Behavior of Liquid Propellant Explosions.

The Fireball Hypothesis was developed to describe the phenomena which take place from the time of ignition through the formation of the fireball. Since no information was available about the happenings inside an exploding missile, the hypothesis had to be formulated and mathematical relationships developed to express the quantitative behavior. For this purpose the Fireball Hypothesis was divided into four regions. They are

A. The region where ignition produces phenomena which develop into the detonation phenomenon.

B. The region where the reaction front and the shock front travel together through the propellants.

C. The region where the shock front and the reaction front separate, interact, and travel from one medium into others.

D. The region in which the shock wave travels through the atmosphere as an air shock and where the fireball grows and develops separately and behind the shock wave.

These four regions are graphically presented in Figure IV-1 with the regions distorted since they are of widely different dimensions.

To verify the Fireball Hypothesis, two 25,000 lb LOX/RP Explosive Experiments and one 200 lb Cold Flow and Explosive Experiment were completely instrumented with a thermocouple grid, a method developed by Dr. Farber and his group, in the hope to be able to measure phenomena inside the exploding missile. High speed camera coverage was to measure the phenomena on the outside. With the internal and external events tied to a common absolute time basis, the phenomena could be followed from the start of the failure to the formation of the combustion products cloud.

It was hoped, through this procedure, to:

1. Correlate the mixing phenomena of true propellants with laboratory experiments employing inert fluids for simulation.

2. Substantiate experimentally part or all of the Fireball Hypothesis proposed.

Some of the specific objectives were to determine by this experimental procedure part or all of the following:

After failure but before ignition:

a. The three dimensional mixing front or boundary of the mixing region.

b. The degree of mixing at a particular point.

c. The degree of turbulence at a particular point.

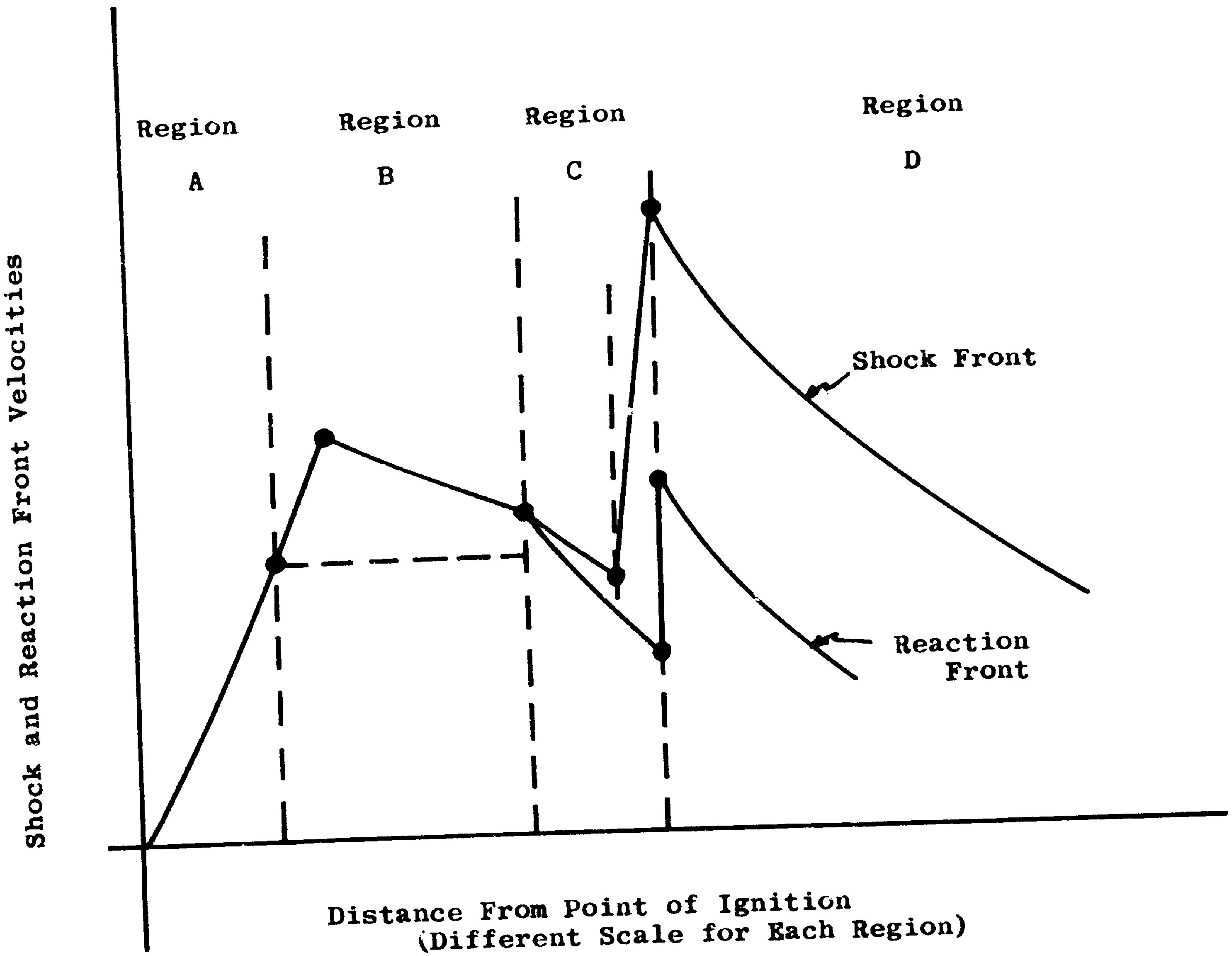


Figure IV-1 Fireball Hypothesis, Describing the Shock Wave And Reaction Front Behavior in Liquid Propellant Explosions.

After ignition:

d. The location of the point or points of ignition.

e. The time delays from initiation of failure to start of mixing, to ignition.

f. The propagation of the reaction front.

g. The propagation of the shock front.

h. The separation of the shock front and reaction front.

i. The interaction, if any between the two fronts.

j. The emergence of the fronts into the atmosphere.

k. Other phenomena and events obtainable by detailed analysis.

Figure IV-2 presents the experimentally obtained velocities as a function of distance from the point of ignition. There was only one point of ignition.

In region A a velocity of about 7500 fps is reached in the 25,000 lb experiments. In region B the shock and reaction fronts separate, with the shock front reaching the tank walls first and then bouncing back and forth while the tank walls are beginning to burst, and emerge almost simultaneously with the shock front reaching a peak velocity of almost 28,000 fps quickly attenuated and the reaction front a peak velocity of over 18,000 fps.

With smaller propellant quantities the extreme values are slightly smaller.

Figure IV-3 shows the velocity as a function of time, indicating that the whole process takes only a few milliseconds.

Figure IV-2 can be compared with the Fireball Hypothesis and it can be seen that the hypothesis is in remarkable agreement with the observed and measured facts.

Much more detail about this work and the results can be found in the references.

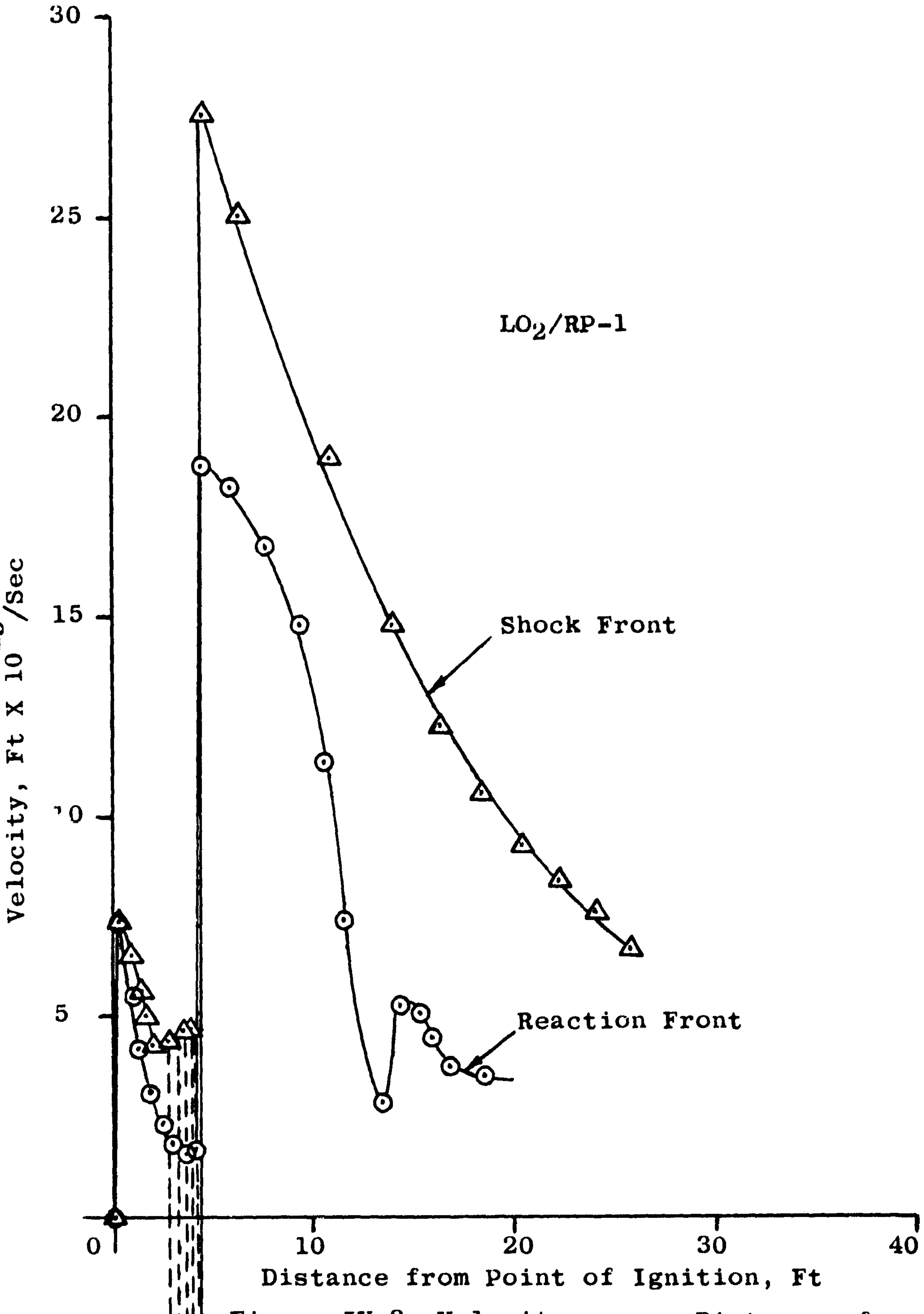


Figure IV-2 Velocity versus Distance of Shock Wave and Reaction Front (25,000 lb LO_2/RP-1 Explosion Experiment)

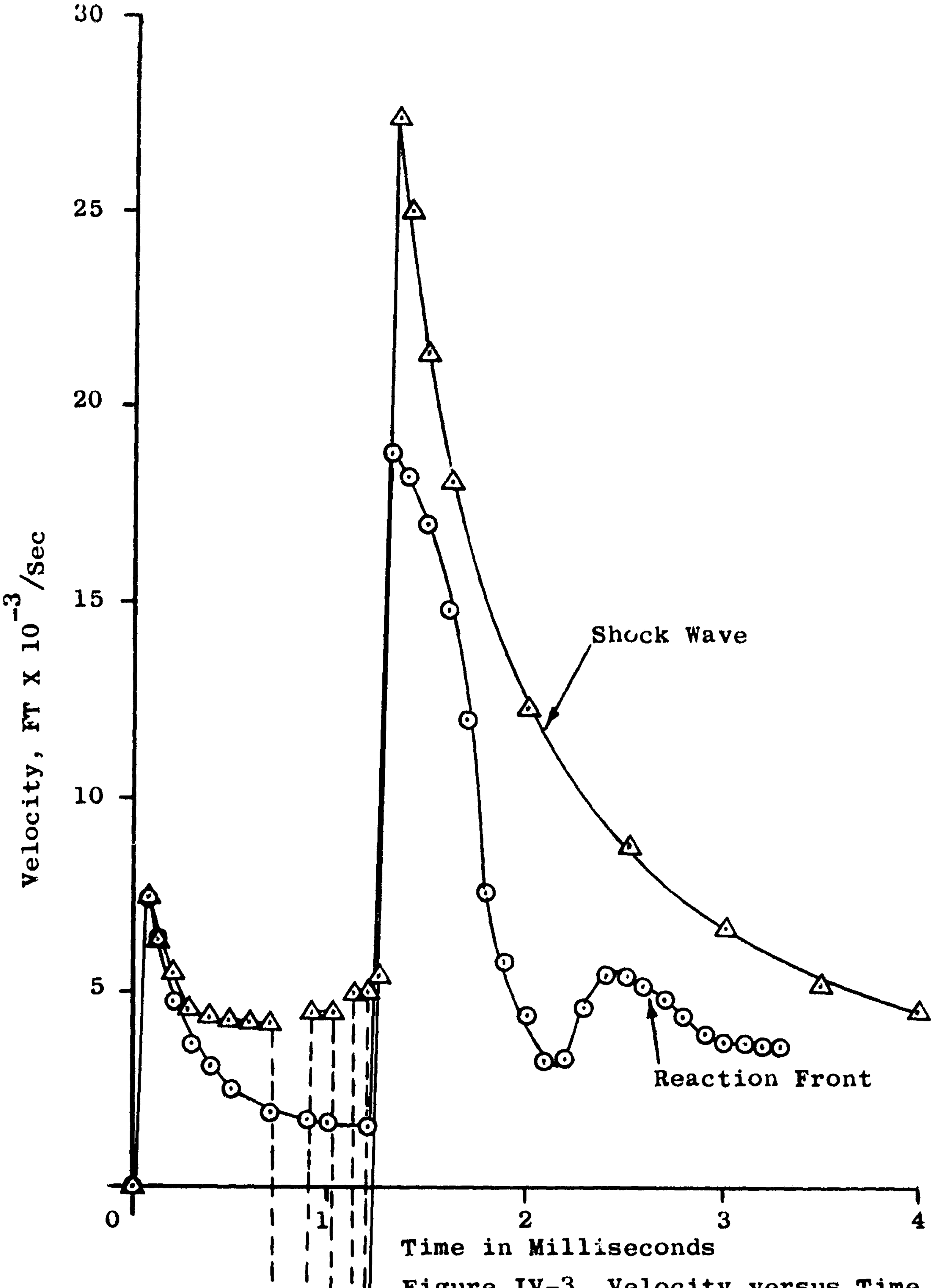


Figure IV-3 Velocity versus Time of Shock Wave and Reaction Front (25,000 lb LO_2/RP-1 Explosion Experiment)

V. Fireball and Post Fireball Combustion Products Cloud History and Composition.

In the previous sections the phenomena have been traced from the initiation of the failure, through the mixing, ignition, shock front and reaction front propagation, inside and outside the exploding missile.

To complete the picture the reaction front is looked at in more detail in its later stages, first forming the fireball and then the combustion products cloud.

The previous work and that by others has given information on the

a. Volume of the fireball and combustion products cloud.

b. The pressure pushing the reaction front.

c. The temperature of the fireball and combustion products cloud.

The three above estimates have been taken as input for a rather elaborate computer program to calculate the composition of the fireball and combustion products cloud as a function of time. To be able to do this, thermal equilibrium was assumed throughout the fireball, which due to the high turbulence is believed to be reasonable.

The above input information of volume, pressure and temperature, since experimental verification is possible, is believed to be better than such things as fuel burning rates, etc. used by others.

Figure V-1 gives the volume time function for the combustion products of a 100,000 lb LH_2/RP-1/LOX/10% F liquid propellant explosion with an explosive yield of 4.5 percent.

Figure V-2 presents the pressure time function for the same liquid propellant explosion.

Figure V-3 presents the temperature time relationship for the above liquid propellant explosion, approximated by linear segments indicating the late burning of some of the propellants during the expansion of the fireball.

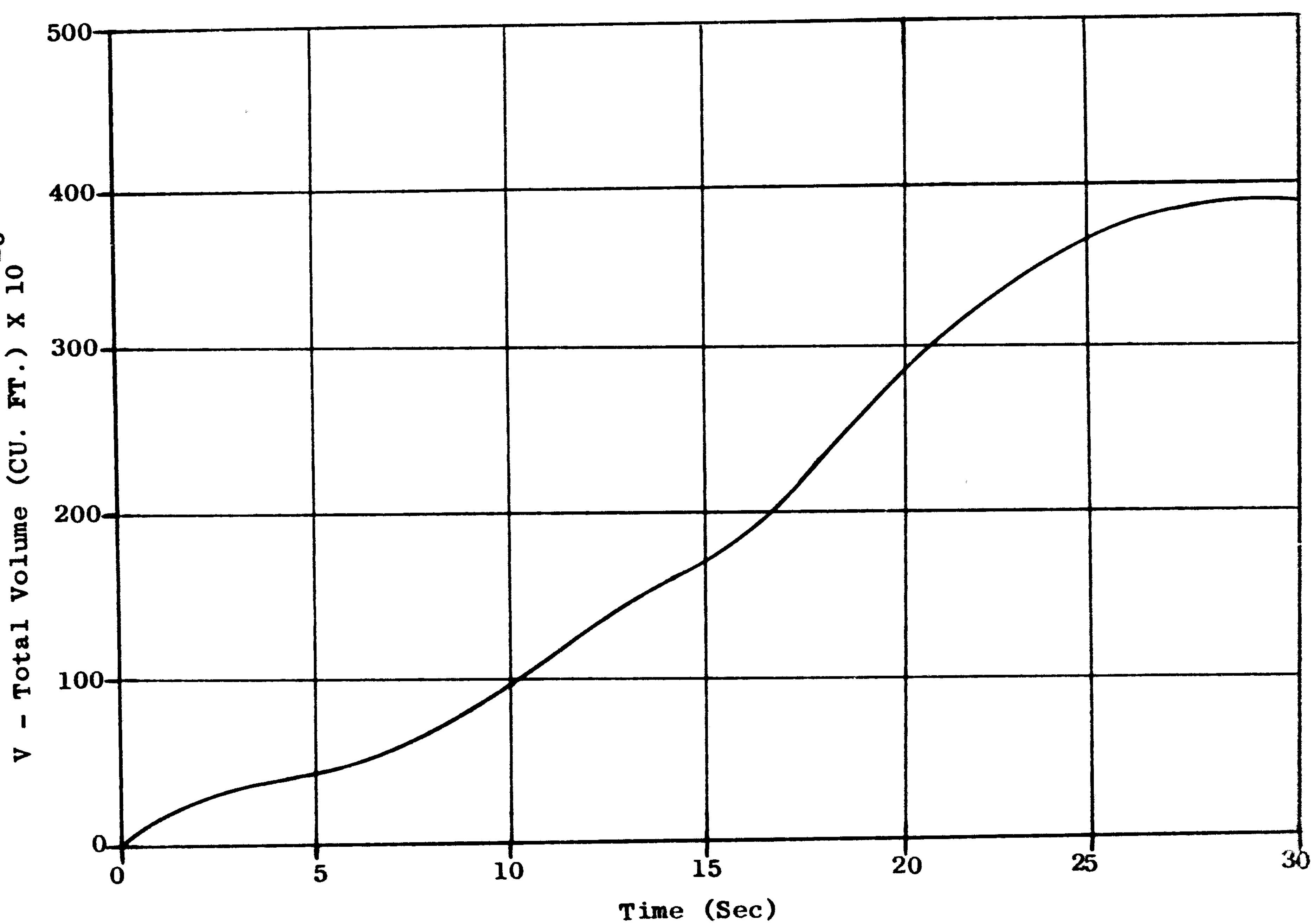


Figure V-1 Volume-Time Function for $LH_2/RP\text{-}1/LO_2$ + 10% F Liquid Propellant Explosion Products (Yield = 4.5 Percent)

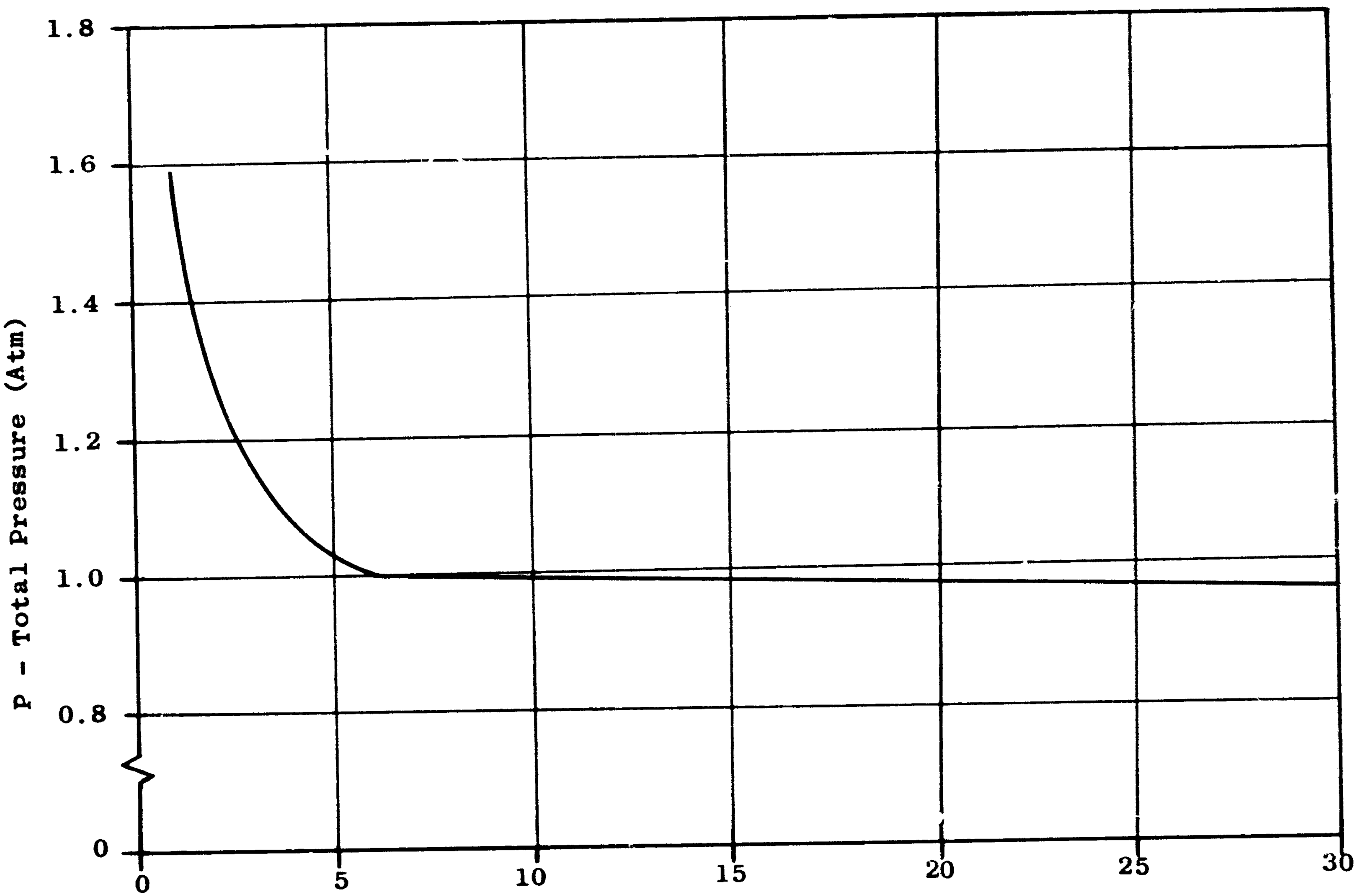
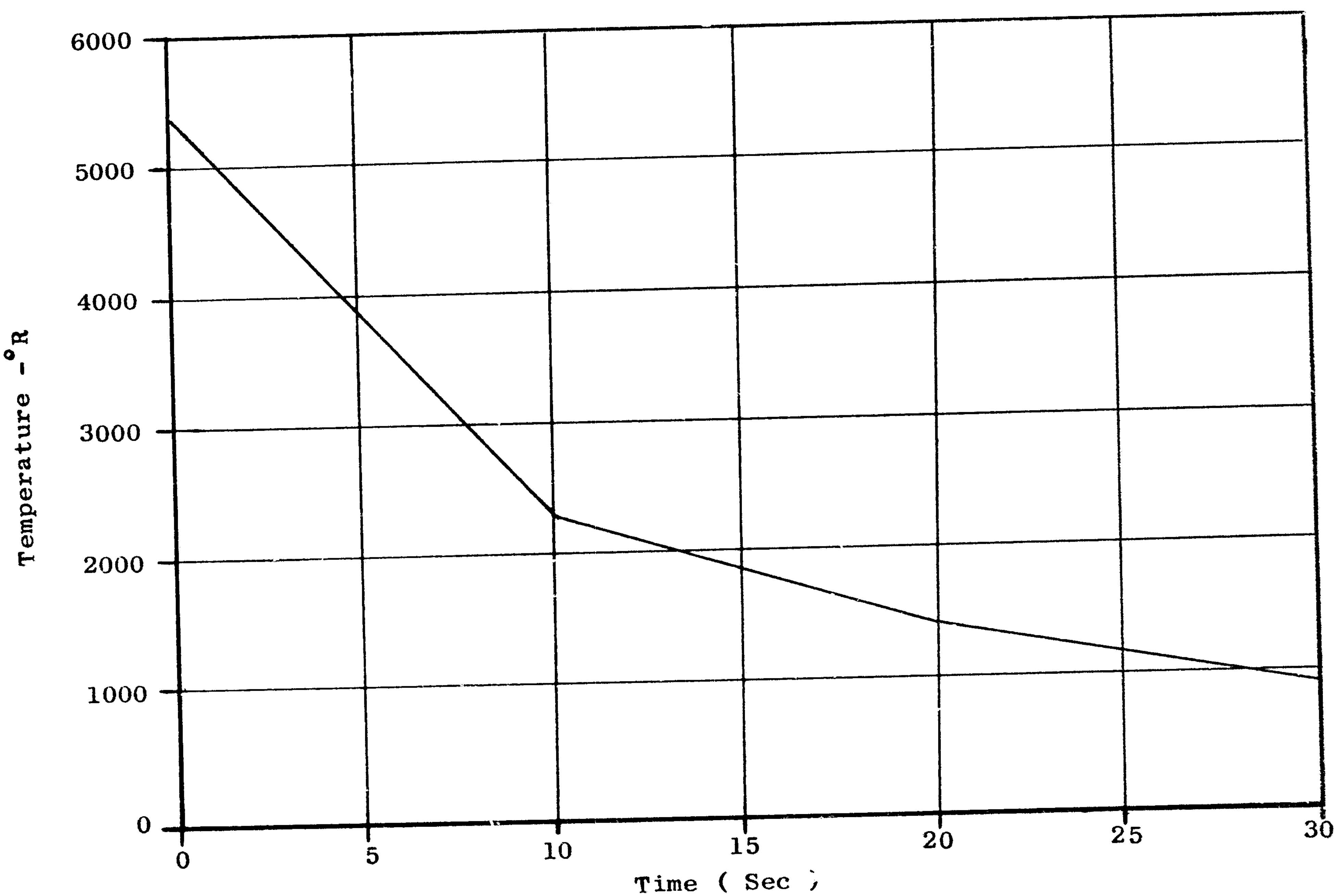


Figure V-2 Typical Pressure-Time Function for Liquid Propellant Explosion Products (Yield = 4.5 percent)



<u>Figure V-3</u> Typical Temperature-Time Function for Liquid Propellant Explosion Products (Yield = 4.5 percent)

Using the above three curves as input the composition at any time, for equilibrium conditions, can be calculated. The results from such calculations are presented here in Figure V-4.

The complete work up to this point allows the tracing of the phenomena of liquid propellant explosions from the initiation time of the failure through ignition till a cool combustion products cloud is produced. Thus, this work encompasses the complete processes of liquid propellant explosions from beginning to the end.

VI. Saturn V Destruct System Analysis

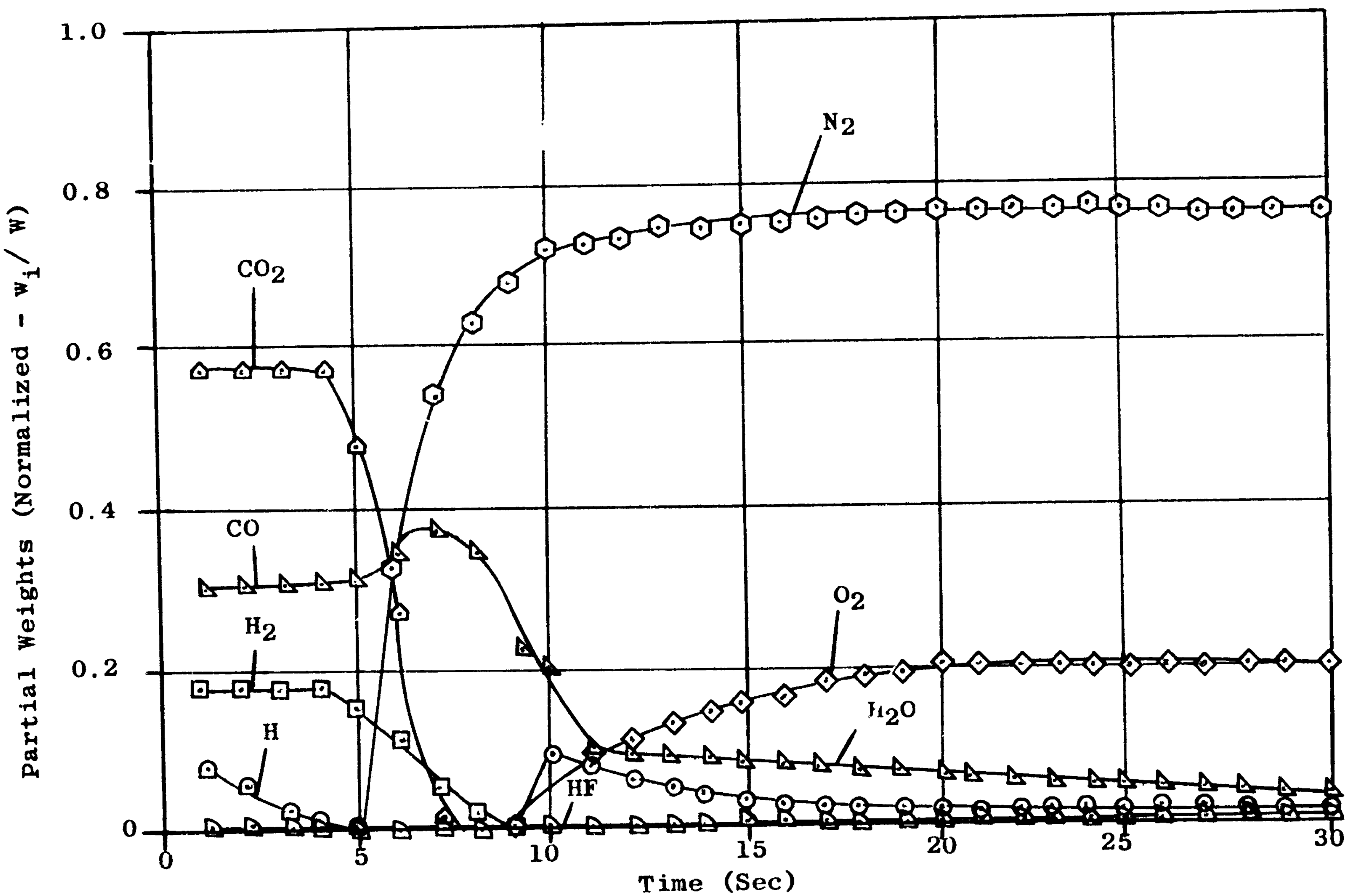
Having methods, developed by Dr. Farber and his group, which make it possible to systematically analyze liquid propellant rocket explosion from the initiation of failure through the combustion products cloud, the University of Florida was asked to apply the above methods to the evaluation of the Saturn V destruct system.

This request came as a result of the suggestion by the above group that it may be better, in case of forced abort, to destroy the rocket in a known manner with a predictable explosive yield, rather than letting nature takes its course.

This work is now in progress but some preliminary results are available.

The Saturn V destruct system was designed to be propellant dispersal system with the fuel being emptied on one side and the oxidizer on the opposite side through explosively cut openings. This forms splash puddles on the launch pad which will mix both as liquid puddles and as vapor clouds above.

The result of explosive yield versus time obtained from the SEVEN CHART APPROACH for this case is presented in Figure VI-1. It is indicated by the results that a yield of about 14 percent could be attained theoretically



<u>Figure V-4</u> Weight Composition of the Combustion Products from LH_2/RP-1/LO_2 + 10%F Liquid Propellant Explosion (Yield = 4.5 percent)

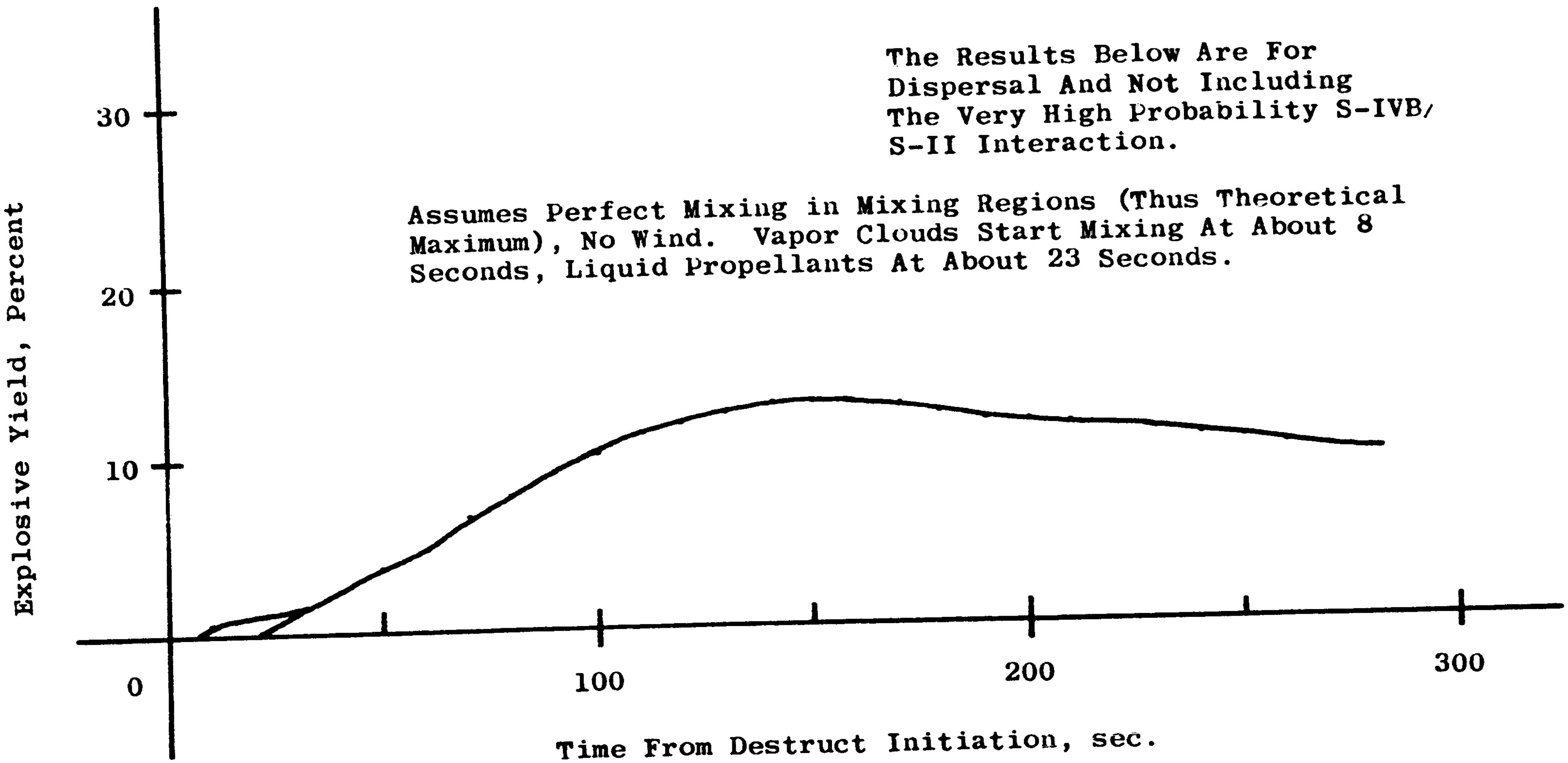


Figure VI-1 Theoretical Explosive Yield Prediction - Saturn V (Destruct Spill) if it were possible to delay ignition for almost 3 minutes after the tankage is opened by the linear charges.

A time delay of almost 3 minutes has extremely low probability of occurring with all the potential ignition sources present. So it is expected that actual ignition will occur very early in the process and therefore the yield will be low as also predicted by the other methods.

This analysis is based upon information furnished by NASA as to the effects of the destruct system on the Saturn V tankage, namely opening slots 2 and 3 feet wide and the length of the charges. There exists some uncertainty about this.

The analysis by the University of Florida further uncovered the very high probability that the destruct system will not act as a dispersal system but that the cutting of a 47 inch diameter hole into the bottom of the LOX tank of the S-IVB will drop the engine and thrust cone of that stage which in turn will cut a hole into the LH_2 tank of the S-II. This will allow LOX to pour on top of LH_2 producing a primary explosion which may propel the engine and thrust cone upward through the S-IVB, producing a larger secondary explosion, and through the service module and payload.

This last and much more serious effect is being investigated now, as well as alternatives to the present destruct method, such as pancake charges, etc.

Again the value of the analysis methods developed is demonstrated, and hopefully will be used in the future in evaluating proposed designs so that undesirable features are prevented from reaching the final stages.

This paper had to be necessarily brief since a great amount of material was covered. The details, however, can be found in the references cited.

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*Many more references are cited in the above references to complete the picture on the studies in this field.