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Vol. 2 of 3

Final Report: TNT Equivalency Study for Space Shuttle (EOS)

Volume II: Technical Discussion

Prepared by SYSTEMS PLANNING DIVISION

71 SEP 30

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

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THE AEROSPACE CORPORATION

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Report No. ATR-71(7233)-4, Vol II

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FINAL REPORT: TNT EQUIVALENCY STUDY FOR SPACE SHUTTLE (EOS)

Volume II: Technical Discussion

Submitted by

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PREFACE

This study was initiated as Subtask 1, TNT Equivalency Study to NASA Study C-II, Advanced Missions Safety Studies. Other studies in this series are Subtask 2, Safety Analysis of Parallel versus Series Propellant Loading of the Space Shuttle (Aerospace Report No. ATR-71(7233)-1) and Subtask 3, Orbiting Propellant Depot Safety Study (Aerospace Report No. ATR-71(7233)-3).

This study was supported by NASA Headquarters and managed by the Advanced Missions Office of the Office of Manned Space Flight. Mr. Herbert Schaefer, the Study Monitor, supported by Mr. Charles W. Childs of the NASA Safety Office, provided guidance and counsel that significantly aided this effort.

Study results are presented in three volumes; these volumes are summarized as follows:

Volume I: Management Summary Report presents a brief, concise review of the study content and summarizes the principal conclusions and recommendations.

Volume II: Technical Discussion provides a discussion of the available test data and the data analysis. Details of an analysis of possible vehicle static failure modes and an assessment of their explosive potentials are included. Design and procedural criteria are suggested to minimize the occurrence of an explosive failure.

Volume III: Appendices contains supporting analyses and backup material.

ABSTRACT

This study reevaluates the existing TNT equivalency criterion for LO_2/LH_2 propellant. It addresses the static, on-pad phase of the space shuttle launch operations and was performed to determine whether the use of a TNT equivalency criterion lower than that presently used (60%) could be substantiated. The large quantity of propellant on-board the space shuttle, 4×10^6 lb, was considered of prime importance to the study.

Furthermore, a qualitative failure analysis of the space shuttle (EOS) on the launch pad was made because it was concluded that available test data on the explosive yield of LO_2/LH_2 propellant was insufficient to support a reduction in the present TNT equivalency value, considering the large quantity of propellant used in the space shuttle. The failure analysis had two objectives. The first was to determine whether a failure resulting in the total release of propellant could occur. The second was to determine whether, if such a failure did occur, ignition could be delayed long enough to allow the degree of propellant mixing required to produce an explosion of 60% TNT equivalency since the explosive yield of this propellant is directly related to the quantities of LH_2 and LO_2 mixed at the time of the explosion.

The analysis indicates that the occurrence of such a failure is unlikely and that a TNT equivalency of 20% would be a more realistic value for the static, on-pad phase of the space shuttle launch operations.

ACKNOWLEDGEMENTS

The principal participants in this study and their chief areas of responsibility are: R. R. Wolfe, Study Manager; P. P. Leo and R. P. Toutant, Hazards Analysis; O. A. Refling, Probability Analysis; and E. F. Schmidt and J. R. Smith, Data Evaluation and Analysis.

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Note: The appendices are published separately, as Vol. III of this series. This list of appendix titles is included for the reader's convenience.

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1. INTRODUCTION

1.1 BACKGROUND

Investigators of the explosive phenomena of propellants have suggested that the current TNT equivalency value for LO_2/LH_2 propellant may be too high. If the existing equivalency criterion could be lowered for the space shuttle, there would be a potential for lower siting, facility and operational costs. A TNT equivalency value of 20% has been suggested.

1.2 STUDY OBJECTIVES

The objective of this study was to evaluate and recommend a TNT equivalency criterion for LO_2/LH_2 propellant applicable to the static, on-pad operational phase of the space shuttle, the new criterion to be as low a value as possible consistent with a reasonable level of confidence and hazard expectation. Further, the data were to be developed in a manner that would support a proposal to the Armed Services Explosive Safety Board (ASESB) requesting concurrence with the recommended criterion.

1.3 STUDY SCOPE

The study was confined to the static, on-pad phase of space shuttle (EOS) vehicle operations, i.e., from the start of propellant loading to launch. Dynamic impacts following launch were not addressed.

No additional testing was included in the study; therefore, the data analysis was a reevaluation of the results of prior test programs and studies.

A gross failure analysis was performed using the preliminary configurations and hardware definitions from the Phase B Space Shuttle Studies.

1.4 STUDY PLAN

1.4.1 Approach

The general plan followed in this study was to collect and analyze existing data, perform failure mode analysis, and establish suggested criteria.

1.4.2 Resources/Date Base

Many NASA and contractor technical reports and other documents were reviewed in the course of the study. References to specific reports used are given throughout the report in the sections to which they apply.

2. DATA ANALYSIS

2.1 LITERATURE SEARCH

A literature search was made for documents dealing with LO_2/LH_2 explosions. Of the documents reviewed, twenty-five contained information directly applicable to this study (see Section 2.3).

In addition, the search identified the principal investigating organizations and sources of LO_2/LH_2 explosive test data. Table 1 lists the principal investigators, all of whom analyzed test data, and indicates those who produced their own experimental data.

Table 1. Principal Investigators

Organizations	Produced Test Data
A. D. Little	Yes
Aerojet General	Yes
Bellcomm	No
NASA MSC	No
NASA MSFC	Yes
University of Florida	Yes*
URS	Yes

*The University of Florida instrumented two tests in the URS Project Pyro test series and performed laboratory-scale simulation tests in support of their analytical studies. These studies are discussed in Appendix C, Vol. III.

2.2 DETERMINATION OF EXPLOSIVE YIELD

Propellant explosive yield is determined by comparing measured shock-wave characteristics with those of TNT. TNT is generally accepted as the standard of comparison for explosive yield although it is recognized that the shock-wave characteristics of liquid propellant explosions resemble those of TNT only in the far field. The characteristics of explosive yield on which the comparison is based are peak overpressure and positive phase impulse. The latter is the area under the time-history curve of overpressure for the positive pulse measured at a given distance from the source.

Propellant explosive yield in the far field is given by:

$$\text{Yield (\% TNT)} = \frac{\text{Equivalent Weight of TNT}}{\text{Total Propellant Weight}} \times 100$$

where

the equivalent weight of TNT is that weight of TNT that would produce a yield equal to the yield resulting from an explosion of a given weight of propellant, and the total propellant weight is the total weight of propellant available at the time of the explosion.

2.3 OVERVIEW OF AVAILABLE LO_2/LH_2 EXPLOSION TEST DATA

This phase of the study involved examining and comparing test data from all pertinent experimenting agencies. Although all investigators reported yields in terms of TNT equivalence, the basis for comparing the available data varied (pressure yield, impulse yield, and an average of these were used). Therefore, a common baseline had to be established before any comparison could be made; pressure yield was selected.

The data were converted to pressure yield by superimposing the raw experimental data on the Ballistic Research Laboratory (BRL) curves for TNT explosions (see Ref. 1). No attempt was made to adjust any of the data points or to provide mathematical best fits to the TNT curves since the number of data points did not appear to justify such an effort. Instead, a curve was visually faired through the data points; the terminal yield was then determined by visual approximation. The independently determined yields are tabulated in Appendix A (see Vol. III of this series) along with the values reported by the experimenters.

The faired curves were of two general types. An example of the first type (see Fig. 1) shows the test yield increasing with distance from the explosion and eventually fairing into the 25% TNT curve. The pressure yield assigned in this case was thus 25%.

In the second example (see Fig. 2), the test yield first decreases with distance from the explosion, then increases, and is apparently still increasing at the last recorded data point. No attempt was made to extrapolate the data curve since it could not reasonably be faired into the TNT line at any distance. There is no obvious basis for adjusting any of the data points on the assumption that one or more may be spurious and thus changing the slope of the curve. In this case, the highest yield indicated by the data (50%) was used. It was noted in this investigation that a large majority of the test data plotted produced curves of the first type (see Fig. 1) rather than the second (see Fig. 2).

Pressure yields for all available data, determined as described above, are shown in Table 2 and plotted in Fig. 3. Also, bar representations of the range of yields reported by NASA-MSFC, for which no tabulated data were available, are shown in Fig. 3.

In addition, Fig. 3 provides an overview of the available LO_2/LH_2 test data and clearly shows that the bulk of the testing has been conducted with propellant quantities of 225 lb or less. It is also evident that, for small-scale propellant very wide range of yields can be produced, depending on the conditions under which the explosion occurs.

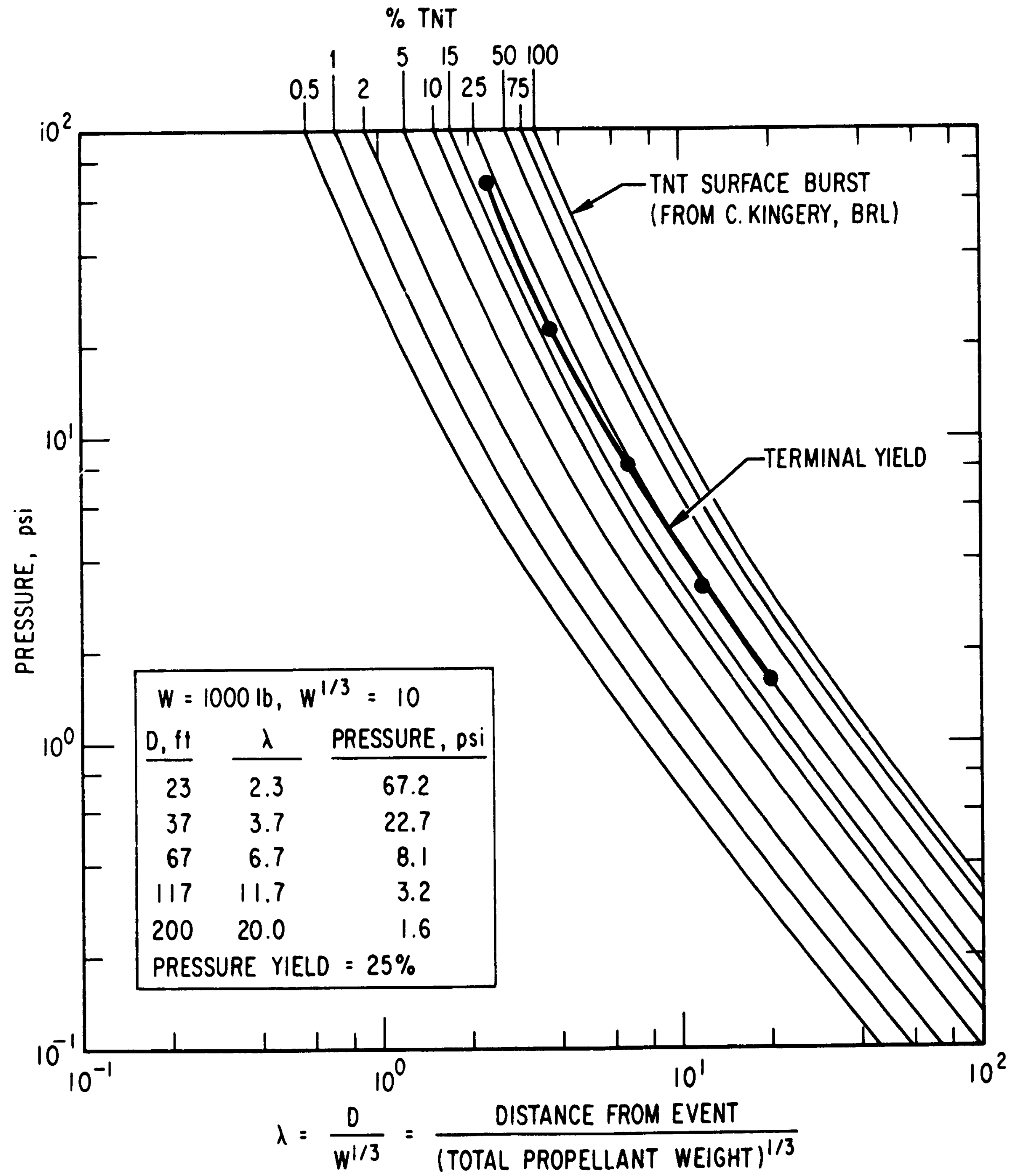

Fig. 1. Example of Terminal Yield Determination: URS Test No. 213

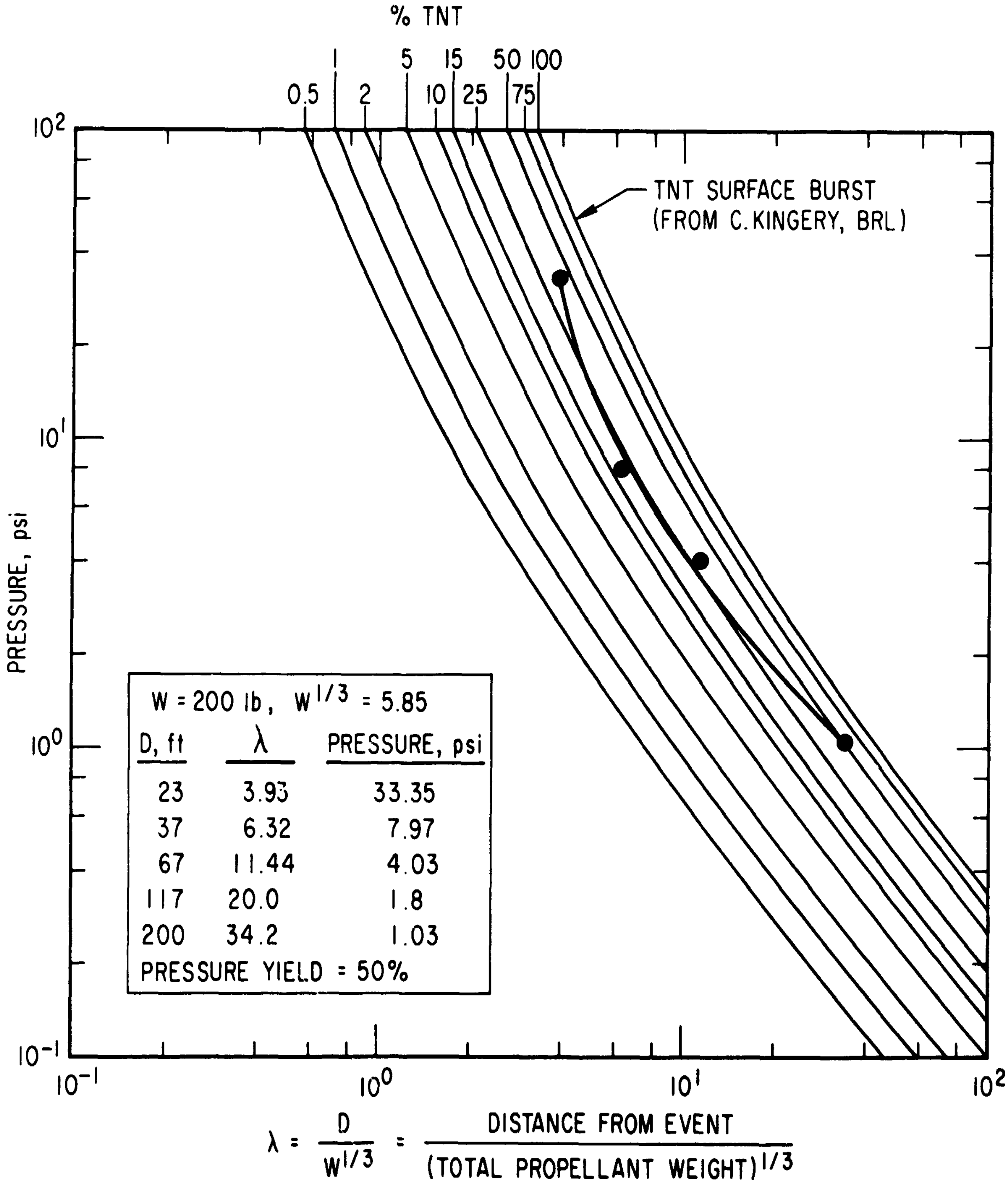

Fig. 2. Example of Terminal Yield Determination: URS Test No. 226

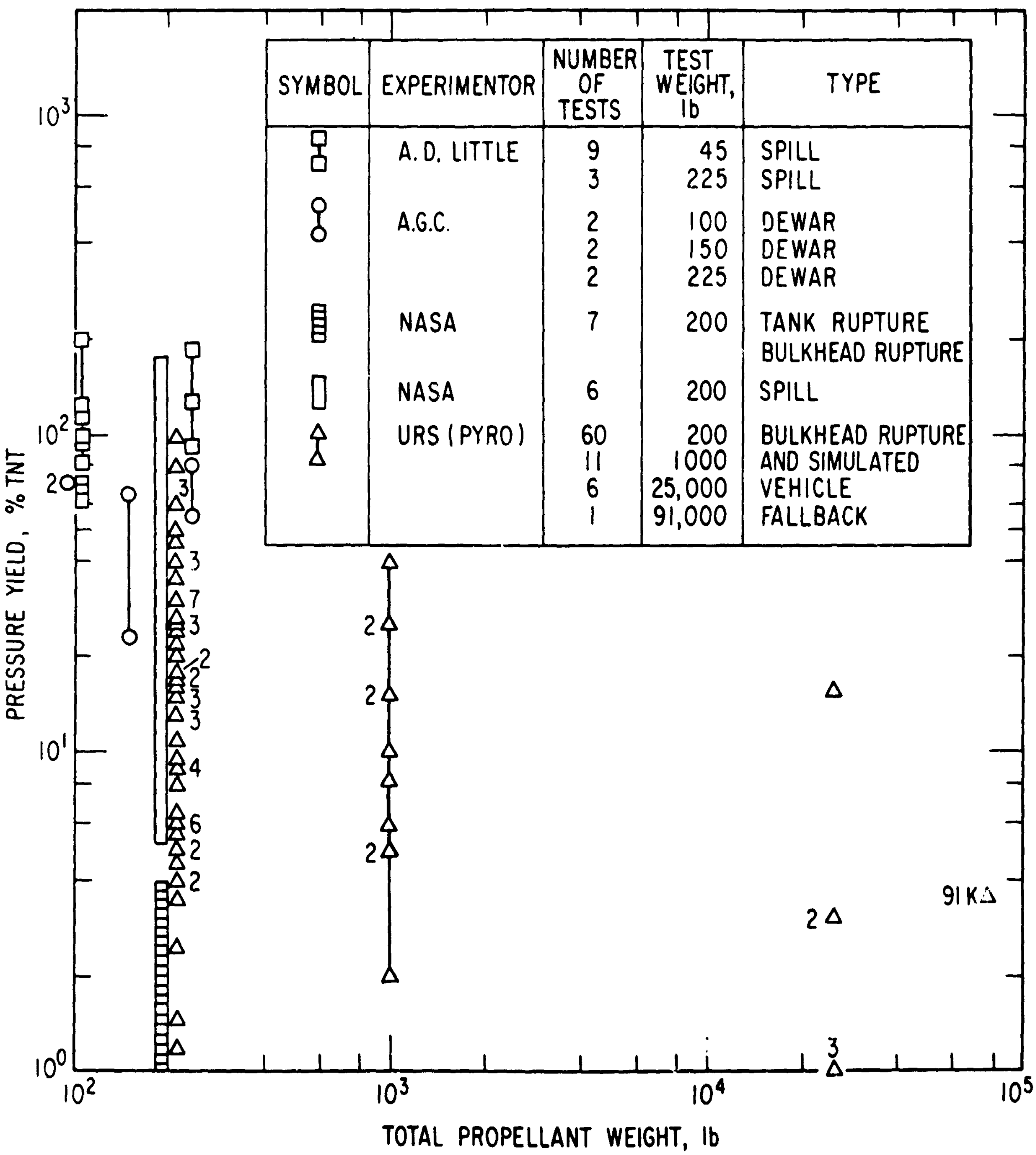

Fig. 3. Overview of All LO_2/LH_2 Explosion Data Points

Table 2. Pressure Yields Determined Graphically from Investigators' Test Data

Investigator	Test Method	Test No.	Propellant Weight, lb	Pressure Yield, %TNT
A. D. Little (see Ref. 2)	Spill	C-2	45	63
		C-3		68
		C-6		70
		C-1		82
		C-4		95
		C-5		99
		C-7		115
		C-8		125
		C-9		198
		G-1	225	91
		G-3		127
		G-2		185
AGC (see Ref. 3)	Dewar	1	100	70
		2		70
		6	150	23
		5		65
		4	225	55
		3		80
URS (see Ref. 4)	CBM	055	200	1.5
		057		1.2
		053		2.5
		199		4
		054		4
		200		6
		052		6
		173		6
		091		6.5
		118		9
		169		9.5
		138		13
		051		17
		092		18
		090		22
		167		24
		093		25
		094		25
		172		30
		050		80
		210	1000	2
		265		5
		212		10
		213		25
		281	25,000	0.05
		277		0.05
		279		0.05
		062	91,000	3.5

Table 2. Pressure Yields Determined Graphically from Investigators' Test Data (Continued)

Investigator	Test Method	Test No.	Propellant Weight, lb	Pressure Yield, %TNT
URS	CBGS-V	164	200	3.5
		161		5
		104		5.5
		105		6
		165		8
		116		9
		115		9
		152		11
		153		13
		19[illegible]		15
		184		16
		230		18
		231		20
		203		25
		103A		26.5
		201		30
		225		30
		254		30
		150		30
		160		30
		252		40
		204		40
		151		40
		113		45
		226		50
		229		60
		251		60
		114		60
		195		100
		211	1000	5
		216		6
		266		8
		264		15
		215		15
		217		25
		262		40
		289	25,000	3
		290		3
		283C		15
URS	CBGS-H	132	200	4.5
		133A		5
		131		6
		185		6
		186		9
		224		13
		183		15
		196		15
		223		17
		228		30
		253		35

Also shown in Fig. 3, but not so readily acceptable, is the indication that when large quantities of propellant are involved (1000 lb or more), low terminal yields and small dispersion of yields are apparently experienced. The reluctance to accept this trend results from the facts that few large-scale tests were conducted and few variations of simulated failure modes were employed. Whether or not total propellant mixing for large-scale releases can be obtained is not conclusively demonstrated by the available data. Therefore, it cannot be concluded that yields higher than those indicated for large-scale tests cannot be achieved.

Examination of the small-scale test results shows that the highest yields occurred in the spill tests. These were designed to achieve rapid, thorough mixing with the objective of producing high yields. There is no conclusive experimental evidence that larger quantities of propellant will behave similarly, so there are no bases for evaluating scale effect or for establishing the credibility of such a failure mode for larger quantities. Similarly, the dewar tests, designed to promote rapid mixing by suddenly creating a large propellant interface area, do not extend over a range of propellant weights large enough to establish scale effects. On the basis of these considerations, both the spill and the dewar test results were excluded from further analysis.

The data remaining include only the Pyro and NASA tank-test results. Since no tabulated data were available for the NASA tests, no data points could be plotted; these test results also were excluded. Thus, the Pyro test series, which represents only two basic failure modes, remained as the basis for analytical consideration.

2.4 DATA EVALUATION AND ANALYSIS

This section briefly summarizes the evaluation and analyses of the Project Pyro LO_2/LH_2 data as performed by URS and Bellcomm. In addition, an independent evaluation of the data is presented that uses data-point groupings different from those used in the URS or Bellcomm evaluations. The use of

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different groupings illustrates some of the difficulties encountered in trying to arrive at a completely defensible conclusion based on the available data.

2.4.1 URS Analyses

Project Pyro was designed to provide an empirical basis for the development of a generalized method for predicting the blast environment resulting from the explosion of liquid propellant. Three test configurations were used in this program; they are referred to as Confined by Missile (CBM), Confined by Ground Surface - Vertical (CBGS-V), and Confined by Ground Surface - Horizontal (CBGS-H). These configurations are described in detail in Appendix B (see Vol. III of this series).

The approach used by URS was to conduct a large number of small-scale tests to determine the effects of various parameters on yield and then to conduct a limited number of large-scale tests to verify the persistence of these relationships. Tables summarizing those LO_2/LH_2 explosion tests judged valid by URS are given in Appendix A (Vol. III of this series). These tables present the test configurations and the terminal yields. The reported yields are approximate averages of the terminal pressure yields and the impulse yields. The data points excluded from the analysis by URS are also indicated in these tables.

A significant criterion employed by URS for accepting a test for analysis was the control of ignition delay following tank failure since one of the test objectives was the determination of the effect of propellant-mixing time on yield. In several tests, particularly in those involving large propellant weights, auto-ignition apparently occurred. The results of these tests were excluded from the URS analysis because one of the required test conditions was violated.

The general analytical approach used by URS was to formulate by trial the general relationships between yield and the variables investigated. Statistical analyses were then performed, using these relationships to determine which of the trial equation forms and parameter combinations best explained the observed variation in yield.

The two parameters that URS found to have the most significant effect on yield are the manner in which the LO_2 and LH_2 mix (the failure mode) and the ignition delay following tank failure. Yield prediction equations were developed for the two basic failure modes tested (CBM and CBGS); in these equations, yield is expressed as a function of scaled time. The use of scaled time is based on the URS postulate that ignition delay scales geometrically with propellant weight; this leads to the scaled time t^* being ignition delay time t divided by the cube root of the propellant weight. This relationship is written:

$$t^* = \frac{t}{w^{1/3}}$$

A brief discussion of the results of the URS analyses of the CBM and CBGS cases follows.

2.4.1.1 Confined by Missile (CBM) - URS

The URS CBM prediction equation and its corresponding curve, extracted from Ref. 4, are shown in Fig. 4. A legend identifying the tests used to develop the equation has been added to the figure as well as numbers identifying the test number associated with each data point. The prediction equation was based on an analysis of all nonspurious CBM cases except those having a tank-length-to-tank-diameter (L/D_t) ratio of 1.8 and a rupture-diaphragm-diameter-to-tank-diameter (D_o/D_t) ratio of 1. The latter restriction excluded three 200-lb tests. Also excluded as spurious are the data points for three 25,000-lb tests and a 91,000-lb test because all of these apparently exploded due to earlier-than-planned ignition. Two 200-lb, scaled, S-IV configuration tests with an L/D_t of 1.8 and a D_o/D_t of 0.083 were also excluded. The data

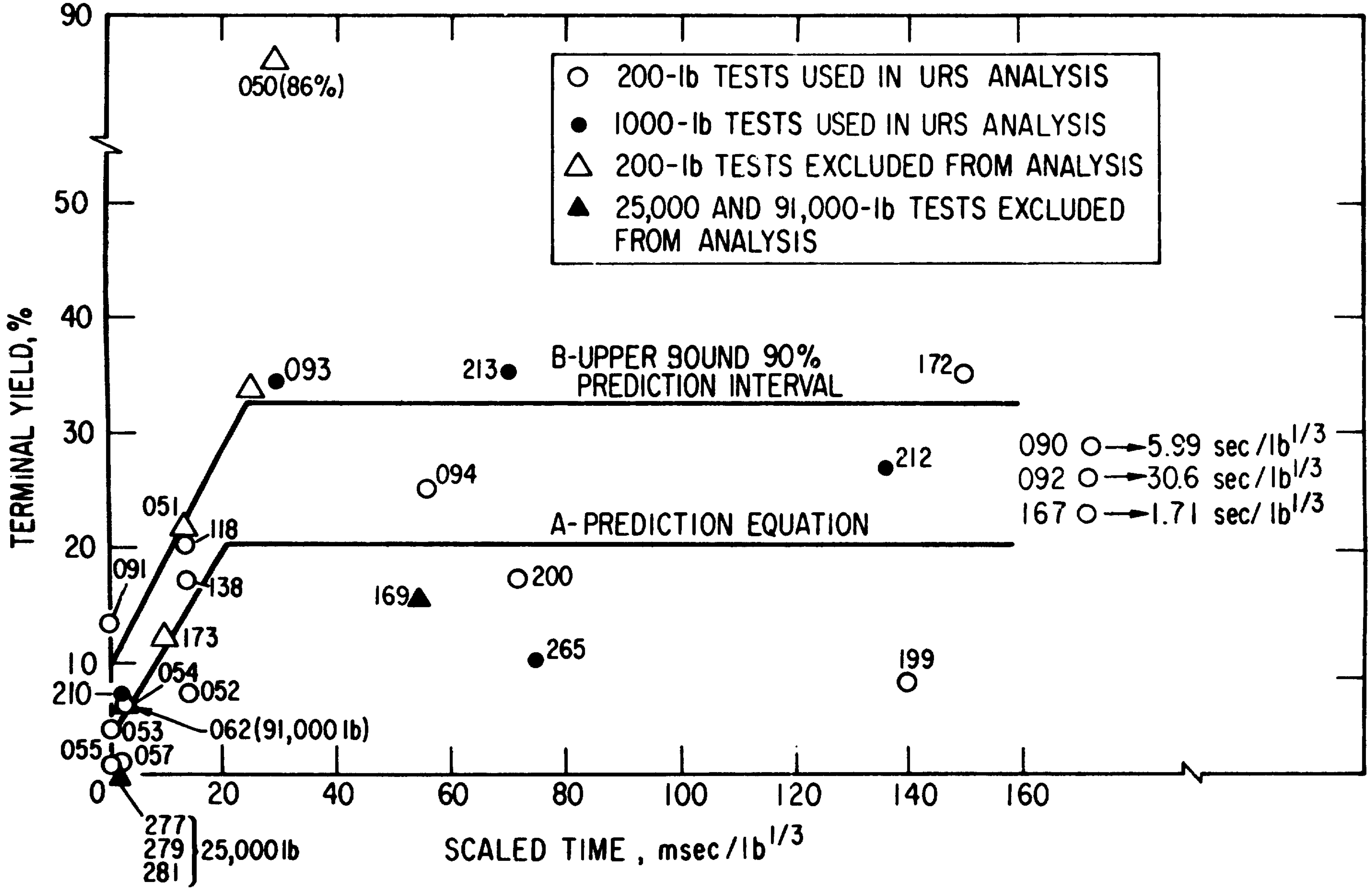

Fig. 4. Comparison of URS Prediction Equation for CBM Case with Experimental Data

points for these nine tests have been added to Fig. 4 to show their relationship to the prediction curve.

The analytical approach used appears to be sound, and the prediction curves reasonable for the data points on which the analysis was based. However, the expected effect of ignition delay on yield for the 200-lb tests was not well demonstrated, nor was the repeatability of yield for similar ignition delays. The data on which the prediction equation is based consist of fourteen tests at 200 lb and four tests at 1000 lb of LO_2/LH_2. As discussed in Sec. 2.3, the lack of large-scale test results and the wide scatter of small-scale data at a given scaled time limit confidence in using this prediction method for vehicles with propellant weights in the millions-of-pounds range.

2.4.1.2 Confined by Ground Surface - Vertical (CBGS-V) - URS

Figure 5, extracted from Ref. 4, is a plot of the CBGS-V prediction curves. Superimposed on this figure are the data points used in the analysis. The CBGS-V analysis was limited to data for tanks with an $L/D_t = 1.8$. Excluded from the analysis were the yields for two 200-lb tests, five 1000-lb tests, and three 25,000-lb tests, all with $L/D_t = 1.8$. These were apparently excluded because these explosions were self-ignitied or otherwise did not satisfy the test condition criteria.

The data indicate a definite increase in yield with increased impact velocity, with very high yields at velocities corresponding to the drop heights that could be expected with space shuttle vehicles involving large propellant weights. As in the case of the CBM analysis, however, eighteen data points are for 200-lb tests and two are for 1000-lb tests. For the same reasons discussed in the CBM case, little confidence could be placed in applying these curves to very large vehicles.

2.4.2 Bellcomm Analysis

Bellcomm performed an independent statistical analysis of the Project Pyro data. They concluded that a simple regression analysis of yield vs propellant

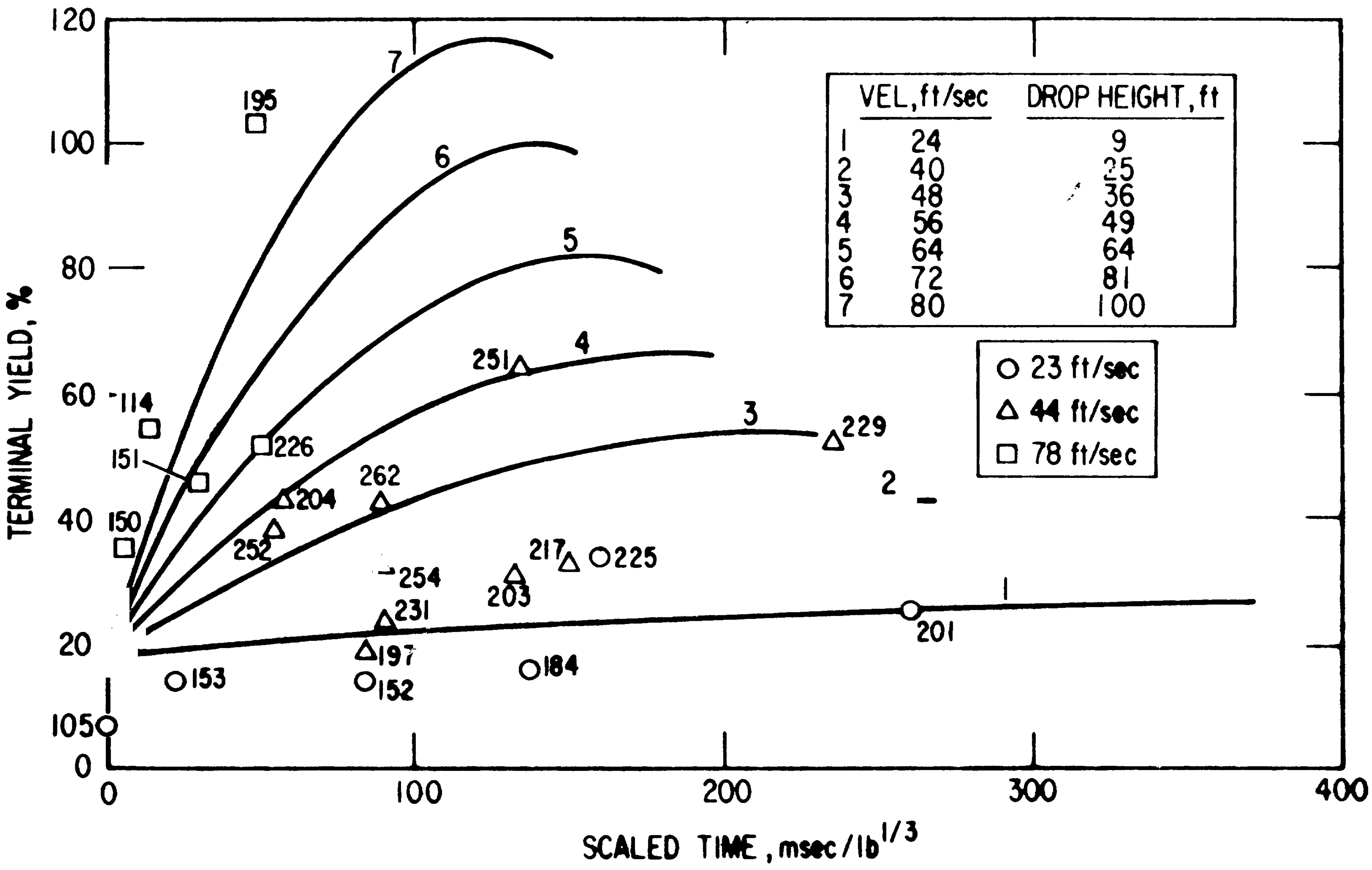

Fig. 5. Comparison of URS Prediction Equation for CBGS-V Case with Experimental Data

weight was a better approach than that used by URS, considering the previously discussed limitations of the Pyro data. The results of their analysis of the CBM and CBGS cases for LO_2/LH_2 are shown in Figs. 6 and 7. Bellcomm performed separate analyses of pressure and impulse yields (only the former has been reproduced here), whereas URS used an average of the two. Both investigators used the same definition of "spurious" tests[1], but if one compares the data used in their analyses, some disagreement is indicated as to the tests that fit the definition (see Appendix A, Vol. III of this series).

2.4.2.1 Confined by Missile (CBM) - Bellcomm

The Bellcomm analyses of the CBM case (see Fig. 6) were taken directly from Ref. 5. These results were based on data from tests involving only those tank configurations with an L/D_t ratio of 1.8 and a D_o/D_t ratio of 0.045. Of the tests conducted with this configuration, three 200-lb, one 1000-lb, and three 25,000-lb tests were excluded from their analyses. The data points not used were excluded because of autoignition and/or very low yields. The regression line of yield vs propellant weight is strongly influenced by the single simulated S-IV test point.

2.4.2.2 Confined by Ground Surface (CBGS) - Bellcomm

The Bellcomm analysis of the CBGS case was based on the same series of tests used by URS; in these tests, the propellant tank impact velocity was 44 fps. Figure 7 presents the calculated regression curve and the data points used. The yields shown are those calculated by Bellcomm. Excluded from the calculation were the data from one 200-lb test, three 1000-lb tests, and two 25,000-lb tests because the explosions were autoignited. It is obvious from an inspection of Fig. 7 that the regression line of yield vs propellant weight would have been significantly altered had the additional data points been considered.

[1] Spurious tests are those that experienced a failure mode other than the planned, controlled mode (tank or diaphragm rupture due to pressurization, premature fire, etc.). Such failures generally resulted in premature ignition.

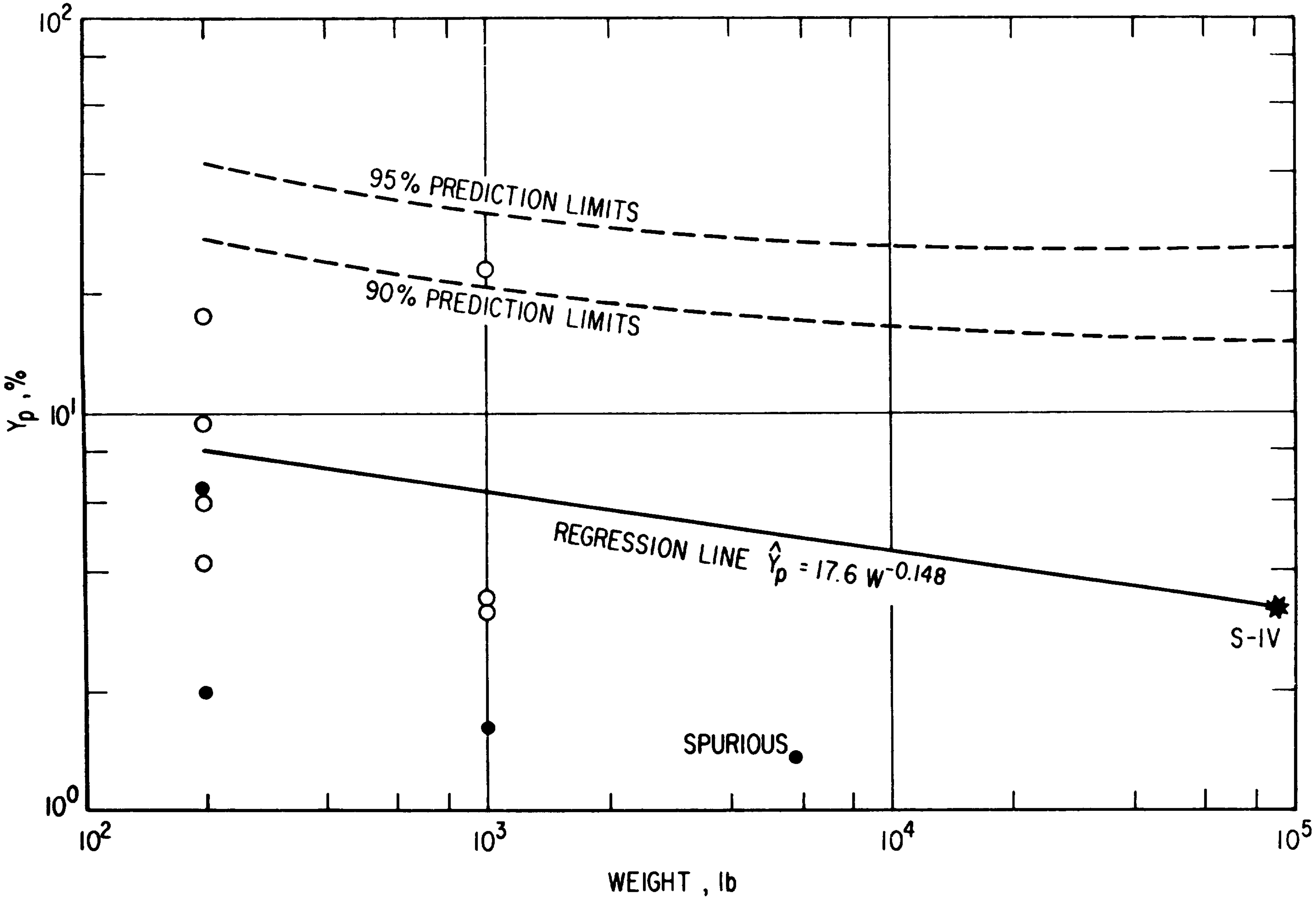

Fig. 6. Bellcomm LO_2/LH_2 Yield Prediction Equation for CBM Case

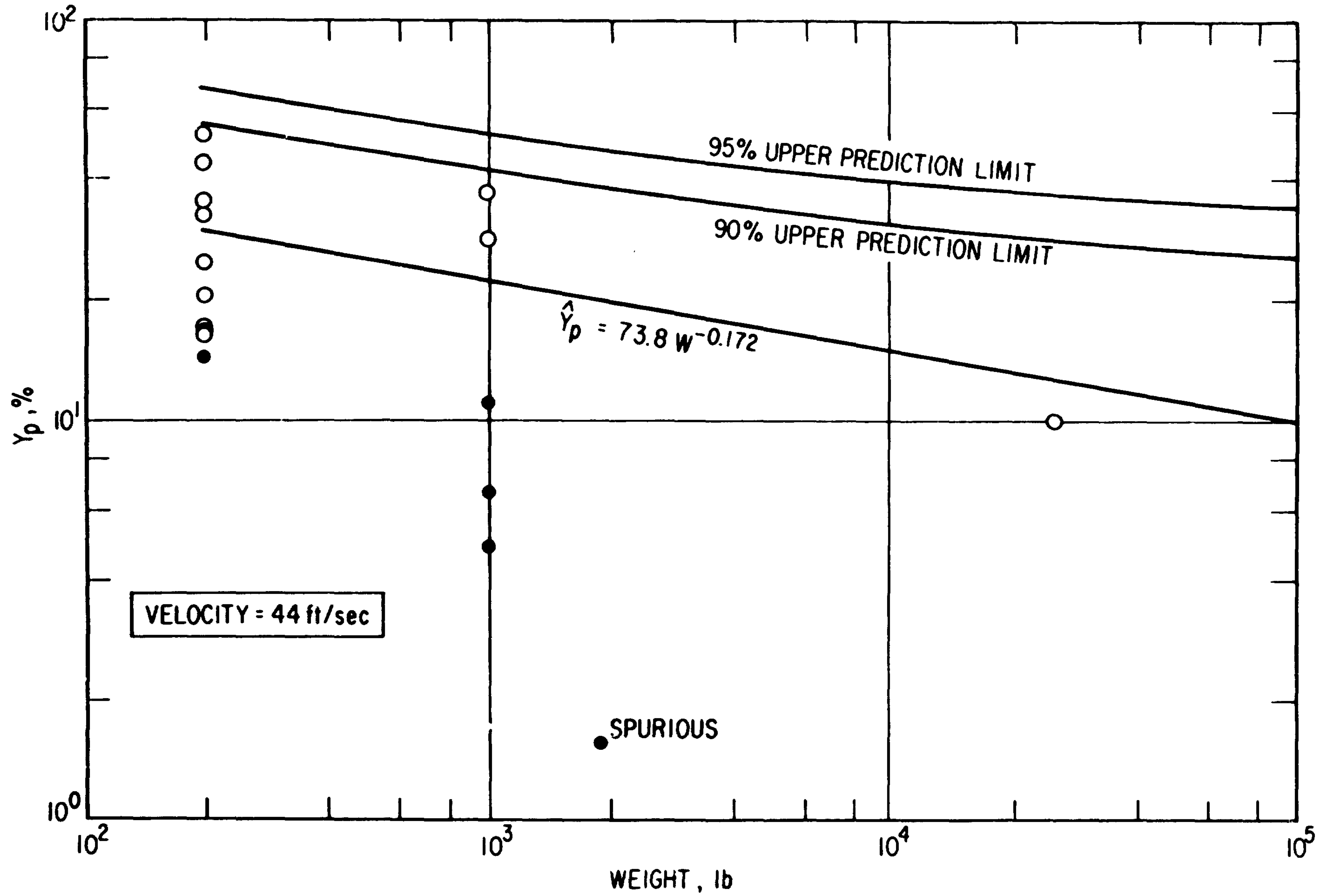

Fig. 7. Bellcomm LO_2/LH_2 Yield Prediction Equation for CBGS-V Case

The Bellcomm analysis indicates a decrease in yield with propellant weight but with rather large prediction limits. Although this analysis represents a different approach to the analysis of the data from that employed by URS, confidence in the results of either approach is limited by the lack of sufficient large-propellant-weight data.

2.4.3 The Aerospace Corporation Analysis

2.4.3.1 Effect of Data Point Population

As discussed earlier, an undesirable disparity exists in the number of data samples available at the various propellant test weights. This is particularly true since the data population decreases as the propellant weight approaches the magnitude of interest. With the Project Pyro data, this disparity would exist even if the results of all tests conducted were used as data points. Both URS and Bellcomm excluded several large-scale tests from their analyses primarily because ignition occurred earlier than the planned time. Thus, the small number of data samples at the larger propellant weights are further diminished.

It can be argued that self-ignition test results could be used as data points on the basis that, statistically, a certain number of these explosions occurred in spite of efforts to control ignition. There is certainly no evidence that self-ignition cannot occur in an actual failure. The relative validity of this approach and of that used by URS and Bellcomm becomes somewhat academic when one considers that there are too few large-scale data points to support a conclusive statistical analysis in any case. However, this second approach is suggested simply as a means of examining the effect of additional data points (real rather than assumed) on the analytical results.

Such an examination has been made in both the CBM and the CBGS cases; the result of adding data points is illustrated in Figs. 8 and 9. The Bellcomm analysis format has been used for convenience. For consistency, pressure yields recorded in Table 2 are shown; they were used in calculating the regression lines.

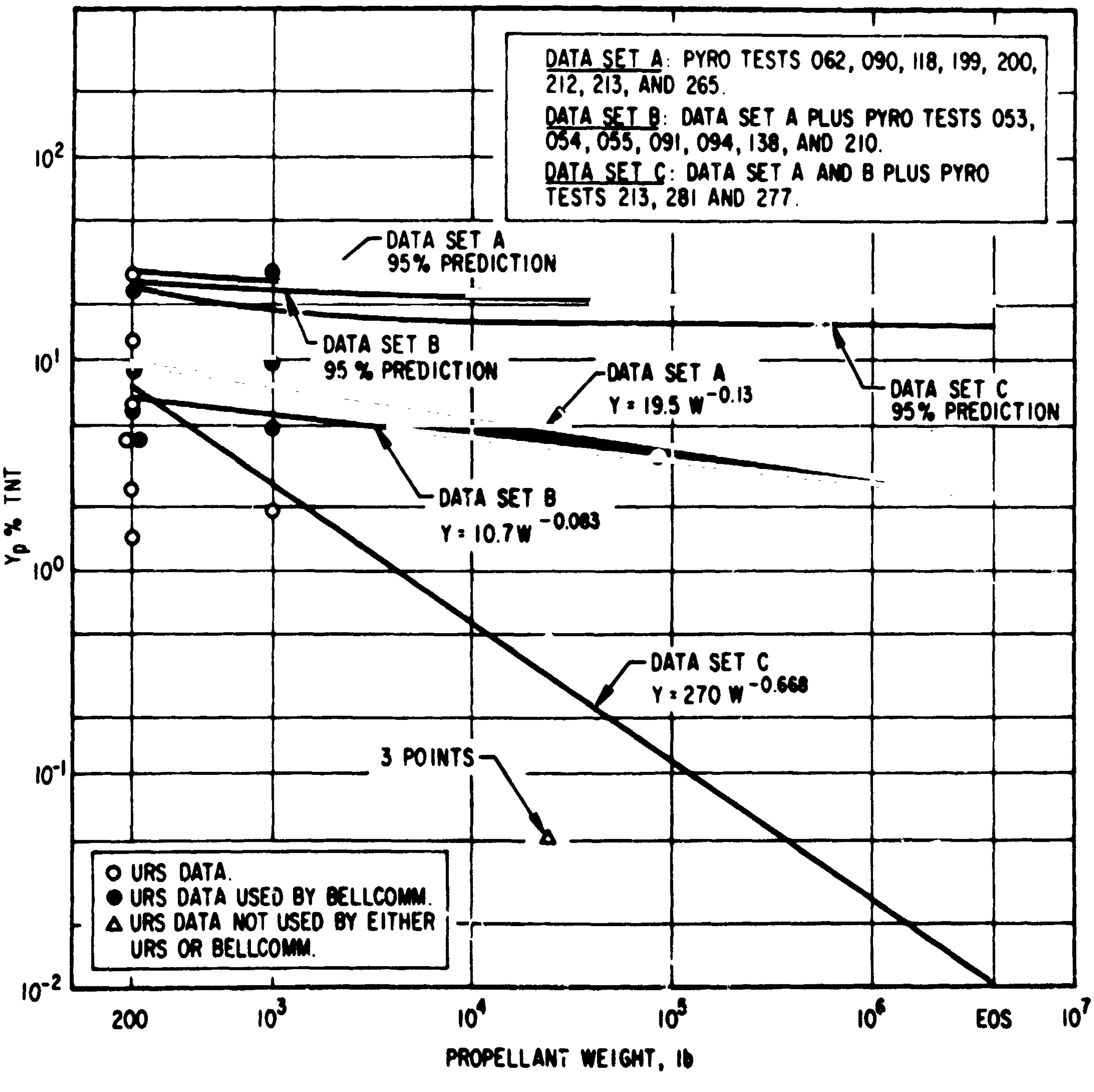

Fig. 8. Effect of Data Point Sets on LO_2/LH_2 Yield Prediction Equation, CBM Case

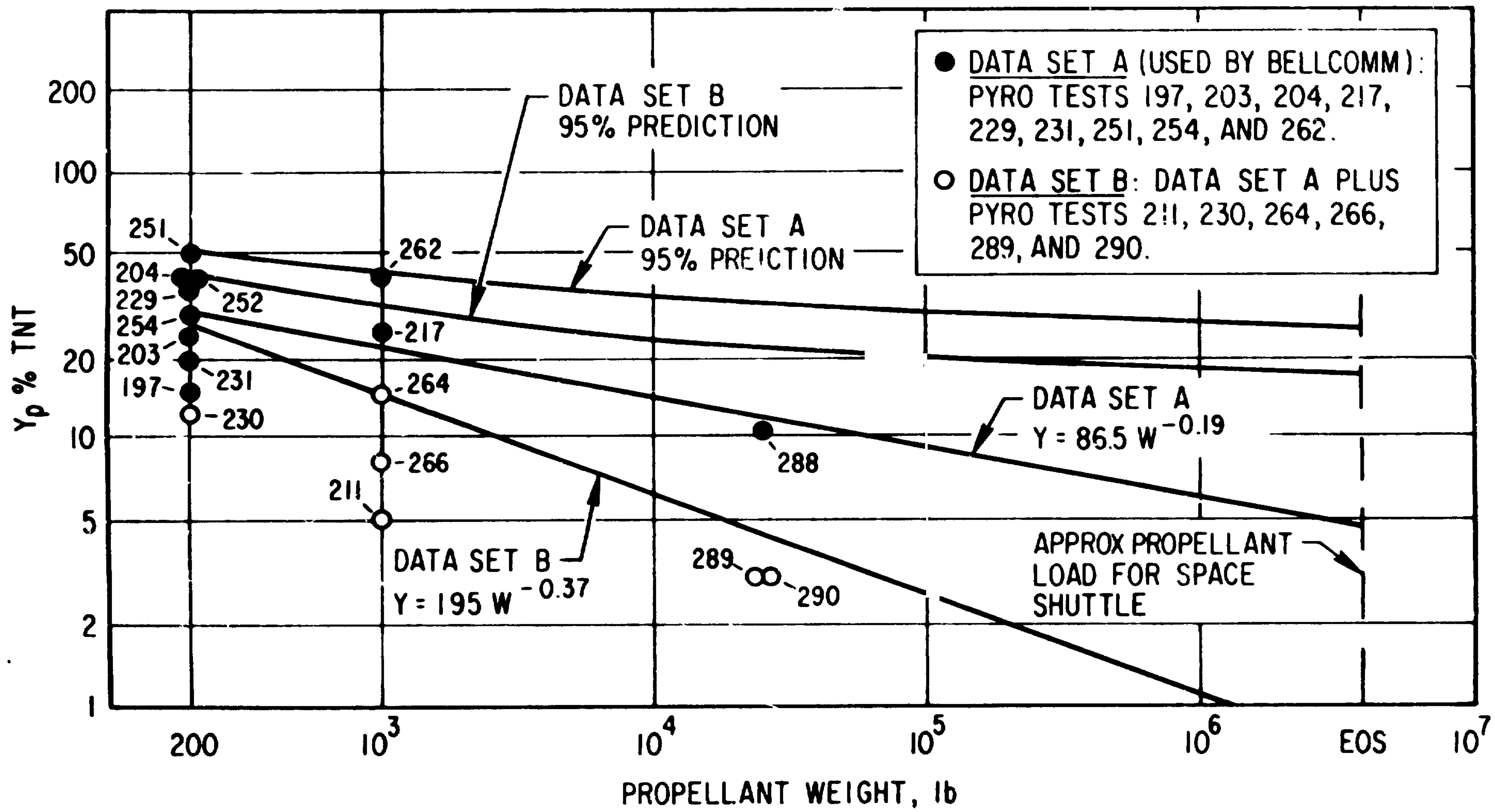

Fig. 9. Effect of Data Point Sets on LO_2/LH_2 Yield Prediction Equation, CBGS Case

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2.4.3.2 Confined by Missile (CBM) - Aerospace

The Bellcomm analysis of the CBM case was based on data from tests involving only those tank configurations with an L/D_t of 1.8 and a D_o/D_t of 0.45. Of the tests conducted with this configuration, one 1000-lb and two 200-lb tests were excluded as spurious from the analyses. Data Set A (see Fig. 8) shows the points considered by Bellcomm. The three tests previously excluded by Bellcomm were included in The Aerospace Corporation's comparative analysis. In addition, four 200-lb tests with an L/D_t of 5.1 and a D_o/D_t of 0.45 were added since both URS and Bellcomm concluded that the effect of L/D_t ratio (for D_o/D_t of 0.45) on yields is slight. The total number of these data points comprise Data Set B. Three 25,000-lb CBM test results were not included in either Data Set A or B since all had extremely low yields. Even though it is assumed that higher yields are possible because significantly higher ones were recorded for both the 1000-lb and 91,000-lb propellant weights, these three 25,000-lb CBM data points were added to Data Set B to obtain Data Set C.

Figure 8 compares the regression of pressure yield with propellant weight for the tests used in the Bellcom analyses (Data Set A) with similar regressions for the larger groups of tests (Data Sets B and C) used by The Aerospace Corporation. It can be seen that the inclusion of additional tests in Data Set B had little effect on the CBM regression line, primarily because of the strong influence of the single 91,000-lb point and the fairly even distribution of the additional 200-lb test yields about the original line. Both lines have been extended to a propellant weight of 4×10^6 lb (as indicated in Fig. 8) to illustrate the unreasonably large extrapolation required to approach the space shuttle propellant weight. The 95% prediction lines show little change in yield with propellant weight. The regression line for Data Set C shows a marked change in slope as the result of considering three low-yield points at 25,000 lb of propellant. In addition, the 95% prediction line indicates lower yield values as propellant weights increase; this also is attributable to the same three low-yield, 25,000-lb data points.

2.4.3.3 Confined by Ground Surface (CBGS) - Aerospace

Both URS and Bellcomm based their analyses of the CBGS case on data from a series of tests in which the propellant tank impact velocity was 44 fps. This series involved a greater range of propellant weights (200, 1000, and 25,000 lb) than did those with impact velocities of 23 fps and 78 fps. Of the tests in the 44 fps series, Bellcomm excluded the data from one 200-lb test, three 1000-lb tests, and two 25,000-lb tests because they were self-ignited. The reduced series of test points is identified as Data Set A. These six tests were added in the comparative analysis of the CBGS case; the total group of data points comprise Data Set B.

Figure 9 compares the regression of pressure yield with propellant weight for the tests used in the Bellcomm analysis (Data Set A) with a similar regression for the larger group of tests (Data Set B). The inclusion of the self-ignited CBGS tests results in a considerable change in the slope of the regression line. In this case, the change effects a reduction in predicted yield at any given weight because the additional tests were all low-yield. Extrapolation to large propellant weights, in the range of 4×10^6 lb, results in the prediction of extremely low yields. This approach demonstrates the sensitivity of the slope of the regression line to the addition of low-yield data points where none or only a few originally existed. Obviously, the addition of a few high-yield points at the 1000-lb and the 25,000-lb weights would significantly increase the predicted yield for large propellant weights.

2.4.4 Assessment of Available Data and Analyses

Since the current LO_2/LH_2 explosive safety criterion of 60% TNT equivalency is not identified with any specific failure mode, one might consider grouping all available LO_2/LH_2 explosion data from Project Pyro for analysis, regardless of the failure mode. Furthermore, one could stipulate that the only requirements for the validity of the test data to be used are that the simulated failure mode is credible and that an explosion has occurred. The URS Project

Pyro data plotted in Fig. 10 generally satisfies these requirements for the two basic failure modes tested. This approach permits the use of all currently available test results (78 data points) for evaluating propellant quantity scaling effects. Figure 10 shows, however, that considerable disparity in data population exists between any two given test propellant weights. For a statistical analysis to be meaningful, the number of data samples at each propellant weight should be nearly equal. Despite the obvious limitation of the plotted data points in this respect, a simple regression analysis was performed, and the results are shown. However, this regression cannot be considered very significant because of the uncertainty created by the effect of the few widely scattered large-scale test yields on the slope of the curve. Little confidence could be placed in yields predicted by extrapolation of such data to propellant weights in the r illions-of-pounds range.

The analyses conducted by Bellcomm and those presented here have yielded a series of prediction equations. These equations, which are summarized in Table 3, illustrate the sensitivity of the prediction equation to the inclusion or exclusion of large-propellant-quantity data points. While it is certainly more conservative to omit low-yield points and thus obtain a higher predicted yield, one wonders whether still higher yields might have been obtained had more tests been performed.

The URS hypothesis that yield is a function of the normalized ignition delay time ($t^* = t/w^{1/3}$) is a reasonable approach. The hypothesis assumes that the time interval between propellant contact and ignition time t is known. For prediction purposes, a value of t^* must be assumed that will result in the maximum yield that may occur. Establishing a proper value for t^* would be difficult, as is shown by the wide spread of yields obtained from tests using 200 lb of propellant. Further, URS indicated that a range of yields similar to that of the 200-lb test might have been obtained at the higher test weights if more extensive testing had been done.

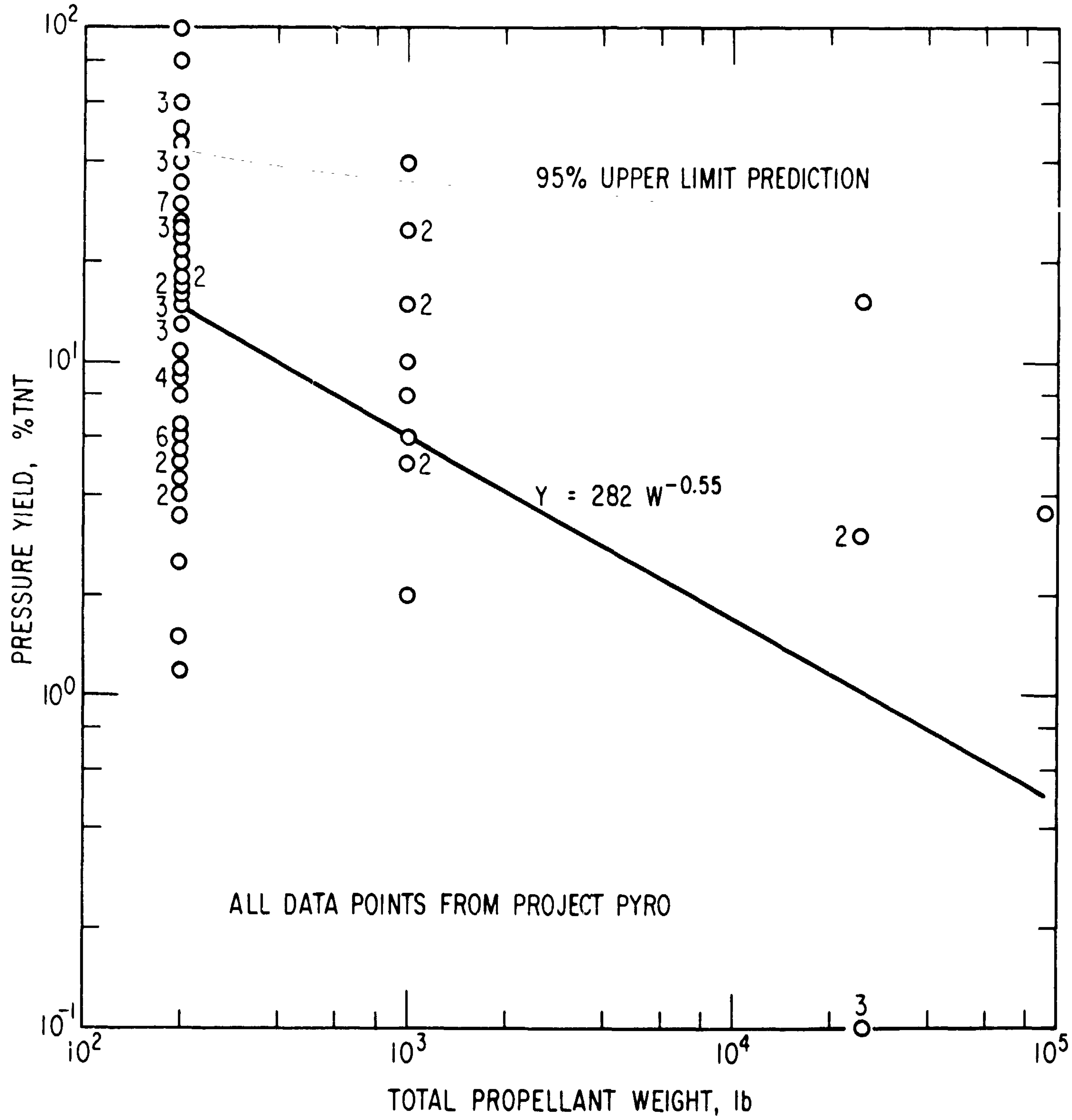

Fig. 10. Regression Analysis of LO_2/LH_2 Pressure Yield vs Propellant Weight

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Table 3. LO_2/LH_2 Explosive Yield Prediction Equations

CBM Case	
Bellcomm	$Y_p = 17.6\ W^{-0.148}$
Independent	
Data Set A	$Y_p = 19.5\ W^{-0.13}$
Data Set B	$Y_p = 10.7\ W^{-0.083}$
Data Set C	$Y_p = 279\ W^{-0.668}$
CBGS Case (44 fps)	
Bellcomm	$Y_p = 7.38\ W^{-0.172}$
Independent	
Data Set A	$Y_p = 86.5\ W^{-0.19}$
Data Set B	$Y_p = 195\ W^{-0.37}$

It was an aim of Project Pyro to provide a generalized explosive yield-predicting tool, but the data covers only two basic failure modes. In order to predict explosive yields for other failure modes, it would be necessary to compare those other failure modes with the two for which data have been taken and to extrapolate the results to larger- or smaller-yield values for the new projected failure modes.

Using the Project Pyro data, Bellcomm notes that yield plotted vs propellant weight shows a qualitative decrease in yield with increased propellant weight. If one assumes that the available data points represent a statistically valid data population, the regression line proposed by Bellcomm could be considered valid; however, the lack of sufficient data points at the higher propellant weights raises doubts as to the validity of such an assumption. These doubts are further reinforced by examination of the Project Pyro data grouping analysis, which demonstrated the effect of adding or subtracting test points, particularly in regions where few data points exist.

The analytical approach to predicting explosive yields developed by Dr. Farber (see Appendix C, Vol. III of this series) is comprehensive and thorough but, again, additional large-scale data points are needed to arrive at an acceptable confidence level when one extrapolates to large propellant quantities.

2.5 SUMMARY OF DATA ANALYSIS

Examination of the available LO_2/LH_2 explosion data clearly shows that explosive yields vary over a wide range and that this variability depends on the failure mode or, stated in another way, on the mixing mechanisms involved. Explosive yield depends on the amounts of LO_2 and LH_2 actually mixed before an ignition source is available. The time available for this mixing to take place, the interface area between the LO_2 and the LH_2, the turbulence induced by velocity or heat transfer between the LO_2 and the LH_2, and the energy level of the ignition source are prime factors in the resulting yield. The rather wide spread of explosive yields observed under supposedly identical test configurations and procedures cannot be explained by the recorded data, and the effects of prime factors and their interaction have not been isolated quantitatively.

Figure 3, which shows all of the LO_2/LH_2 data points taken by the principal investigators, illustrates two things: Only Project Pyro provides test data for propellant quantities over 225 lb, and mixing mechanisms or failure modes other than the two considered in Project Pyro have not been investigated for propellant quantities greater than 225 lb. Therefore, it seems appropriate to consider Project Pyro data as the only basis for considering the scaling of LO_2/LH_2 explosive yields to higher propellant weights, recognizing that Project Pyro provides data points for only two basic failure modes. Further, insufficient large-scale data points are available to permit positive, quantitative assessment of the explosive yields for propellant quantities in the millions-of-pounds range.

It is acknowledged that within the framework chosen by each of the investigators and with the assumptions that have been made based on the evaluation logic employed, little, if any, fault can be found with the execution of any of the analyses. However, conclusive proof in support of any of the prediction approaches used by the various investigators cannot be substantiated on the strength of the available data.

2.6 CONCLUSIONS OF DATA ANALYSIS

It is concluded that insufficient data exist to technically substantiate a generalized reduction in the existing TNT equivalency criterion for LO_2/LH_2 propellant. However, an acceptable rationale may be developed based on an on-pad failure modes and effects analysis that would justify a waiver to reduce the TNT equivalency criterion specifically for the space shuttle. Such an analysis would take into account the vehicle and launch-site configurations and the quantity of propellant involved.

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3. FAILURE ANALYSIS

3.1 GENERAL

A failure modes and effects analysis was performed to assess the explosive hazards of the space shuttle vehicle during ground operations. Specifically, the study was confined to the static on-pad time interval between initial propellant loading and vehicle liftoff (see Fig. 11).

Since the vehicle design and operational criteria are in the development phase, the failure analysis is, of necessity, a qualitative, top-level effort. The vehicle configurations and propellant weight used throughout the analysis are shown in Figs. 12 through 17. Recommended tank structural design criteria (see Ref. 6) are presented below:

- Leakage rather than rupture shall be the most probable failure mode.
- The tank shall withstand a collapsing pressure differential during the drain cycle (a pressure equalization system may be substituted)
- Recommended safety factors (to be verified or modified by best available design technique):

Component	Factors		
	Yield	Ultimate	Proof
Pressurized Lines and Fittings	-	2.5	1.50
Main Propellant Tank	1.1	1.4	1.05
Pressure Vessels (Other Than Propellant Tanks)	-	2.0	1.50

It is emphasized that the study was confined to on-pad conditions during the interval between the start of propellant loading and vehicle liftoff. However, in determining probable failure modes, the study could consider the contributions of the launch pad and the ground equipment to the result of a failure only generally because their configurations are still incompletely defined.

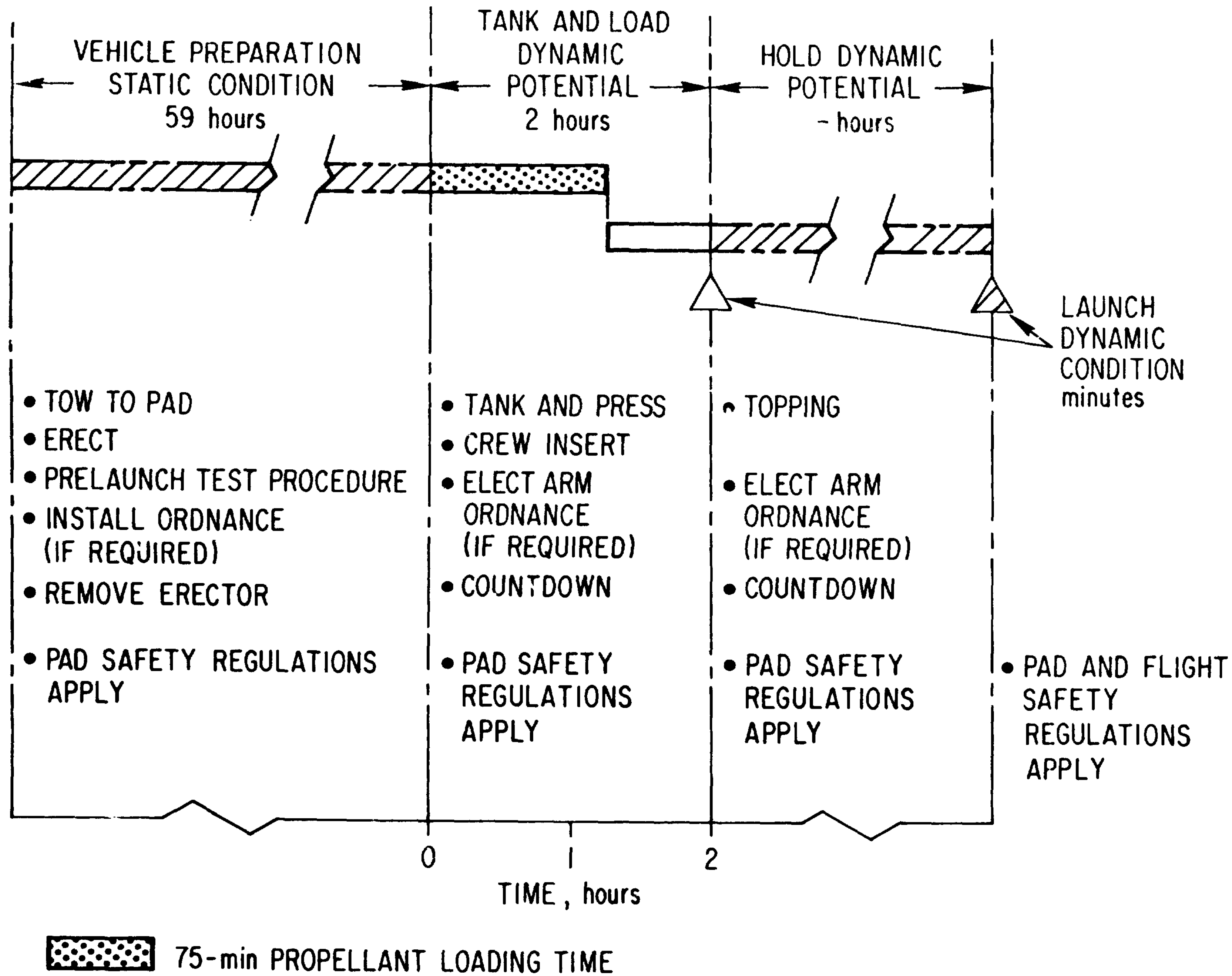
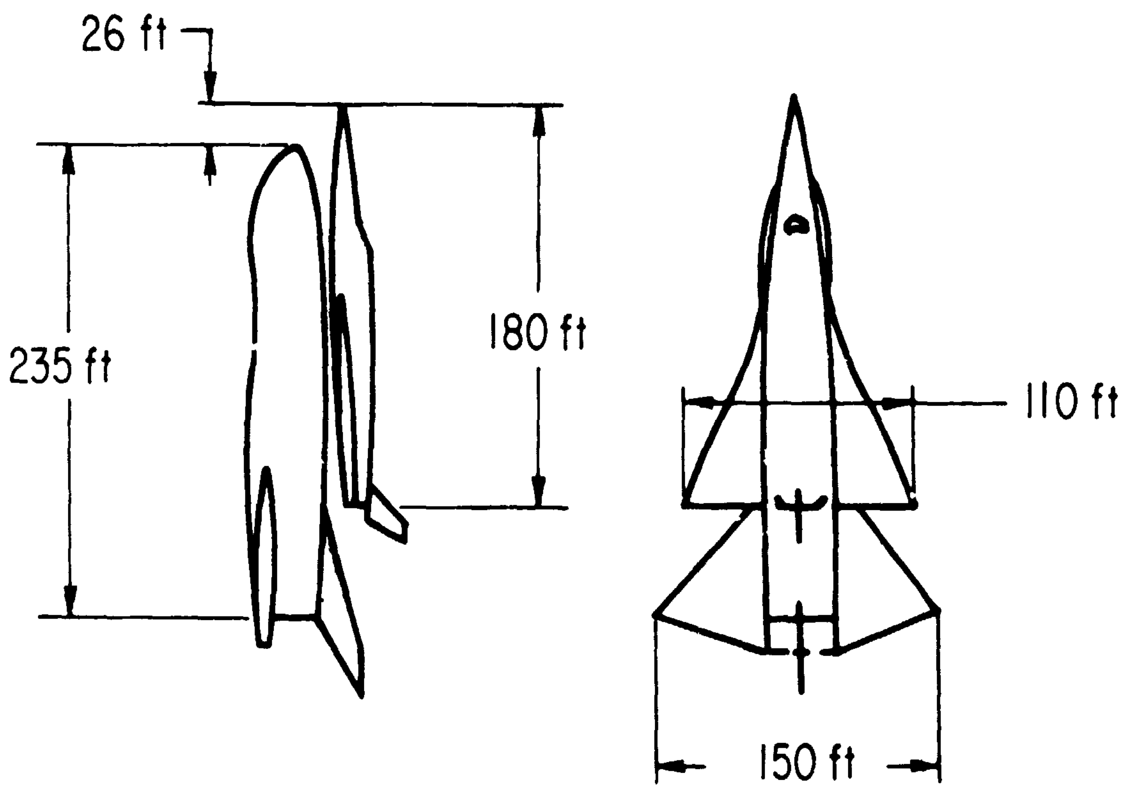


Fig. 11. On-Pad Prelaunch Activities



WEIGHT DATA, lb × 10^6	BOOSTER	ORBITER
GROSS LIFTOFF WEIGHT	4.2	0.8
TOTAL LOADED PROPELLANT	3.4	0.6
LO_2	2.9	0.5
LH_2	0.5	0.1

NOTE: DIMENSIONS AND WEIGHTS ARE APPROXIMATE

Fig. 12. Typical Vehicle Configuration

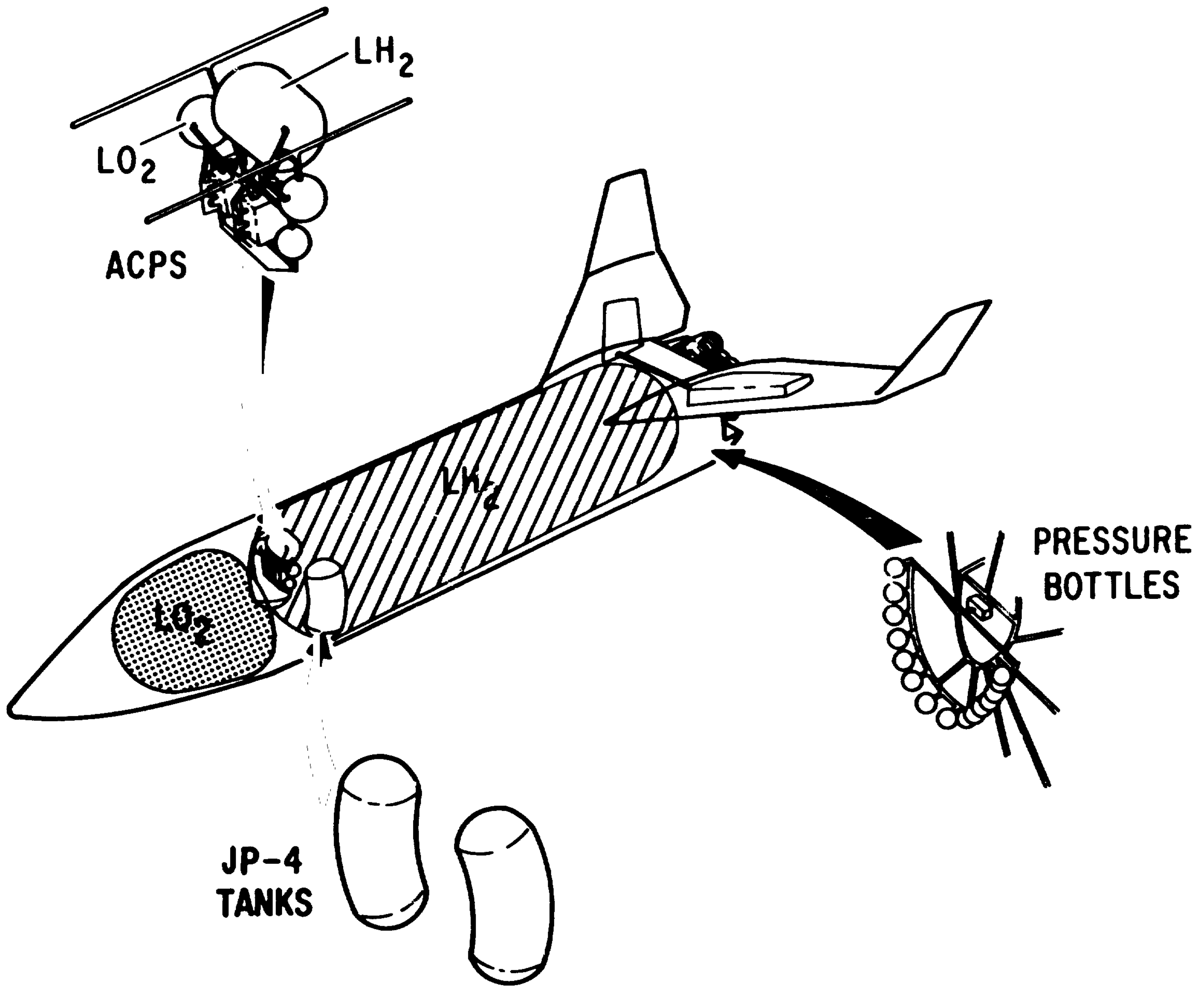


Fig. 13. Typical Booster Propellant Tank Arrangement

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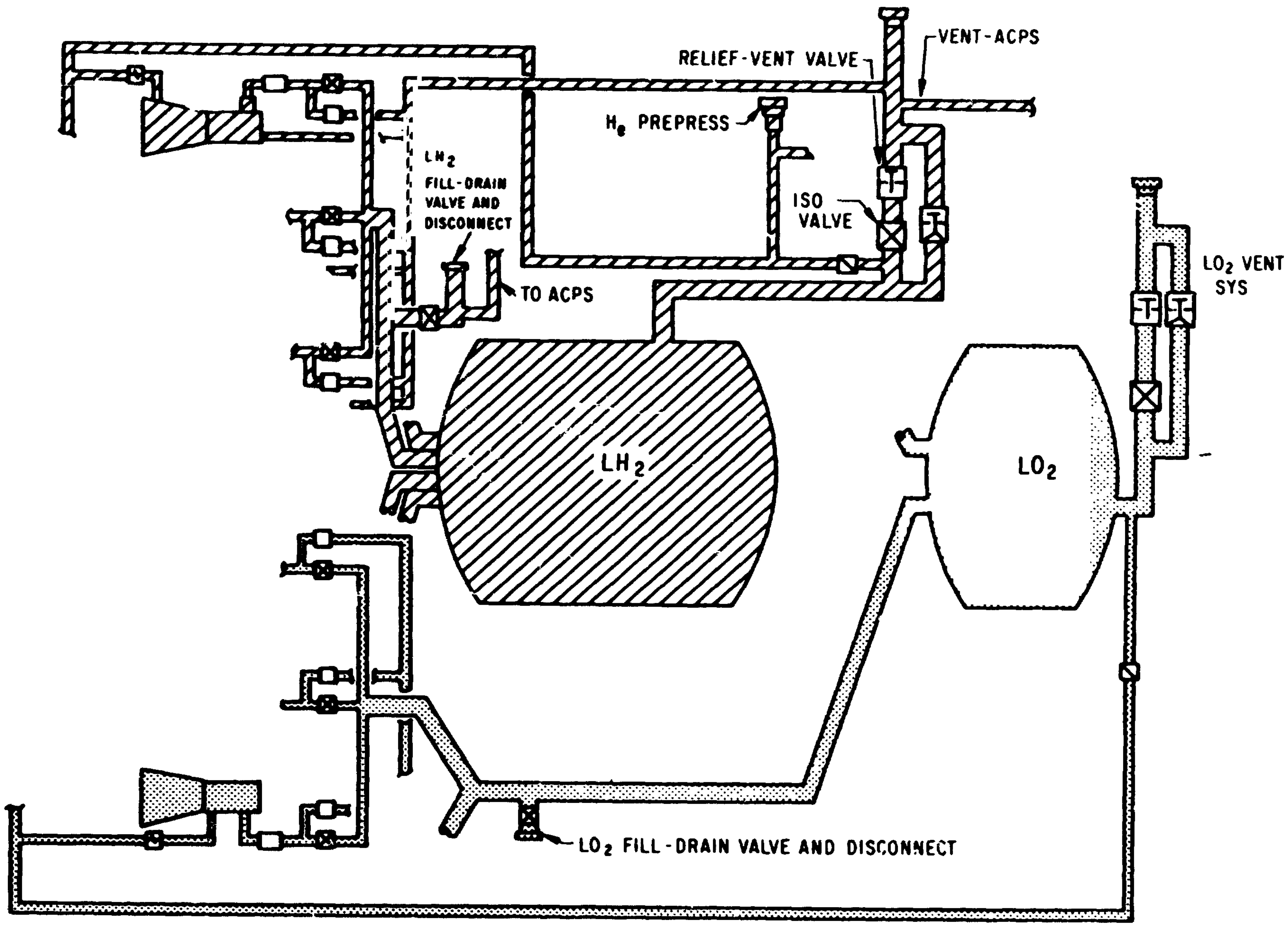

Fig. 14. Schematic of Typical Booster Main Propulsion System

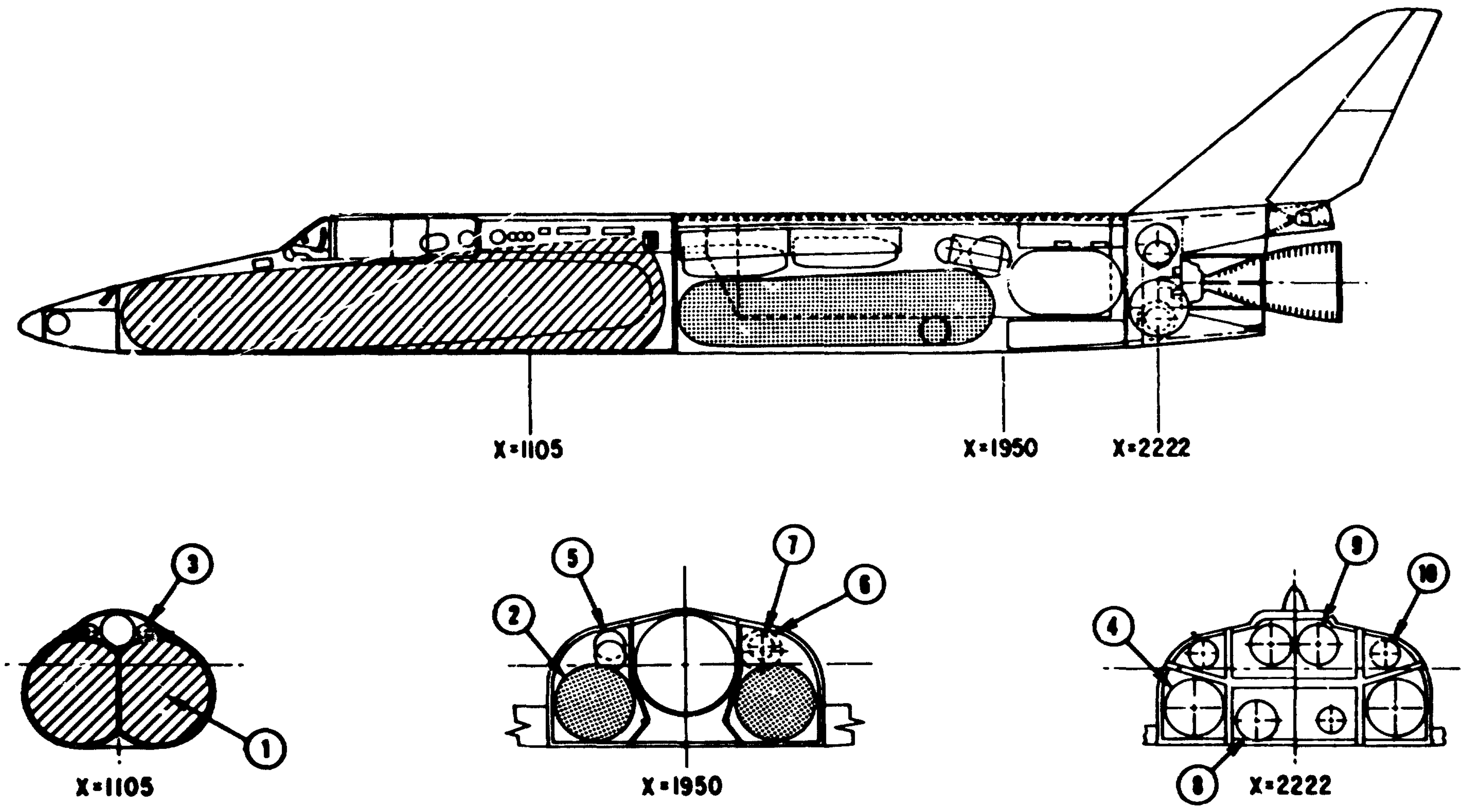

Fig. 15. Typical Orbiter Propellant Tank Arrangement (Separate Tanks)

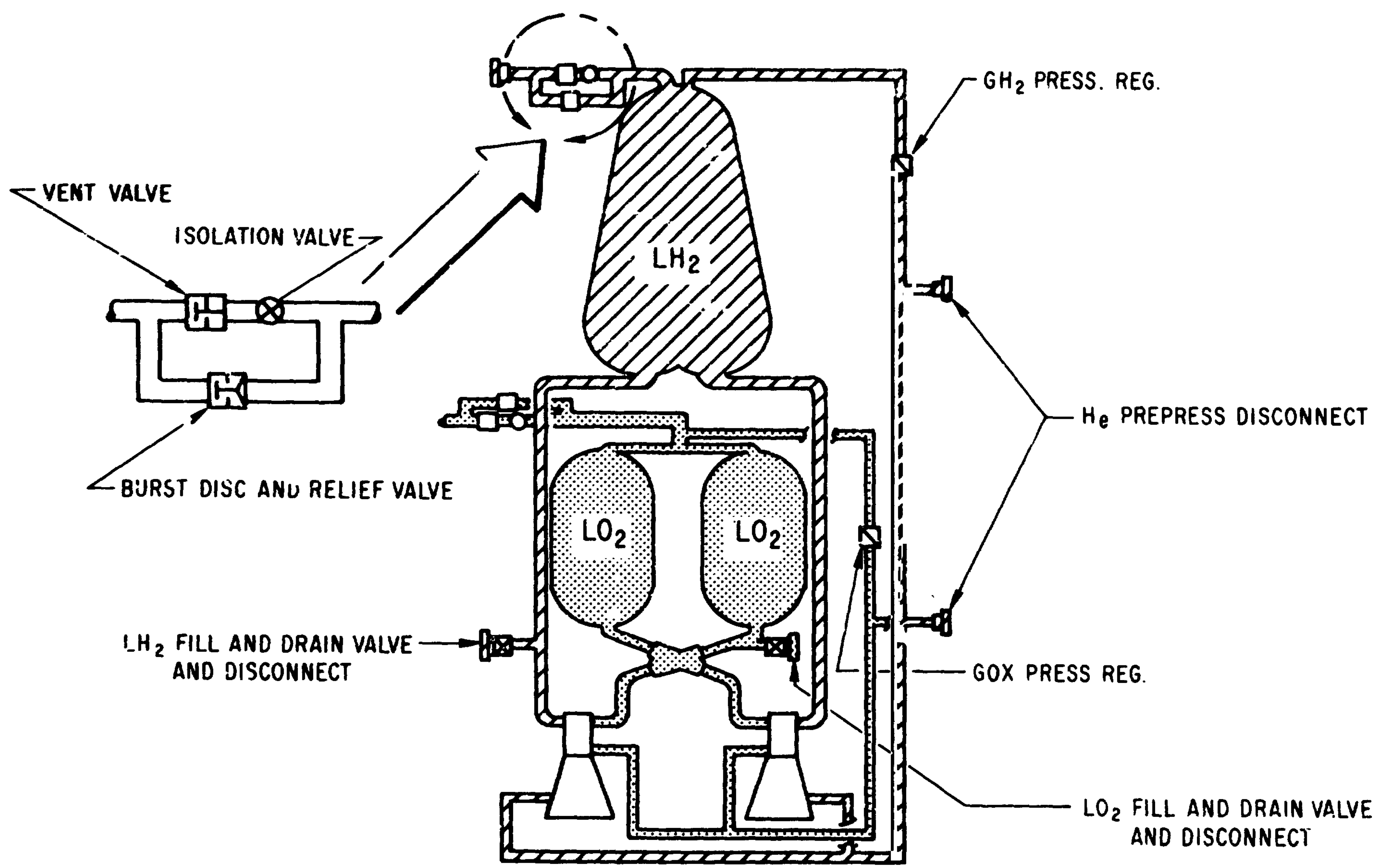

Fig. 16. Schematic of Typical Orbiter Main Propulsion System (Separate Tanks)

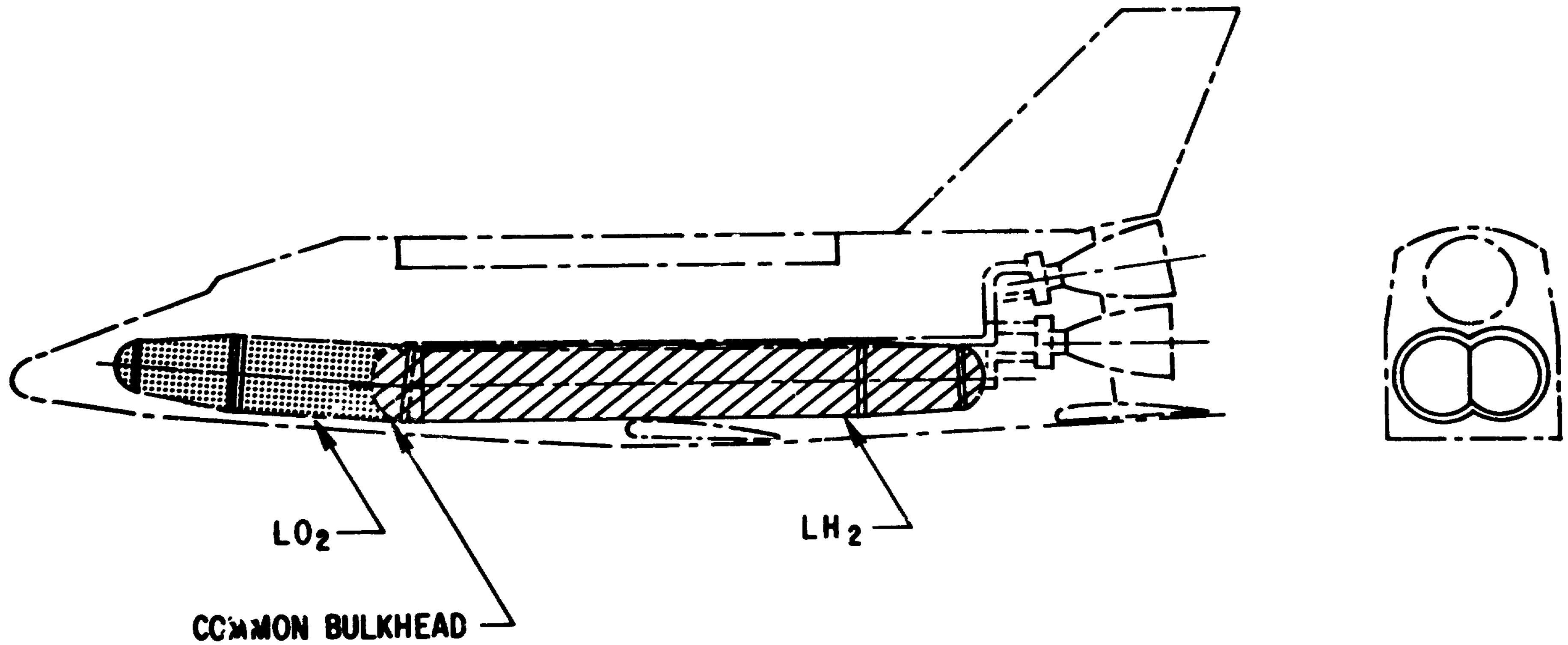

Fig. 17. Typical Orbiter Main Propellant Tank Arrangement (Common Bulkhead Tank)

Consideration of probable failure modes suggests preventive action that could be implemented during vehicle design to provide an inherently less hazardous condition. Corrective action may be in the form of sensors that would initiate certain operating procedures and emergency actions and thus minimize hazards. Suggested preventive measures will be described as they are developed in the failure mode analysis, which was conducted in conjuntion wtih the fault tree definition; they are summarized in Sec. 3.3.6.

3.2 FAULT TREE

A fault tree was developed to systematically identify the events that could lead to a catastrophic failure (in this study, a catastrophic failure is defined as an explosion). Figure 18 presents the top level of the fault tree and shows the basic conditions (a propellant source, mixing, and an ignition source) deemed necessary to produce a catastrophic failure. The conditions identified in Fig. 18 will be discussed in greater detail in the sections that follow. Although the main tanks are obviously included in the vehicle systems category, their size, function, and degree of exposure warrant a separate classification.

The primary conditions analyzed are listed below. With the exception of leakage in the vehicle systems, these conditions were analyzed for failures contributing to the gross release of propellant:

- Vehicle tank(s) ruptured
  - Tank overpressure
  - Tank collapse
  - Orbiter dropped
  - Vehicle tipover
  - Lightning strike
  - Fire
  - Tank struck by foreign object
- Vehicle propellant system failure

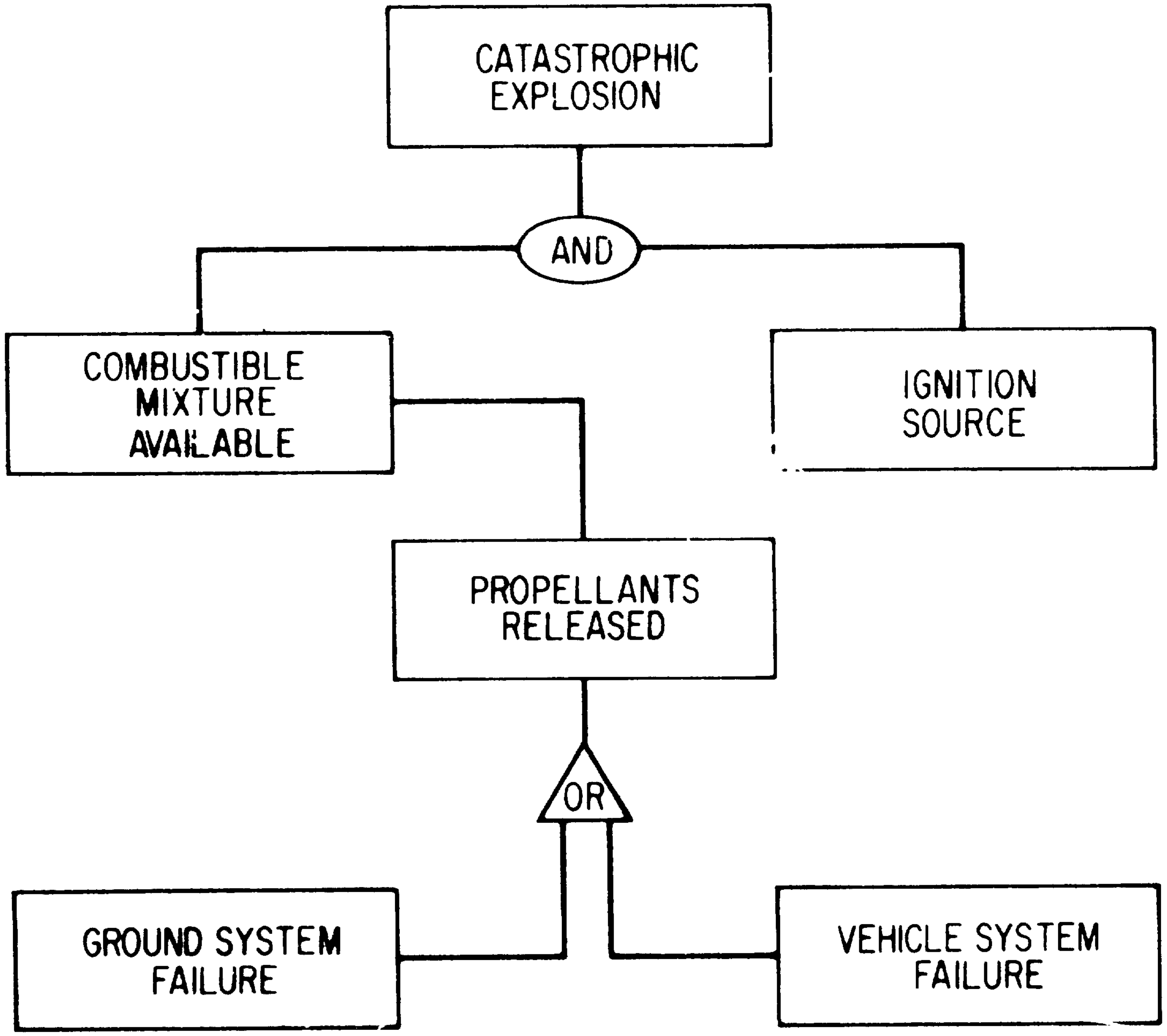

Fig. 18. Fault Tree - Top Level

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3.3 ANALYSIS

3.3.1 Vehicle Tank(s) Ruptured

Figure 19 presents an expansion of the fault tree that was developed to identify events resulting in the rupture of one or more of the main propellant tanks. At this point in the analysis, only failure potentially capable of a gross propellant release were considered and analyzed.

3.3.1.1 Tanks Overpressurized

Events that could result in propellant tank failures due to internal overpressure were placed in two main categories: gaseous overpressure and hydraulic overpressure. Gaseous overpressure results mainly from failures in vehicle systems; hydraulic overpressure results mainly from failures in the GSE branch of the propellant loading system.

3.3.1.1.1 Gaseous Overpressure

Failures in three subsystems were identified and evaluated as potential sources of gaseous overpressure. The systems involved are the vent, pressurization, and fill and drain systems (see Fig. 20). The evaluation of the subsystems will be discussed in the following paragraphs.

3.3.1.1.1.1 Vent/Pressure Relief System Failure

Vent system failures can occur in either the vehicle or ground equipment branches of the system. Failure of the ground vent system as a source of vehicle overpressurization was considered so remote as to be negligible and is therefore not further evaluated.

The vehicle vent system evaluated in this study was taken from contractor reports and is shown schematically in Fig. 21. The schematic shows that the vent and pressure relief functions are placed in parallel; a failure of both functions would be required before the tanks would be subjected to an overpressure condition. The events that would produce such a failure are shown in a partial expansion of the fault tree (see Fig.22).

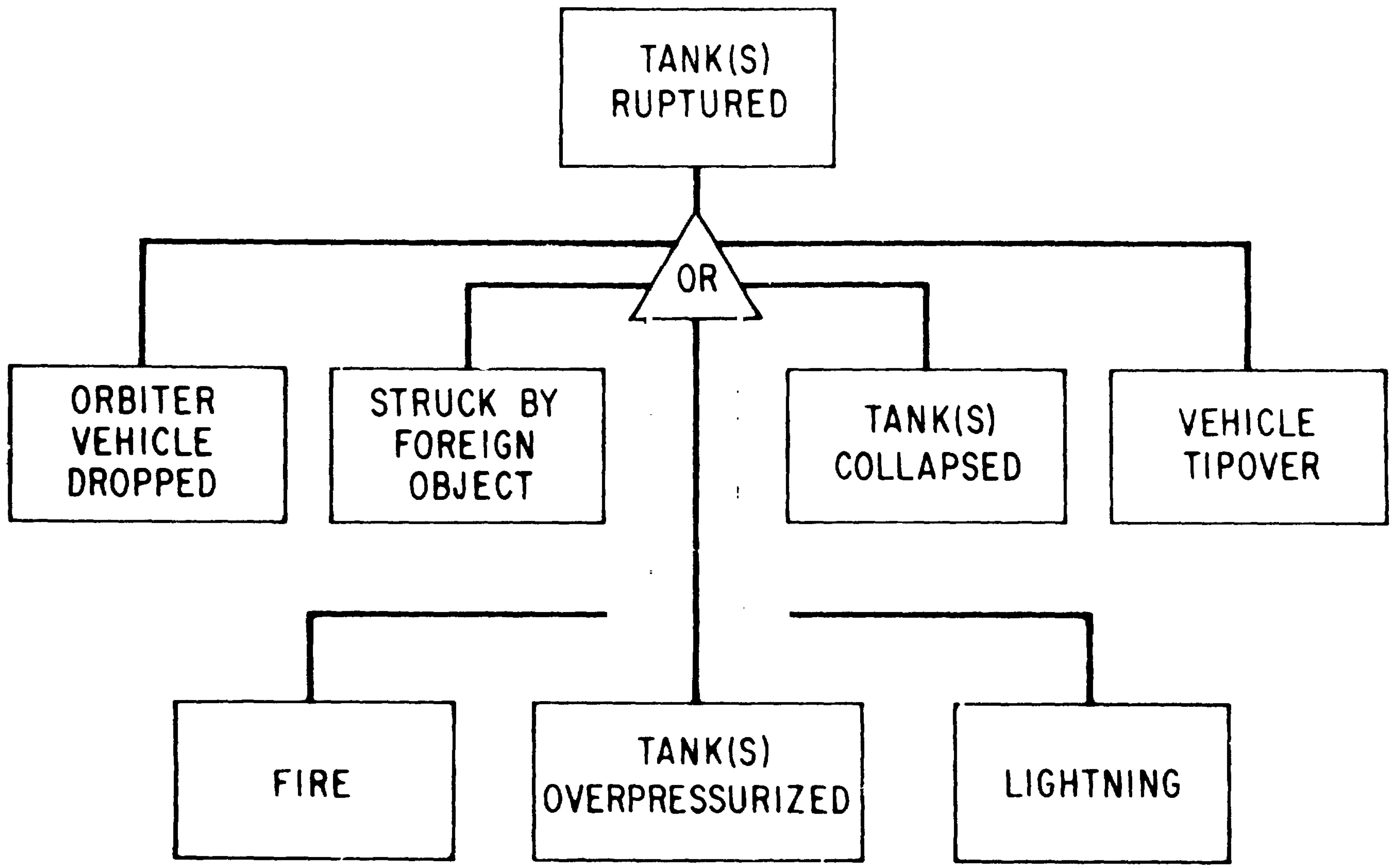

Fig. 19. Fault Tree - Propellant Tank Rupture

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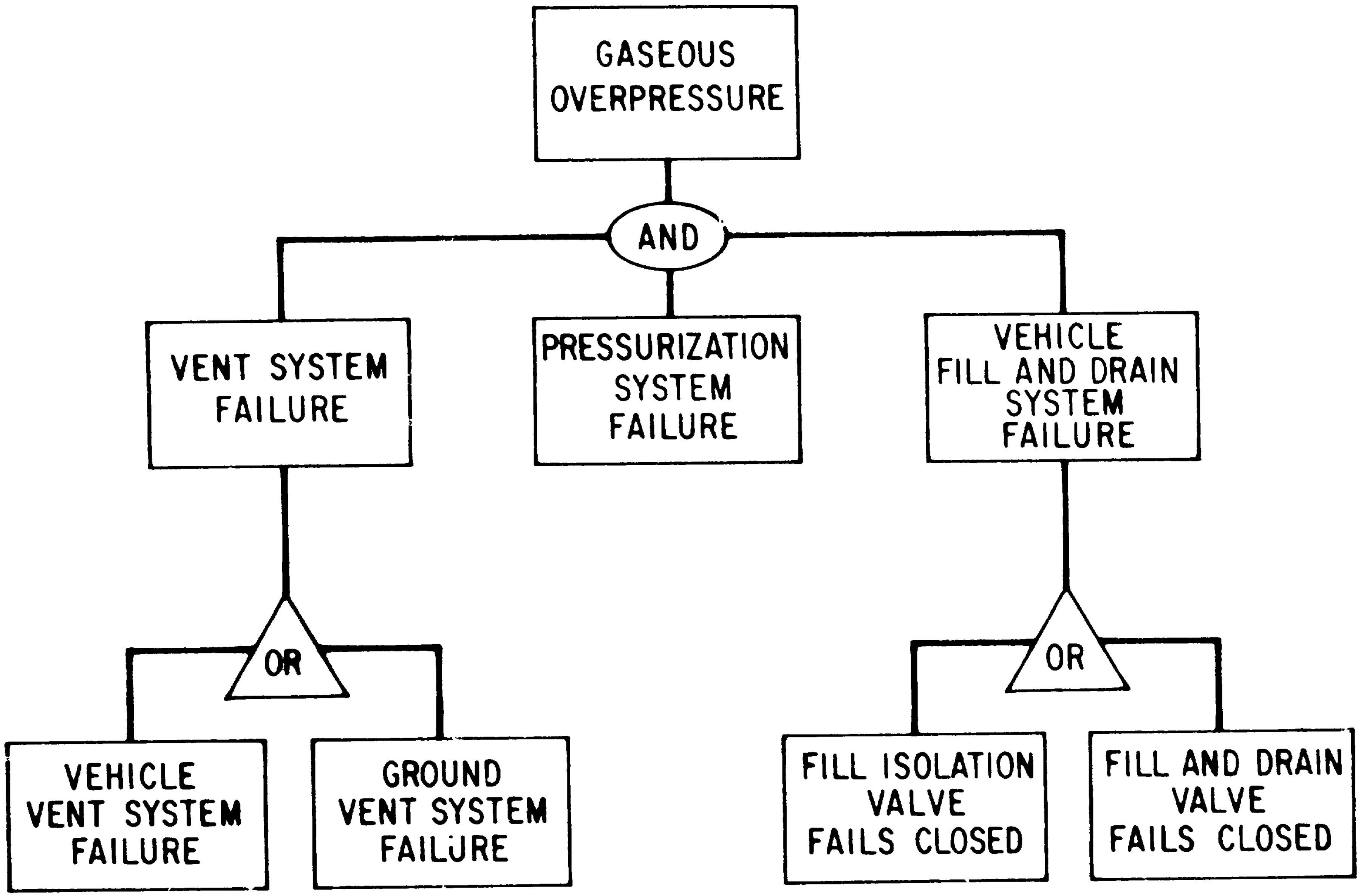

Fig. 20. Fault Tree - Gaseous Overpressure

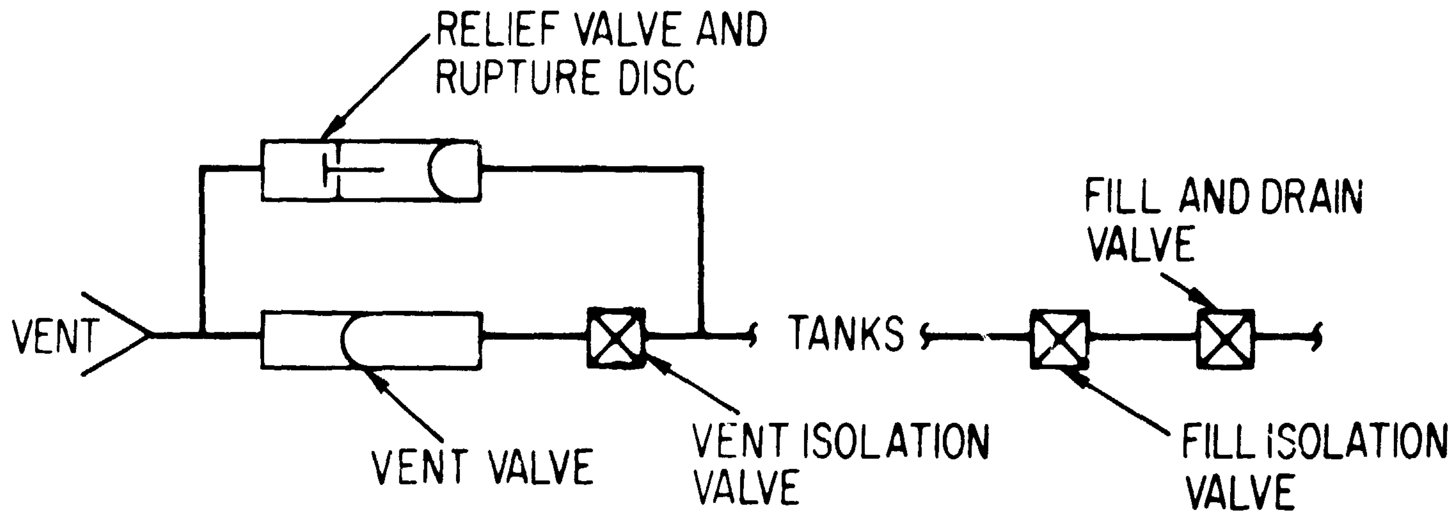

Fig. 21. Schematic - Vehicle Vent and Fill and Drain Systems

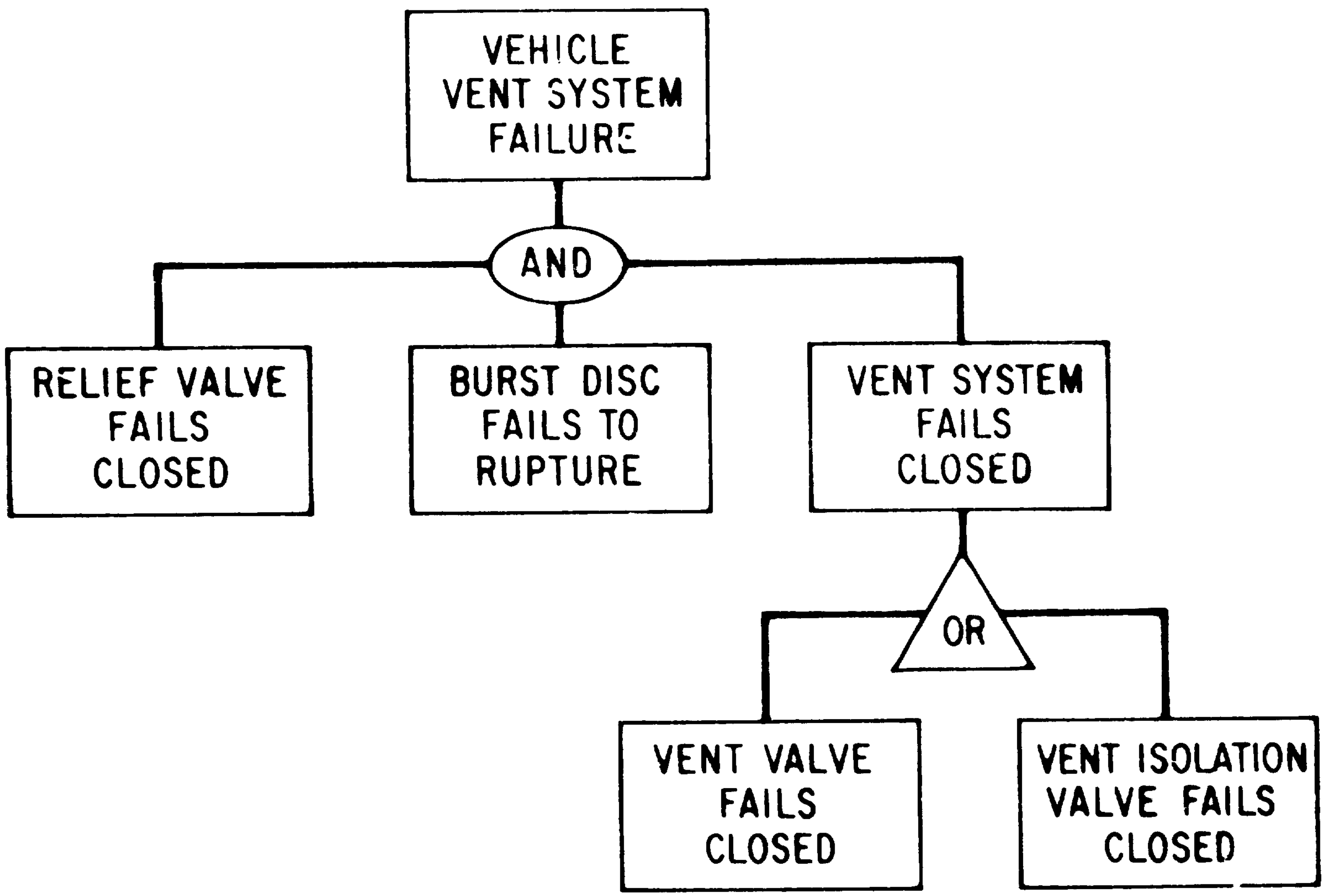

Fig. 22. Fault Tree - Vehicle Vent System Failure

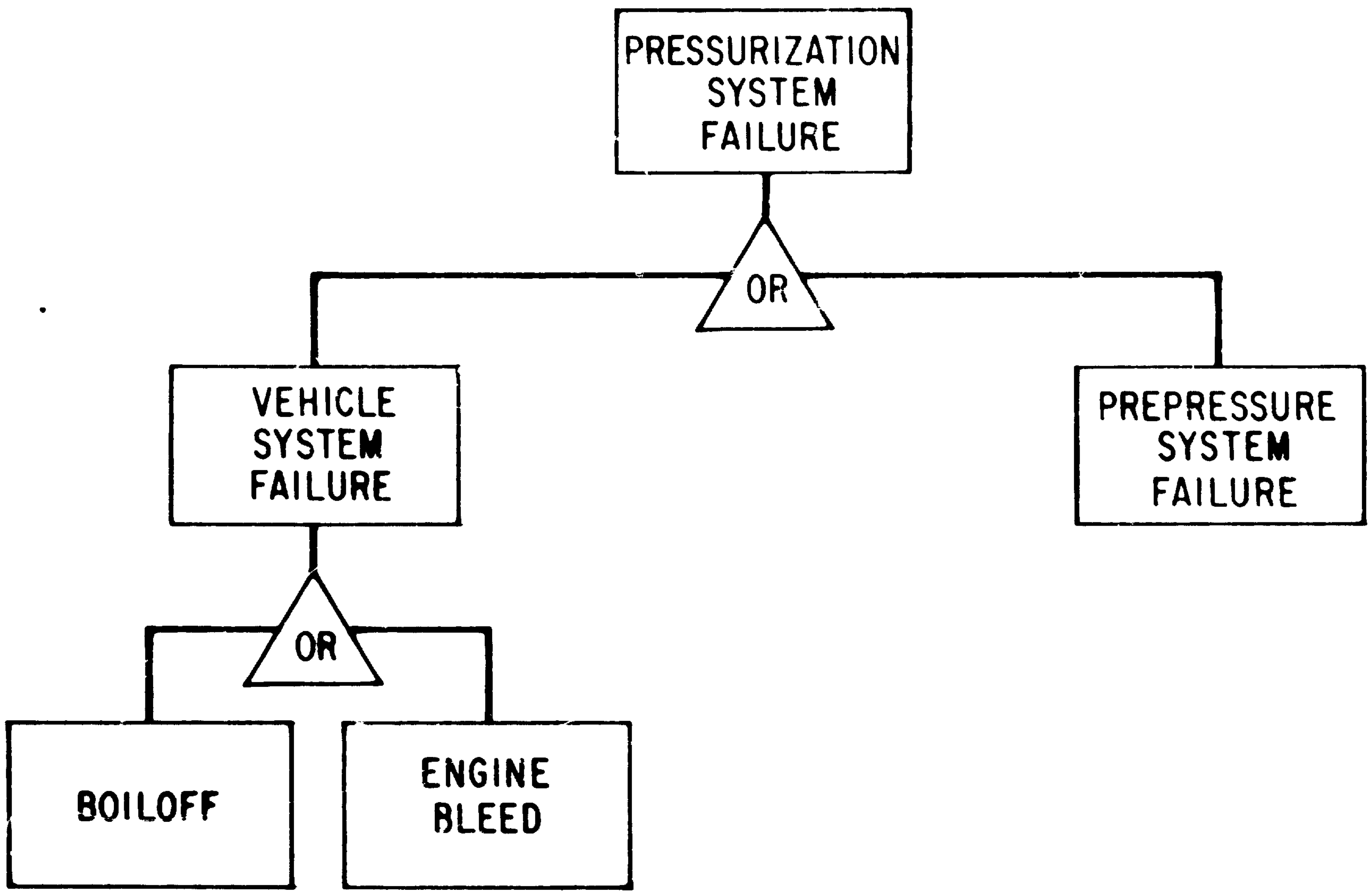

Fig. 23. Fault Tree - Pressurization System Failure

A failure mode and effects analysis based on these events was conducted; the results are presented in Table 4. Failure rates of components comprising similar systems in the Saturn V are also presented in this table. The data indicate that the failure rates of these components are so low that this type of failure is unlikely. The remarks column shows that if both of these systems should fail, the fill and drain system might be used to drain the tank(s) and thereby relieve the pressure buildup.

3.3.1.1.1.2 Fill and Drain System Failure

A failure of the fill and drain system would not of itself result in a gaseous overpressurization of the propellant tanks. However, since this system was considered as a backup in case of a dual failure of the vehicle vent and pressure relief systems, an analysis of failures that could negate this function is appropriate. It should be noted that the system can provide this backup capability for a limited time only, i.e., until it is disconnected before launch.

The components of the fill and drain system pertinent to this analysis are shown in Fig. 21; they are the fill and drain valve and the fill isolation valve. A failure analysis for these components is also presented in Table 4. This analysis suggests that the failure rates for these components is low (based on data for similar valves in the S-V) and that system failure at these points would be unlikely.

3.3.1.1.1.3 Pressurization System Failure

Two systems that provide for pressurization of the main propellant tanks (see Fig. 23) were evaluated as potential sources of tank rupture due to overpressurization. The systems were the ground pressurization system, which prepressurizes the tanks prior to engine start, and the engine-bleed system, which maintains pressure after engine ignition.

Components of these systems were subjected to a failure analysis (see Table 4), which indicates that a malfunction of these systems would not result in overpressurization of the tanks. In addition, contractor data indicate that the

Failure (and Cause)	Operating System	Subsystem	Major Component (and Failure Mode)	Comp Failu
Propellant Tank Rupture (Gaseous Overpressure)	Vehicle Vent System		Vent Valve (Fail to Open or Remain Open)	1.47 pp
			Vent Isolation Valve (Fail to Open or Remain Open)	3.20 pp
	Pressure Relief System		Burst Disc (Fail to Rupture)	
			Relief Valve (Fail to Open or Remain Open)	1.47 pp
	GSE Pressurization System		Regulator (Regulates High)	672 ppr
			(Regulates Low)	250 pp
			Shutoff Valve (Fails to Close)	16 ppm
			Pressure Switch (Fails to Actuate and Close Shutoff Valve)	14 ppm
	Vehicle Fill and Drain System		Disconnect (Premature Disconnect)	
			Fill and Drain Valve (Fail to Open)	1.47 pr
			Fill Isolation Valve (Fail to Open)	3.20 pp
	Vehicle Pressurization System		Engine Bleed Check Valve (Fails to Open) (Fails to Close)	1 ppm/ 17 ppm
	Propellant Tanks		Propellant Tank Insulation (Insulation Damaged-Excessive Boiloff)	

[1]Based on Saturn data, ambient conditions, 90% confidence (see Ref. 7)

[2]Prior to disconnect for launch (see Ref. 7)

	Component Failure Rate[1]	Effect of Failure	Remarks
	1.47 ppm/cy 3.20 ppm/cy	Increases Internal Pressure in Propellant Tanks. If Not Relieved Will Result in Rupture of Propellant Tank. Propellant(s) Released: Potential Fire or Explosion	Backed Up by: Burst Disc/Relief Valve Fill and Drain System[2]
	1.47 ppm/cy		Backed Up by: Vent System Fill and Drain System[2]
	672 ppm/hr 250 ppm/hr 16 ppm/cy 14 ppm/hr		Backed Up by: Isolation Valve Vehicle Vent and Pressure Relief Systems Vehicle Fill and Drain System[2] Will Not Overpressurize Tank Backed Up by: Vehicle Vent and Pressure Relief Systems Vehicle Fill and Drain System[2]
	1.47 ppm/cy 3.20 ppm/cy		Utilized to Reduce Tank Pressure if Both Vent and Relief Systems Fail during Prelaunch Operations
	1 ppm/cy 17 ppm/cy		Will Not Cause Tank Overpressure
			Backed Up by: Vehicle Vent and Pressure Relief Systems Vehicle Fill and Drain System[2]

Table 4. Failure Analysis - Propellant Tank Rupture

FOLDOUT FRAME 2

(2)

ponent re Rate[1]	Effect of Failure	Remarks
	Increases Internal Pressure in Propellant Tank(s). If Not Relieved Will Result in Rupture of Tank(s).	Backed Up by: System Redundancy, Continual Monitor, and Manual Override Provisions
	Propellant(s) Released: Potential Fire or Explosion	
m/hr n/cy n/hr	Internal Tank Pressure Negative with Respect to Ambient Tank. Walls May Collapse. Propellant(s) Released: Potential Fire or Explosion.	Design Criteria Requires Tanks Capable of Withstanding Collapsing Pressure Pressure Equalization System an Acceptable Alternate
/cy		
	Orbiter Dropped, Tanks Ruptured, and Propellants Spilled. Potential Fire or Explosion, Loss of EOS Vehicle Orbiter Dropped, Tanks Ruptured, and Propellants Spilled Potential Fire or Explosion, Loss of EOS Vehicle	Separation Mechanism Must Service 3-g Launch Loads 1.5 Safety Factor Recommended Accessible for Rigorous Inspection Prior to Each Flight Not a Likely Failure Mode Under 1-g Static Conditions Inadvertent Actuation Preventable by Providing Safe/Arm Switch and Interlock Mechanism to Prevent Arming Prior to Liftoff Shielding of Ordnance Combined with Extensive EMI Control Program Will Minimize Probability of Actuation by Spurious Signal
	Possible Propellant Release Lightning also Provides Ignition Source	Occurrence Can Be Minimized by: Not Fueling Vehicle When High Storm Probability Is Forecasted; Proper Grounding of Vehicle Low Yield Expected: Short Mixing Time

Table 4. Failure Analysis - Propellant Tank Rupture (Continued)

FOLDOUT FRAME 2

vent/pressure relief systems are capable of maintaining tank pressure within specifications when either of the pressurization systems is operating at full capacity.

Consideration of overpressure due to excessive boiloff as a result of insulation damage completes the analysis of possible tank rupture modes due to gaseous overpressure. Here again, the capacity of the vent/pressure relief systems would be more than adequate to handle the increased pressure. Also, the possibility is extremely remote that the insulation damage necessary to produce such a high rate of boiloff would escape detection prior to propellant loading.

3.3.1.1.2 Hydraulic Overpressure

The possibility of bursting the tanks because of hydraulic (as well as gaseous) overpressure was considered (see Fig. 24). This failure would result in the overfilling of the propellant tank(s) and the subsequent buildup of hydraulic pressure, culminating in tank rupture.

An analysis of this failure is also presented in Table 4. In this case, the adverse pressure would result from a failure in the flow control segments of the propellant loading system. Before this event could occur, however, a failure in both the automatic and the manual override segments of the system would be required. System redundancy and manual override provisions would be expected to preclude the occurrence of this type of failure. Further, no data were found to indicate that a failure of this nature had occurred in prior propellant loading systems. Based on these considerations, hydraulic overpressure is discounted as a failure leading to the gross release of propellant.

3.3.1.2 Tank Collapse

A collapsing failure of the tanks occurs when an adverse pressure differential, in excess of structural capabilities, exists across the tank wall due to an internal tank pressure lower than the external pressure. Two events are considered that are capable of initiating a tank collapse; these events are rapid draining of the tank during detank operations and failure of the engine

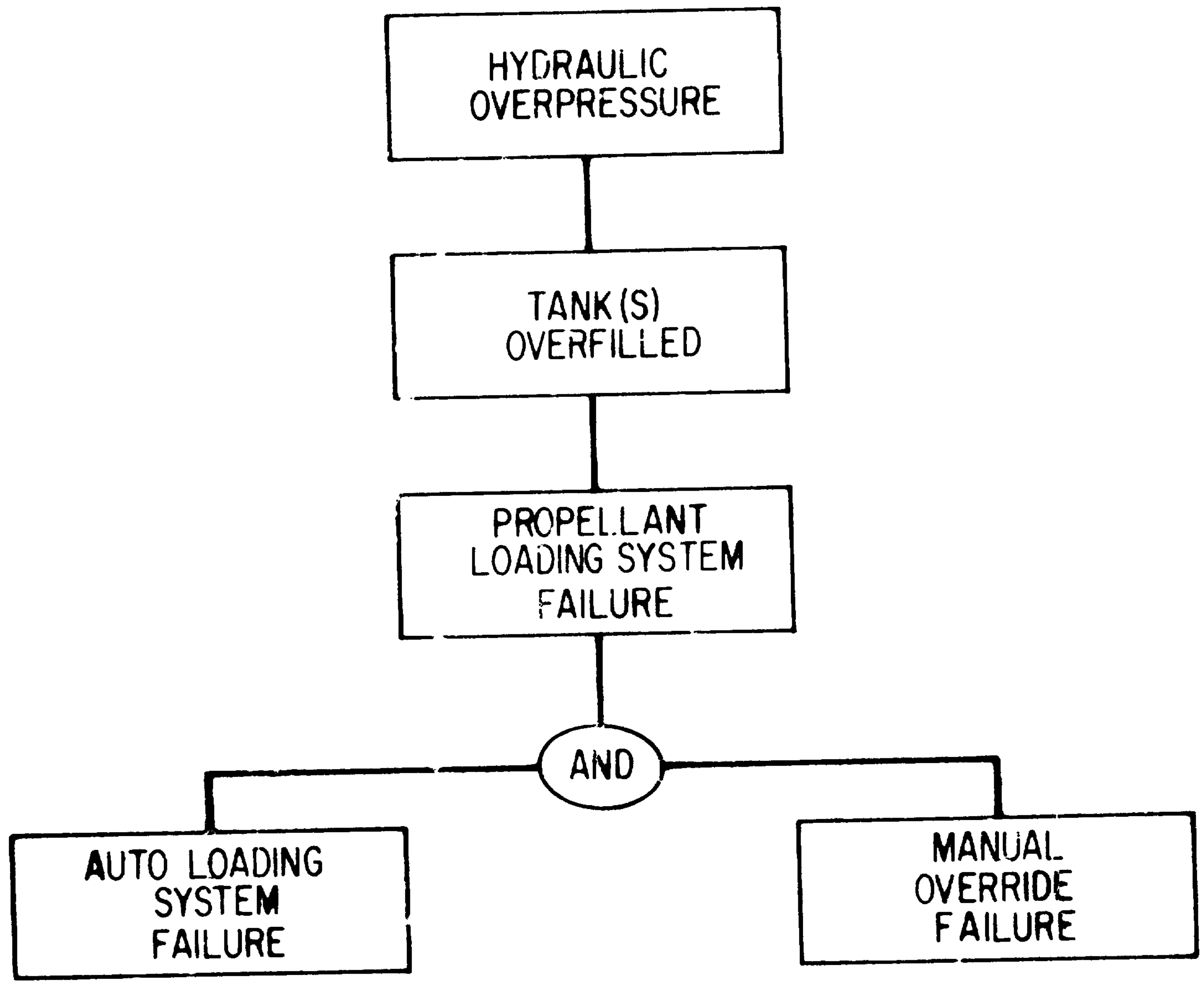

Fig. 24. Fault Tree - Hydraulic Overpressure

bleed check valves in the lines that provide engine bleed and maintain tank pressures when the engines are running (see Fig. 25). A failure analysis of the two events is presented in Table 4. A third event, too-rapid chilldown of the tank prior to loading, was also considered but was omitted from the analysis since only small quantities of propellant would be on-board at that time.

Present design requirements are that the tanks be designed to be capable of sustaining the collapsing pressures resulting from these events. A pressure equalization system may be used in lieu of this structural requirement to maintain internal pressure within the structural capabilities of the tank. At the time of this study, most contractors indicated a preference for the pressure equilization system. The low failure rate for critical components in this type of system (see Table 4) indicates that tank collapse due to a failure of this system is remote. Although a pressure equalization system will probably be used, it is still possible that the tank will maintain its structural integrity despite a collapsing pressure differential as a result of meeting other structural requirements.

All booster engines supply bleed pressure to maintain the required pressure within the propellant tanks. Contractor reports indicate that tank pressure can be maintained within design requirements with as many as four inoperative engines. Since a single engine-out is cause for launch abort, the probability of tank collapse due to lack of adequate engine bleed pressure is remote.

Based on this analysis, the probability of tank collapse as a mechanism for the gross release of propellant is considered minimal.

3.3.1.3 Orbiter Vehicle Dropped

Structural failure and premature separation were evaluated as events that would result if the orbiter vehicle were to drop from the booster. Structural failure was considered to occur in the separation mechanism. Premature

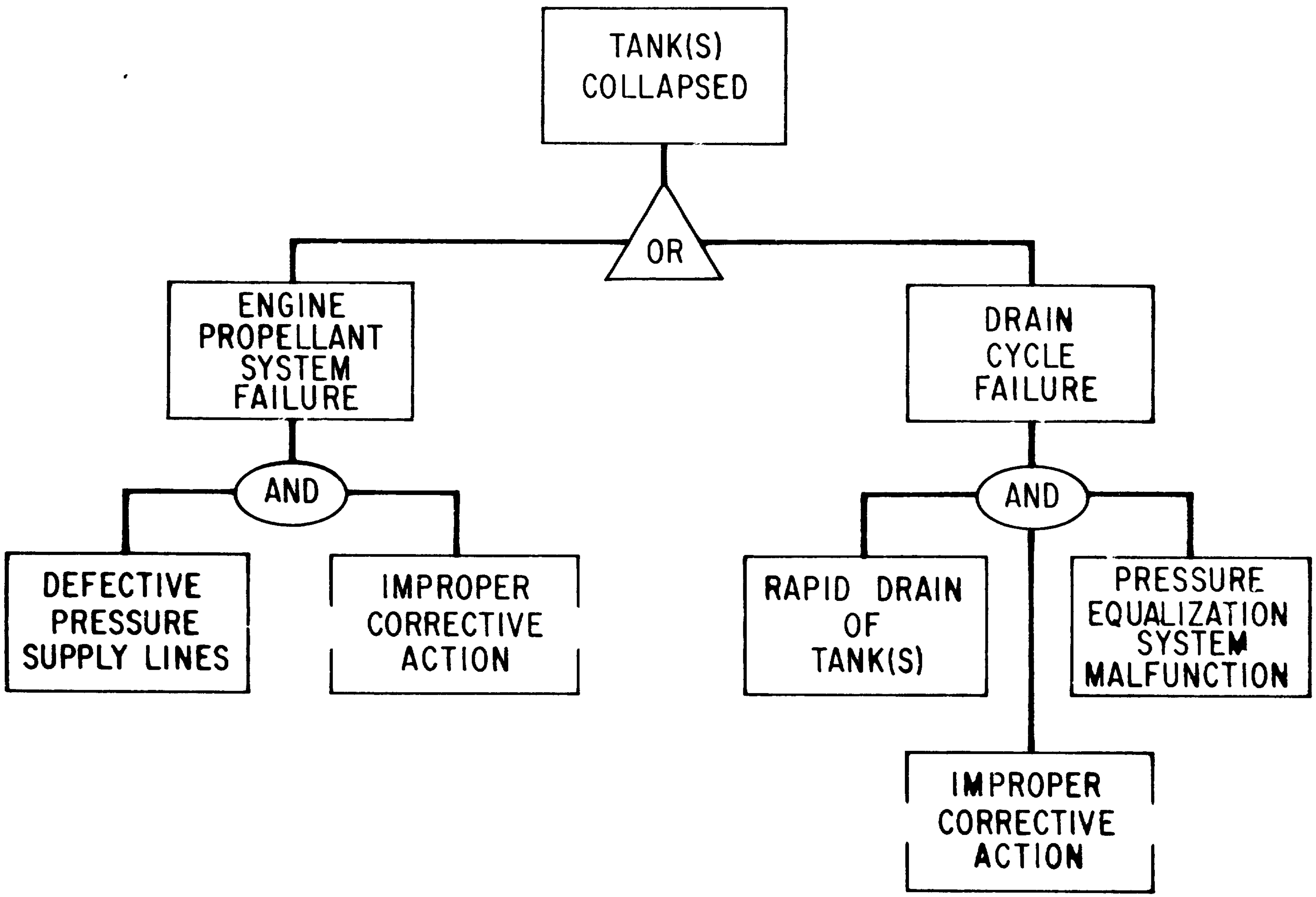

Fig. 25. Fault Tree - Tank Collapse

separation was assumed to occur as the result of inadvertent ignition of the ordnance associated with the separation system. The sequence of failures leading to the dropping of the orbiter from the booster is shown in the partial fault tree (see Fig. 26).

As indicated in the failure analysis (see Table 4), the support structure comprising the separation mechanism is designed to sustain 3-g launch loads with a recommended safety factor of 1.5. In addition, the mechanism is situated so as to be readily accessible for rigorous postflight and/or preflight inspections. Therefore, a structural failure of the support mechanism is not expected to occur when the structure is subjected to the 1-g, static, on-pad environment.

Premature separation can occur if the actuation ordnance is ignited via an inadvertent, normal actuation signal or a spurious signal. The former can be prevented by providing a firing-switch guard and system interlocks to prevent arming the system prior to liftoff. Spurious signals have, on very few occasions, ignited rocket vehicle ordnance in the past. However, proper shielding of ordnance combined with an extensive EMI control program has been successful in preventing ordnance actuation via spurious signals in current programs (e.g., the lightning strike on the Apollo 12 flight). The analysis indicates that premature on-pad separation of the shuttle vehicles due to accidental firing of the system ordnance will be preventable.

Therefore, it is considered improbable that structural failure or inadvertent actuation of the separation mechanism would cause the orbiter vehicle to fall from the booster during static, on-pad operations, thereby causing the propellant tanks to rupture and release gross quantities of propellant.

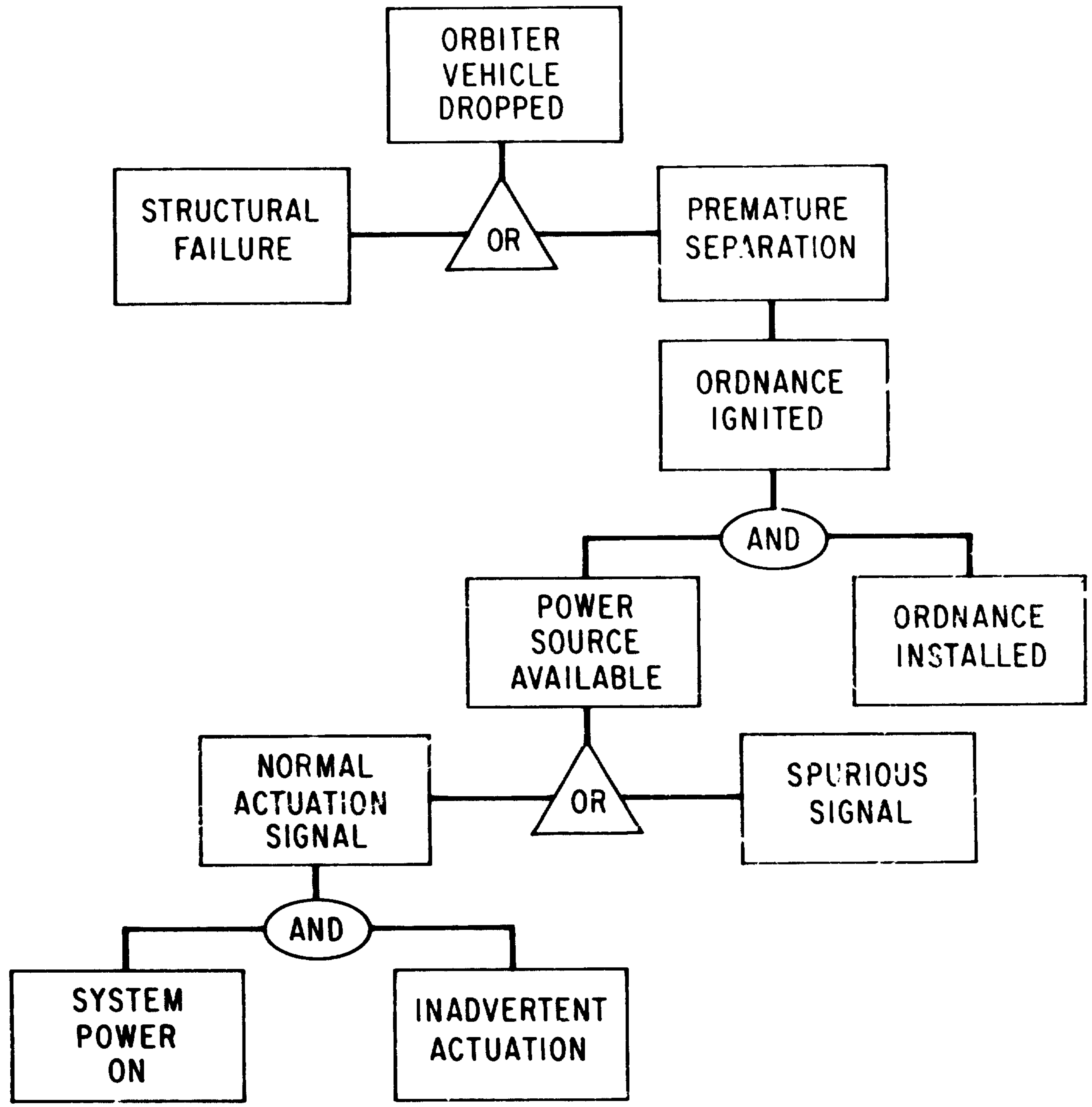

Fig. 26. Fault Tree - Orbiter Vehicle Dropped

3.3.1.4 Vehicle Tipover

Four events that were considered potentially capable of causing tipover of an assembled and loaded vehicle are indicated in Fig. 27. Of these, only tipover due to wind effects was evaluated.

Tipover due to vehicle or launcher structural failure was not evaluated since the structures involved were not defined at the time of this study. However, this type of failure appears improbable based on experience with current vehicles and launch systems. Simularly, lack of data precluded analysis of earthquake effects.

3.3.1.4.1 Wind Effects

Recommended structural design wind parameters for the space shuttle are shown in Fig. 28. It is suggested (see Ref. 6) that the vehicle on the launcher be capable of sustaining the wind loads developed by a 72.1-knot wind measured at an altitude of 60 ft during the windiest two-week exposure. The recommended wind data were extrapolated, and a design wind velocity of 69 knots at a 30-ft altitude was obtained. A comparison of this data with wind data recorded for the Eastern (ETR) and Western (WTR) Test Ranges (see Table 5) indicates that the winds to be expected during periods when the vehicle is on the launch pad will be well below the design requirments, not only for the 99-percentile winds but for maximum winds as well. Further, a wind-brace arm extending from the launch umbilical tower may assist the vehicle to resist wind loads. With respect to hurricane winds, sufficient advance warning is provided, and the range is closed to launch operations; therefore, a loaded vehicle would not be on the pad during a hurricane.

3.3.1.5 Lightning Strike

The last event evaluated as a potential source of a gross release of propellant was failure due to a lightning strike (see Table 4).

A proper grounding and lightning-arrestor system for the vehicle and launcher will preclude damage to the vehicle during on-pad operations (e.g., the multiple

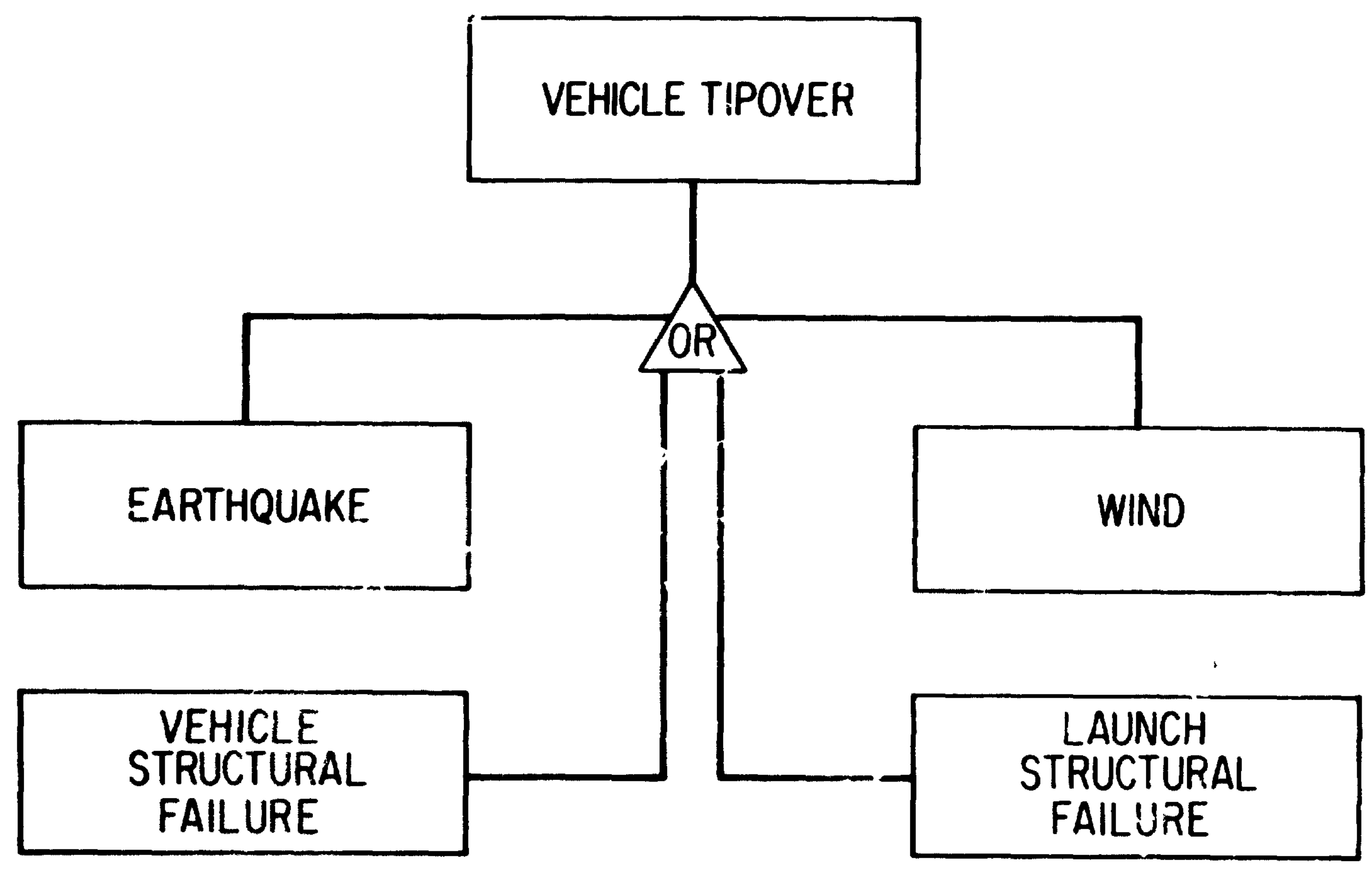

Fig. 27. Fault Tree - Vehicle Tipover

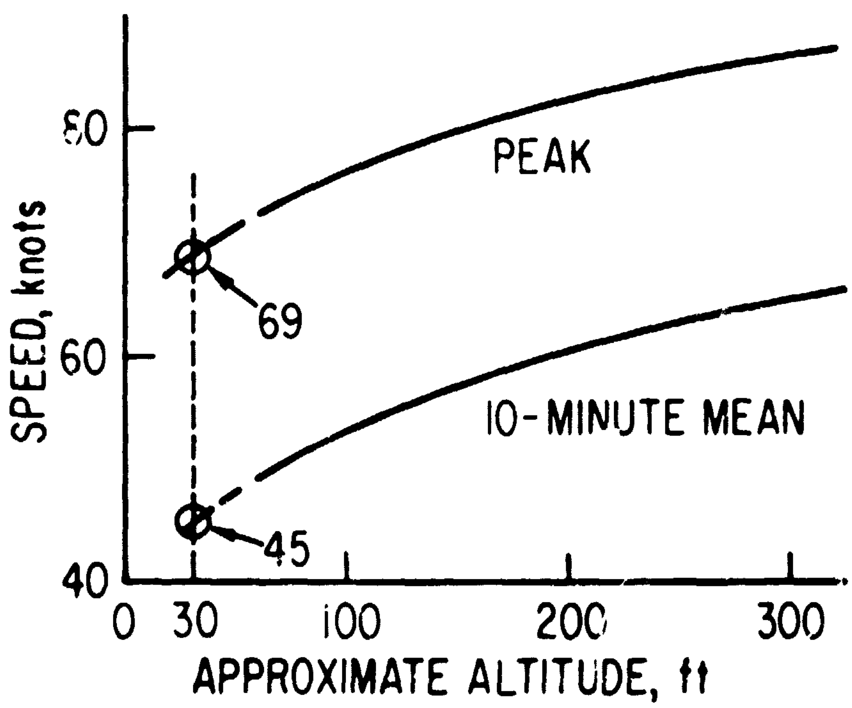

Fig. 28. Vehicle Tipover Due to Wind

Table 5. Surface Winds Summary[1]

Location	Most Frequent Direction	99-Percentile Winds		Maximum Winds[2]	
		Speed, knots	Direction	Speed, knots	Worst Month
ETR	E	17 - 21	All	28 - 40	October
WTR	NW	22 - 27	SE, NW, NNW	28 - 33	April

[1] From ETAC data, measured at 30-ft altitude

[2] Frequency of occurrence > 0.05%

strikes reported while the Apollo 15 vehicle was on the launch pad). Further, it is expected that propellant would not be loaded during periods of high electrical storm probability. The short time (two hours) required to load and launch the vehicle tends to ensure this position.

Finally, in the unlikely event that lightning should strike and rupture the propellant tanks, the energy released would produce a nearly instantaneous ignition of the propellant); this would tend to produce a low explosive yield because the mixing time required to produce a yield approaching 60% TNT equivalency would not be available.

3.3.2 Vehicle Propellant System Failure

The preceding paragraphs discussed vehicle failure modes that could produce a gross release of propellant. In the following paragraphs, the consequences of propellant leakage, particularly of LH_2, and the effect of GN_2 as a suppressant will be discussed. The discussion will be summarized in the failure analysis (see Table 6).

Potential sources of propellant leakage, either gaseous or liquid, are presented in Fig. 29. Gaseous propellant leakage warrants special consideration since gaseous component leakage was reported to be a significant source of Saturn hardware discrepancies. However, any leakage would present a potential hazard if the leakages were allowed to accumulate within the vehicle or were not properly vented. In addition, although leakage appears as a major contributor of component discrepancies, normal inspecification leakage of a large number of components may be a potential source of an explosive atmosphere. Ignition of such an atmosphere may produce a relatively low-order explosion; however, the result could be the rupture of a propellant tank and the release of large quantities of propellant, producing a higher-order secondary explosion. The net explosive effect will be further discussed in Sec. 3.3.5.

3.3.2.1 Gaseous Leaks

Component leakage appears to be a major source of discrepancy in the acceptability of components (see Ref. 8). Design criteria applicable to

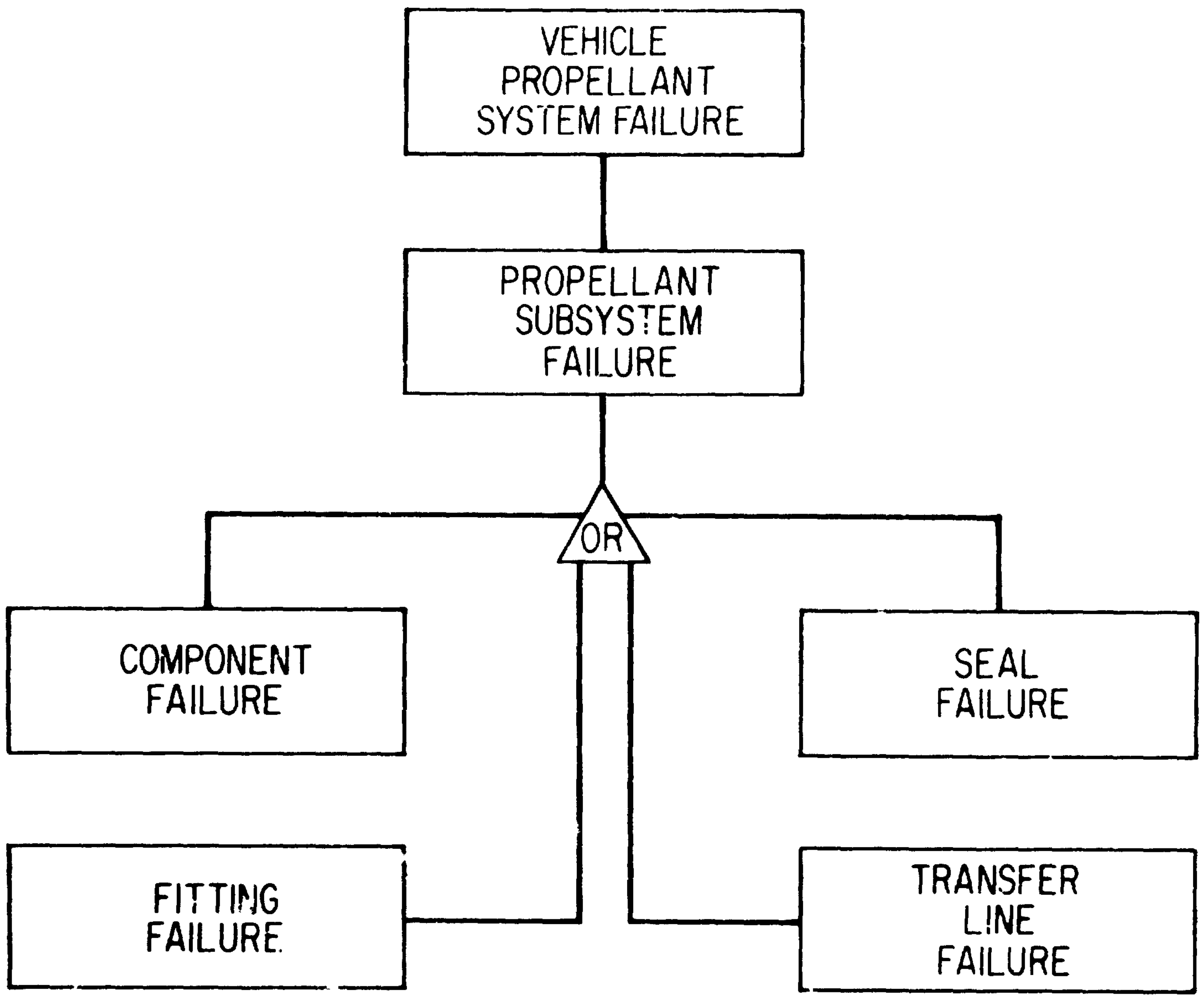

Fig. 29. Fault Tree - Vehicle Propellant System Failure

Table 6. Failure Analysis - Vehicle Propellant System Leakage

Failure (and Cause)	Operating System	Major Component (and Failure Mode)	Component Failure Rate [1]	Effect of Failure	Remarks
Vehicle Propellant System Leakage **(Failure of Subsystem Components)**	Propellant Supply and Pressurization Subsystems	Valves		The Following Effects May Result from Leakage Rates within or in Excess of Design Specifications:	N_2 Purge Will Dilute Combustible/ Explosive Mixture and Tend to Minimize Effect
		(Check)	1.41 ppm/cy	Fuel or Fuel-Rich Hot Gas Released Forming Combustible/Explosive Mixture with Air	Sensors Combined with Sampling of Purge Gas Would Detect Leaks and Allow for Corrective Action Before Condition Becomes Critical
		(Shutoff)	5.68 ppm/cy		
		(Vent and Relief)	0.40 ppm/cy		
		(Solenoid)	0.98 ppm/cy		
		Pressure Switches	1.89 ppm/cy	Hot Gas May also Be Energy Source for Ignition	
		Pressure Transducer	295.46 ppm/hr		
		Pressure Regulator	780.0 ppm/hr	Liquid Fuel Released	Proper Design and Location of Joints Can Minimize Occurrence
		Fittings		Impinges on Other Fluid Lines and Freezes Contents	
		Seals			
		Lines (External Propellant Leakage)		Freezes Air and Forms Explosive, Shock-Sensitive Liquid	N_2 Purge Will Minimize Occurrence
				Liquid Fuel and Oxidizer Released	N_2 Purge Will Dilute Combustible/ Explosive Mixture and Tend to Minimize Effect
				Combine to Form Explosive Mixture	Sensors Combined with Sampling of Purge Gas Would Detect Leaks and Allow for Corrective Action Before Condition Becomes Critical
				LO_2 or GO_2 Released	Hazardous if It Impinges on Hot Surface (e.g., Gas Generator Wall or Turbine Exhaust Duct of APU or ACPS System)
				Combines with Vehicle Components or Contaminants to Form Combustible Mixture	N_2 Purge Will Dilute Mixture and Tend to Minimize Effect
					Sensors Combined with Sampling of Purge Gas Would Detect Leaks and Allow for Corrective Action Before Condition Becomes Critical
					Proper Design and Location of Joints Can Minimize Occurrence
				Liquid or Gaseous N_2/He Released	No Explosive Potential, However, It May Precipitate Malfunctions That Are Hazardous to Vehicle

[1] Based on Saturn Data, ambient conditions, 90% confidence (see Ref. 7)

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the space shuttle (see Ref. 6) specify that the probable failure mode in service shall be leakage rather than catastrophic failure when assurance of safe-life cannot be provided by proof test. Requirements being defined for space shuttle components tend to place tighter restrictions on leakage rates (see Ref. 9). This in itself may result in significant impact on the component development. Furthermore, multiple reuse of these components and requiring them to meet these stringent levels may pose development problems. If this should prove to be the case, use of an inert gas purge would be one method of alleviating the problem. The approach taken in this study was that maximum allowable leakage of H_2 components would be similar to that of Saturn S-II components as stated in Ref. 9. The S-II (see Refs. 10-12) thus provided a baseline in terms of maximum total allowable leakage for components and engines and a basis (see Ref. 13) for calculating GN_2 purge requirements to maintain an inert atmosphere in the purged compartments.

Total leakage rates from booster and orbiter components were estimated as described above; they are shown in Table 7. Estimates of space shuttle compartment volumes were obtained from Ref. 14. They were considered to be isolated volumes adjacent to the propellant tank ends and vehicle base and are shown as shaded areas in the vehicle sketches under Table 8. An estimate of the H_2 leak distribution throughout the vehicle was made (see Table 7). Based on these considerations and the S-II experience (see Refs. 10 and 13), GN_2 purge rates of 2150 lb/min and 600 lb/min were estimated for the booster and orbiter vehicles, respectively. Such specifics as location of purge gas inlets and vents and the elimination of combustible pockets by selective purging of portions of the vehicle must be established as the vehicle configuration and the location of components are further defined.

The concentration of GN_2 that will suppress combustion in GH_2 atmospheres is approximately 50% by volume (see Ref. 15). Assuming a 65% N_2 concentration, an estimate of the time required for leakage to raise the H_2 concentration

Table 7. Leak/Purge Rate Comparison - EOS to S-II

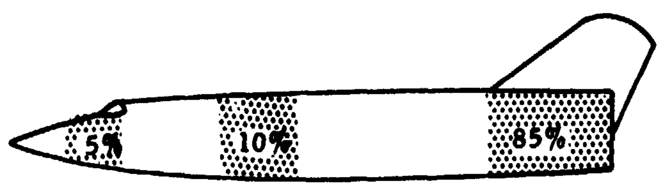
	S-II	Booster	Orbiter
Leak Rate, scim	12.0×10^3	43.5×10^3	26.4×10^3
Volume Requiring Purge, ft^3	12.0×10^3	21.1×10^3	12.0×10^3
GN_2 Purge Rate,* lb/min	500	2,150	600
Time to Reach 35% GH_2 by Vol, hr	10.1	3.9	2.8

*Assumes vehicle tank area purged to min 95% GN_2 atmosphere prior to fueling

Table 8. GN_2 Dilution Required to Suppress GH_2 Explosive Potential

Reported Limits			Suggested Limits		
Constituent	% Volume	% Weight	Constituent	% Volume	% Weight
GN_2	50	93.3	GN_2	65	97.3
GH_2	50	6.7	GH_2	35	3.7

BOOSTER



ORBITER

to 35% by volume within the vehicle compartments is approximately three to four hr; these volumes are based on the S-II purge rates (see Table 7). This assumes that there is an initial concentration of 100% GN_2 in the vehicle spaces surrounding the tank and engine compartment prior to a leak, uniform dispersion of leakage H_2, and constant leakage of all components at the maximum rates allowable by the component specifications. Although this may appear to present a tolerable condition in terms of the time to reach undesirable H_2 concentrations, the assumptions of uniform leakage and dispersion of H_2 throughout the vehicle are not sufficiently conservative. Therefore, the use of a GN_2 purge should be considered a means of preventing a rapid, localized buildup in the H_2 concentration.

Means for venting the propellant tanks safely must be provided. The vent lines must lead to a position on the vehicle that will allow the dispersal of H_2 away from oxygen and away from ground sources of ignition.

Some other considerations (see Refs. 16 and 17) affecting the flammability of GH_2 and its suppression are the following:

- Hydrogen is flammable in air at atmospheric pressure and room temperature over the range of 4 to 75% by volume. As the temperature drops, the flammable range narrows.
- Hydrogen is flammable in an oxygen atmosphere at atmospheric pressure and room temperature over the range of 4 to 94% by volume.
- Unconfined GH_2-air mixtures are not likely to be detonated by nonexplosive energy initiators such as sparks or flames. Partially confined mixtures may detonate. Enrichment of unconfined H_2-air mixtures by the addition of O_2 will not cause detonation if the air content exceeds 60% by volume and if a nonexplosive ignition source is present.
- Detonations are likely with near-stoichiometric H_2-O_2 mixtures, high-energy ignition sources, confinement, and long flame paths.

Gaseous oxygen leaks should present relatively little hazard unless the leakage rate is high, or GH_2 is simultaneously leaking into the same space, and a source of ignition exists. However, N_2 purge rates should be adequate to suppress initiation of combustion if the components leak at their maximum allowable rate. Osygen, of course, supports combustion and would intensify any combustion in process at the time of a leak.

Even with the leakage technology associated with current H_2 components, the suppressant gas requirements do not appear excessive. The dry N_2 purge that will be used to prevent condensation on vehicle tanks may also be included as a portion of the gaseous leak hazard suppressant. The total requirement is based on the distribution of the H_2 leakage sources and their rates, together with the volume of the purged spaces adjacent to the propellant tanks.

3.3.2.2 Liquid Leaks

Accumulation of LH_2 or O_2 from a small-scale leak is not likely to occur. Both have such low boiling points that any small flow of liquid would vaporize during its escape from the system.

Sudden release of a sufficiently large quantity (as in the case of a tank puncture) can create a large accumulation of liquid. If the liquid remained within the vehicle after an LH_2 tank puncture, the H_2 vapor concentration in the vehicle would increase rapidly, possibly beyond the upper flammability limit. With an otherwise inert atmosphere (air having been excluded by the N_2 purge), the flammability hazards associated with the leak would be reduced.

On the other hand, if the H_2 remained liquid as it passed through the vehicle, flowed as liquid onto the launch pad, and accumulated there, it would potentially be both a flammability and an explosive hazard. The resulting liquid pool would tend to evaporate, forming highly flammable concentrations in the pad area around the vehicle. Blast pressures, if any, produced by the burning of vapors above a pool of LH_2 are small (see Ref. 16). Winds would not increase the burning rate; however they would assist in dispersal of the H_2 vapors over a large area.

A certain amount of air would condense in the event of a large spill and would form a shock-sensitive LH_2/solid O_2 mixture. The shock stimulus required for the explosion of such cryogenic mixtures is quite low; therefore, it represents an explosive source that could subsequently involve the larger volume of propellant. Unless such an explosion initiated the spillage, however, experience appears to indicate that the fire hazard from a large spill exceeds the explosion hazard.

Water vapor significantly affects the thermal energy radiated from an H_2 flame (see Ref. 16); thus the use of a water deluge in the event of a large spill would moderate any H_2 burning.

Dilution of liquid cryogenic explosive mixtures with H_2 does not reduce the impulse or the explosive yield when the ignition source is a detonation (see Ref. 17).

The hazards resulting from LO_2 spills are well known. Liquid oxygen, when mixed with organic substances, is explosive. The gas evaporating from a liquid pool would support combustion of anything flammable, including substances normally considered reasonably fire resistant. Since it is slightly denser than air, the GO_2 would tend to lie over a surface and to flow downwards, particularly in the absence of winds that might tend to disperse it. Any flammable substance, combined with either LO_2 or GO_2 and a source of ifnition, would cause a fire (or perhaps an explosion) that could then involve the vehicle propellant tanks. If a detonation were the energy source initiating an explosion, the availability of H_2, the time involved, and the quantity mixed with oxidizer would determine the magnitude of the explosive yield of the propellant in the vehicles.

3.3.3 Ignition Sources

In order for a combustible mixture to burn or explode, an energy source must initiate the process. If a low-level energy source that might normally initiate

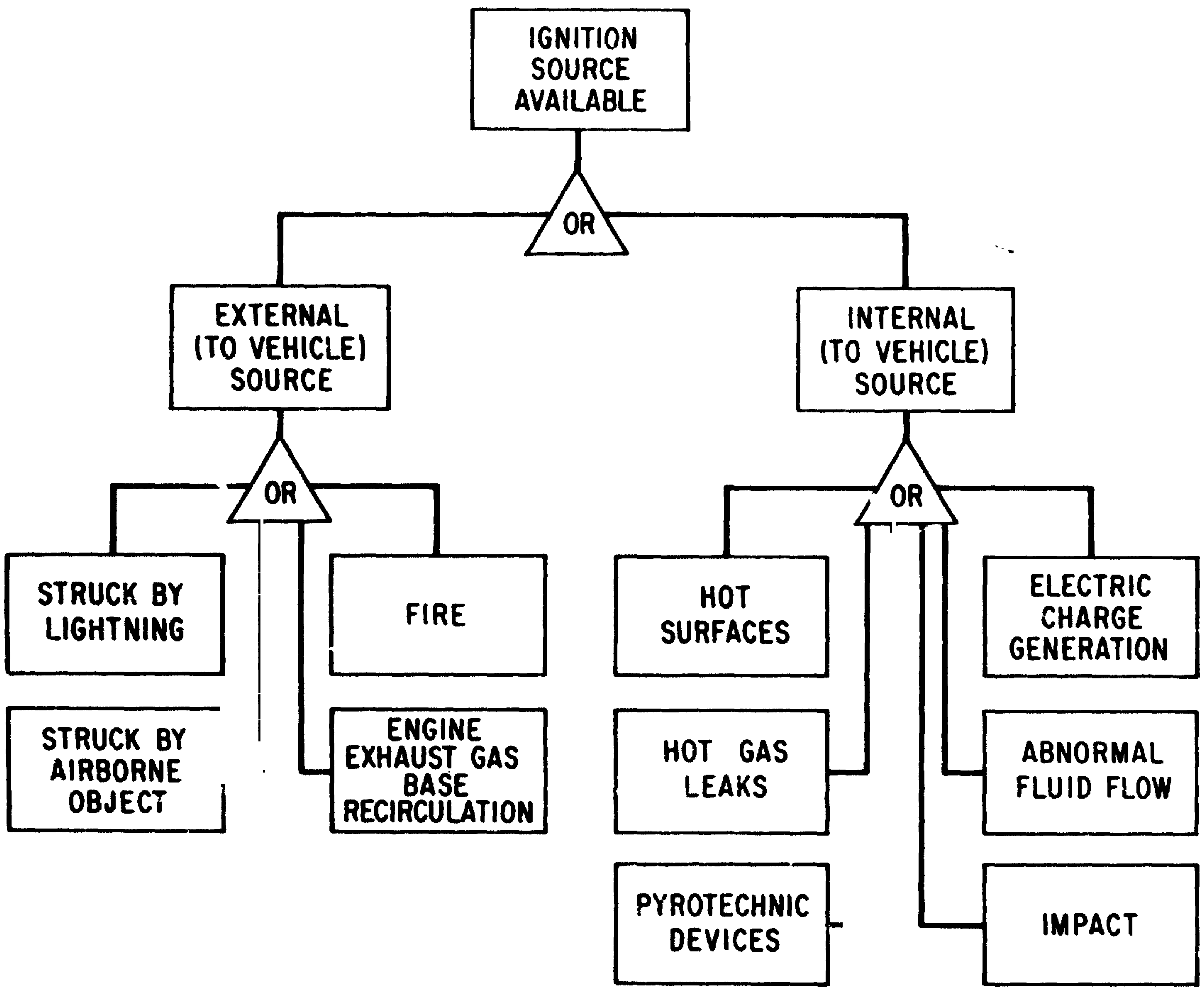


Fig. 30. Fault Tree - Ignition Source

a fire occurred in a confined space, an explosion could result. An uncontrolled ignition source without a suitable combustible mixture would not necessarily pose an immediate problem although it could subsequently initiate a propellant hazard. The more obvious ignition sources such as lightning, a fire originating outside the vehicle, and frictional energy due to accidental impact are presented in Fig. [illegible]. The somewhat less obvious but ever-present ignition sources such as hot surfaces of APUs, heat exchangers, and ACPS sources; and recirculation of hot gases during the ignition transient of the main engines are also considered. In addition, the generation and discharge of electrostatic charges may be sufficient to ignite a combustible mixture.

Abnormal fluid-flow conditions such as waterhammer in liquid systems and compressive heating in gaseous systems are of concern in the oxidizer lines, where this form of concentrated energy release might be sufficient to initiate a reaction between the O_2 and its container.

Constant attention should be given during design and development of the components, systems, and vehicle to devising means of eliminating or minimizing the occurrence of such sources. Some considerations are provided in Tables 9 and 10. Care should be exercised to isolate source of energy such as APUs or heat exchangers, to provide inert gas purges to dilute gaseous combustible mixtures, and (in some cases) to act as explosion suppressants. Locating such hardware outside potential pockets of combustible accumulation is desirable. Warning sensors that will initiate appropriate and timely action should be located in the areas of both known and potentially uncontrolled energy sources. Screens or barriers should be used to isolate components that may be particularly hazardous. Design of all electrical circuits and connections should be in accordance with applicable provisions for their use in hazardous atmospheres.

Table 9. Failure Analysis-Internal Ignition Sources

Failure (and Cause)	Operating System	Major Component (and Failure Mode)	Effect of Failure	Remarks
Ignition Source - Internal to Vehicle	Turbine(s) Heat Exchanger(s) Gas Generators	Hot Gas Seals/ Connectors (Leakage)	The Following Effects May Result from Leakage within or in Excess of Design Specifications Ignition of Combustible/ Explosive Mixtures that May Exist Release of Hot Fuel or Oxidizer-Rich Gases: Potential Source of Fire or Explosion	N_2 Purge Will Dilute Combustible/ Explosive Mixtures and Tend to Minimize Effects of Hot Gas Leaks
(Hot Gas Leaks)	Main Engines	Combustion Chamber Preburner/Main Burner Hot Gas Burnthrough or Combustion Instability as a Result of Mixture Ratio Disruption Due to: Hydrogen Valve(s) Close Prematurely during Engine Operation Intermittent Closure of Propellant Valves during Malfunction Shutdown of Engines Failure of O_2 Valve(s) to Close during Malfunction Shutdown Intermittent Opening of Propellant Valve during Engine(s) Start Transient Main Burner or Preburner (Coolant Passage Blocked)	Ignition of Combustible/ Explosive Mixtures That May Exist Impact Damage to Adjacent Engines May Release Raw Propellants and Initiate Explosive Hazard in Base Area	Hazard May Be Minimized by: Firewall and Heat Shield Isolating Engines from Vehicle Sensors to Detect Malfunction and Close Engine Pre-Valves (May Not Respond Rapidly Enough to Prevent Consequences of Malfunction) Can Be Prevented by: Maintaining Fuel within Allowable Particulate Content

Table 9. Failure Analysis-Internal Ignition Sources (Continued)

Failure (and Cause)	Operating System	Major Component (and Failure Mode)	Effect of Failure	Remarks
(Hot Surfaces)	Turbopump	Turbine/Pump Bearings (Overheated Bearings)	Ignition of Combustible/ Explosive Mixtures That May Contact Surface	Install Sensor and Control System to Detect Overheating and Command System Shutdown Before It Becomes Critical
	Gas Generators	High Combustion Chamber Wall Temperature (Generally Normal Operating Mode)		Isolate and/or Insulate Combustion Chamber
	APU or ACPS	Turbine Exhaust Duct		Isolate and/or Insulate Exhaust Duct
(Impact)	(Main Engines)	Turbines and Turbopumps (Wheel Disintegration or Loss of Blades)	Debris Ejected Potential Penetration of Propellant Tanks, Sufficient Energy Released to Ignite Propellants	Occurrence/Consequences of Failure Can Be Minimized by: Speed Sensors and Control System to Regulate Overspeed Designing Case to Contain Internal Structural Failures
(Abnormal Fluid Flow)	Liquid Propellant Transport	Fluid Lines and Valves (Waterhammer)	Generates Concentrated Energy Source, Potential Ignition Source in Presence of Combustible Mixture	Not a Likely Occurrence
	Gaseous Propellant Transport	Fluid Line and Valves (Adiabatic Compression Heating)	Generates Concentrated Energy Source, Potential Ignition Source in Presence of a Combustible Mixture	
	Propellant Drain	Propellant Tanks and Lines	Electrical Discharge with Sufficient Energy to Ignite Combustible Mixtures	Not a Likely Occurrence with Properly Grounded Vehicles
	Any System Containing Rotating Machinery in Operation at Low Temperature	Propellant Pumps, etc. (Ignition of Pyrotechnics)	Generation of EMF Resulting from Rotating Components Forming Potential Source of Spurious Signal That Could Result in Premature Ignition of Pyrotechnics and Result in Ignition of Combustible Mixture	Not a Likely Occurrence with Properly Grounded Vehicles

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Table 10. Failure Analysis-External Ignition Sources

Failure (and Cause)	Operating System	Major Component (and Failure Mode)	Effect of Failure	Remarks
Ignition Source - External to Vehicle (Lightning)	Loaded Vehicle on Pad	Vehicle (Fire/Explosion Due to Lightning Strike)	Potential Source of Propellant Release and Ignition	Can Be Minimized by: Not Erecting Vehicle When High Storm Probability Is Forecast Proper Grounding of Vehicle
(Fire in GSE)	GSE Electrical Hydraulic Loaded Vehicle on Pad	GSE (Fire)	Potential Ignition Source for Combustible Mixtures Due to Propellant Leakage	Effect Can Be Minimized by: Maintaining GSE as Remote to Vehicle as Possible Adequate Deluge or Other Fire-Suppressant Techniques
(Struck by Airborne Object)	Loaded Vehicle on Pad	Vehicle (Fire/Explosion Due to Propellant Tank(s)' Penetration by Airborne Object)	Potential Source of Propellant Release and Ignition	Not a Likely Occurrence: Object Would Have to Penetrate Heat Shields and External Structure to Strike Tank Vehicle Would Not Be Executed in High Wind Condition Minimal On-Pad Exposure Time Vehicle Partially Protected by Launcher Structure
(Engine Exhaust Gas Recirculation)	Propulsion Ground Launch System	Engines Flame Deflector (Engine Damage and/or Fire in Base Area)	Overheating, Damage to Engines, and/or Fire in Base Area Potential Release of Propellants with Available Ignition Sources Resulting in Fire or Explosion	Proper Design of Deflector Inlet Will Minimize Occurrence by: Preventing Inlet Choke Consideration of Staggered or Multiple Engine Starts or Shutdowns on Inlet Flow Conditions

3.3.4 Evaluation of Explosive Potential

3.3.4.1 Considerations Based on Existing Criterion

The present 60% TNT equivalency criterion for LO_2/LH_2 propellant is based on the total propellant weight on-board a vehicle (in this instance, 4×10^6 lb). Further, the criterion is predicated on the total release and mixing of propellant prior to ignition.

The distribution of the main propulsive propellant within a typical two-stage space shuttle vehicle is shown in Fig. 31. The key information in this figure is the fact that the propellant is contained in five separate tanks, two in the booster and three in the orbiter. It is obvious, therefore, that to obtain a total release of propellant as stipulated by the present criterion would require the simultaneous failure of five propellant tanks in two vehicles. The improbability of the occurrence of failures that could produce a gross release of propellant was discussed in Sec. 3.3.1. Further, many energy sources are available on the vehicle, including the energy resulting from the failure, that are capable of igniting large propellant spills before mixing sufficient to develop yields approaching the 60% TNT equivalency value can take place.

3.3.4.2 Multiple Tank Failures

In order to have an explosion involving all the propellant from two or more tanks (one or more of which must contain LH_2), the rupture of the individual tanks would have to occur essentially simultaneously to allow the degree of propellant mixing necessary to result in a high-order explosion rather than a fire.

There are thirty-one combinations in which the five main propellant tanks on the space shuttle could fail. The explosive yield of each failure was evaluated on the basis of the current 60% TNT equivalency criterion, which assumes the total release and mixing of all propellant in the tanks involved. The resulting yields were used to establish a yield ratio that relates the

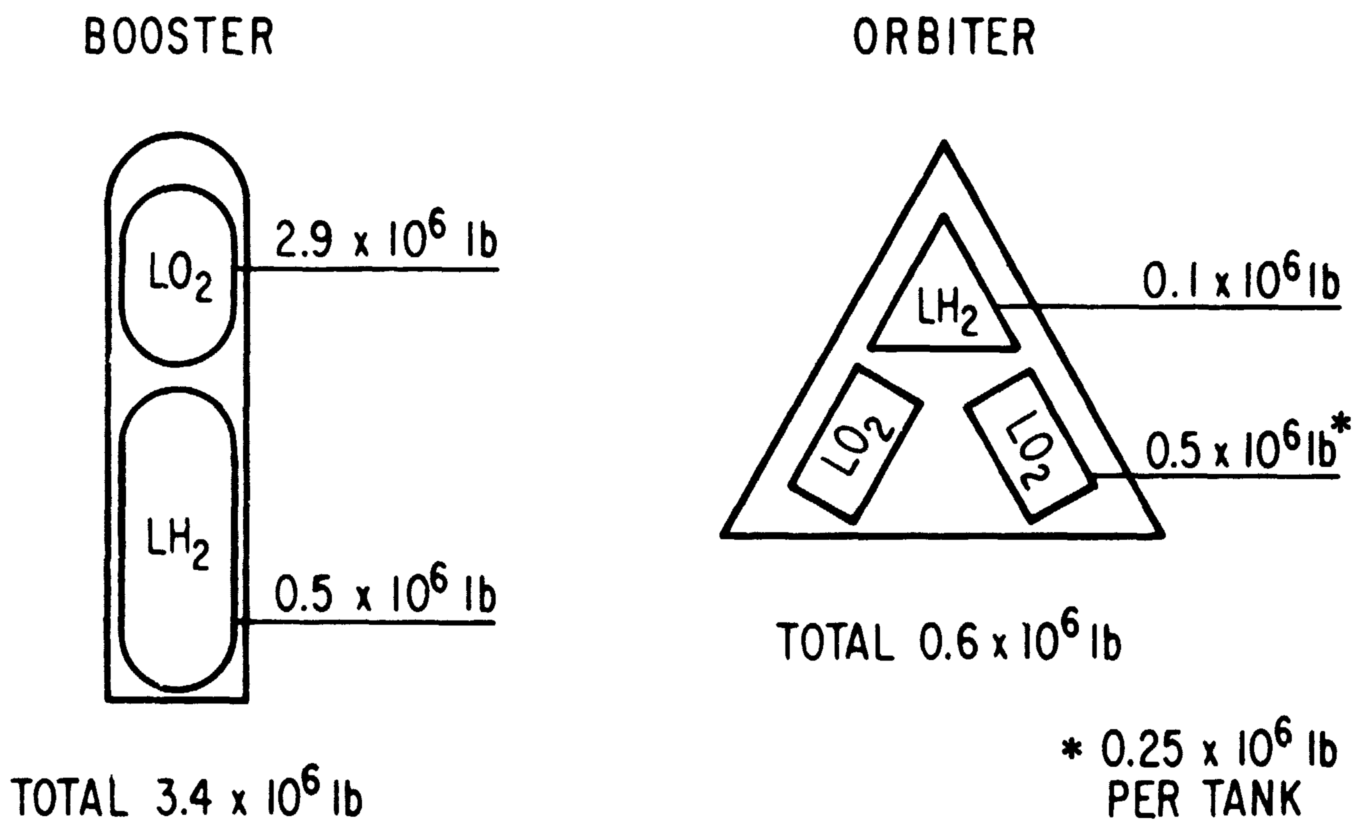

Fig. 31. Propellant Distribution

calculated yield of the particular tank failure combination to the total propellant on-board the vehicle, 4×10^6 lb. (The details of the evaluation are presented in Table 11.)

The results indicate that only twelve of the thirty-one failure combinations will produce yields in excess of 20% TNT equivalency of the total vehicle (see Table 12). By way of comparison, a gross static failure of the entire orbiter (failure mode 12, Table 11) produces a 9% yield, and failure mode 30, which includes all tanks except the booster LO_2 tank, indicates a yield of only 16.5%. Moreover, these all involve multiple tank failures, and all but one involve both the booster and the orbiter vehicles. The probability of the simultaneous failure of two or more of the propellant tanks, at least one of which must be a LH_2 tank, is very remote. Further, the only opportunity for the total quantity of the released propellant to combine would be on the ground; this would require the LH_2 released from the orbiter tank to travel essentially the full length of the vehicle without encountering an ignition source, an improbable situation.

3.3.4.3 Single Tank Failures

If a failure should occur in the propellant tanks, it would be most likely to be a single tank failure. Of the five possible single tank failures, only the failures of the two LH_2 tanks are of interest for the purpose of this study. The ASESB 60% criterion also pertains to H_2/air mixtures; LO_2 is considered a fire hazard rather than an explosive hazard. The yield-ratio calculations (see Table 11) show equivalent TNT yields of 1.5 and 7.5% for failure of the orbiter and booster LH_2 tanks, respectively.

If the ruptured tank were an O_2 tank, it was assumed that an explosion would not occur, but that a fire might result. Explosions of other propellant aboard the vehicle as a result of the fire would be of a low order since the fire will act as a nearly instantaneous ignition source and preclude the propellant mixing required to obtain a high explosive yield.

Table 11. Evaluation of Explosive Yield Due to Possible Combinations of Tank Failures

Failure Mode	Tanks and Propellant Weights					Number of Tanks	Total Weight of Propellant Released			Yield, Weight of TNT, 60% Equivalency	Yield Ratio, % TNT
	Booster		Orbiter								
	LO_2	LH_2	LO_2, No. 1	LO_2, No. 2	LH_2		LO_2	LH_2	LO_2/LH_2		
1	2.9	-	--	--	-	1	2.9	-	--	0	0
2	-	0.5	--	--	-		--	0.5	--	0.3	7.5
3	-	-	0.25	--	-		0.25	-	--	0	0
4	-	-	--	0.25	-		0.25	-	--	0	0
5	-	-	--	--	0.1	1	--	0.1	--	0.06	1.5
6	2.9	0.5	--	--	-	2	--	-	3.4	2.04	51.0
7		-	0.25	--	-		3.15	-	--	0	0
8		-	--	0.25	-		3.15	-	--	0	0
9	2.9	-	--	--	0.1		--	-	3.0	1.8	45.0
10	-	0.5	0.25	--	-		0.75	-	--	0	0
11	-	0.5	--	0.25	-		0.75	-	--	0	0
12	-	0.5	--	--	0.1		--	0.60	--	0.36	9.0
13	-	-	0.25	0.25	-		0.50	-	--	0	0
14	-	-	0.25	--	0.1		--	-	0.35	0.21	5.25
15	-	-	--	0.25	0.1	2	--	-	0.35	0.21	5.25
16	2.9	0.5	0.25	--	-	3	--	-	3.65	2.19	54.75
17		0.5	--	0.25	-		--	-	3.65	2.19	54.75
18		0.5	--	--	0.1		--	-	3.50	2.10	52.50
19		-	0.25	0.25	-		3.40	-	--	0	0
20		-	0.25	--	0.1		--	-	3.25	1.95	48.75
21	2.9	-	--	0.25	0.1		--	-	3.25	1.95	48.75
22	-	0.5	0.25	0.25	-		--	-	1.00	0.60	15.00
23	-	0.5	0.25	--	0.1		--	-	0.85	0.51	12.75
24	-	0.5	--	0.25	0.1		--	-	0.85	0.51	12.75
25	-	-	0.25	0.25	0.1	3	--	-	0.60	0.36	9.00
26	2.9	0.5	0.25	0.25	-	4	--	-	3.90	2.34	58.50
27		0.5	0.25	--	0.1		--	-	3.75	2.25	56.25
28		0.5	--	0.25	0.1		--	-	3.75	2.25	56.25
29	2.9	-	0.25	0.25	0.1		--	-	3.50	2.10	52.50
30	-	0.5	0.25	0.25	0.1	4	--	-	1.10	0.66	16.50
31	2.9	0.5	0.25	0.25	0.1	5	--	-	4.00	2.40	60.00

Note: All weights are in millions of pounds.

Table 12. Multiple Tank Failures Producing Yields in Excess of 20% TNT Equivalency

Booster		Orbiter			Number of Tanks	Total Weight	Yield, Weight of TNT, 60% Equivalency	Yield Ratio, % TNT
LO_2	LH_2	LO_2 Tank No. 1	LO_2 Tank No. 2	LH_2				
2.9	0.5				2	3.4	2.04	51.0
2.9				0.1	2	3.0	1.80	45.0
2.9	0.5	0.25			3	3.7	2.19	54.8
2.9	0.5		0.25		3	3.7	2.19	54.8
2.9	0.5			0.1	3	3.5	2.10	52.5
2.9		0.25		0.1	3	3.3	1.98	48.8
2.9			0.25	0.1	3	3.3	1.98	48.8
2.9	0.5	0.25	0.25		4	3.9	2.34	58.5
2.9	0.5	0.25		0.1	4	3.8	2.25	56.3
2.9	0.5		0.25	0.1	4	3.8	2.25	56.3
2.9		0.25	0.25	0.1	4	3.5	2.10	52.5
2.9	0.5	0.25	0.25	0.1	5	4.0	2.40	60.0
	0.5	0.25	0.25	0.1	4	1.1	0.66	16.5

Note: All weights are in millions of pounds

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3.3.4.4 Propagation of an Explosive Failure

Although it is improbable that all five propellant tanks would be involved in an initial explosive failure, it is reasonable to expect that a failure of a magnitude sufficient to rupture a propellant tank would propagate so as to include all tanks.

This expectation is based on the consideration that the initial explosive event would result in a low-order yield with respect to the explosive potential of the total on-board propellant. The debris, pressure wave, and/or fire resulting from this event could rupture one or more of the adjacent propellant tanks and result in a secondary explosion. The yield of the secondary explosion, although possibly exceeding the magnitude of the initial explosion, would not be expected to approach the current 60% TNT equivalency criterion because the fire and energy release of the initial explosive event would provide a ready ignition source for any propellant released in subsequent failures. The nearly instantaneous ignition of this propellant would not allow the propellant-mixing time required to develop high-order explosive yields. Most of the propellant released in sequential failures of this nature would only add to the existing deflagration and would not increase the overall explosive yield. Estimates of the explosive yields resulting from the failures of a Saturn S-IVB stage during test and a Centaur vehicle during launch tend to confirm this rationale. In both instances, the explosive yield (based on total on-board propellant) was estimated to be less than 10% TNT equivalency.

3.3.5 Evaluation of Yield Probability

Studies for other vehicles have indicated that the probability of the occurrence of a failure such as a tank rupture, which could result in the explosion of LH_2 and LO_2, is very low. For instance, data from an analysis for the Titan IIIM vehicle indicated that the probability of a tank rupture during the time period from T minus 30 to T minus 0 min was approximately 0.4×10^{-6}. It is generally considered that the probability of a tank rupture on the pad would also be very low.

In spite of the anticipated low probability of the occurrence of a situation that could result in an on-pad explosion, there is the question of the magnitude of the explosion if such an event should occur. A statistical development of the yield of exploding propellant for a multitank vehicle configuration such as the one used on the EOS was performed; it is presented in detail (see Appendix D, Vol III of this series).

In that analysis, probability density function models for the yield of an explosion were first developed. The properties of these models were then used to establish composite probability density functions, considering the fact that various EOS tank combinations (hence, different quantities of propellant) would be involved in the explosion. The composite probability density functions were then used as the basis for probability statements relative to the equivalent TNT yield of an EOS fully loaded with LO_2/LH_2 propellant.

The results of this analysis indicate that if a failure should occur, the probability of attaining a yield approaching 60% TNT equivalency of a fully loaded space shuttle is low. Table 13 shows the probabilities of exceeding 20, 60, and 100% TNT equivalency yields as indicated by each of the models. It will be noted that Model 4 indicates only a 6% probability of exceeding a yield of 20% TNT equivalency (see Fig. 32).

I should be noted, however, that the probability density function for Model 4 is based on experimental data obtained from a series of tests that consisted predominantly of small-scale (200 lb) tests for which yields as high as 100% TNT equivalency were reported. The test series also included a few tests involving propellant weights of 1000, 25,000 and 91,000 lb for which TNT equivalencies were reported in the range of approximately 40 to 3.5%, the TNT equivalency decreasing as propellant test weight increased.

There is some concern that this experimental data might not be a good statistical sample for use in the analysis since few tests were run using

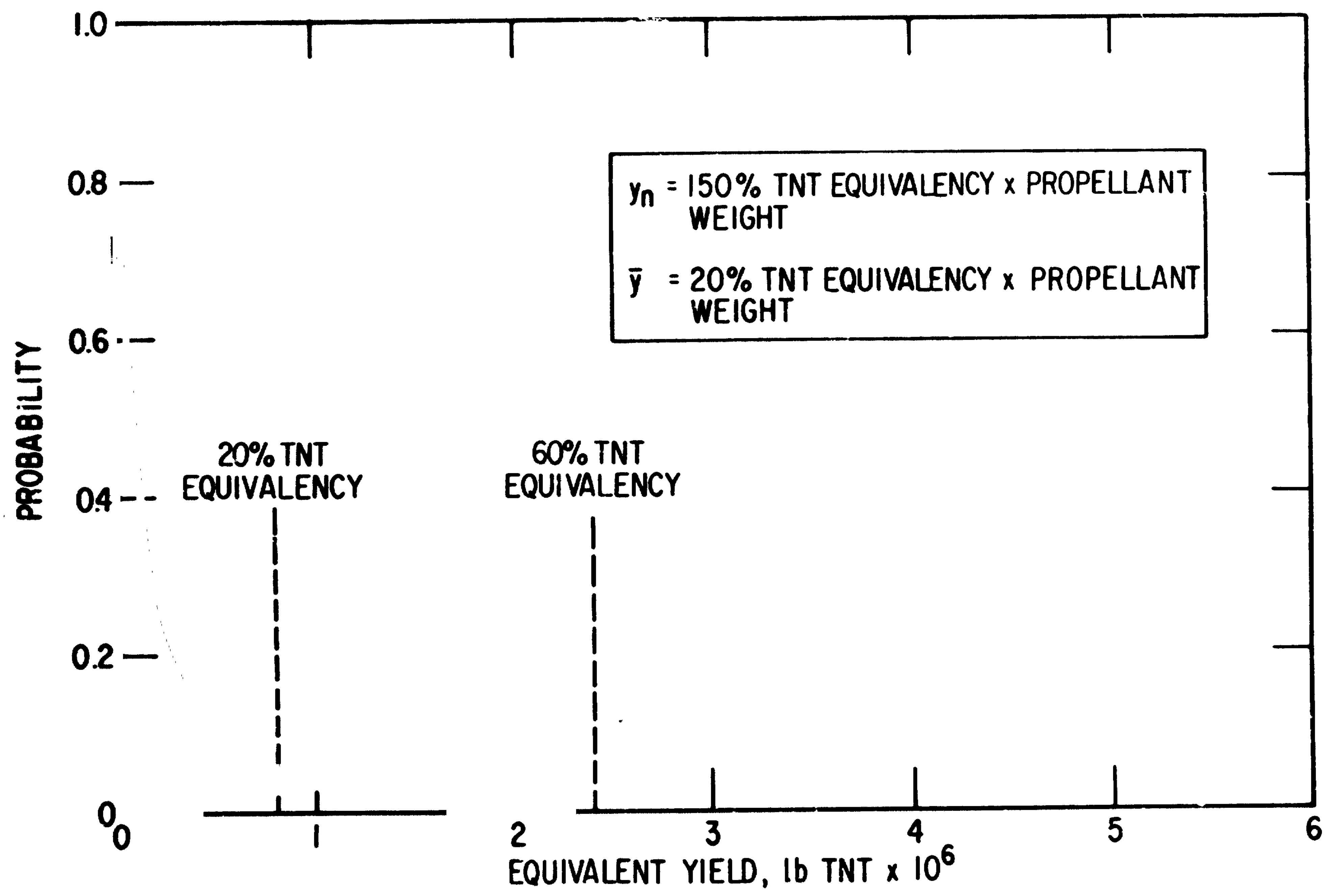

Fig. 32. Probability of Exceeding a Given Yield - Model 4

Table 13. Probability of Exceeding a Given % TNT Equivalency

Model	% TNT Equivalency		
	20	60	100
1	0.19	0.04	0.0
2	0.19	0.06	<0.01
3	0.06	<0.01	<0.01
4	0.06	<0.01	<0.01
5	0.19	0.09	0.03

large propellant quantities, and the manner in which the LO_2 and LH_2 were brought together in the tests might not correspond to failure modes anticipated for the space shuttle. For instance, the small number of tests involving large propellant quantities might be the basis for concern that Model 4 is biased towards low yields. On the other hand, the results of the failure analysis for the static, on-pad phase of space shuttle operations indicate that the TNT equivalency for the large propellant quantities on-board the space shuttle might be expected to produce yields lower than those indicated by Model 4. It therefore appears that Model 4 might actually be conservative from the standpoint of yields to be expected in the event of an explosive failure involving the main propellant tanks of the space shuttle.

3.3.6 Summary of Suggested Preventive or Remedial Criteria

Recommendations for reducing the on-pad hazards fall into three categories:

- Prevention or isolation of hazardous combustible conditions and ignition sources
- Installation of sensors within the vehicles and on ground systems to detect an impending hazardous condition

- Initiation of timely actions such as venting, unloading propellant, and use of fire suppressants if a potentially dangerous condition is detected.

The area that will provide the greatest benefit is the prevention or isolation of hazardous conditions. Requirements established early in the program will help to preclude hazards by:

- Designing the propellant tanks to preclude collapse under adverse draining conditions.
- Avoiding tank bulkheads common to both LO_2 and LH_2.
- Avoiding placement of high-pressure gas storage bottles within propellant tanks.
- Providing adequate overpressure relief where fluid lines, components, or tanks may be subjected to localized high temperatures.
- Incorporating debris shields between main propellant tanks and between subsystems or components subjected to high pressures and high rotational speeds.
- Maximizing the use of compatible and nonflammable materials.
- Purging the vehicle compartments with dry N_2 to maintain an inert, nonflammable atmosphere. Such an atmosphere should be established prior to propellant loading. Care should be exercised in locating purge gas inlets and outlets to avoid nonpurged pockets in which H_2 might accumulate.
- Jacketing flanged connections to collect any H_2 leakage and vent it overboard.

Since leaks (especially of GH_2) are probable, sensors capable of detecting a hazardous atmosphere or fire within the vehicle should be included and should provide for termination of propellant loading or increase of N_2 purge flow, if needed. The sensing/warning system should be designed to minimize the occurrence of false warnings and yet provide a minimal reaction time in the event of an emergency.

The initiation of timely action would depend on the type of threshold detection and on the sensitivity of the sensor systems. It should be incorporated into a system to increase the flow of GN_2 as a diluent or fire suppressant or to initiate a water deluge to reduce the possible thermal effects.

It is recommended that a program of designing for minimal hazard be rigorously pursued at the component, subsystem, and system levels for the vehicle and ground equipment. As systems become better defined and specific data become available, periodic reassessment of specific flammability and explosive hazards will be required.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The current 60% TNT equivalency criterion for LO_2/LH_2 propellant is based on the total weight of propellant in the vehicle. The criterion predicates that a total release and mixing of propellant will occur prior to ignition.

The distribution of propellant in the space shuttle (EOS) is such that a simultaneous failure of five separate propellant tanks, two in the booster and three in the orbiter, would have to occur to produce a total release of propellant. The failure analysis indicates that this is an improbable failure mode for the space shuttle. However, should such a failure occur, the only opportunity for the total quantity of propellant to combine would be outside the vehicle. It is not reasonable to expect that the released propellant would escape ignition during the time required to allow such a combination of propellant.

If a tank failure were to occur, it would be most likely to be the outcome of an initial failure in some other system (e.g., a low-yield explosion due to gaseous propellant leakage from seals or components or to debris resulting from a high-pressure bottle failure). It is expected that the energy available in a failure of this nature would be sufficient to ignite the propellant before any appreciable mixing could occur. Therefore, the resulting explosive yield would be low, and most of the propellant released would be consumed in the ensuing deflagration. It is also expected that, should this type of failure occur, it would probably propagate throughout the vehicle. As this failure progressed throughout the vehicle, additional low-yield explosions might occur; however, they are not expected to be additive, nor is the yield of any individual explosion expected to exceed a TNT equivalency of 20% of the total propellant initially on-board the vehicle. This rationale is supported by the

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yields reported for the failures of a Centaur vehicle and a Saturn S-IVB stage. The TNT equivalency estimated for both of those failures was less than 10% of the on-board propellants.

A conservative statistical analysis indicates that if a tank failure should occur, there is only a 6% probability that it would exceed a TNT equivalent yield of 20% of the total on-board propellants.

Therefore, it is concluded that a value of 20% TNT equivalency is a more realistic criterion to apply to the LO_2/LH_2 propellant of the space shuttle (EOS) during its static, on-pad phase of operations than the presently used value of 60%. While the analysis of available LO_2/LH_2 explosion test data does not permit extrapolation of the data to the large propellant quantities of the space shuttle or its use as a firm basis for such a conclusion, the apparent trend of this test data combined with the results of the failure analysis tends to support a lowering of the TNT equivalency value.

4.2 RECOMMENDATIONS

Based on the results of the failure and statistical analyses, it is recommended that the 60% TNT equivalency criterion for LO_2/LH_2 propellant currently applied to the static, on-pad phase of space shuttle (EOS) operations be lowered to a value of 20% based on the total weight of propellants on-board the vehicle.

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