Vol. 1 of 3

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

Volume I: Management Summary Report

Prepared by SYSTEMS PLANNING DIVISION

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Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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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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1. INTRODUCTION

The existing 60% TNT equivalency requirement for LO_2/LH_2 propellant is considered too conservative and too restrictive for use as a siting criterion for the space shuttle program.

A reduction of this criterion would relax siting and operational constraints and effect a savings in facilities costs. It therefore becomes appropriate to review this criterion with respect to both existing test data and the results of a failure mode analysis of the shuttle vehicle in the static, on-pad configuration in order to determine whether a reduction in this criterion could be justified.

2. STUDY OBJECTIVES AND CONSTRAINTS

2.1 OBJECTIVES

The major objective of this study was to evaluate and recommend a new TNT equivalency criterion for LO_2/LH_2 propellant for application to the static, on-pad operational phase of the space shuttle. The new criterion is to have 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.

2.2 CONSTRAINTS

No additional tests were conducted. Therefore, the data analysis phase of this study was confined to the study of data produced by prior test programs. Most of this data was found not to be pertinent to this study.

Design and operational criteria for the space shuttle were in the development phase; the failure analysis was therefore a gross, top-level effort. A further reduction in recommended criteria may become possible as vehicle design progresses and details become more fully defined.

3. RELATIONSHIP TO OTHER NASA EFFORTS

The results of this study have a direct impact on several areas of the space shuttle program. The most significant of these are the following:

- Identification of hardware design areas and of interface and operational constraints that should be considered to minimize both the probability of failure and the explosive potential should such a failure occur
- Development of the normal operational and contingency safety plans
- Establishment of facilities requirements to aid the Space Shuttle Facilities Group in its site selection efforts

4. METHOD OF APPROACH

The general plan followed in this study was to:

- Collect and analyze existing data
- Perform failure mode analyses
- Evaluate and recommend new criteria

5. RESULTS

5.1 GENERAL

Since this study was designed primarily to support the site selection and facilities planning activities, it was confined to the static, on-pad phase of operations, i.e., the time interval between the start of propellant loading and launch, including any hold time.

The vehicle configuration and propellant weights used throughout the study are those shown in Fig. 1.

5.2 DATA ANALYSIS

5.2.1 Principal Investigators

The principal investigators whose test data and/or reports were selected for analysis are the following:

- A. D. Little, Inc.
- Aerojet General Corp.
- Bellcomm, Inc.
- National Aeronautics and Space Administration
- University of Florida
- URS Corp. (Project Pyro)

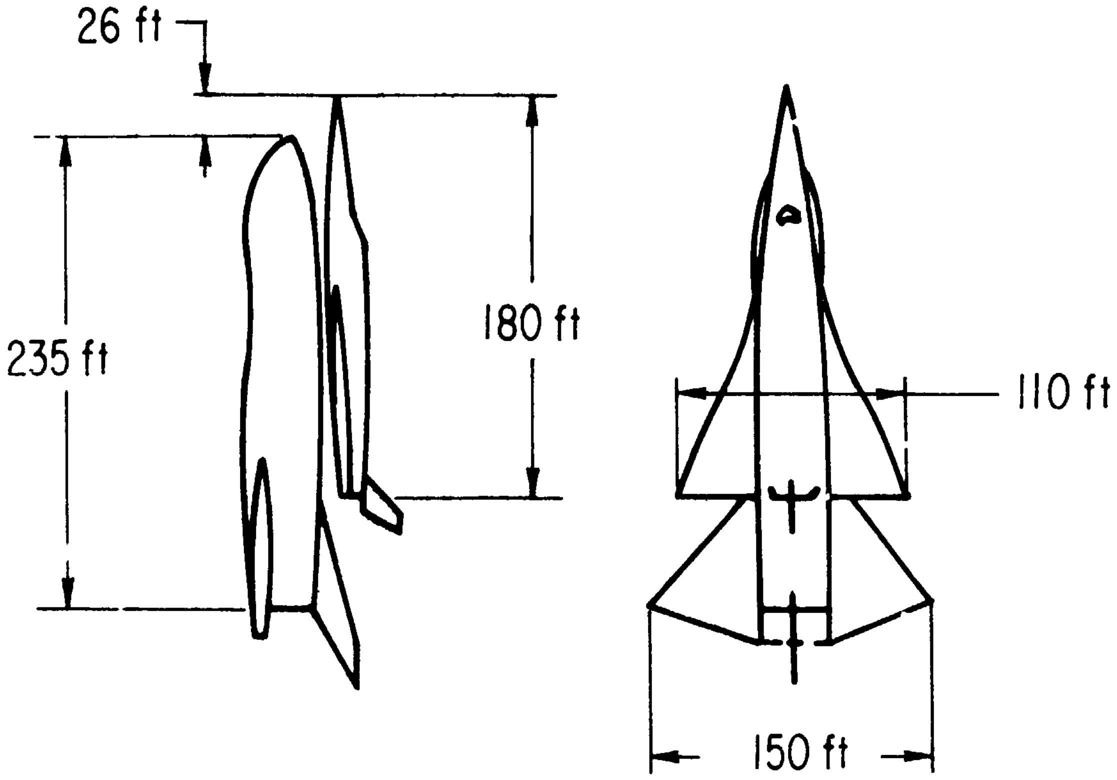
5.2.2 Definition of Explosive Yield

Explosive yield is defined:

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

5.2.3 Available Test Data

A summary of test data from the major LO_2/LH_2 propellant test programs is presented in Table 1. Most of these tests were conducted with propella quantities of 225 lb or less; only 18 tests are reported for propellant weights in the 1000 to 91,000-lb range.



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. 1. Typical Vehicle Configuration

Table 1. Test Data Summary

Investigator	Type of Test	No. of Tests	Propellant Weight, lb	Pressure Yield Range, % TNT
A. D. Little (1962)	Spill	9	45	63 - 198
		3	225	91 - 185
Aerojet-General (1963)	Contact Area (Interface)	2	100	70
		2	150	23 - 65
		2	225	55 - 80
National Aeronautics and Space Administration (1964)	Spill	6	200	6.3 - 144
	Bulkhead/Tank Rupture	7	200	0.3 - 1.3
URS (Project Pyro) (1965-1967)	Bulkhead Rupture	59	200	1.5 - 100
	and	11	1,000	2 - 40
	Simulated Vehicle Fallback	6	25,000	0.05 - 15
		1	91,000	3.5

5.2.4 Data Selected for Analysis

Only Project Pyro reports provide test data for propellant test weights in excess of 225 lb; the largest was 91,000 lb. Pyro data were therefore selected as the basis for the analysis. Data from the spill and the contact-type tests were excluded from the final analysis. The configurations and objectives of these tests were not considered representative of potential space shuttle failures.

5.2.5 Data Indications

It is indicated in Table 1 that explosive yields vary over a wide range. The data indicate a trend towards a smaller range and a lower maximum-yield value as propellant test weights increase. This downward trend may be questioned, however, since it is based on significantly fewer tests and test configurations than were employed in the small-scale tests.

5.2.6 Data Evaluation

The available test data do not define the explosive yields of LO_2/LH_2 propellant in sufficient detail to support a recommendation for a generalized reduction in the existing 60% TNT equivalency criterion; therefore a failure analysis was performed.

5.3 FAILURE ANALYSIS

5.3.1 Fault Tree

Figure 2 presents the top of the fault tree. The tree was developed to a level sufficient to identify failures that could lead to the release and possible ignition of propellant. Typical conditions analyzed are listed below:

- Tank overpressure
- Tank collapse
- Orbiter dropped
- Vehicle tipover
- Lightning strike
- Fire
- Tank struck by foreign object
- Vehicle propellant system failure

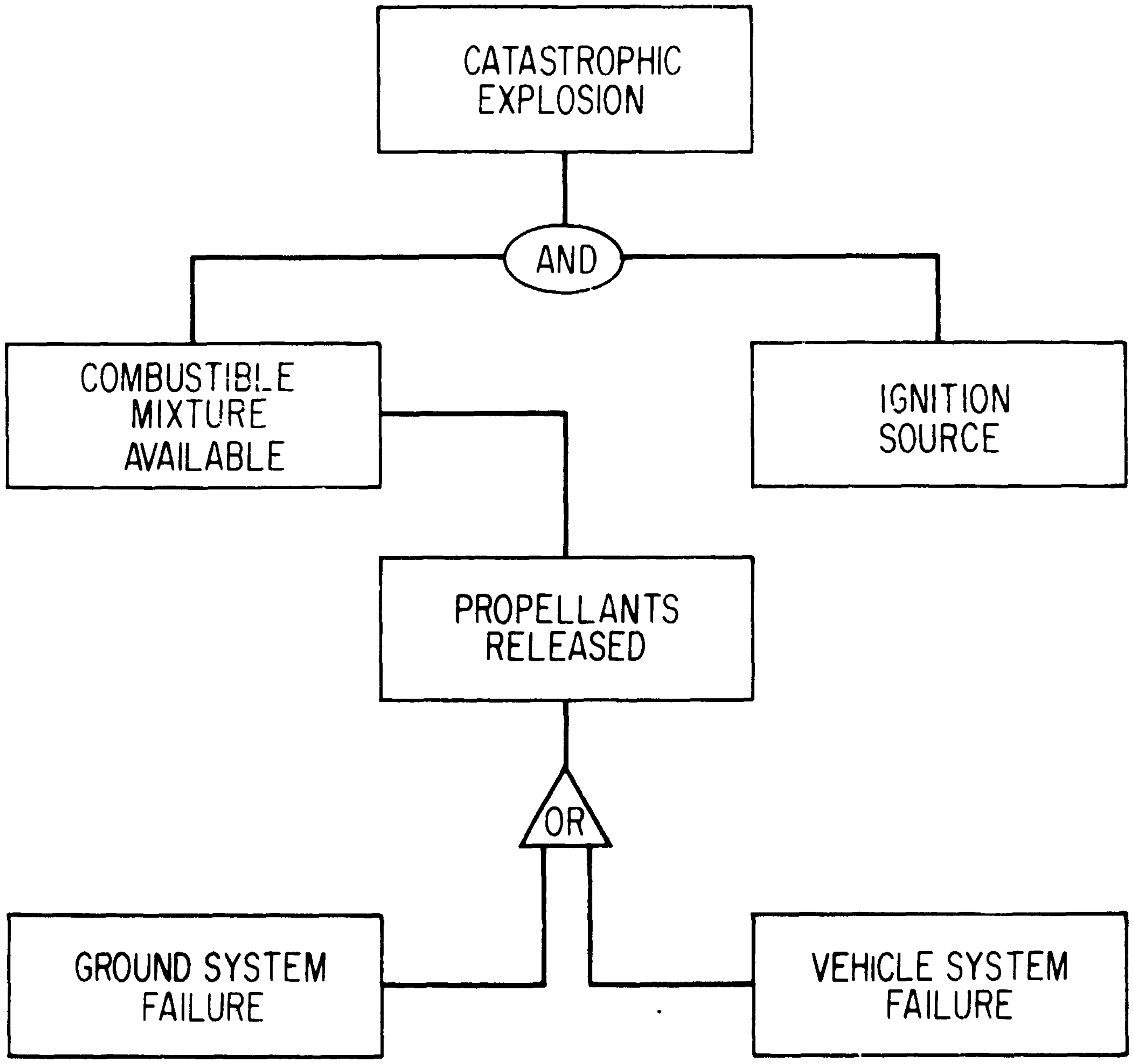


Fig. 2. Fault Tree - Top Level

5.3.2 Assessment of Explosive Potential

5.3.2.1 Existing Criterion

The existing 60% TNT equivalency criterion is based on the total weight of propellant on-board the vehicle. In addition, it assumes a total release and mixing of the LO_2 and LH_2 prior to ignition.

5.3.2.2 Multiple Tank Failures

Figure 3 shows the distribution of the main propulsion propellant on-board the space shuttle. If one assumes that a multiple failure of these tanks were to occur and that ignition could be delayed long enough to produce a TNT explosive yield equivalency of 60% of the weight of the propellant spilled, then the yields shown in Table 2 might be obtained. However, the analysis indicates that the simultaneous failure of multiple tanks is an extremely remote possibility, particularly in combinations involving both vehicles. Further, the analysis demonstrates that the nature of many of the ignition sources precludes a delay sufficient for appreciable mixing prior to ignition. Therefore, the resulting yields should be low.

Table 2. Explosive Yield for Some Tank Failures

Source	No. Tanks	Propellant Released, 10^6 lb	Yield Ratio,[1] % TNT
Orbiter Total	3[2] 1	0.6	9.0
All Except Booster LO_2	4	1.1	16.5
Booster Total	2	3.4	51.0
Vehicle Total	5	4.0	60.0

[1] $\text{Yield Ratio} = \frac{0.6 \times \text{Weight of Propellant Released}}{\text{Total Propellant Weight}} \times 100$

[2] Orbiter May Have Three Separate Tanks or One Tank with Common Bulkhead

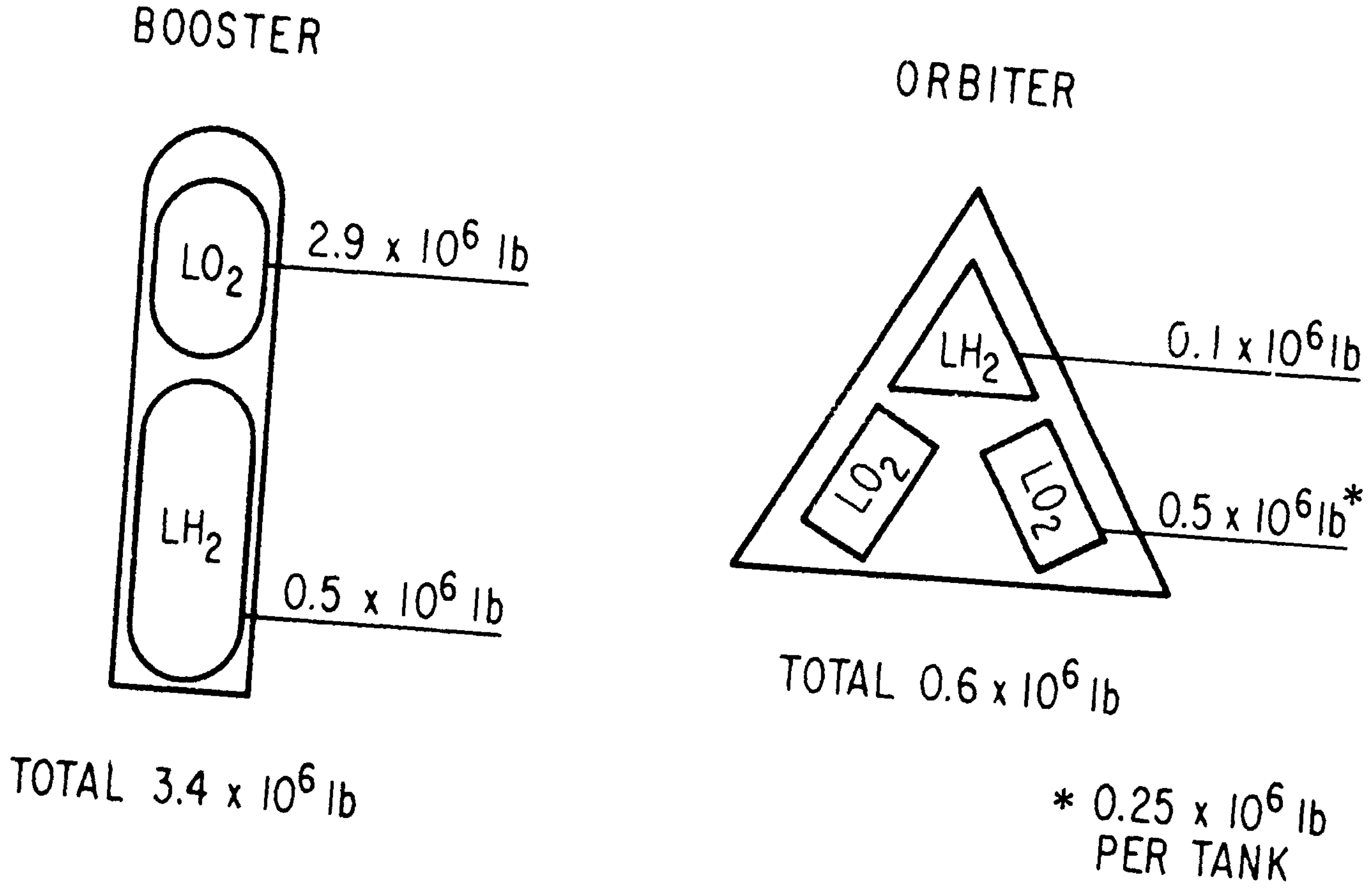


Fig. 3. Propellant Distribution

5.3.2.3 Single Tank Failures

The analysis shows that single tank failures resulting in gross propellant release are also unlikely. However, should a single tank failure occur, the most critical would be the failure of the LH_2 tanks. If one assumes that such a gross failure were to occur in either the booster or the orbiter LH_2 tank (with a 60% TNT equivalency), the maximum yield would correspond to 7.5% of the total weight of propellant on-board the vehicles for a booster failure and 1.5% for an orbiter failure. The explosion from these single tank failures could rupture additional tanks and release their propellant. Since the fire produced by the initial failure would provide a nearly instantaneous ignition source, mixing time for the secondary propellant release would be very short, and a correspondingly low explosive yield would result. Most of the propellant released in the secondary failure would probably only add to the magnitude of the existing fire.

5.3.2.4 Vehicle Propellant System Leakage

Accumulation of GH_2 due to leakage in the vehicle propellant system can result in low-energy explosions. These explosions could rupture adjacent propellant tanks and result in relatively high-order secondary explosions.

A leak-detection system coupled with a GN_2 purge system capable of maintaining the minimum suggested GN_2/GH_2 ratio (see Table 3) will inhibit explosions due to GH_2 leakage. This assumes that the system purges the areas in which leakage might occur to a minimum 95% GN_2 atmosphere prior to propellant loading. It also assumes that the GH_2 from maximum allowable leakage of all components is uniformly dispersed.

Table 3. Suggested Minimum GN_2/GH_2 Ratio to Inhibit Explosion

Constituent	Vol %	Wt %
GN_2	65	97.3
GH_2	35	3.7

6. CONCLUSIONS

The failure analysis indicates that 20% TNT equivalency is a realistic value for the space shuttle during the static, on-pad phase of operations. However, the existing test data are considered insufficient to support a recommendation for a generalized reduction in the current explosive hazard criterion for LO_2/LH_2 propellant. This conclusion is based on the assumption that the final vehicle configuration will be similar to the one analyzed.

7. SUGGESTED ADDITIONAL EFFORT

The desirability of additional testing at high propellant test weights should be considered. A cost study is suggested to assess the cost vs return of such a test program. If feasible, an in-depth test plan should be developed to assure the maximum data return for the minimum testing.

It may become appropriate to reevaluate this study when the vehicle design becomes firm. Such an analysis might result in a lower TNT equivalency value for the space shuttle than can be substantiated at this time.