

Explosive Equivalence of Hydrocarbon Propellants

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Abstract

The purpose of this report is to report the analysis of test and launch vehicle flight failure data for the explosive equivalence of liquid oxygen and RP-1 (LO₂/RP-1) and other hydrocarbon-based energetic liquid bipropellants. Revision to the values used in Defense Explosives Safety Regulation (DESR) 6055.09 [1] are recommended. The focus will be on revisions for LO₂/RP-1 but other combinations (LO₂/ethanol and LO₂/JP-5) will be addressed.

This revision is intended to apply to DoD facilities siting and construction for operations involving these energetic liquids. It governs the uses of energetic liquids for launch vehicles, rockets, missiles, space vehicles, and associated static test installations. The yield criteria will envelop test facilities and launch pads for the pre-launch/pre-ignition state, on-pad engine firing conditions, and post-launch hazards relative to near-pad incidents. Additional assessments are included that apply to other operational facilities and conditions.

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1. Introduction

This report is a follow-on to preliminary observations made at the time the liquid oxygen/liquid hydrogen (LO₂/LH₂) cryogenic analysis was performed, as noted in Reference [2]. Appendix A discusses the results of that proposal and the Department of Defense Explosives Safety Board (DDESB) Liquid Propellant Working Group (LPWG) decision.¹ In addition to Appendix A's recap of the LO₂/LH₂ DDESB decision, Appendix B gives a backup discussion on hydrocarbon bipropellants related to prediction methods, auto-ignition, blast asymmetry, impact (dynamic mixing) sensitivity, TNT (trinitrotoluene) equivalence of liquid propellants, and failures.

During the period of LPWG deliberations, the preliminary observations for liquid oxygen/hydrocarbon propellants were presented and plans for updating those explosive criteria were put into place. However, due to other priorities, these plans were deferred [3][4]. This report presents the follow-on assessments that were deferred at that time. In addition, an addendum is being prepared to update [6] to incorporate the latest findings from this most recent effort and will provide background to this report. For continuity this report will repeat the general material included in [2] with added information; however, only the current data relative to the liquid oxygen/hydrocarbon bipropellants will be included so the [2] paper may prove useful as background as well.

As a consequence of the noted actions, during the past two decades this area has remained dormant, with no additional tests or analyses performed for these propellant combinations. This report presents the results of these latest activities and requests that an adjustment to the criteria be made accordingly. In this report the hydrocarbon propellants are subcategorized as the kerosenes and alcohols. Other hydrocarbon bipropellant combinations have been proposed and tested in the past (e.g., gasoline) but have not been used operationally, so they must be addressed separately. Similarly, other cryogenic combinations have been proposed (e.g., LF₂/LH₂ and LO₂/LCH₄), but only LO₂/LH₂ has been used, so that was the only combination addressed in the [2] paper.

The data used in the initial release of the 6055.9-STD document accounted for the difference in yield noted during early testing of the LO₂/RP-1 propellant combination for missile programs and represented the overarching conclusions as adjusted for propellant mass, i.e. 10% TNT for test stands and 20% TNT (up to 500,000 lb) for launch pads. In addition to revising the explosive standard for LO₂/LH₂ the LPWG entertained a potential change to the LO₂/RP-1 standards based on updated test and missile failure data. These test and failure data were reanalyzed and presented to the LPWG as documented in [5]. However, the preliminary observations as briefed to the LPWG that showed potential liquid oxygen/hydrocarbon yield criteria included both RP-1 and ethanol (C₂H₅OH) data. For this current report, these data were segregated into separate findings. Also, additional test and failure data were uncovered after these preliminary plots were prepared and are included herein. In addition to the LO₂/RP-1 and LO₂/ethanol data, testing with LO₂/JP-5 and other LO₂/kerosene-based jet fuel propellant combinations (LO₂/JP-4 and LO₂/RJ-4) were uncovered.

The following recommendation options are consistent with the decisions made by the DDESB LPWG relative to the LO₂/LH₂ Yield Curve. However, use of the Option 1 yield curves incorporates the finding that liquid bipropellant explosive yields vary with mass and cannot be accurately approximated with a constant TNT % EEW. This report includes recommendations for LO₂/RP-1 and LO₂/ethanol, plus tentative information relative to the LO₂/JP-5 combination. For the other kerosene-based combinations tested (JP-4 and RJ-4), too few tests were conducted to arrive at reasonable values, but observations can be made for them by comparing them to similar tests conducted at the same time with the other

¹ The Working Group was later renamed as the Energetic Liquids Working Group (ELWG) as its scope expanded to include other liquids beyond propellants, but "LPWG" is used throughout this report

commodities. It is acknowledged that LO₂/RP-1 is the only kerosene-based combination in current use and there is no longer a system using ethanol or other alcohols; however, recommendations for inclusion are made for consistency, to differentiate the various combinations, and for the historical record.

2. Background

No definitive analysis has been found defining the current explosive yield values in the Defense Explosives Safety Regulation (DESR) 6055.09 for the liquid oxygen/hydrocarbon propellant combinations, i.e., TNT equivalences of 10% for static test stands and 20%/10% for launch pads. However, per [6] these values can be traced to the 1961 Joint AF-NASA Hazards Analysis Board report. It is believed that these values resulted from extrapolating the Atlas propellant testing done by Broadview Research Corporation during 1957 and 1958. Reports can be found, however, from the 1961 period that ascribe yields ranging from 25% to 56% [24] and from 20% to 38% [52] at 250,000 lb of LO₂/RP-1 propellant.

In the early 1960s attention was placed on the new, high-energy LO₂/LH₂ propellants planned for the Atlas-Centaur and Saturn launch vehicles. This testing and the results are discussed in detail in [2]. The primary testing was done by A. D. Little Company and involved the tripropellants LH₂, LO₂, and RP-1 being planned for Saturn. This test program is discussed below.

Other than for the A. D. Little Saturn test program, the only other significant testing done with LO₂/RP-1 was performed by Project PYRO. It is evident that the PYRO data was not used to re-evaluate the LO₂/RP-1 criteria, and it is unknown whether any additional discussions took place in this time frame. This report is the first known effort to re-assess the explosive potential and appropriate yield values for the various liquid oxygen/hydrocarbon combinations since the mid-1960s.

3. Recommendation Summary

3.1 LO₂/RP-1

The recommended change to the LO₂/RP-1 liquid propellant explosive equivalence is to replace the current 10% and 20% TNT values with the explosive equivalence from the recommended LO₂/RP-1 yield curves shown in Figure 1 below. Two options are submitted for DDESB consideration. The first recommendation (Option 1) is to use the LO₂/RP-1 yield curves throughout; however, an optional solution (Option 2) is provided that replaces the yield curves with a constant percent equivalency above 300,000 lb as was done (at 200,000 lb) for LO₂/LH₂. For operations other than static test stands (ST) and launch pads (LP)—i.e., other potential explosive sites (PES) and quantities less than W_{Pmin} , a separate explosive yield is recommended. The following describe the methods:

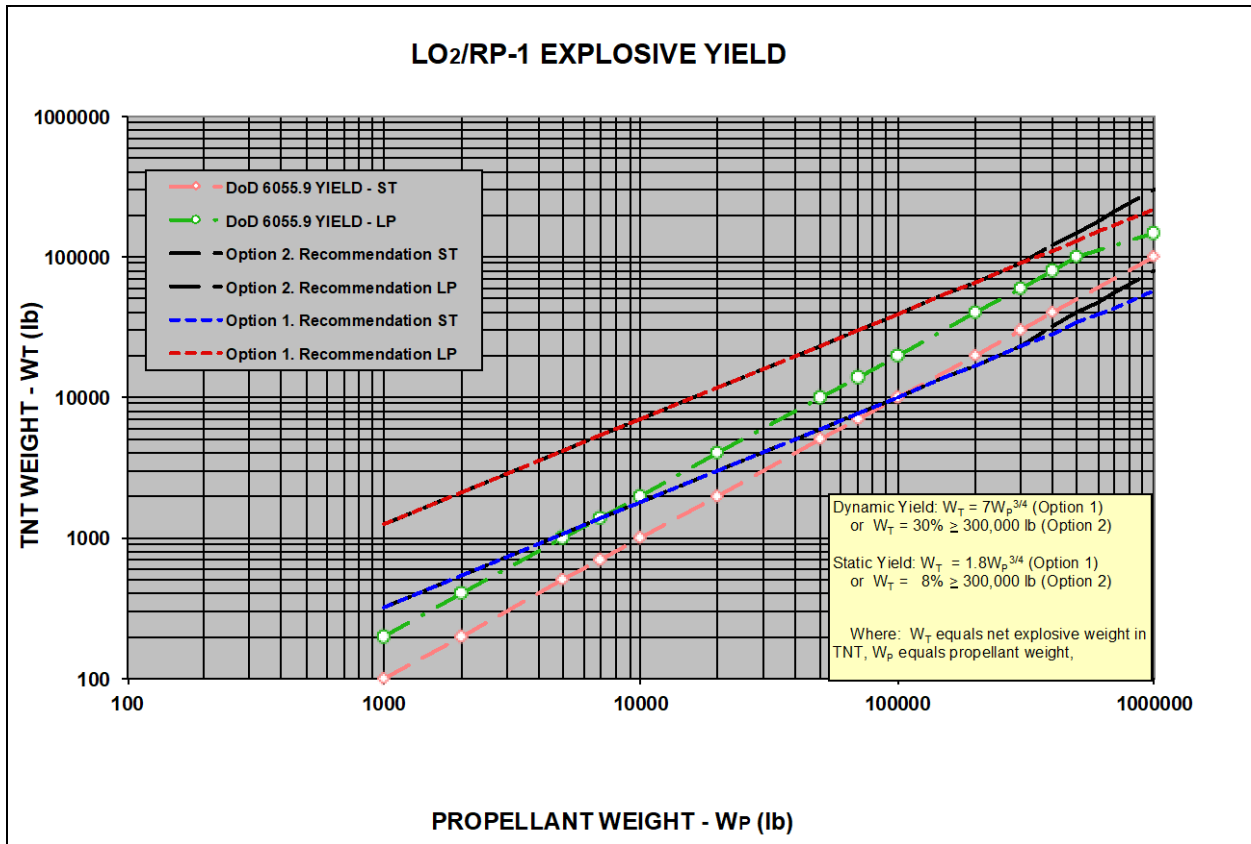


Figure 1. LO₂/RP-1 proposed explosive yield curves.

3.1.1 Static Test Stand (ST)

For launch vehicles, missiles, stages, engines, or components on static test stands, determine the equivalent explosive weight (EEW) in pounds of TNT using the LO₂/RP-1 Static Yield Curve:

Option 1: $W_T = 1.8W_P^{3/4}$ for all $W_P \geq W_{Pmin}$

Option 2: $W_T = 1.8W_P^{3/4}$ for $W_P < W_{Pmax}$ & $\geq W_{Pmin}$
 $W_T = 8\%W_P$ for $W_P \geq W_{Pmax}$

3.1.2 Launch Pad (LP)

For launch vehicles or missiles in the launch configuration determine the equivalent explosive weight (EEW) in pounds of TNT using the LO₂/RP-1 Dynamic Yield Curve:

$$\text{Option 1: } W_T = 7W_P^{3/4} \text{ for all } W_P \geq W_{P_{\min}}$$

$$\text{Option 2: } W_T = 7W_P^{3/4} \text{ for } W_P < W_{P_{\max}} \ \& \ \geq W_{P_{\min}} \\ W_T = 30\%W_P \text{ for } W_P \geq W_{P_{\max}}$$

where W_T = net explosive weight (in lb) TNT, and
 W_P = propellant weight (in lb) as defined in [1], V5.E4.5.6.1 and V5.E4.5.6.2, and
 $W_{P_{\max}} = 300,000$ lb, and
 $W_{P_{\min}} = 1,000$ lb

For example, while both options result in a W_T yield of 90,000 lb TNT (or 30%) at 300,000 lb W_P Option 1 drops to 220,000 lb (or 22%) at 1,000,000 lb, whereas the constant 30% TNT factor of Option 2 results in a 300,000 lb yield at 1,000,000 lb.

3.1.3 Other Potential Explosive Sites

For operations other than launch vehicles, space vehicles, missiles, stages, engines, or components on static test stands, launch vehicles or missiles in the launch configuration, and for quantities $< W_{P_{\min}}$, determine the equivalent explosive weight (EEW) in pounds of TNT using the following:

$$\text{Options 1 \& 2: } W_T = 125\%W_P$$

3.2 LO₂/Ethanol

The recommended change is to include LO₂/ethanol as a separate liquid bipropellant combination, and replace the current 10% and 20% TNT explosive equivalence values (that are inferred) with explicit values for this combination using the recommended LO₂/ethanol yield curves shown in Figure 2 below using the following methods:

3.2.1 Static Test Stand (ST)

For launch vehicles, missiles, stages, engines, or components on static test stands, determine the equivalent explosive weight (EEW) in pounds of TNT using the LO₂/ethanol Static Yield Curve:

$$\text{Option 1: } W_T = 2.1W_P^{3/4} \text{ for all } W_P \geq W_{P_{\min}}$$

$$\text{Option 2: } W_T = 2.1W_P^{3/4} \text{ for } W_P < W_{P_{\max}} \ \& \ \geq W_{P_{\min}} \\ W_T = 9\%W_P \text{ for } W_P \geq W_{P_{\max}}$$

3.2.2 Launch Pad (LP)

For launch vehicles and missiles in the launch configuration determine the equivalent explosive weight (EEW) in pounds of TNT using the LO₂/ethanol Dynamic Yield Curve:

$$\text{Option 1: } W_T = 8.2W_P^{3/4} \text{ for all } W_P \geq W_{P_{\min}}$$

Option 2: $W_T = 8.2W_P^{3/4}$ for $W_P < W_{Pmax}$ & $\geq W_{Pmin}$
 $W_T = 35\%W_P$ for $W_P \geq W_{Pmax}$

where W_T = net explosive weight (in lb) TNT, and
 W_P = propellant weight (in lb) as defined in [1], V5.E4.5.6.1 and V5.E4.5.6.2, and
 W_{Pmax} = 300,000 lb, and
 W_{Pmin} = 1,000 lb

3.2.3 Other Potential Explosive Sites

For operations other than launch vehicles, space vehicles, missiles, stages, engines, or components on static test stands, launch vehicles or missiles in the launch configuration, and for quantities $< W_{Pmin}$, determine the equivalent explosive weight (EEW) in pounds of TNT using the following:

Options 1 & 2: $W_T = 145\%W_P$

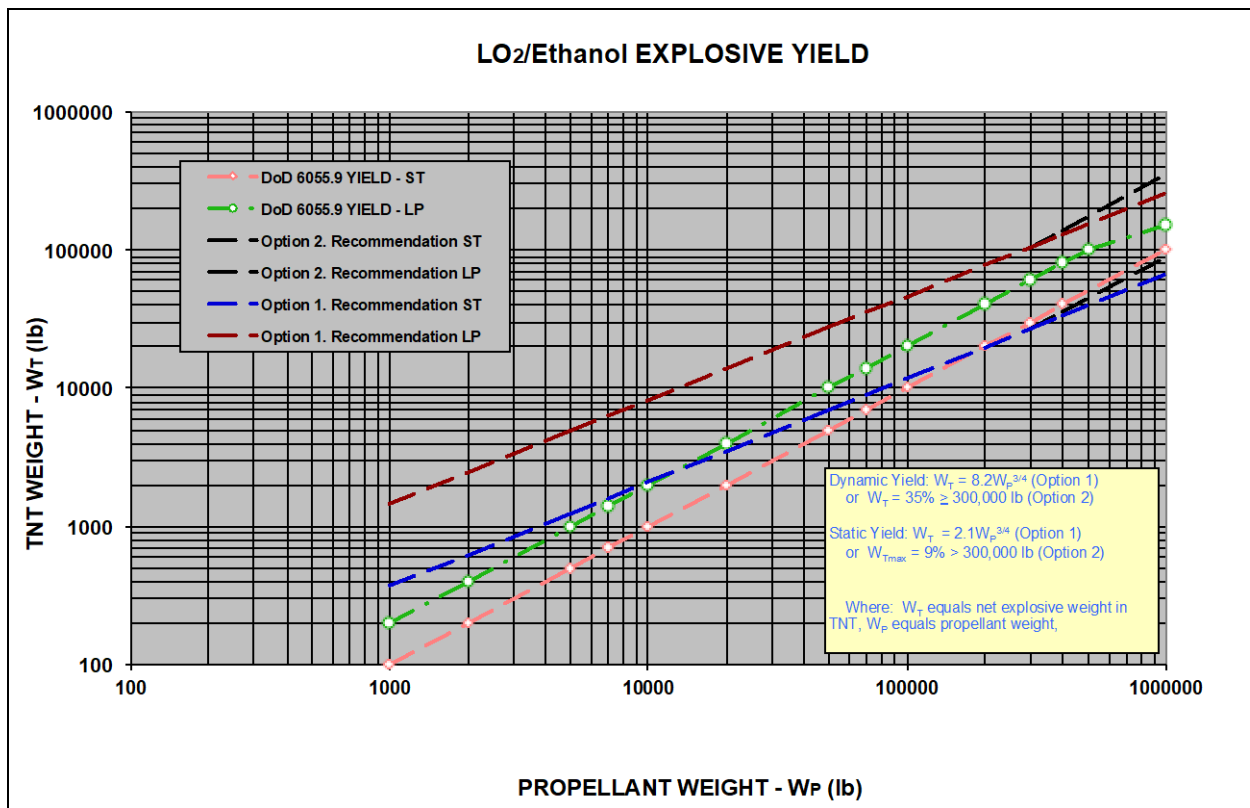


Figure 2. LO₂/ethanol proposed explosive yield curves.

3.3 LO₂/Jet Fuel (tentative)

For the LO₂/JP-5 liquid propellant combination, there is adequate data to make an observation regarding potential explosive equivalence. At the present time there are inferred equivalence values of 10% and 20% TNT in [1]. However, an explosive equivalence can be approximated using the recommended LO₂/ethanol yield curves shown in Figure 2, adjusted for differences noted in the test programs using the following methods:

4. Test and Failure Overview

4.1 Propellant Test Programs Overview

Table 1 and Table 2 below show a matrix of liquid propellant test programs that have been reviewed [10]–[48]. The table gives the experimenter, program, date, propellant combinations (cryogenic LO₂/LH₂, hypergolic pairs, LO₂/hydrocarbons (HC), and LO₂/LH₂/RP-1 tripropellants), and mixing method.

Table 1. Liquid Propellant Test Programs

Agency/Test Program	Propellant			
	LO ₂ /LH ₂	Hyper	LO ₂ /HC	TRI
NAVY/PUSHOVER (1948)				
Vehicle Toppling			X	
NAVY/NRL (1949)				
Propellant Mixing			X	
ROCKETDYNE/FIELD LAB (1954/1955)				
Propellant Mixing			X	
Ground Spill			X	
Impinging Streams			X	
ARMY/REDSTONE (1956)				
Vehicle Destruct			X	
NAVY/JUPITER (1956)				
Propellant Mixing			X	
Ground Spill			X	
Vehicle Destruct			X	
Tank Fallback			X	
Tank Fallback-Water			X	
Underwater			X	
BROADVIEW/ATLAS (1957–1961)				
Ground Spill			X	
Tank Rupture-Ground			X	
Tank Fallback			X	
Tank Rupture-In Silo			X	
A. D. LITTLE/CENTAUR (1960)				
Gas Phase	X			
Rapid Intertank Mixing	X		X	X
Ground Spill	X		X	X
A. D. LITTLE/SATURN (1961)				
Ground Spill	X		X	X
ROCKETDYNE/STORABLE (1961)				
Ground Spill		X		
Tank Rupture		X		
ROCKETDYNE/TITAN II (1961)				
Ground Spill		X		
Tank Rupture-Ground		X		
Tank Rupture-In Silo		X		

Table 2. Liquid Propellant Test Programs (continued)

Agency/Test Program	Propellant			
	LO ₂ /LH ₂	Hyper	LO ₂ /HC	TRI
MARTIN MARIETTA/TITAN II (1962)				
Vehicle Destruct		X		
NASA MSFC/SATURN I (1963)				
Vehicle Destruct			X	
AEROJET/GEMINI (1963–1964)				
Distributed Mixing*		X	X	
Intertank Mixing		X	X	
Tank Fallback		X	X	
URS/PYRO (1963–1968)				
Confined-By-Missile Mixing	X	X	X	
Confined-By-Ground Mixing	X	X	X	
Tank Fallback		X		X
High-Velocity Impact	X	X	X	
Command Destruct		X		
Donor		X		
AEROJET/APOLLO (1965)				
Distributed Mixing*	X	X	X	
NASA MSFC/SATURN (1965)				
Ground Spill	X		X	
Intertank Mixing	X		X	
Command Destruct	X		X	
NASA WSTF/LSHOE (1990–1995)				
Distributed Mixing*	X			
NASA WSTF/PRC (1994–1995)				
Distributed Mixing*		X	X	
NASA WSTF/HOVI (1996)				
Tank Fallback	X			

*Distributed Mixing is also referred to elsewhere as Immersion Mixing.

4.2 Failure History Overview

Data was obtained and analyzed [49]–[64] from the near-pad failures of 33 liquid propellant launch vehicles. These included the vehicles types shown in Table 3. Of the 33 failures studied, two were static test stand failures, thirty failed on or near the launch pad/silo, one occurred in-flight, six failures occurred prior to engine ignition, thirteen failures were instrumented, seven failures were destruct cases, and explosive data has not been obtained for four events.

Table 3. Liquid Propellant Launch Vehicle Failure History

Vehicle	Failures	Propellant
ANTARES	1	LO ₂ /RP-1/ HTPB
ATLAS	5	LO ₂ /RP-1
ATLAS-CENTAUR	1	LO ₂ /RP-1/LH ₂
FALCON 9	1	LO ₂ /RP-1
JUPITER/JUNO	3	LO ₂ /RP-1
N-1	1	LO ₂ /Kerosene
NAVAHO	1	LO ₂ /Ethanol/JP-4
REDSTONE	1	LO ₂ /Ethanol
SATURN S-IV	2	LO ₂ /LH ₂
SPACE SHUTTLE	1	LO ₂ /LH ₂
THOR	4	LO ₂ /RP-1
TITAN I	3	LO ₂ /RP-1
TITAN II	4	N ₂ O ₄ /A-50
TITAN 34D	1	PBAN/N ₂ O ₄ /A-50
VANGUARD	1	LO ₂ /RP-1
V-2	1	LO ₂ /Ethanol
Delta II	1	HTPB/LO ₂ /RP-1
Long March	1	N ₂ O ₄ /UDMH/LO ₂ /LH ₂

5. Review of Past LO₂/Hydrocarbon Test Projects

Following is a brief discussion of the liquid oxygen/hydrocarbon explosive test projects. The discussions are organized according to the experimenter.

5.1 U.S. Navy

Explosive tests were conducted by the Navy to understand the risks associated with deploying liquid propellant missiles on-board Navy ships. These tests were conducted by the David Taylor Model Basin (DTMB), the Naval Research Laboratory (NRL), and the Underwater Explosions Research Division (UERD) of the Norfolk Naval Shipyard.

5.1.1 Operation PUSHOVER

In order to understand the hazards associated with employing missiles on-board ships, the Navy performed two large-scale tests in 1948. The test series involved toppling fully loaded V-2 missiles to determine the explosive potential and blast damage. The tests were called PUSHOVER No. 1 and PUSHOVER No. 2. The V-2 missiles contained 19,400 lb of LO₂/ethanol and involved intentionally toppling each missile and allowing it to rupture and spill its contents on the ground. Each test resulted in a time delay interval between impact and explosion, during which propellant mixing occurred. Overpressure measurements were made during one test. Considerable damage was observed to the deck structure with debris scattered to 600 ft. Yield estimates range from ~20% to ~40% TNT.

5.1.2 NRL Mixing Tests

Extensive follow-on LO₂/ethanol explosive studies were conducted by the Naval Research Laboratory in 1949. Results are TBS.

5.1.3 Jupiter Casualty Study

The Jupiter missile tests were conducted by the UERD in 1956 as follow-on to the LO₂/ethanol tests discussed above and as an extension of the Rocketdyne Field Laboratory testing of LO₂/ethanol and LO₂/JP-5 discussed below. Above-ground testing included numerous small quantity mixing tests, spill tests, free-air premixed tests, and explosive effects on ship structures using 5 lb and 52 lb of LO₂/JP-5 and LO₂/RJ-4 mixtures; simulated missile destruct tests at 1/8 scale of the Jupiter missile using 190 lb of LO₂/JP-5 and LO₂/RJ-4 mixtures in both vertical and horizontal orientations; a 1/8 scale (190 lb) fallback test on a simulated warhead magazine to assess potential magazine damage; and destruct tests using a section of Jupiter tankage with 810 lb of LO₂/JP-5. Underwater testing included small-quantity tests and 52 lb tests of both LO₂/JP-5 and LO₂/RJ-4 mixtures. All larger-scale tests were instrumented with pressure gauges and film, but only the destruct and fallback data were reported. The 52 lb tests were performed by remotely dumping the propellants into an elevated container and initiating the mixture after a 10 sec time delay. Pressure sensors were also located above ground to gather free-air data. The destruct tests were instrumented at 13 ft and 35 ft locations, while the fallback test was instrumented at 25 ft and 50 ft. In the destruct tests the tanks were split using a primer cord and the propellants dumped onto the magazine deck, where a small JP-5 fire was started prior to destruct. All destruct tests resulted in negligible yields while the fallback test was on the order of 17% TNT. The fallback test was deemed sufficient to damage the magazine and exhibited the most severe damage observed in any test performed in these studies. The liquid propellant missile test program concluded that these mixtures were too hazardous for use aboard ship and the Polaris solid-motor program was the preferred option.

5.2 Rocketdyne

Explosive tests were conducted by the Rocketdyne Field Laboratory in order to assess the risks to test stands and supporting infrastructure for rocket engines being developed for new missile programs such as Jupiter and Navaho. The test program also investigated suppression methods in the event of a spill. In both test series, stoichiometric solutions were mixed and gels allowed to form prior to initiation. No auto-ignition events were noted. The tests were conducted in two test projects in 1954 and 1956. The tests in 1954 used stoichiometric mixtures of LO₂/ethanol and LO₂/JP-5 for comparison at 1 lb, 25 lb, and 500 lb mixtures. All propellant tests were conducted by dumping the mixtures simultaneously into a shallow pit and allowing varying delay times prior to initiation. Suppression tests were conducted by adding various quantities of water or a water/soap solution to the mixtures prior to initiation. There were 221 total 1 lb mixture tests, including 19 using LO₂/JP-4, 102 using LO₂/JP-5, and 100 using LO₂/ethanol, some of which included water. The 25 lb spill tests were instrumented at only one location while the 500 lb spill tests were instrumented at 25 ft and 50 ft locations with a 10 sec ignition delay. Conclusions included an observation that peak explosions occurred for LO₂/JP-5 gels at ignition delays around 10 sec as they began to tail off above 20–25 secs as the fuel solidified and the LO₂ boiled off. For LO₂/ethanol the peak time extended to 20 sec.

The tests in 1956 again used stoichiometric mixtures of LO₂/ethanol and LO₂/JP-5 but only used LO₂/ethanol for comparison in 1 lb tests (18 tests). In addition to 123 total 1 lb tests, LO₂/JP-5 was tested at 1 lb increments up to 10 lb (32 tests) and also at 15.25 lb, (4 tests), 20 lb (1 test), 30.5 lb (50 tests), 61 lb (69 tests), 91.5 lb (5 tests), 122 lb (7 tests), 152.5 lb (5 tests), 500 lb (5 tests), 610.5 lb (1 test), and 1,000 lb (3 tests) mixtures. Two test configurations were used. One employed impinging propellant streams into a pit, while the other dumped propellant containers simultaneously into a shallow pit allowing varying delay times prior to initiation. The impinging streams were difficult to control, and this test configuration gave spurious results as only 2 of 107 tests produced useable data. Two locations were used depending on the quantity.

The smaller-quantity tests were performed adjacent to a rock embankment between two existing masonry walls. The rock outcropping was about 40 ft tall and was used to separate the explosions from the equipment and personnel. However, it is clear from the pressure readings that this produced significant reflected components. This test configuration lends a significant degree of uncertainty in the results. Pressure sensors were located at two distances for each test through 500 lb and multiple locations for the 1,000 lb tests. Conclusions included a finding that the LO₂/JP-5 explosions were more energetic than standard explosives and a recommendation that 100% TNT equivalence be used for safety purposes. A follow-up assessment of these data by Rocketdyne's Analysis Department concluded that the appropriate yields ranged from 25% to 56% TNT, depending on reaction time delay of the mixture.

5.3 U.S. Army ABMA

The Army Ballistic Missile Agency (ABMA) investigated implementing a deliberate self-destruct capability on the Redstone missile during testing in 1956. The testing was done with Redstone tankage and center section using LO₂/ethanol to determine the reduced explosive potential due to missile malfunction. Results are TBS.

5.4 Broadview Research Corporation

From 1957 through 1961, the Broadview Research Corporation conducted a series of explosive tests in order to investigate the explosive potential of the Atlas missile. This project was intended to characterize the hazard potential of the Atlas LO₂/RP-1 propellant combination. The initial work used LO₂/JP-4 propellants. These tests were conducted using 4 lb and 42 lb quantities in spill tests at vehicle mixture

ratios. Scale model testing was then performed using 42 lb and 250 lb of LO₂/RP-1 in simulated tankage with the propellants oriented as in flight at flight mixture ratios. The testing simulated missile failures in seam-rip and fallback modes. These tests were conducted on a flat pad, a simulated missile launcher, and a simulated missile silo. Pressure sensors were located at various distances along three or four axes for each test.

A follow-on test program was conducted that investigated the explosive potential of large liquid propellant missiles in underground silos. Since prior studies had determined that the overall explosive efficiency of these propellants depended on the time of initiation and that when well mixed exceeded the yield of typical high explosives, the hazard potential was dependent on specific failure conditions. Therefore, the assumed full-scale in-silo failure scenario consisted of seam rip. To address the full-scale failure scenario, a series of failures were simulated with various scale models (1/40, 1/18, and 1/10) that were judged adequate to extrapolate to full-scale. The LO₂/RP-1 propellant weights associated with these scales were 4 lb, 42 lb, and 250 lb quantities. The majority of tests were conducted with the missile suspended in fully lowered position, the silo otherwise empty with a scaled lid in place, failure simulated by seam rip, then sparking ignition from various locations in the silo. The variety of conditions included early bottom only sparking, delayed bottom sparking, and a shroud-insulated missile. Pressure sensors were located along the silo walls, in the tunnels, and above ground to analyze the in-silo as well as external effects. As a result of these tests, 20% was taken as the upper limit of TNT yield for an in-silo Atlas maximum credible event (MCE) explosion.

5.5 A. D. Little Company

Beginning in early 1960, the A. D. Little Company performed a series of LO₂/LH₂ experiments for the Centaur and Saturn programs. The LO₂/LH₂ tests consisted of small-scale (3 lb and 4 lb) tank mixing and small- to medium-scale (45 lb and 225 lb) spill tests. The tank mixing tests consisted of vertically oriented dewars that were shattered almost simultaneously. In the spill tests, unpressurized tanks were positioned above ground then tipped, resulting in the mixing of the impinging streams. This mixture was then initiated with explosive charges of C-4 or other initiator. The objective of this project was to predict the blast effect of the Atlas-Centaur or Saturn vehicles should they fail at launch. Pressure data were collected along one gage line. Tests were performed for LO₂/RP-1 and tripropellant LO₂/LH₂/RP-1 combinations in addition to the cryogenic LO₂/LH₂ tests. The LO₂/LH₂/RP-1 spill tests consisted of small- (9 lb and 35 lb), medium- (110 lb and 530 lb), and large-scale (44,000 lb) tests. Experimental results were calculated as TNT equivalent yield for these experiments. These calculations were not based on the total quantity of propellant used in the experiment, but on the quantity of propellant that was estimated to have mixed. Two of the small-scale and all large-scale tests ignited prematurely. However, the large-scale tests were all tripropellant mixtures.

5.6 NASA Marshall Space Flight Center (MSFC)

Beginning in 1964, NASA/MSFC performed a series of LO₂/LH₂ tests to compare results using a spill mode to tests using simulated tank geometries. The objective of these tests was to address the validity of the TNT equivalence of LO₂/LH₂ developed by A. D. Little for the Saturn/Apollo program. The premise for the test program was that the spill test methods previously used to establish TNT equivalence were not representative of realistic failure modes and resulted in excessively high yields. This position was based on the post-accident investigations of full-scale Saturn S-IV stages. Both of these failures were confined-by-missile (CBM) types of failures.

The spill mode experiments used an apparatus very similar to the A. D. Little tests. The simulated tank experiments included destruct tests as well as a CBM configuration. The CBM tests used an apparatus consisting of a single tank separated by a glass diaphragm, and the destruct tests were separate tanks with

external cutters. In the CBM apparatus, explosive charges were used to break the diaphragm or the tanks and allow the LH₂ and LO₂ to mix. Pressure data were taken along three gauge lines, which were a total of 80 degrees apart. All tests were medium-scale (200 lb). An equal number of LO₂/RP-1 tests were also performed for comparison. Self-ignition occurred in a third of the spill tests and all of the simulated tank experiments.

During some of the experiments, MSFC also noted that the apparent TNT equivalence was biased because the center of the explosion was shifted closer to the transducer station than expected. In another spill experiment that self-ignited, the LH₂ ignited in air during the spilling process but before coming into contact with the LO₂. Recorded pressures were not significant and suggested that most of the LH₂ was consumed by a GH₂/air reaction. Yields from the simulated tank failures were significantly less than those from the spill tests, and the LO₂/RP-1 yields were greater than for LO₂/LH₂. No appreciable yield was recorded during the CBM experiments. From the CBM experiments, MSFC concluded that the siting criteria for LO₂/LH₂ vehicles were “unnecessarily conservative and should be re-examined.”

5.7 Aerojet-General

In 1965, Aerojet-General conducted experiments that supported hazard assessments for the Apollo program. The objective was to reduce the uncertainty in quantifying the explosive potential by controlling/maximizing the propellant mixture. Previous tests were performed by Aerojet-General in 1963 and 1964 for the Gemini program using LO₂/RP-1 and N₂O₄/A-50, and additional LO₂/RP-1 and N₂O₄/A-50 tests were performed during this Apollo test series. In these experiments, glass dewars containing LO₂ were distributed and immersed throughout a metal pan containing LH₂. An external shock was transmitted through the metal pan to rupture the glass dewars, resulting in instantaneous mixing of the propellants. Tests were performed with an oxidizer/fuel weight ratio of 5, while the contact area was varied. The tests were all medium-scale (100 lb and 225 lb). Pressure data were taken along three gauge lines approximately 120 degrees apart, radiating from the center of the test apparatus. Similar to MSFC experiments, the LH₂ and LO₂ reacted spontaneously and self-ignited when the LO₂ dewars were shattered.

5.8 URS Corporation (Project PYRO)

Project PYRO was the largest of the liquid propellant explosion studies. This was an extensive experimental project conducted in the early- and mid-1960s to establish the blast environment for the three common liquid propellant combinations—LO₂/RP-1, LO₂/LH₂, and N₂O₄/A-50. In the PYRO LO₂/RP-1 experiments, propellant quantities ranged from medium (200 lb) to large-scale (25,000 and 94,000 lb) at a 2.25:1 mixture ratio. In total, 73 successful LO₂/RP-1 tests were performed, ~18% of which were reported to auto-ignite. Four series of experiments were conducted to simulate a variety of postulated failure modes. These were identified as confined-by-missile (CBM), confined-by-ground surface (CBGS), high-velocity impact (HVI), and a full-scale test. The PYRO CBM apparatus was similar to the MSFC CBM apparatus consisting of a single tank separated by a glass diaphragm. However, in the PYRO tests the diaphragm was broken using a cutter ram driven by an explosive charge.

In the CBGS experiments the glass diaphragm in the tank was broken by dropping the tank from a tower onto a cutter ram. The CBGS tests were conducted in both vertical and horizontal tank orientations (CBGS-V and CBGS-H) while four vertical tests inverted the propellant orientation. The full-scale test simulated a Titan I first stage. Two large-scale tests were planned, but only one provided data. For the CBM, CBGS, and the full-scale test, three gauge lines, approximately 120 degrees apart, extended radially from the center of the test site.

Results were given as a function of time delay and failure mode. In general, the PYRO CBM tests resulted in maximum TNT far-field equivalent yields of 53% for small-scale (200 lb), 17% for medium-scale (1,000 lb), and 3% for full-scale (94,000 lb) tests. The CBGS tests resulted in maximum TNT far-field equivalent yields of 58%, 59%, and 85% for small-scale (200 lb), 76% and 81% for medium-scale (1,000 lb), and 34% for large-scale (25,000 lb) tests as a function of drop height. The 200 lb HVI impact tests resulted in maximum TNT far-field equivalent yields of 19% and 64% as a function of impact surface. One CBGS tripropellant LO₂/LH₂/RP-1 test was conducted in which a two-stage vehicle failure was simulated. The bottom stage consisted of 1,000 lb of LO₂/RP-1, while the upper stage held 200 lb of LO₂/LH₂. Drop height was intermediate to the bipropellant tests and resulted in an average TNT far-field equivalent yield of 66% overall.

5.9 NASA White Sands Test Facility (WSTF)

Beginning in the early 1990s a series of propellant tests were performed at the NASA WSTF. The tests were separated into three programs. The first was the Large-Scale Hydrogen/Oxygen Explosion (LSHOE) test program, the second was the Propellant Reaction Characterization (PRC) test program, and the third was the Hydrogen/Oxygen Vertical Impact (HOVI) test program. LSHOE was a joint Air Force/NASA/DoE program that was intended to address the LO₂/LH₂ explosive potential to support analysis of the Cassini spacecraft radioisotope thermoelectric generator (RTG) safety issues resulting from the failure of the Titan IVA launch vehicle. PRC testing was an extension of the LO₂/LH₂ distributed mixing tests performed by LSHOE in order to characterize the maximum yield from other possible propellant mixtures resulting from a Titan IVA/Centaur failure. HOVI was a Japan-funded test program conducted in 1996 to study cryogenic explosions from propellant tank fallback impacts. The test programs included development of hydrodynamic mixing and reaction models. LSHOE planned to conduct a series of distributed mixing tests of medium-scale (150 lb and 500 lb), followed by a large-scale test of at least 10,000 lb of LO₂/LH₂. However, the LSHOE tests were discontinued prior to completing the large-scale test, and the PRC tests were performed in their stead. The PRC tests included immersion testing of 150 lb mixtures of LO₂/MMH, N₂O₄/MMH, N₂O₄/LH₂, LO₂/RP-1, and H₂O₂/Jet-A. Two LO₂/RP-1 tests were performed at 150 lb and one at 100 lb, while two 150 lb H₂O₂/Jet-A tests were performed. One of the 150 lb tests was a stoichiometric mixture. The LO₂/RP-1 PRC tests were all conducted at a relatively medium-to-high interface area ratio and yielded TNT equivalencies of 60% to 98%. It was noted by Taylor, who performed the post-test analysis for all three test programs, that the relatively large yield of the LO₂/RP-1 tests compared to LO₂/LH₂ was “striking.” The H₂O₂/Jet-A tests on the other hand were conducted at much lower interface area ratios and yielded TNT equivalencies of 16% to 18%.

6. LO₂/Hydrocarbon Explosive Assessment

6.1 Assessment Methodology

Due to observed differences in explosive yield assessment methods used by the various experimenters and analysts, as part of the original study [6] all liquid propellant explosion data were analyzed using a consistent methodology. The approach used was as follows:

- Data values were corrected as needed where calibration data were available
- Identified instrumentation faults were discarded
- Yields were calculated in terms of overpressure
- Far-field measurements were averaged
- All data recalculated using Kingery's surface-burst factors to establish TNT % yields

The TNT percent yields derived for all tests and failures were then compiled by mass and mixing scenario. To accomplish this the following mixing scenarios were defined:

STATIC MIXING

- Propellant spills from tank rupture/leakage
- Inter-tank bulkhead rupture
- Vehicle destruct test cases included
- Static conditions ≤ 10 ft/sec

DYNAMIC MIXING

- Vertical fallback impact
- Horizontal fallback impact (toppling)
- Vehicle destruct flight failures not included
- Dynamic conditions ≤ 150 ft/sec

HIGH-VELOCITY IMPACT MIXING

- Powered impact
- HVI conditions > 150 ft/sec

DISTRIBUTED (IMMERSION) MIXING

- Matrix of propellant immersed within a bath

DONOR MIXING

- Secondary reaction resulting from initial (smaller) explosion
- Data included in Dynamic Mixing

6.2 LO₂/Hydrocarbon Vehicle Failures

Results of the independently performed explosive yield analyses from data obtained from [49]–[64] for the liquid oxygen/hydrocarbon propellant launch vehicle failures are tabulated in Table 4 below by vehicle. Included are the propellant type and quantity, failure mode and estimated explosive yield

resulting from the failure reaction. The Atlas-Centaur failure was analyzed for single stage as well as total vehicle yield using the pressure instrumentation data and reconstruction of the accident scenario.

Table 4. LO₂/Hydrocarbon Launch Vehicle Failures

Vehicle	k lb	Mode	Propellants	Yield (%)
ANTARES	532	Fallback	LO ₂ /RP-1	Unk
ATLAS				
Atlas 9C	250	Toppling ²	LO ₂ /RP-1	11.5%
Atlas 51D	250	Donor ²	LO ₂ /RP-1	1.9%
Atlas 48D	250	CBM ²	LO ₂ /RP-1	2.8%
Atlas 11F	250	Fallback ²	LO ₂ /RP-1	1.5%
Atlas 3D	250	Destruct @ 4000' ²	LO ₂ /RP-1	0%
ATLAS-CENTAUR				
Atlas-Centaur 5	254	Fallback/Donor ²	LO ₂ /RP-1/LH ₂	4.5%
Falcon 9				
Falcon 9 V9 ¹	1,140	CBM	LO ₂ /RP-1	Unk
JUPITER				
Jupiter 9A	60	Impact	LO ₂ /RP-1	11%
Jupiter 23	60	Impact ²	LO ₂ /RP-1	4.7%
JUNO II				
Juno II 16	109	Destruct @ 60' ²	LO ₂ /RP-1	0%
NAVAHO				
Navaho AT-53	76	Fallback ²	LO ₂ /Ethanol	1.3%
REDSTONE				
Redstone 3	44	CBM	LO ₂ /Ethanol	2.2%
THOR				
Thor 101	100	Fallback	LO ₂ /RP-1	0.9%
Thor 103 ¹	100	CBM ²	LO ₂ /RP-1	2.2%
Thor 107	100	Fallback ²	LO ₂ /RP-1	3.6%
Thor 121	100	Fallback ²	LO ₂ /RP-1	2.0%
TITAN I				
Titan I B-5	209	CBM	LO ₂ /RP-1	1.5%
Titan I C-3	209	Fallback	LO ₂ /RP-1	2.0%
Titan I J-2	209	Destruct @ 500'	LO ₂ /RP-1	0%
VANGUARD				
Vanguard TV-3	16	Fallback ²	LO ₂ /RP-1	3.3%
V-2				
V-2	19	Fallback	LO ₂ /Ethanol	43%
N-1				
N-1 5L	5,500	Fallback	LO ₂ /Kerosene	17%–45%
¹ Pre-Ignition Event				
² Instrumented Failure				

6.3 LO₂/Hydrocarbon Data Assessment

The plots in Figure 3 through Figure 10 the results of this assessment. Figure 3 and Figure 4 below include all liquid oxygen/hydrocarbon data points (LO₂/RP-1, LO₂/ethanol, LO₂/JP-5, and other jet fuels) whether from tests or failures. Each data set is identified by mixing mode. The data were then assessed for large-scale ($\geq 1,000$ lb) conditions and the 95% upper limits established for each data set (i.e., static or dynamic mixing) for each propellant combination.

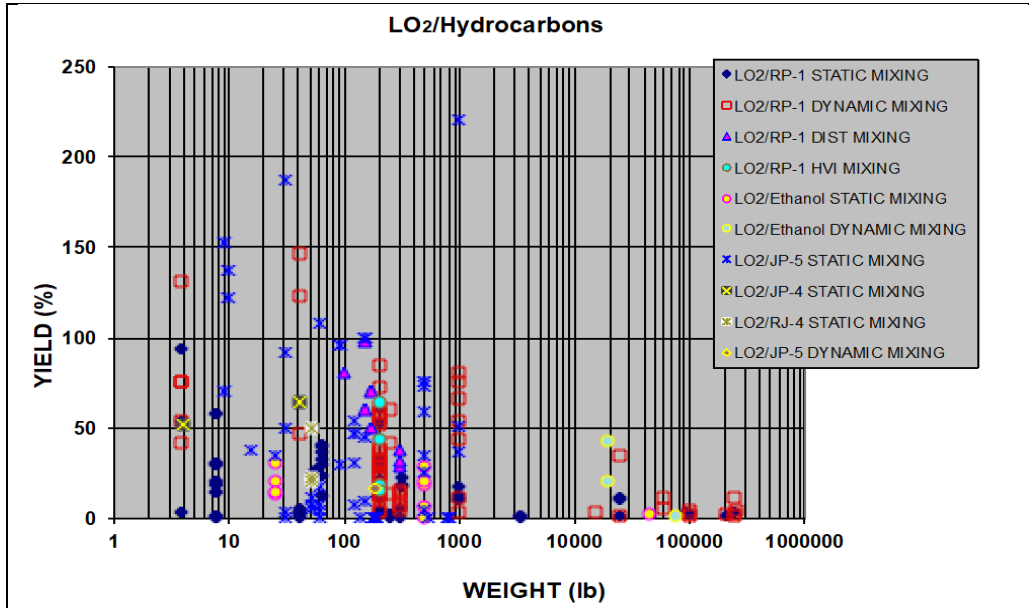


Figure 3. EEW yields for LO₂/hydrocarbons.

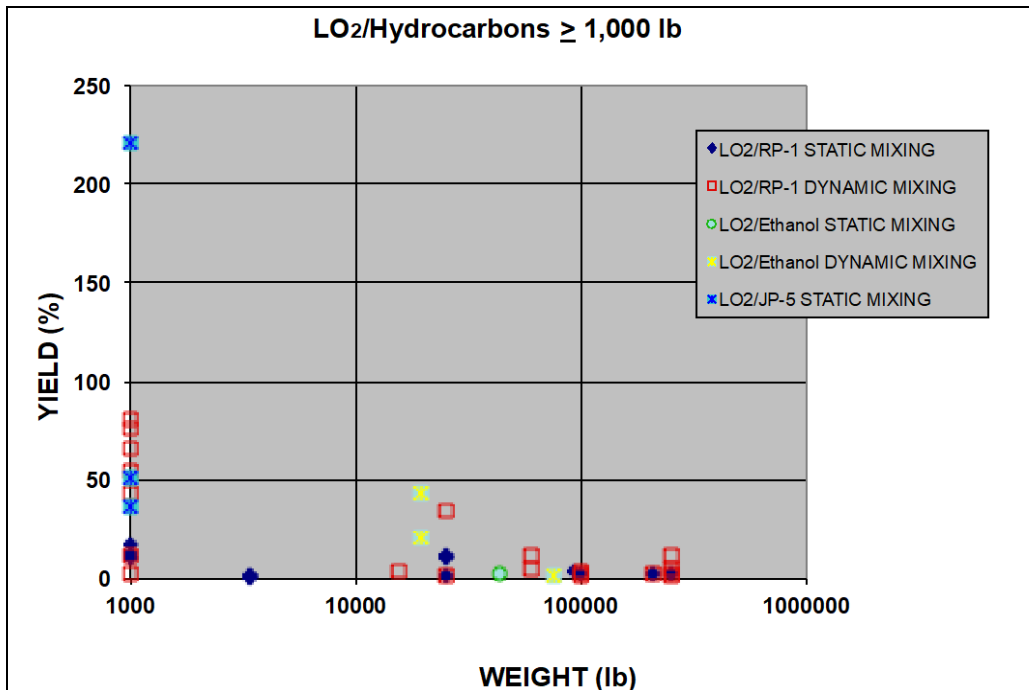


Figure 4. EEW yields for LO₂/hydrocarbons $> 1,000$ lb.

6.3.1 LO₂/RP-1 Data

Figure 5 shows all RP-1 data and Figure 6 includes the 95% upper confidence level for static and dynamic mixing modes for the data $\geq 1,000$ lb.

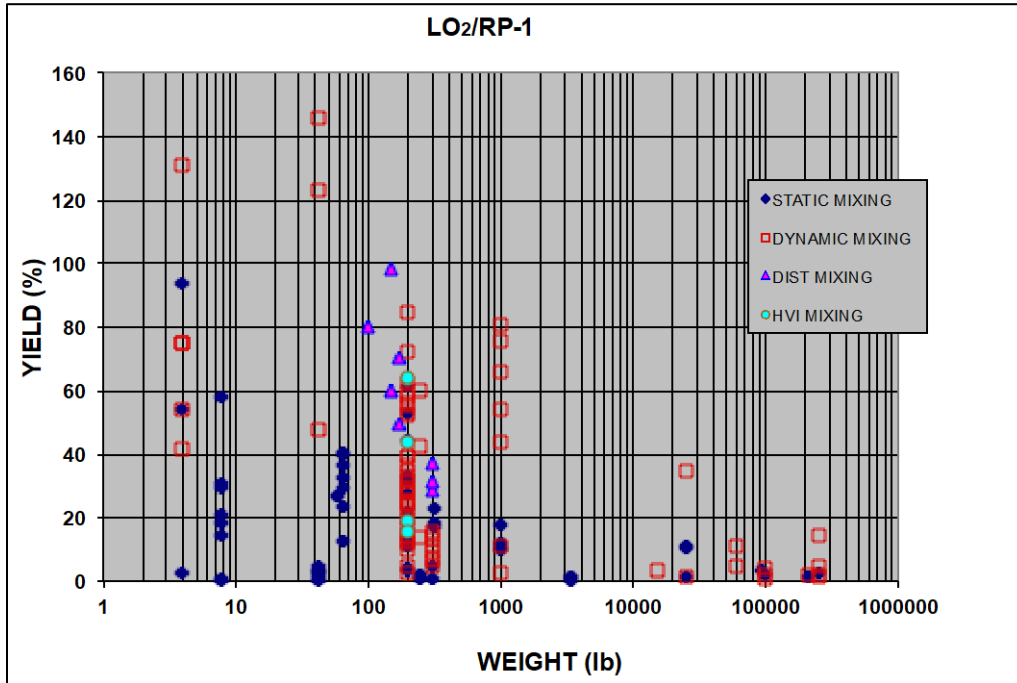


Figure 5. EEW yields for all LO₂/RP-1 tests/failures.

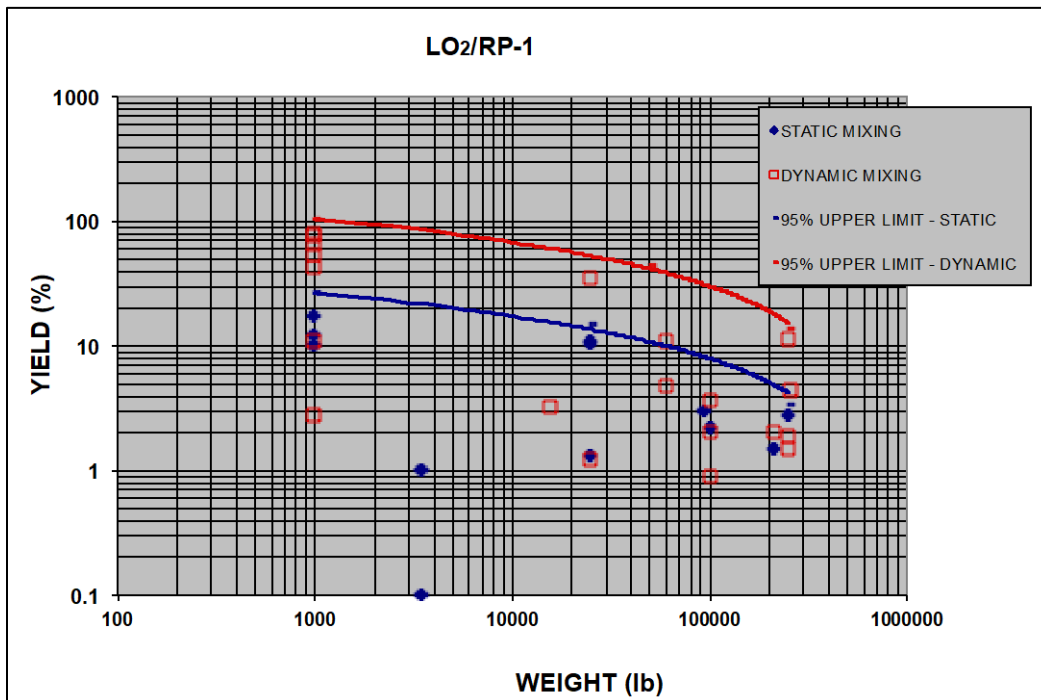


Figure 6. 95% confidence limit for LO₂/RP-1 EEW yields.

6.3.2 LO₂/Ethanol Data

Figure 7 shows all ethanol data obtained to date while Figure 8 compares the ≥ 500 lb ethanol data including 95% upper limit values to LO₂/RP-1 $\geq 1,000$ lb data and 95% upper limit plots.

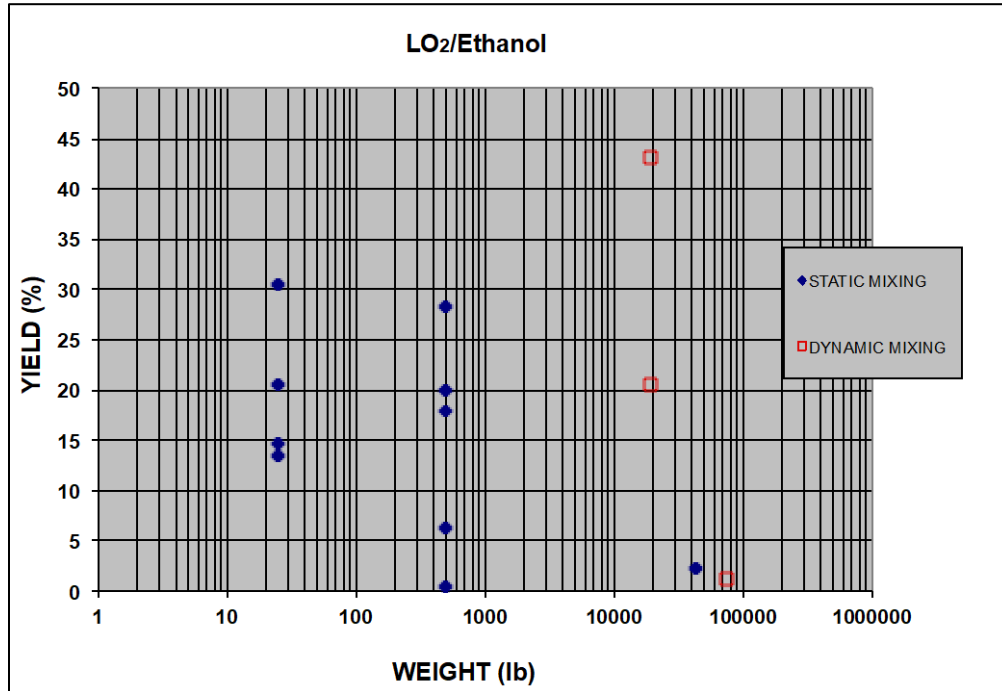


Figure 7. EEW yields for all LO₂/ethanol tests/failures.

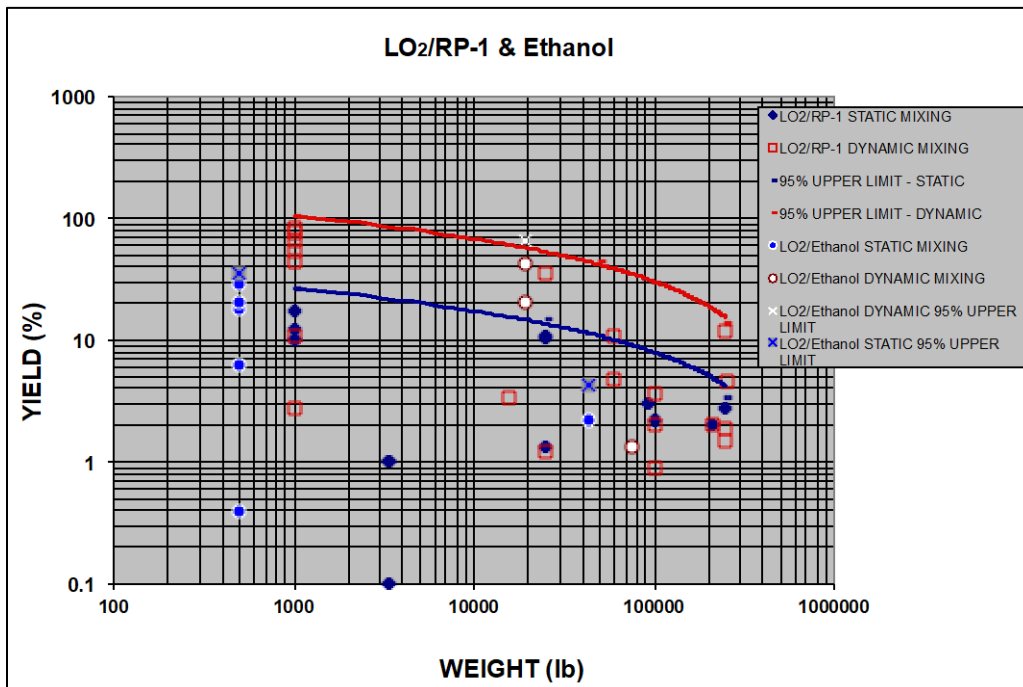


Figure 8. 95% confidence limit for LO₂/RP-1 & LO₂/ethanol EEW yields.

6.3.3 LO₂/Jet Fuel Data

Figure 9 shows all jet fuel data obtained to date, and Figure 10 compares the JP-5 and ethanol data to LO₂/RP-1 upper 95% confidence level data for static and dynamic mixing modes.

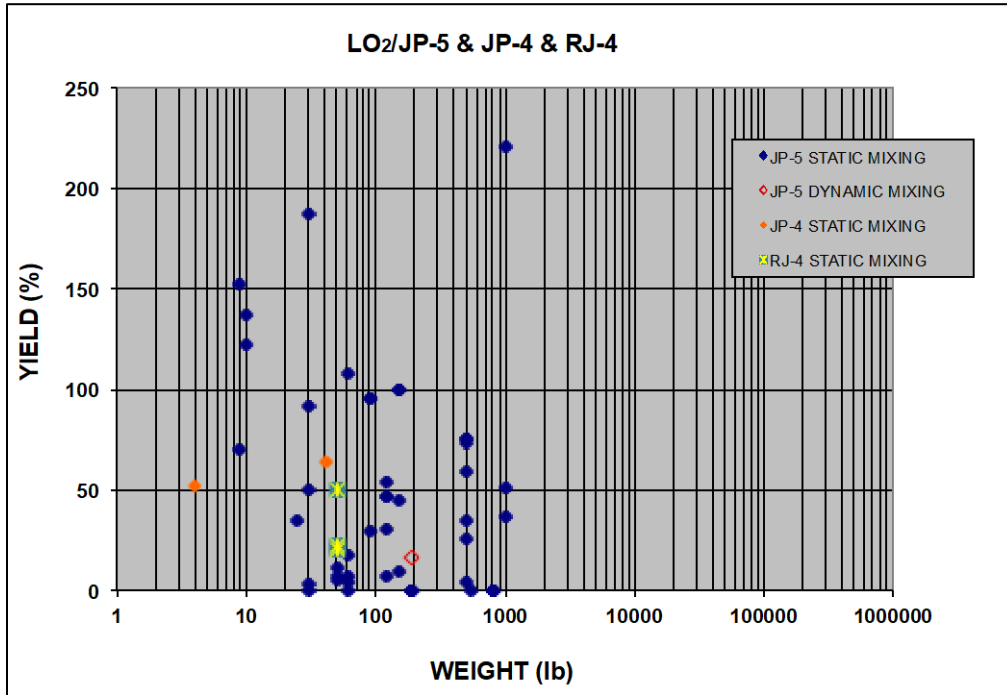


Figure 9. EEW yields for all LO₂/jet fuel tests/failures.

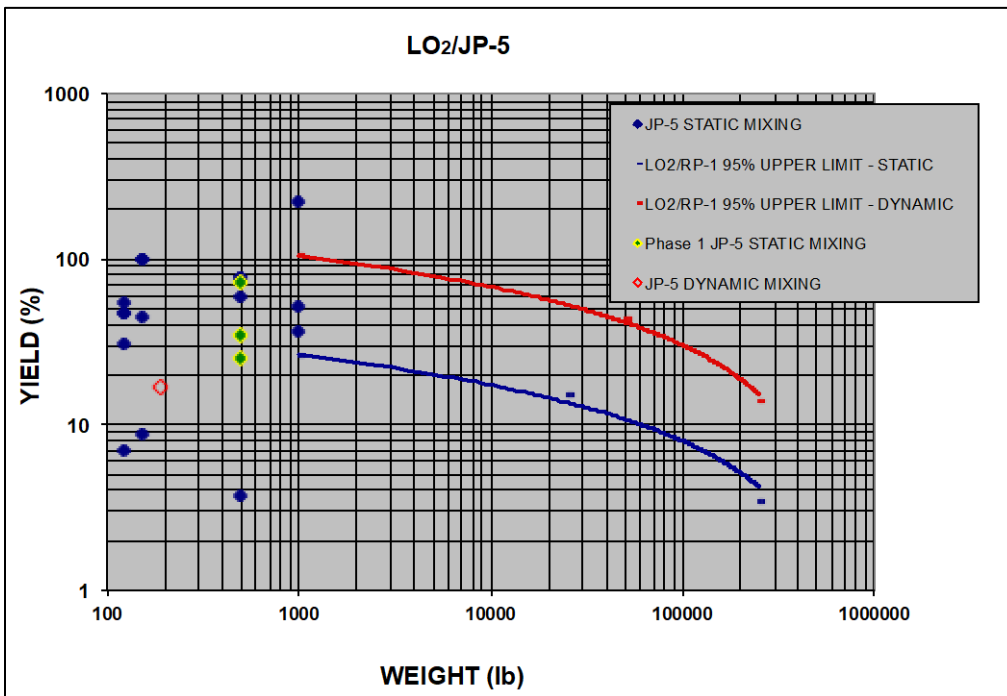


Figure 10. 95% confidence limit for LO₂/RP-1 & LO₂/JP-5 EEW yields.

6.4 Discussion

6.4.1 LO₂/RP-1 Results

As mentioned above, since the initial assessments presented in [2], several updates were made for this analysis. One modification is the data segregation by propellant combination rather than combining all liquid oxygen/hydrocarbon propellant combinations into a single assessment. The other change involved acquiring more complete sets of the raw Pad Abort Measurement System data for the respective failures and re-assessing. Lastly, additional test reports were obtained and those data incorporated as well. The plots above reflect the changes in this assessment. The primary differences between the preliminary data of [2] and this final assessment stem from the separation of the LO₂/RP-1 and LO₂/ethanol data. By separating the data, a true LO₂/RP-1 yield assessment can be made. These LO₂/RP-1 yields still reflect the influence of dynamic mixing relative to static conditions.

One area of discussion is to revisit the comparison of LO₂/RP-1 and LO₂/LH₂ in terms of explosive potential as determined from their relative yields. Two plots were updated that compare the two propellant combinations to the various tripropellant LO₂/RP-1/LH₂ test results as shown in Figure 11 and Figure 12 below. It is clearly evident from this data that the LO₂/RP-1 reaction dominates the tripropellant results. These two plots are important to understand the relative yields between the cryogenic LO₂/LH₂ and LO₂/hydrocarbon bipropellant combinations. Additional comparisons will be made later, but the observations made during the initial studies documented in [2], and other papers from that time, substantiate the conclusion that the current approach being used to establish LO₂/hydrocarbon EEWs is not valid.

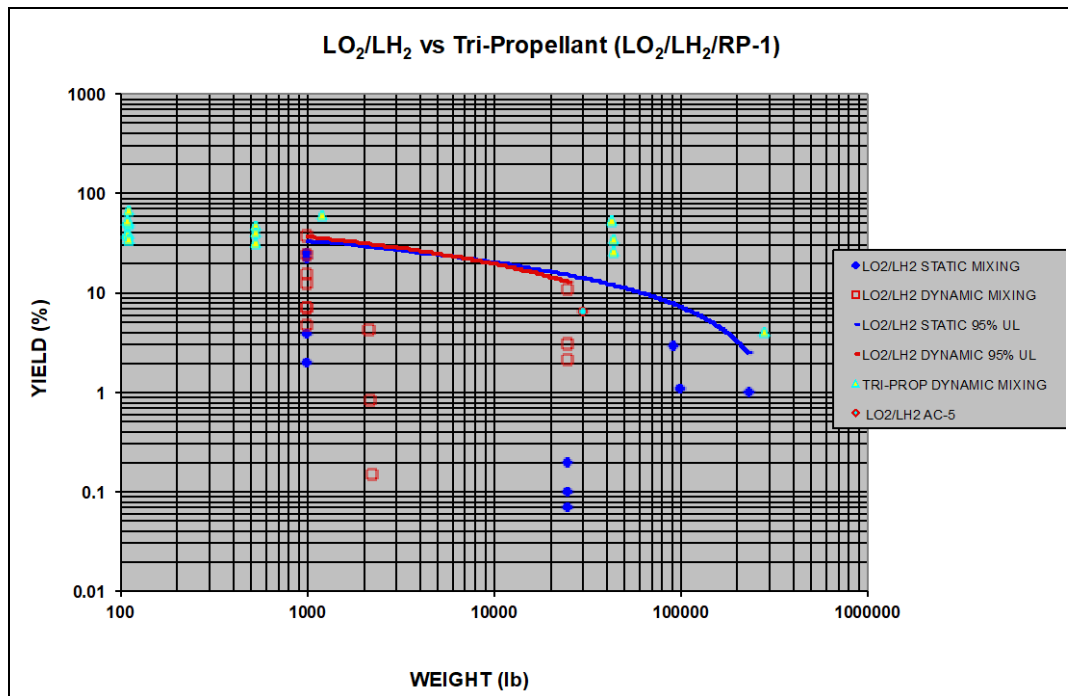


Figure 11. Tripropellant EEW yield comparison to LO₂/LH₂.

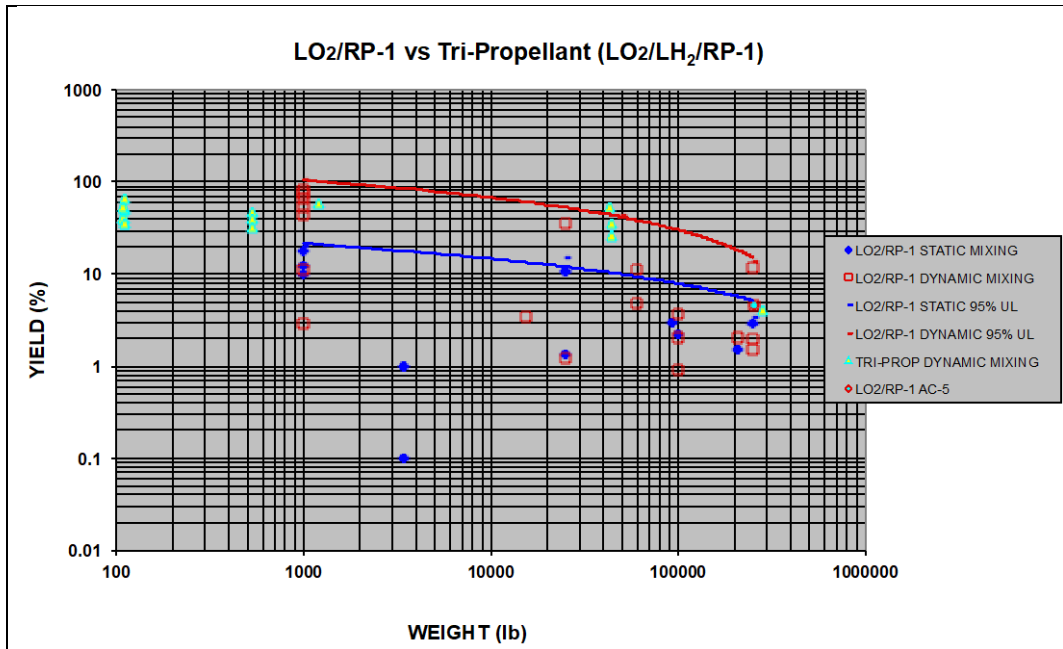


Figure 12. Tripropellant EEW yield comparison to LO₂/RP-1.

As a result of these findings, a new approach was taken to be able to establish the equivalent explosive yield (EEW) of any energetic bipropellant combination as a function of available propellant mass. In this report, updated LO₂/RP-1 yield curves were created using the revised data set shown in Figure 5. The yield curve is created by converting the percent yield vs. propellant weight plots in Figure 6 into TNT weight (W_T) vs. propellant weight (W_P) plots for both the static and dynamic 95% upper limit cases and performing curve fits.

The resulting yield curves as shown in Figure 13 are $W_T = 1.8W_P^{3/4}$ for static and $W_T = 7W_P^{3/4}$ for dynamic conditions. Similar to the preliminary LO₂/RP-1 assessment and the LO₂/LH₂ yield assessment discussed in Appendix A, the data in Figure 6 above infers that LO₂/RP-1 may reach a limiting yield condition under both static and dynamic mixing conditions. This is often attributed to the auto-ignition of these propellants limiting the mixed mass prior to initiation as discussed in Appendix B. However, discussion of other failure data in Appendix B suggests that this limiting condition assumption may not be valid under certain dynamic and vehicle configuration conditions. Therefore, attempting to implement a maximum limit approach is not recommended and is not pursued in Figure 13.

In Figure 13 the yield curves are shown along with the current DESR 6055.09 values. The results are conclusive in that the static results for vehicle-scale quantities are somewhat less than the current 10%, but the dynamic yields are greater than the current 20% at the same scale. In fact the LO₂/RP-1 Dynamic Yield Curve does not decay to the 20% level until $W_P = 1,500,000$ lb, when $7W_P^{3/4} = 300,031$ lb W_T . An additional finding is that the current practice of reducing the percent yield from 20% to 10% for W_P quantities > 500,000 lb cannot be substantiated. This was apparently an attempt to account for mass-scaling but no evidence can be found as to how it was derived. The yield curve equations proposed here, and as established for the LO₂/LH₂ criteria, more realistically represent the mass/yield function. Additional justification for implementing these yield curves can be seen in Figure 18 of Appendix B.

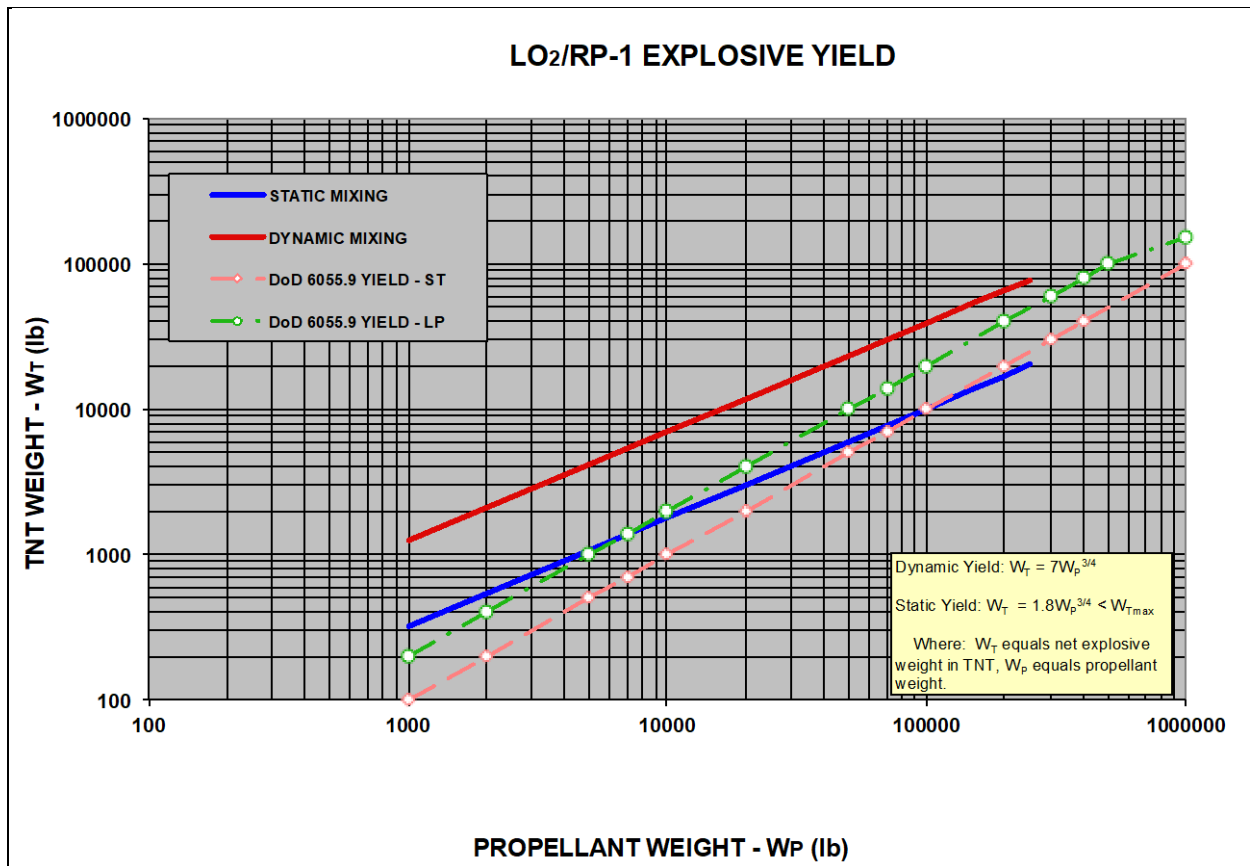


Figure 13. LO₂/RP-1 yield curves and current DESR 6055.09 values.

Using these data, an updated transition yield curve was developed similar to that for LO₂/LH₂, as described in Appendix A. This transition plot is shown below in Figure 14 and is identified as recommendation Option 2 in the assessment. It results in establishing constant percent yield values of 8% for static and 30% for dynamic mixing at 300,000 lb. Thus the factor of 2 difference currently used in the criteria (10% vs. 20% up to 500,000 lb) is in reality nearly a factor of 4 difference between dynamic (launch pad) and static (test stand) conditions. It can also be observed that under static conditions LO₂/LH₂ (at 14%) is twice as energetic as LO₂/RP-1 but half as energetic under dynamic conditions. This again is due to the much stronger propensity for auto-ignition of LO₂/LH₂. This also explains a troubling observation noted over the years regarding the damage associated with full-scale liquid oxygen/hydrocarbon failures when compared to LO₂/LH₂, which at the time had a threefold greater yield value (60% vs. 20%) in the criteria.

Figure 14 also includes the LO₂/RP-1 yield curves identified as recommendation Option 1. The LO₂/RP-1 Dynamic Yield Curve is greater than the current 20% in all cases up to 1,000,000 lb and would be as high as 70% at 10,000 lb. However, the yield curve crosses under 30% at 300,000 lb W_P, which will benefit larger boosters. At W_P = 1,000,000 lb the yield would be at 22% (220,000 lb TNT), whereas today the effective yield would be 15% (150,000 lb TNT). In the static case the yield curve would be above the current 10% up to 100,000 lb then drop below 10% for all cases above that weight. It would also drop below 8% at 300,000 lb and be at 6% (60,000 lb TNT) at 1,000,000 lb. Therefore 300,000 lb is the crossover between the two options for both cases. Using the yield curve approach will benefit the larger boosters and test stands.

The yield curves should not be applied to quantities less than 1,000 lb or to operations other than those involving launch vehicles, space vehicles, missiles, stages, engines, or components on static test stands or launch vehicles or missiles in the launch configuration. For quantities < 1,000 lb or for other potential explosive sites, the distributed mixing test (DMT) data from Figure 5 was used to establish a maximum credible yield given the uncertainty of operating conditions and small quantities. Therefore for these conditions the TNT EEW should be 125% W_p .

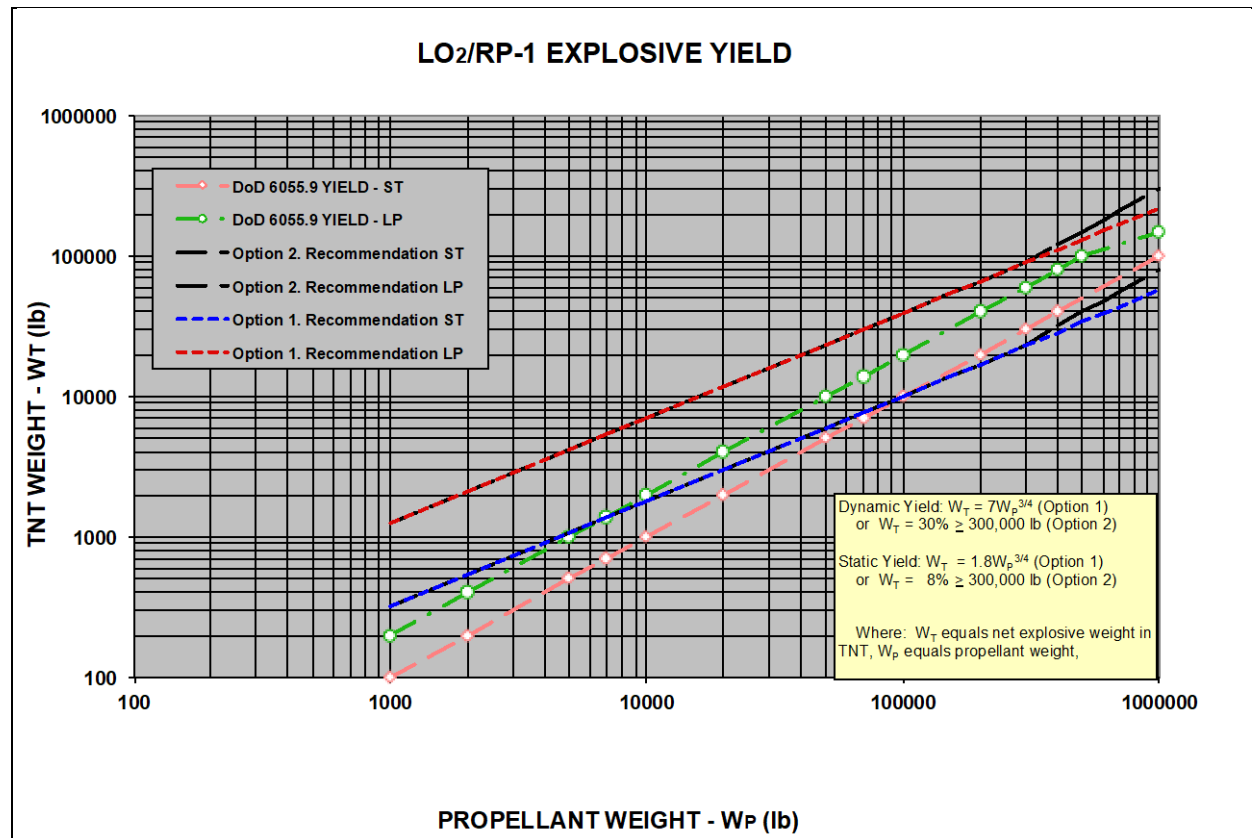


Figure 14. Proposed LO₂/RP-1 EEW recommendations and current DESR 6055.09 values.

6.4.2 LO₂/Ethanol Results

Although large-scale data is limited, a common scale assessment indicates that the LO₂/ethanol reaction is estimated to be on the order of 20% more energetic than LO₂/RP-1. Similar yield curve plots were also created for LO₂/ethanol that resulted in $W_T = 2.1W_p^{3/4}$ for static and $W_T = 8.2W_p^{3/4}$ for the dynamic case. Yield curve transition values at $W_p = 300,000$ lb are 9% for static and 35% for dynamic mixing. Recommendation options similar to those for LO₂/RP-1 were presented in Figure 2 and won't be repeated here. For quantities < 1,000 lb or for other potential explosive sites the LO₂/RP-1 distributed mixing (DMT) data were extrapolated to establish a maximum TNT EEW for LO₂/ethanol of 145% W_p .

6.4.3 LO₂/JP-5 Results

Results for the other available LO₂/hydrocarbon propellant data are problematic due to the test configurations and limited reporting. This can be seen in the above data plots in Figures 9 and 10. The Rocketdyne data was kept separate between the two test programs. The data were organized as Phase 1 and Phase 2 due to test configuration issues. The JP-5 data were also corrected for face-on overpressure measurements using TNT calibration data. The distributions can be seen to not only far exceed any other

like propellant combinations, but also in one case exceed theoretical values, and are highly inconsistent within each test series. It should be pointed out that determining a yield estimate was not the intent of the Rocketdyne test program, therefore, these issues did not affect their conclusions. However, for purposes of completeness, a similar scale assessment can be made that implies (at low confidence) that these propellants could be somewhat more energetic than LO₂/ethanol. The similar yield curves would therefore be $W_T = 2.2W_P^{3/4}$ for static and $W_T = 8.6W_P^{3/4}$ for the dynamic case. Although tentative, these values could be used in lieu of performing a comprehensive test program; however, for this assessment it is recommended that the LO₂/RP-1 EEW method be substituted for all LO₂/jet fuel combinations until an adequate test program is performed.

7. Findings and Recommendations

The findings and recommendations shown below encompass the results of both the prior analyses along with the specific results of this latest LO₂/hydrocarbon assessment.

7.1 Findings

- Although explosions produced by liquid propellants are significantly different from TNT, the explosive yield in the far-field approximates that of TNT
 - Therefore TNT equivalence is an acceptable criterion for test stand and launch pad siting
- Liquid propellant yields vary with mixing conditions, particularly the LO₂/hydrocarbon combinations
- Liquid propellant combination sensitivity to physical environment varies
 - Due to differences in reaction phase
- Prediction models of explosive yield that do not include large-scale test and failure data can be in error by an order of magnitude
- Liquid propellant % yield decreases as mass increases
 - Therefore yield curves rather than constant % TNT equivalence is a more appropriate criterion
- Liquid propellants tend to react spontaneously (Figure 19)
- Launch vehicle explosions often display yield asymmetry (See Figure 20)
- Limited or biased test conditions can result in significant under- or over-prediction of explosive yields under vehicle failure conditions
- LO₂/RP-1 static vs. dynamic yields differ by a factor of 4
 - These results agree with the findings of Project PYRO's CBGS conclusion
- Cryogenic LO₂/LH₂ propellant yields are governed by a gas phase spontaneous-reaction mechanism
- Liquid LO₂/LH₂/hydrocarbon tripropellant yields are dominated by the LO₂/hydrocarbon reaction
- Cryogenic LO₂/LH₂ propellants can achieve maximum TNT yields under static mixing conditions, while LO₂/hydrocarbon propellants achieve maximum TNT yields under dynamic conditions

- LO₂/hydrocarbon propellants represent a greater explosive hazard than cryogenic LO₂/LH₂ under typical vehicle failure conditions
 - Except for static conditions and high-velocity impact
- Reaction time delay governs net explosive yield
 - However, this cannot be generalized for other cryogenic combinations
- Liquid propellant combinations tested to date do not act like HD 1.1 explosives
 - Only mixed quantities explode as rapid deflagration
 - Far-field effects are due to significant afterburning
 - Near-field effects analysis requires propellant-specific explosive data
 - Reaction is usually spontaneous
 - Pressure fields do not emulate TNT
 - Reaction mass detonation not observed - Except for small quantities
- Miscible combinations may display HD 1.1 behavior
- Mixing time vs. time of reaction determines participation
- Explosive hazards must be validated by comprehensive (distributed, static, and dynamic) test programs
- Dynamic modes include:
 - Fallback, toppling, impact, donor
- Static modes include:
 - Tank rupture, inter-tank rupture, line leakage, fire
- Explosive yield of launch vehicles is affected by their configuration and accident sequence
 - For large vehicle quantities, mixing time prior to ignition is the primary contributor to explosive yield
- To reduce the launch vehicle explosive yield below the composite values, hazard analyses are necessary
 - These would be unique for each vehicle/combination
 - Requires performing rigorous failure analyses

7.2 Recommendations

As a result of this assessment, two recommendation options are included regarding the explosive yield values for the liquid oxygen/hydrocarbon combinations for launch pads, test stands and other potential explosive sites (PES). These are identified as Options 1 and 2 below.

- Recommend replacing the explosive criteria for each liquid oxygen/hydrocarbon bipropellant combination as noted
- Combinations include: LO₂/RP-1, LO₂/ethanol, and tentatively LO₂/jet fuel
- Two recommendation options are offered for consideration by the DDESB

7.2.1 Recommendation for LO₂/RP-1

Option 1:	Launch Pad:	$W_T = 7.0W_P^{3/4}$ for all $W_P \geq W_{Pmin}$
	Test Stand:	$W_T = 1.8W_P^{3/4}$ for all $W_P \geq W_{Pmin}$
	Other PES:	$W_T = 125\%W_P$
Option 2:	Launch Pad:	$W_T = 7.0W_P^{3/4}$ for $W_P < W_{Pmax}$ & $\geq W_{Pmin}$ $W_T = 30\%W_P$ for $W_P \geq W_{Pmax}$
	Test Stand:	$W_T = 1.8W_P^{3/4}$ for $W_P < W_{Pmax}$ & $\geq W_{Pmin}$ $W_T = 8\%W_P$ for $W_P \geq W_{Pmax}$
	Other PES:	$W_T = 125\%W_P$

7.2.2 Recommendation for LO₂/Ethanol

Option 1:	Launch Pad:	$W_T = 8.2W_P^{3/4}$ for all $W_P \geq W_{Pmin}$
	Test Stand:	$W_T = 2.1W_P^{3/4}$ for all $W_P \geq W_{Pmin}$
	Other PES:	$W_T = 145\%W_P$
Option 2:	Launch Pad:	$W_T = 8.2W_P^{3/4}$ for $W_P < W_{Pmax}$ & $\geq W_{Pmin}$ $W_T = 35\%W_P$ for $W_P \geq W_{Pmax}$
	Test Stand:	$W_T = 2.1W_P^{3/4}$ for $W_P < W_{Pmax}$ & $\geq W_{Pmin}$ $W_T = 9\%W_P$ for $W_P \geq W_{Pmax}$
	Other PES:	$W_T = 145\%W_P$

7.2.3 Recommendation for LO₂/JP-5

Option 1:	Launch Pad:	$W_T = 8.6W_P^{3/4}$ for all W_P
	Test Stand:	$W_T = 2.2W_P^{3/4}$ for all W_P
Option 2:	Modify footnote to allow jet fuel substitution for RP-1.	

where W_T = net explosive weight in lb of TNT, and
 W_P = propellant weight in lb as defined in [1], V5.E4.5.6.1, and V5.E4.5.6.2, and
 W_{Pmax} = 300,000 lb represents the transition value, and
 W_{Pmin} = 1,000 lb is the minimum value applicable to the yield curves

8. Acronyms and Abbreviations

A-50	Aerozine-50
ABMA	Army Ballistic Missile Agency
C ₂ H ₅ OH	ethanol (ethyl alcohol)
CBGS	confined-by-ground surface
CBM	confined-by-missile
DDESB	Department of Defense Explosives Safety Board
DESR	Defense Explosives Safety Regulation 6055.09
DMT	distributed mixing test
DTMB	David Taylor Model Basin
EEW	equivalent explosive weight
ELWG	Energetic Liquids Working Group
HC	hydrocarbon
H C/D	hazard class/division
HOVI	hydrogen/oxygen vertical impact
HVI	high-velocity impact
IBD	inhabited building distance
LP	launch pad
LPWG	Liquid Propellant Working Group
LSHOE	large-scale hydrogen/oxygen explosion
MCE	maximum credible event
MMH	monomethylhydrazine
MSFC	Marshall Space Flight Center
NEW	net explosive weight
NRL	Naval Research Laboratory
PES	potential explosive site
PRC	Propellant Reaction Characterization
PTRD	public transportation route distance
RP-1	Rocket Propellant-1
RTG	radioisotope thermoelectric generator
ST	static test (stand)
TBS	to be supplied
TNT	trinitrotoluene
UERD	Underwater Explosions Research Division
W _P	propellant weight
W _T	TNT weight
WSTF	White Sands Test Facility

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Appendix A. Review of Revision to DDESB Explosive Criteria for LO₂/LH₂

Due to efforts by the author and others, the LO₂/LH₂ explosive criteria used in DoD 6055.9-STD were revised in 1998. The author examined the effects of liquid propellant explosions over a period of years in support of a variety of launch vehicle programs. This effort resulted in the formation of the DDESB Liquid Propellant Working Group (LPWG) in 1994.² Between 1995 and 1997 the subject of the adequacy of the then current explosive standards for liquid propellants [7] was discussed at LPWG meetings. This culminated in a paper and presentation by the author to the LPWG and the DoD Explosives Safety Testing Steering Group on 25 and 26 June 1997 with recommended revisions to the LO₂/LH₂ criteria and observations pertinent to the other propellant combinations [2][5]. These recommendations were approved by the Board by letter transmittal [8] and subsequently documented in [9].

The recommendations submitted to the Board and the accepted modifications are outlined below.

A.1 Recommendation to the DDESB

The recommended change to the LO₂/LH₂ liquid propellant explosive equivalence was to replace the current 60% TNT value and allow the explosive equivalence to be determined from the recommended LO₂/LH₂ yield curves using the following methods:

A.1.1 Launch Pads

For launch vehicles on the launch pad determine the net explosive weight (NEW) in pounds of TNT using the dynamic yield curve:

$$W_T = 8W_P^{2/3}$$

where W_T equals net explosive weight in TNT, and
 W_P equals propellant weight.

A.1.2 Static Test Stands

For launch vehicles/stages on static test stands determine the net explosive weight (NEW) in pounds of TNT using the static yield curve:

$$W_T = 8W_P^{2/3} \text{ for } W_T \leq W_{Tmax}$$
$$W_{Tmax} = 12,000 \text{ lb}$$

where W_T equals net explosive weight in TNT,
 W_P equals propellant weight, and
 W_{Tmax} represents critical mass yield.

²Footnote: The LPWG was formed in 1994 at the request of the Air Force Safety Center (AFSA/SEWV) to resolve issues associated with the standards pertaining to liquid propellants raised by Tomei and Napadensky. The LPWG was led by the CPIA under the direction of the DDESB. Membership included DDESB, CPIA, several representatives of each military service (USAF, The USA, The USN), NASA (HQ and JSC), FAA/CST, NFPA, DOT, DOE, Sandia Labs, DOH&HS, plus Hyla Napadensky and Aerospace Corporation's Tomei. The scope was expanded, and the title was eventually changed to the Energetic Liquids Working Group (ELWG). The LPWG held six meetings through 1999 and resulted in a complete rewrite of DoD 6055.9-STD, Chapter 9, Section 6, *Energetic Liquids* that included the noted liquid propellant changes (LO₂/LH₂ yield, maximum credible event (MCE) analysis, and launch pad requirements clarification) but in addition completely revised the standards and wording throughout for other commodities. In addition, the Board (Gov't only) approved the MCE analysis and resultant siting for the Delta IV Heavy EELV, which reduced its TNT yield and hence Q-D requirements: the only instance of a launch vehicle MCE siting analysis being implemented to date.

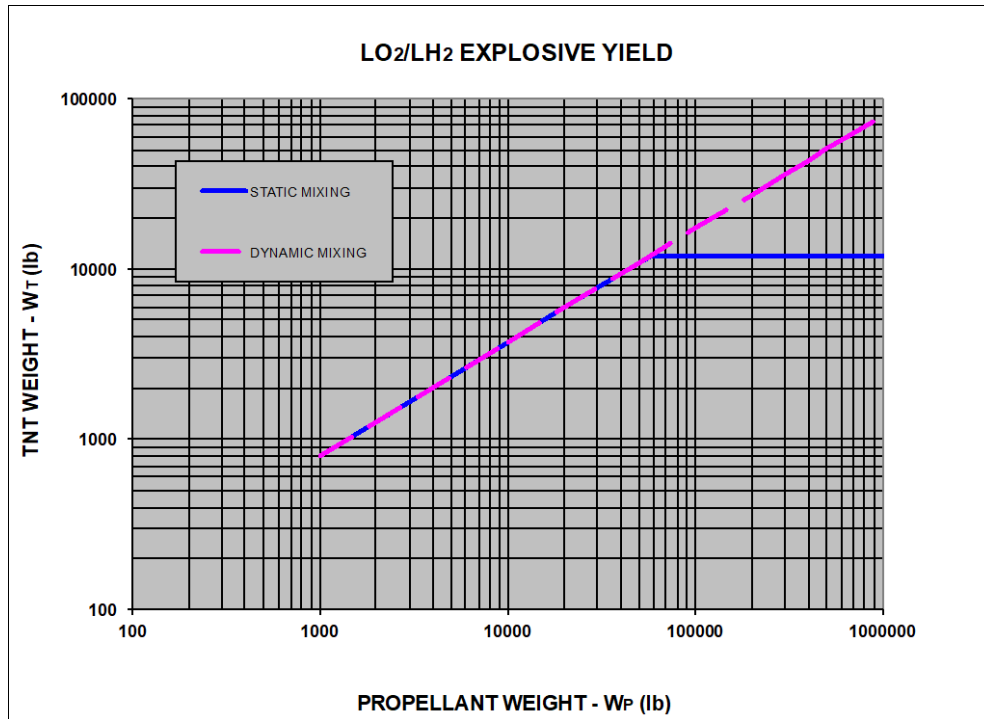


Figure 15. Recommended LO₂/LH₂ yield curves.

These recommendations were based on the finding that LO₂/LH₂ propellants appear to achieve a maximum TNT yield under static conditions, and no difference could be found between explosive yields for these propellants under static or dynamic mixing conditions, as can be seen in the above figure. Rationale for this limiting condition is due to the strong propensity for LO₂/LH₂ to auto-ignite and react spontaneously.

A.2 Decision of the DDESB

After significant discussion the DDESB decided not to incorporate this apparent limit in the LO₂/LH₂ static yield in the criteria. The primary reasons were: 1) limited large-scale dynamic failure data, and 2) uncertainty as to what the actual limit should be. As a result, the DDESB choose instead to transition from the LO₂/LH₂ Yield Curve to a 14% TNT value that corresponded to 200,000 lb in the dynamic yield plot. Therefore, as implemented in the revision to DoD 6055.9-STD, the NEW for LO₂/LH₂ fueled vehicles is to be determined from the greater of the value calculated from the LO₂/LH₂ Yield Curve or 14% TNT. This approach was based on the analysis recommendations that found that at 200,000 lb (90,909 kg) of propellant and above, the 14% value applied to all full-scale vehicles under any failure condition except high-speed impact that does not apply to the DoD explosive standards. It was also the consensus of the Board to incorporate additional recommendations to: 1) clarify the explosive siting standards when applied to launch pads to envelop near-pad accidents involving dynamic events such as fallback, and 2) allow a maximum credible event (MCE) analysis to be submitted if it can be shown that any on-pad failure will not result in a single explosion involving all propellants on-board the various launch vehicle stages.

The resulting impact of the DDESB decision can be seen in the plot below.

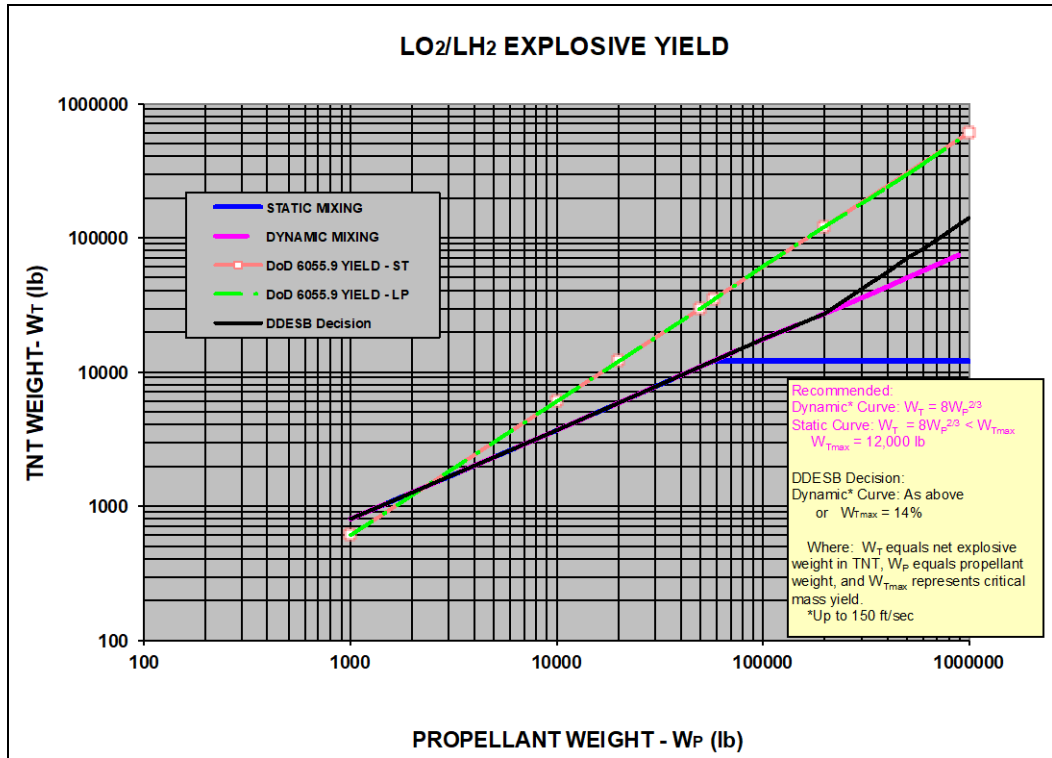


Figure 16. Approved yield curve compared to the 1997 recommendation and prior yield criteria.

Appendix B. Methods and Observations

B.1 LO₂/RP-1 Explosive Yield Prediction Methods

Several prediction methods have been developed by various investigators to estimate the yield for liquid oxygen/hydrocarbon bipropellants. These methods are:

1. Farber/UoF (1965-1973) – Mixing/Yield Model and Critical Mass Method
 - a. Predicts for Mixed Mass
 - b. Auto-Ignition at 2,800 lb for LO₂/RP-1
2. Gunther/BELLCOMM (1969) – Regression Model Based on PYRO
3. Baker/Southwest Research Institute (1978) – 1/6 Scaling Law for Ignition Time

Prediction methods were compared to both 95% upper limit values from the above data assessment and are shown in Figure 17. All of the prediction methods give similar results above 400,000 lb. In comparison to the 95% upper limit curves, it can be seen that our LO₂/RP-1 data assessment is in good agreement with the fall-off predicted by Farber; however, the yield values are similar in only the dynamic mixing case. This fall-off was determined by Farber to be caused by the auto-ignition mechanism of LO₂/RP-1 (see discussion below). His analysis indicated that a critical mass existed that limited the amount of propellant that could be mixed before ignition occurred. He attributed this self-ignition to arcing caused by static charge buildup in the boundary layer between the two liquids. By measuring the charge buildup he established the critical mass needed. Both 95% plots agree with Farber's limiting yield prediction but suggest higher limiting explosive values as a function of mixing conditions and safety factors.

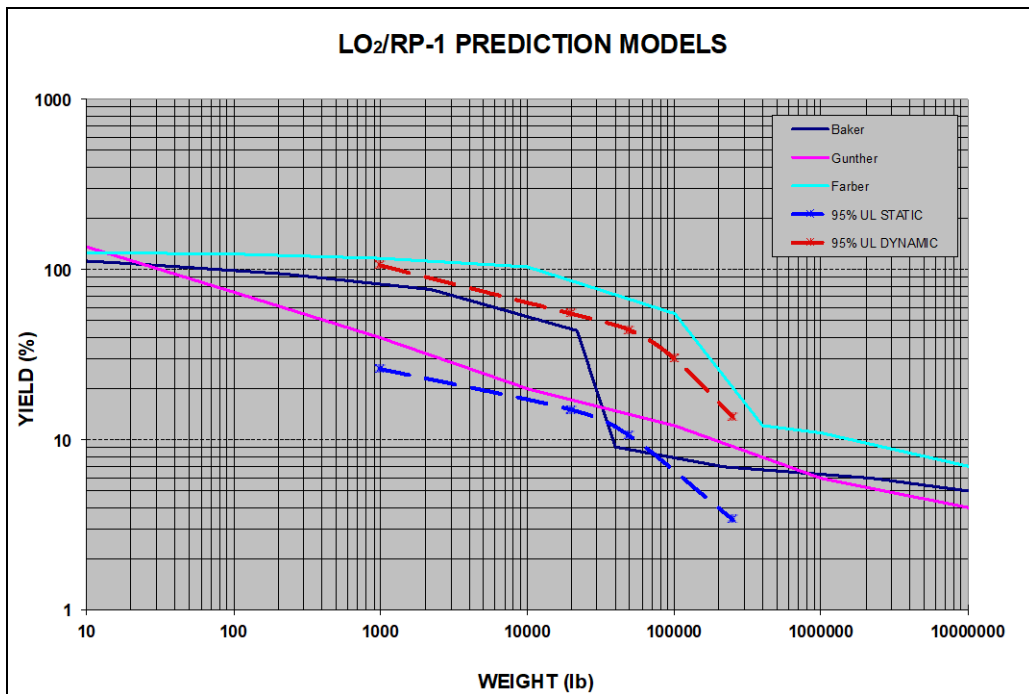


Figure 17. Comparison of LO₂/RP-1 explosive prediction methods.

However, the discussion that follows raises strong questions regarding the validity of the limiting yield assumption. Figure 18 below includes the above prediction methods, our proposed yield curves, the DESR 6055.09 criteria, and the explosive yield estimates from the Soviet N-1 5L failure described below.

Figure 18 shows the disparity between the N-1 failure and the prediction models, although our proposed LO₂/RP-1 Dynamic Yield Curve best approximates the lower estimate. It would seem that all of the models suffer from the data limitation accompanying the use of U.S. launch vehicle failures. All LO₂/RP-1 failures in the U.S. have been limited to vehicles with a maximum of ~250,000 lb of LO₂/RP-1 propellant on-board. All of the prediction models, along with our 95% upper limit curve, track this data limitation.

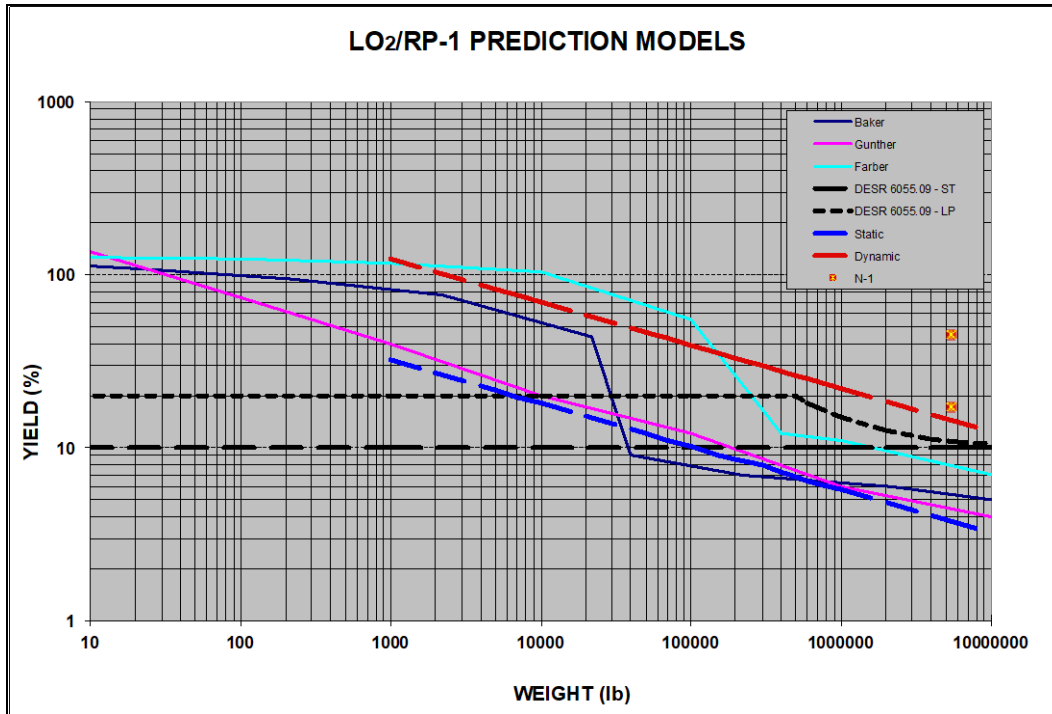


Figure 18. Comparison of LO₂/RP-1 explosive prediction methods with N-1 failure.

B.2 Auto-Ignition of LO₂/Hydrocarbon Propellants

The propensity for liquid propellants to react spontaneously has been previously discussed by several researchers. To examine this phenomenon, liquid propellant spontaneous reactions were determined for all test programs and the data were categorized and auto-ignition reactions identified. Figure 19 below gives auto-ignition event statistics for all LO₂/LH₂ and LO₂/RP-1 tests.

As can be seen in Figure 19, the LO₂/RP-1 combination has a much lower probability of auto-ignition particularly at low weight quantities. Although a variety of mechanisms have been postulated and some measured by Farber, it is believed that the LO₂/LH₂ mixing is susceptible to more than one auto-ignition mechanism, making it guaranteed to auto-ignite under any large-scale configuration.

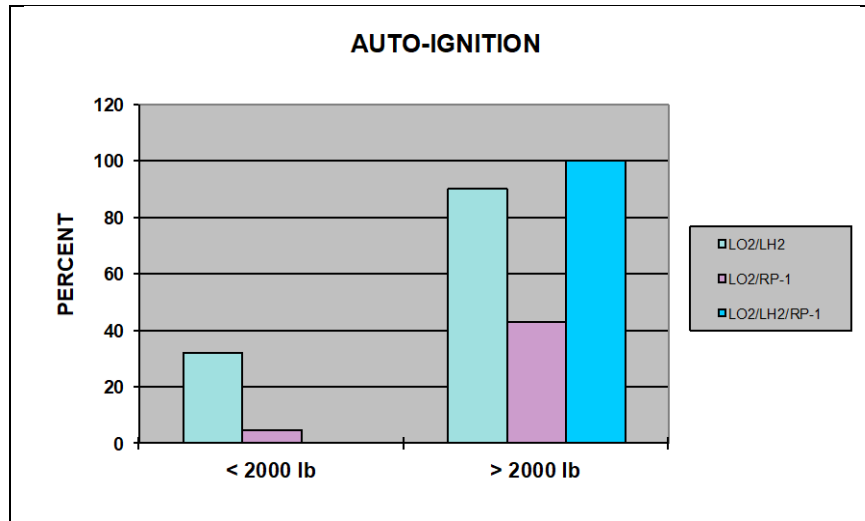


Figure 19. Auto-ignition phenomenon.

B.3 Blast Asymmetry of LO₂/Hydrocarbon Propellants

Liquid propellant explosions are often asymmetric, and all vehicle failures that have been studied exhibited some degree of asymmetry as the explosive pressure fields exhibit a hemi-ellipsoidal rather than hemispherical form. Review of the test and failure data indicates that this is more prevalent in dynamic mixing modes. This is likely due to a variety of conditions related to launch vehicles such as failure dynamics, rupture and spill mechanics, vehicle orientation, and propellant tank configuration, which are all probable contributing factors. This means that using average yield data (as is done by most experimenters and analysts) underestimates the hazard potential for a given explosion direction. However, using only maximum values risks basing the safety criteria on spurious data. Therefore, for both the [2] LO₂/LH₂ recommendations and this assessment, all large-scale ($\geq 1,000$ lb) test and failure cases were assessed for asymmetry. For LO₂/RP-1 the ratio of maximum/average yield was found to range on average from 1.1 to 1.26 where the lowest values correspond to pre-ignition static failure events. These asymmetry factors were therefore applied to the results of the data assessment in deriving the final recommended yield values. These factors were applied to the 95% upper limit curves (see Figure 20) as well as the point values and are inherent in the yield curves.

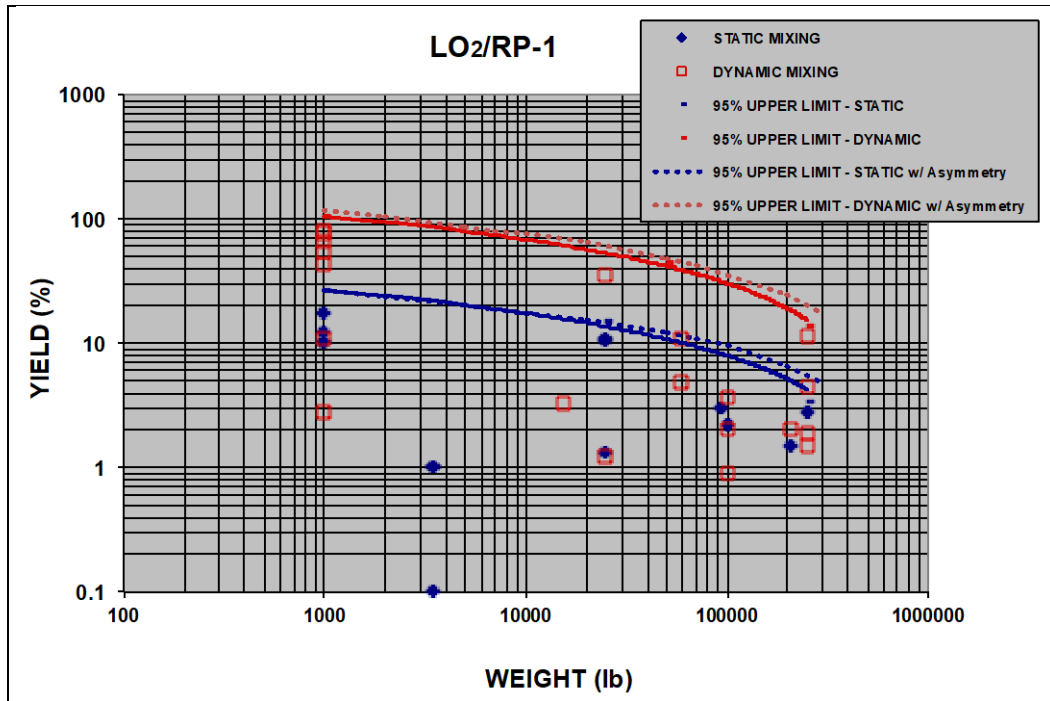


Figure 20. Effect of asymmetry factors on yield estimate.

B.4 Impact Sensitivity of LO₂/Hydrocarbon Propellants

This assessment found a factor of 4 difference in LO₂/RP-1 yields between static and dynamic conditions. This is true for the constant percent yield values of 8% and 30% at 300,000 lb and for lower quantities. This difference to LO₂/LH₂ (i.e., half as energetic under static, but twice as energetic under dynamic conditions) has been long suspected by many investigators. In fact these independently derived results agree with the findings of Project PYRO's CBGS conclusion, wherein their model concluded that the maximum yield for LO₂/RP-1 increases from around 25% to 100% TNT as the impact velocity increases from 10 ft/sec to 50 ft/sec, as shown in Figure 21 below which was taken from the PYRO test report [39]. No other propellant combination has been found to date that exhibits this sensitivity to dynamic mixing at relatively moderate increases in mixing energy, i.e., fallback from less than 40 ft.

This can be readily explained by the inherent nature of the various LO₂/LH₂ and LO₂/hydrocarbon bipropellant combinations (hypergolics are the subject of a separate discussion). The LO₂/LH₂ propellants in fact do not mix, as testing has shown that neither LH₂ nor solid O₂ contributes to the reaction. As discussed above regarding auto-ignition, the LO₂/LH₂ explosive reaction is a function of the combination of gaseous vapor and/or atomized droplet products that react spontaneously when they come together. This was clearly demonstrated in the NASA WSTF HOVI drop tests, which showed that the LO₂/LH₂ reaction is primarily dependent on the time it takes to bring the reaction products together (which is why LO₂/LH₂ has a constant static and dynamic yield). When released separately or at high velocity, larger clouds and hence reactions can occur. In the case of LO₂ and either kerosene or ethanol, the Rocketdyne tests showed conclusively that these can mix and form a "gel," which when initiated create a more reactive explosion. The PYRO CBGS tests demonstrated that any kinetic energy imparted to the mixing process can enhance mixing, and the explosive reaction, given sufficient time delay. This is an inherent probability with any LO₂/hydrocarbon combination since the auto-ignition tendency is much less pronounced. However, there are optimum conditions of both mixing time and mixing energy that influence the final reaction yield. If initiated early or late, or the mixing energy is too great, the products can be affected by phase changes and/or spatial dispersal.

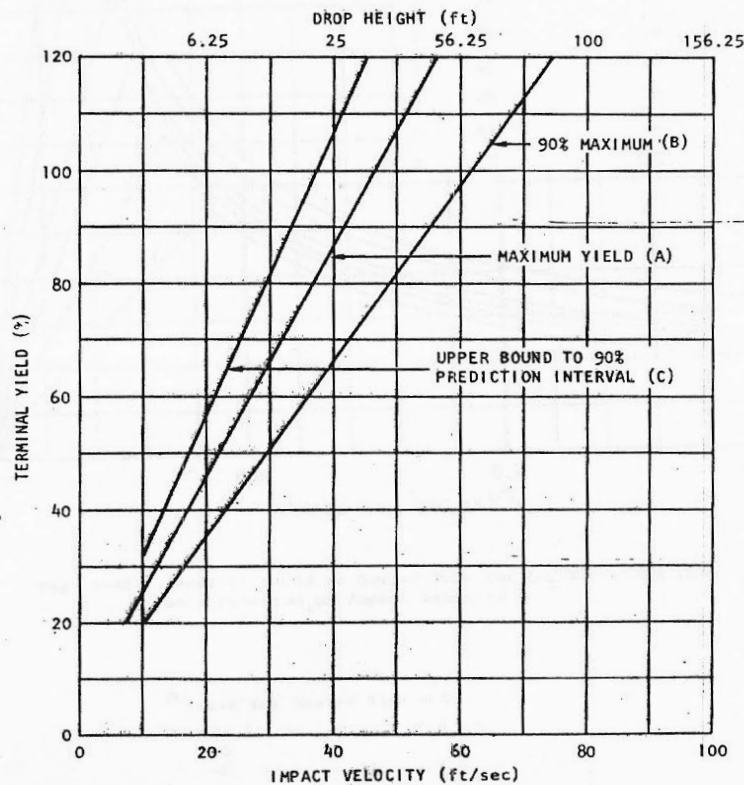


Fig. 5-41. Maximum Terminal Yield vs Impact Velocity for LO₂/RP-1 CBGS Case

Figure 21. LO₂/ RP-1 Yields vs. Impact Velocity from Project PYRO [39]

B.5 TNT Equivalence of Liquid Propellants

It has been well established by many analysts—including this author—that energetic liquids, particularly liquid propellants, do not replicate TNT explosions. For example:

- Near-field overpressures are at least an order of magnitude less than TNT
- Liquid propellant TNT equivalence increases with distance
- Liquid propellant TNT equivalence decreases with increasing propellant weight
- Near-field liquid propellant impulse % yield is greater than pressure yield
- Liquid propellant impulse yield decreases with distance

However, it has also been shown that these liquid propellant blast environments do approach TNT in the far-field. This is generally attributed to the propensity of the reactants to continue to supply energy to a blast wave for a much longer time than that which influences the initial shock interaction with air. Analysis of LSHOE LO₂/LH₂ distributed mixing tests (DMT) shown in Figure 22 [65], demonstrates this phenomenon. Although analysts often take issue with the equivalence approach, this is primarily related to the near-field pressure field interactions with other components within the blast environment. However, relative to the use of this method in DESR 6055.09, facility siting using this method is surprisingly

appropriate. The difference between the overpressure range of interest for inhabited building (IBD) and public transportation route (PTRD) siting using TNT and liquid propellants is seen to be negligible.

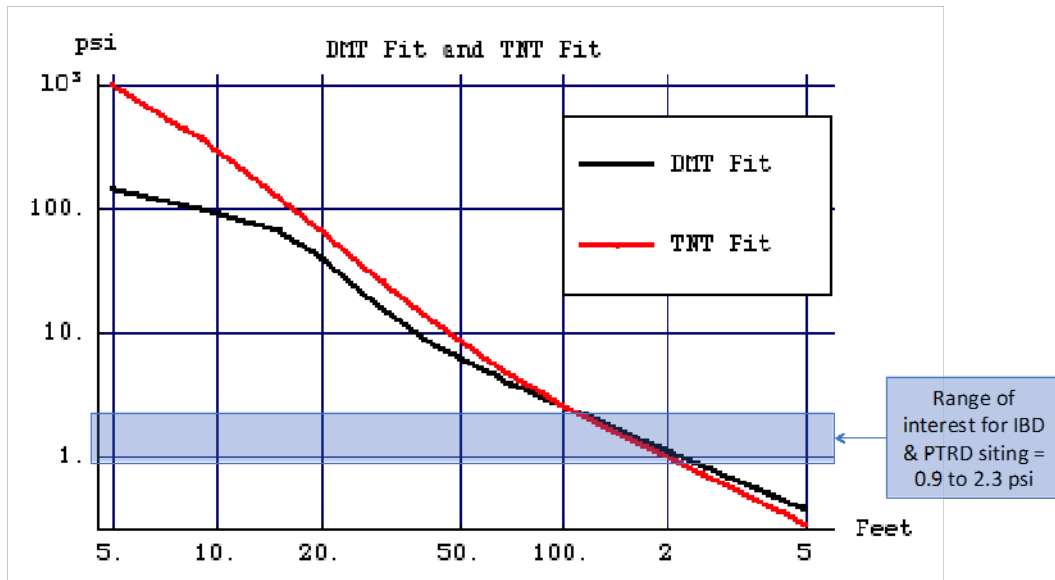


Figure 22. TNT vs. Liquid Propellant Explosive Yield [65]

B.6 Soviet N-1 Failure

On 3 July 1969 a Soviet N-1 (or N1) launch vehicle failed at lift-off and fell back onto launch complex 110R at Tyuratam/Baikonur Cosmodrome in Kazakhstan. It was possibly the largest explosion in the history of rocketry. An assessment by S. Hancock in [63] of the failure was performed since detailed information about launch accidents in the former Soviet Union is difficult to obtain. The Soviet N-1 was part of their planned manned lunar program. Unmanned vehicle N-1 5L lifted off when engine number 8 (of 30) shut down at 0.25 seconds into the flight and exploded, damaging several adjacent engines. A fire erupted and the engines began to shut down. The booster climbed to ~200 m when all engines except number 18 shut down. The booster began to fall back; however, the thrust of engine 18 tipped it from the vertical and the base of the N-1 hit the launch pad at about 45° as it came down and exploded, illuminating the steppe for dozens of kilometers. All of the windows were blown out of the apartment buildings at Area 113 and at the second N-1 launch complex 110L, 6 km away. Windows were reported blown out dozens of miles away. The impact velocity was estimated at less than the theoretical for fallback from 200 m due to powered descent. The N-1 carried 2,500,500 kg (5,501,100 lb) of LO₂/kerosene similar to the LO₂/RP-1 used on U.S. launchers. The propellant was distributed as follows in the various stages: 1,750,000 kg in stage 1, 505,000 kg in stage 2, 175,000 kg in stage 3, 55,800 kg in stage 4, and 14,700 kg in stage 5.

Given that windows were all blown out at 6 km, Hancock used typical window glass breakage at 10–15 millibars (0.15 to 0.22 psi) to give a (hemispherical) TNT equivalent yield of 940,000 lb to 2,450,000 lb of TNT, which corresponds to a TNT equivalence of 17% to 45% for the entire vehicle. These estimates

were considered lower bounds because it is unknown if the blast would have broken windows at a greater range (see Footnote).³

Hancock also attempted to use the Baker critical mass model (see Appendix B) to compare his results and found the overall TNT yield would be 175,377 lb, or 3.2% of the total propellant weight, which is only 1/5 of the estimated minimum yield. Therefore, it was concluded that the critical mass assumption for LO₂/hydrocarbons is not valid. Based on his conclusions, the yield estimates were superimposed onto selected yield plots from this assessment to see how they compared. Figures 23 and 24 show how the N-1 explosion compares with the LO₂/RP-1 data in this report. Based on these results the recommended solution of Option 2 should be acceptable until further analysis of this failure can be done.

FOOTNOTE: Per DESR 6055-09 the overpressure required to break 100% of the windows at 6 km implies an even greater overpressure than that used in the above assessment. See table V1.E8.T3 from Volume 1, Enclosure 8 below.

Table V1.E8.T3. Probability of Window Breakage from Incident Pressure

K-Factor (ft/lb ^{1/3})	Incident Pressure (psi)	Probability of Breakage (%) for Windows Facing PES		
		Window 1 ^a	Window 2 ^b	Window 3 ^c
K _m -Factor [m/kg ^{1/3}]	Incident Pressure [kPa]			
40	1.2			
15.87	8.3	85	100	100
50	0.9			
19.84	6.2	60	100	100
60	0.7			
23.80	4.8	41	100	100
70	0.6			
27.77	4.1	26	100	100
80	0.5			
31.74	3.4	16	94	100
90	0.4			
35.70	2.8	10	76	100
100	0.3			
39.67	2.1	6	55	100
150	0.2			
59.51	1.4	1	8	49
328	0.0655	0	0.1	0.8
130.12	0.45			
a	12 inches x 24 inches x 0.088 inches float annealed (area = 2 ft ²)			
	30.5 centimeters (cm) x 61 cm x 0.223 cm float annealed (area = 0.186 square meters (m ²))			
b	24 inches x 24 inches x 0.088 inches float annealed (area = 4 ft ²)			
	61 cm x 61 cm x 0.223 cm float annealed (area = 0.372 m ²)			
c	42 inches x 36 inches x 0.12 inches float annealed (area = 10.5 ft ²)			
	106.7 cm x 91.4 cm x 0.305 cm float annealed (area = 0.975 m ²)			

3

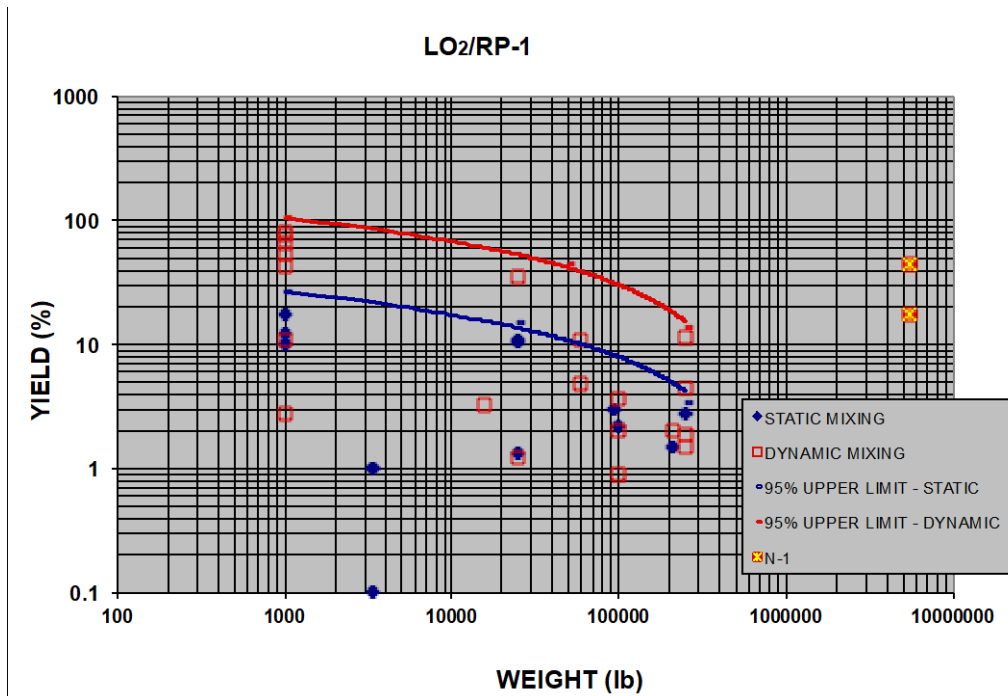


Figure 23. LO2/RP-1 upper limit plots compared to N-1 failure.

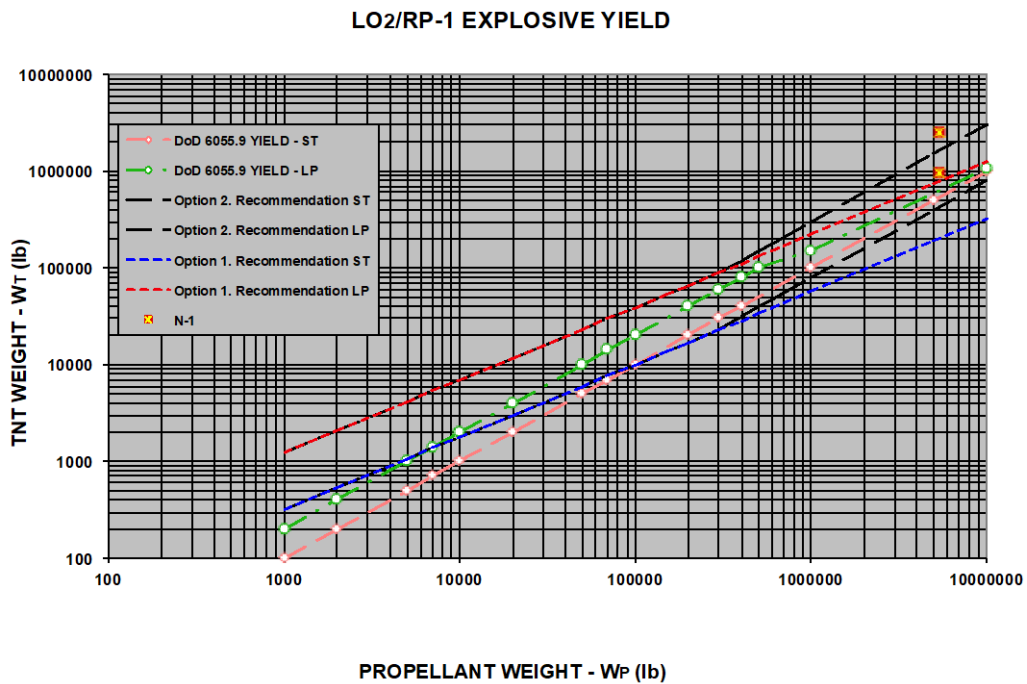


Figure 24. Proposed LO2/RP-1 EEW recommendations compared to Soviet N-1 failure.

B.7 N-1 Failure Observations:

- As the largest launch system explosion on record, this failure should be included in any failure study.

- This accident occurred at an impact velocity between 100 and 300 ft/sec and was likely highly nonsymmetric due to the fallback orientation, therefore this assessment should be considered a range of possible values.
- The N-1 configuration also implies that multiple reactions likely occurred similar to Atlas-Centaur 5 that resulted in a donor impact to the largest explosion.
- The N-1 accident indicates that the concept of a limiting reaction of liquid oxygen/hydrocarbon propellants similar to that of the LO₂/LH₂ cryogenic combination is not valid.
- If possible, a future project to gather more information on this failure would be beneficial to establishing safety risks for these propellant combinations.

External Distribution

REPORT TITLE

Explosive Equivalence of Hydrocarbon Propellants

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