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Peer Review of Launch Environments

Timmy R. Wilson/NESC
Langley Research Center, Hampton, Virginia

January 2011

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December 2, 2010

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Volume I: Assessment Report

1.0 Notification and Authorization

The Constellation Program (CxP) Safety & Mission Assurance (S&MA) requested an independent assessment of the Peer Review of Launch Environments.

A NASA Engineering and Safety Center (NESC) out-of-board activity was approved on October 13, 2010. Mr. Tim Wilson, NESC Deputy Director, was assigned to perform a peer review of a launch environments assessment conducted by Bangham Engineering, Huntsville, Alabama. The Bangham work models propagation of the shock wave and fireball from an exploding launch vehicle based on historical data and visual imagery.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 12/8/10

Mr. Timmy Wilson Date

Significant Contributors:

Dr. Michael Gilbert Date	Mrs. Kelly Currin Date
Mr. Roberto Garcia Date	Dr. Curtis Larsen Date
Dr. Ivatury Raju Date	Dr. David Schuster Date
Mr. Kenneth Johnson Date	Mr. Steven Rickman Date

Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization/Location
Core Team		
Tim Wilson	NESC Deputy Director	LaRC
Kelly Currin	Resident Engineer	KSC
Michael Gilbert	Principal Engineer	LaRC
Roberto Garcia	NASA Technical Fellow for Propulsion	MSFC
Curt Larsen	NASA Technical Fellow for Loads and Dynamics	JSC
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Dave Schuster	NASA Technical Fellow for Aerosciences	LaRC
Ken Johnson	NASA Technical Fellow for Statistics	MSFC
Steve Rickman	NASA Technical Fellow for Passive Thermal	JSC
Chris Johansen	MTSO Program Analyst	LaRC
Administrative Support		
Tina Dunn-Pittman	Project Coordinator	ATK, LaRC
Linda Burgess	Planning and Control Analyst	ATK, LaRC
Christina Williams	Technical Writer	ATK, LaRC

3.1 Acknowledgements

Mr. David Gilmore of The Aerospace Corporation and a member of the NESC Passive Thermal Technical Discipline Team (TDT) is acknowledged for providing numerous documents for this peer review. Mr. Laurence Reinhart of the Jet Propulsion Laboratory (JPL) is acknowledged for identifying additional resources for both liquid and solid propellants.

4.0 Executive Summary

The NASA Engineering and Safety Center (NESC) conducted a peer review of blast effects modeling work begun by Bangham Engineering for Constellation Program (CxP) Safety & Mission Assurance (S&MA). The Bangham work uses empirical data gathered from tests and historical launch vehicle failures to predict blast effects. The NESC concurs with Bangham's approach and with the results presented to date; however the data is limited and the statistical treatment could be stronger. The project would benefit from a more comprehensive attempt to collect relevant data and analyze using more current and advanced statistical tools.

5.0 Background

Catastrophic failures of launch vehicles during launch and ascent are currently modeled using equivalent trinitrotoluene (TNT) estimates. This approach tends to over-predict the blast effect with subsequent impact to launch vehicle and crew escape requirements. Bangham Engineering, located in Huntsville, Alabama, assembled a less-conservative model based on historical failure and test data coupled with physical models and estimates. This white paper summarizes NESC's peer review of the Bangham analytical work completed to date.

6.0 Approach

Experts with backgrounds in Aerosciences, Structures, Dynamics, Passive Thermal Systems, Propulsion, and Statistics were represented on the NESC team. Team members reviewed the Bangham Engineering summary "Accident-Based Empirical Launch Vehicle Blast Modeling," by James Blackwood, dated July 2010, reproduced in Appendix B, interviewed Bangham representatives, conducted a literature search, and inspected the company's launch vehicle explosion database. Findings, observations, and NESC recommendations were developed on the basis of team members' technical expertise. No independent tests or analyses were performed.

6.1 Specific Comments

The team offered the following specific comments in reference to the Bangham Engineering presentation (located in Appendix B).

Page 6 – This chart discusses similitude of liquid oxygen/rocket propellant (LOX/RP) and LOX/ liquid hydrogen (LH2) and uses overpressure as the study variable. However *AIAA-29456-588 Liquid-Propellant Explosions, Fletcher, R. F., Journal of Spacecraft* (Engineering Notes), October 1968, pp. 1227-1229, states that "[I]n most liquid-propellant explosions, the amount of thermal energy exceed the amount of shock energy." So, while this chart focuses on overpressure, given that the thermal energy exceeds the shock energy, the statement that "This allows limited accident data to be statistically relevant for both LOX/RP and LOX/LH2" may be inaccurate for a thermal comparison of the two propellants. The chart on page 21, "Work Remaining," does acknowledge that thermal (and fragmentation) analysis is only partially complete.

Page 6 – The data assessment presented here could be improved and LH2/RP variability better treated with a more complex regression model than was used to build this chart. There is some evidence of sensor saturation, as well as some data structures which may indicate something of interest not fully accounted for.

Page 9 – Minimal data exists to support the blast wave speed assertions made on this chart. There is some evidence of sensor saturation at 2000 ft/sec.

<u>Page 11</u> – The analytical prediction of fireball radius as a function of propellant mass (and time) should be plotted to see how it correlates with the data on the chart. Data in *NASA TM X-53314 Size and Duration of Fireballs From Propellant Explosions*, Gayle, J. B., Bransford, J. W., July 1965, may be beneficial as this reference provides curve fits (although not analytically derived) from incidents and tests relating fireball radius and duration to propellant mass.

<u>Page 12–13</u> – This data represented on this chart may be better described and analyzed by classifying the events according to a fault tree rather than by a single distribution. For each node on the tree, a distribution of warning times could be built, informed by the real world data. An occurrence time distribution and probability of occurrence of each tree node could be included, as well. This will allow designers and risk managers to address the problem of response time realistically.

<u>Page 14</u> – This chart indicates that in-flight data is sparse for a specified altitude regime. Recommend reviewing *AIAA-3542-256 Explosion of Propellants, Fletcher, R. F., Gerneth, D., Goodman, C., AIAA Journal (Technical Notes), April 1966, pp. 755-757.* This white paper, although an analytical study, focuses on the explosion of liquid propellants in vacuum and in an atmosphere with the objective of giving an upper bound to overpressures on a surface near an explosion as well as at a distance from the explosion. While there may not be flight incident or experimental data for this altitude regime, it may be worthwhile to combine ground test, accident data, and analytical predictions over the entire altitude regime to see if trends consistent across the data and analysis emerge. The final result may be a combined empirical and analytical curve. A Bayesian method of leveraging both data and analysis may be useful. The reference *AIAA-99-3776 Blast Wave Stage of Explosion of Launch Vehicle in Flight, Surzhikov, S.T.* also explores, analytically, the effects of altitude on the explosion.

<u>Page 21</u> – In addition to fireball radius and fireball temperature as a function of time, the study should determine and publish environmental (likely analytically derived) heating fluxes as a function of time and distance from the explosion center. Project PYRO, documented in some of the references below, conducted a variety of tests in which convective and radiative heat fluxes as well as fireball temperatures were obtained.

<u>General comments</u> – Assembly and maintenance of an explicit model that organizes and shows the relationships between elements of the conceptual model could help with sensitivity and gap analysis. One may well be in work. If not, a tool as simple as a fault tree could be useful. Bayesian networks (see references) might be very helpful. There are certainly other applicable methods. Due to expense of testing, use of efficient engineering test design methods such as design of experiments (DOE) is strongly encouraged.

7.0 Findings, Observations, and NESC Recommendations

7.1 Findings

The following findings were identified:

F-1. The team concurs with the approach taken and with the results presented to date. However, the data is limited and the statistical treatment could be stronger. The project would benefit from a more comprehensive attempt to collect relevant data and analyze using more current and advanced statistical tools. Data taken and analyses performed should consider the effect of missing data (e.g., data censoring due to saturated sensors).

F-2. The Bangham presentation focuses on overpressure. It appears little—if any—thermal or fragmentation modeling or assessment have been performed.

F-3. Data collected has been captured in a spreadsheet, not a relational database.

7.2 Observations

The following observations were identified:

O-1. Current and future launch sites should be better equipped with instrumentation suitable for collecting pressure / thermal data to improve insight into nominal and off-nominal launch and blast effects.

O-2. A bibliography or list of references used in assembling these data would be helpful for verifying all pertinent data sources have been identified and reviewed.

O-3. In preparation for this peer review, a literature search was performed to obtain data on previous testing and analysis of overpressure, fireball growth, and heat transfer. The references obtained are listed in the Literature Search Results, Appendix A.

O-4. An explicit model which shows dependencies and relationships between the conceptual model elements could be helpful.

O-5. If this work will be used for critical decisions in design, development, and ground and flight operations, NASA-STD-7009, *Standard for Models and Simulations*, should be reviewed for applicability.

7.3 NESC Recommendation

The following NESC recommendation was identified and directed towards the stakeholder:

R-1. Further pursue this effort with a team augmented by data mining, statistical, and subject matter experts. All data collected, including assumptions and data descriptions, should be fully documented in a relational database for future review and analysis.

8.0 Alternate Viewpoints

There were no alternate viewpoints.

9.0 Other Deliverables

There were no other deliverables.

10.0 Lessons Learned

There were no lessons learned.

11.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its

	occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the NESC to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

12.0 Acronyms List

CxP	Constellation Program
DOE	Design of Experiments
JPL	Jet Propulsion Lab
JSC	Johnson Space Center
LaRC	Langley Research Center
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MSFC	Marshall Space Flight Center
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
RP	Rocket Propellant
S&MA	Safety & Mission Assurance
TNT	Trinitrotoluene

Volume II. Appendices

Appendix A. Literature Search Results

Appendix B. Bangham Presentation

Appendix A. Literature Search Results

AIAA-99-3776 Blast Wave Stage of Explosion of Launch Vehicle in Flight, Surzhikov, S.T.

This paper focuses on the "blast wave" stage of the explosion and develops a methodology which is applied at various altitudes (6 km, 25 km and 55 km) for a 155 ton propellant case at each altitude. The paper gives a calculation of the radius of the boundary between scattering explosion products and the surrounding air. The paper also discusses the high temperature region and mentions that experimental data shows that these temperatures may reach 2500-2800 K. Temperatures as the radius of the fireball grows are also explored. The methodology assumes that gaseous explosion products are fully mixed and are scattering with a specified average kinetic energy and the part of the fuel that does not evaporate does not contribute to the gas dynamic field. Also, it is assumed that the explosion takes place over a short period of time so no chemical reactions are assumed to be in progress when the blast wave moves away from the point of detonation.

AIAA 2006-1177 Proposed Approach for Estimate Launch Vehicle Explosive Risk, Claus, R. W., Zampino, E.

The Apollo launch system is used as an example to illustrate to assess explosive risk and expected blast yields for a probabilistic risk analysis. A simple worst-case analysis is explored assuming all propellants are consumed in a single explosion. But the paper also points to sources

DOD Ammunition and Explosives Safety Standards, DOD 6055.9-STD, July 1999.
Tomei, E.J., "Explosive Equivalence of Liquid Propellants," JANNAF PDCS & SEPS Joint Meeting, April 1998.

LockheedMartin TA-9 Final Report no: LM-000071, contract NAS8-01098.
Tomei, E.J., "Propellant Explosive Hazards Study: Volume II Technical Discussions" Aerospace Corp. Report No.: TOR-0089(4025-04)-1.)

that suggest that estimates formulated using this assumption are high by one to two orders of magnitude. However, explosive yield estimates in this paper rely on TNT equivalency. The methodology uses *DOD Ammunition and Explosives Safety Standards, DOD 6055.9-STD* and suggests effective yields for LOX/LH2 and LOX/RP cases. Subsequently, *Kingery, C.N., "AirBlast Parameters Versus Distance For Hemispherical TNT Surface Bursts," U.S. Army Ballistic Research Laboratory Report No. 1344, Sept. 1966* is used to calculate blast wave overpressures. The results of the analysis suggest that TNT effective yields are significantly lower than those presented in the DOD standard.

AIAA 2003-508 Time-Dependent Spectral Radiation of Fire Ball Generated at Rocket Explosion, Surzhikov, S. T., Levine, J.

The paper predicts, via numerical simulation, data on spectral radiation emission of a fireball resulting from a rocket explosion. Two radiative heat transfer methods are used. The ultimate goal is prediction of the fireball spectral signature time dependence calculated over its typical lifetime of approximately 20 seconds. Evolution of the fireball is discussed in stages. The important role of heat transfer via radiation is emphasized. Species considered include: H_2O, H_2, CO, CO_2, O_2 and N_2. Calculations were performed for a completely filled rocket with fuel components: N_2O_4, $C_2H_8N_4$, C_7H_{14}, H_2O_2. The paper provides analytical predictions of fireball growth and temperature as a function of time.

AIAA-97-0810 Comparison of Parachute Fabric Response to Radiation Heat Transfer, Thielman, G. W.

This paper does not deal directly with rocket vehicle explosions or the resulting fireball but it does present how the resulting fireball data is applied to material analysis, in this case, parachute materials. Radiation and fireball heating from a military aircraft crash is to determine the exposure environment and a temperature estimate is given in *Pelch-Blyer, A. C., Tubis, R. I., "Survivability of Parachute Cloth and Human Skin Exposed to Fireball Radiant Heat", NWC TM 5733, May 1986*. Correlations to fuel quantity and fireball radius were taken from published empirical data are given in *High, R. W., The Saturn Fireball, Annals New York Academy of Sciences, 152, art. 1, pp. 441-451, 28 Oct 1968.*

AIAA-30365-793 Liquid-Propellant Rocket Abort Fire Model, Bader, B. E., Donaldson, A. B., Hardee, H. C., Journal of Spacecraft, Vol. 8, No. 12, December 1971.

This paper discusses the severe thermal environment experienced as a result of a fireball during a rocket launch pad abort. Heat flux versus time from the fireball is determined from a model as a function of time for any initial propellant quantity. It is claimed that existing data support the validity of the model. The paper references the original work on thermal radiation from an abort fireball performed by Van Nice and Carpenter in 1965 and referenced in *Van Nice, L. J. and Carpenter, H. J., "Thermal Radiation from Saturn Fireballs," NAS 9-4810, Dec. 1965, TRW Systems, Redondo Beach, Calif*. The paper also cites experimental data on launch abort fireballs in

High, R. W. and Fletcher, R. F., "Estimation of Fireball from Saturn Vehicles Following Failure on Launch Pad," 1181, Aug. 1965, NASA.

Gayle, J. B. and Bransford, J. W., "Size and Duration of Fireballs from Propellant Explosions," TM X-53314, Aug. 1965, NASA.

Pesante, R. E., Nishibayashi, et al, "Blast and Fireball Comparision of Cryogenic and Hypergolic Propellants," 0822-01(01)FP, June 1964, Aerojet-General Corp., Downey, Calif.

Kite, F. D., Webb, D. M., and Bader, B. E., "LaunchHazards Assessment Program, Report on Atlas/Centaur Abort,"SC-RR-65-333, Oct. 1965, Sandia Labs., Albuquerque, N. Mex.

Mansfield, J. A., "Heat Transfer Hazards of Liquid Propellant Explosions," URS 706-5, Feb. 1969, URS Research Company, Burlingame, Calif.

This paper presents a generalized version of an earlier model.

AIAA-29456-588 Liquid-Propellant Explosions, Fletcher, R. F., Journal of Spacecraft (Engineering Notes), October 1968, pp. 1227-1229

This engineering note discusses the detonation and deflagration phases of an explosion and draws comparisons between propellant-related explosions and TNT estimates. With regard to fireballs, the paper states that "[I]n most liquid-propellant explosions, the amount of thermal energy exceed the amount of shock energy. A large amount of air is consumed in the deflagration process, and the prediction of fireball characteristics is based on the availability of this air." Empirical data for fireballs are presented in Figure 6 within the document for various fuel/oxidizer combinations as a function of total liquid propellant weight.

AIAA 2008-6912 Simulation of Propellant Explosions Resulting from Crew Launch Vehicle Tank Failure, Hosangadi, A., Madavan, N. K., August 2008

In summary of the work described, this paper assesses a specific failure resulting from a catastrophic disintegration during ascent of the LH2-LOX tank and the subsequent release of the bulk propellants from the Ares I launch vehicle and involves the interaction at the interfaces between the LH2 and LOX and the surrounding high-speed air, the deformation of the liquid interfaces due to mixing, the vaporization of the liquids, and, finally, the potential combustion of the vapor leading to a possible fireball explosion. The goal of the assessment is to determine the strength and propagation of the blast wave if the mixture ignites and the time scales of the various processes.

AIAA-3542-256 Explosion of Propellants, Fletcher, R. F., Gerneth, D., Goodman, C., AIAA Journal (Technical Notes), April 1966, pp. 755-757

This paper focuses on the explosion of liquid propellants in vacuum and in an atmosphere with the objective of giving an upper bound to overpressures on a surface near an explosion as well as at a distance from the explosion.

NASA TM X-53314 Size and Duration of Fireballs From Propellant Explosions, Gayle, J. B., Bransford, J. W., July 1965

Data from tests and vehicle incidents have been compiled and analyzed with respect to fireball diameters and durations. Both variables were found to be dependent on the cube root of the weight of the combined propellants and independent of the particular propellant combination. Fireball diameters also appear to be roughly dependent on the cube root of the ambient pressures.

For fireball diameter, the scatter of the data about a fitted curve corresponded to a standard error of approximately 30%. Data for fireball durations exhibited a much degree of scatter.

The report also refers to the work performed by the U.S. Air Force Rocket Propulsion Laboratory in connection with Project Pyro.

Fireball diameters and durations were obtained either from the literature or by reduction of photographic records of various tests and incidents. The data used in this study is presented in the report appendix. For RP-1/LOX, data from 47 tests was used and ranged from 10 to 250,000 lbs. For LH2/LOX, data from 23 tests and one incident was used. Propellant weights ranging from 3 to 225 lbs were used. The incident involved 100,000 lbs propellant. For RP-1/LH2/LOX, data from 12 tests was used and ranged from 110 lbs to 44,000 lbs. For N2O4/UDMH-Hydrazine, data from 26 tests was used. Data is also presented for TNT in which 14 explosions was used.

PEP 25 179 Measurement of the Size, Duration and Thermal Output of Fireballs Produced by a Range of Propellants, Merrifield, R., Pyrotechnica, 25, pp. 179-185, 2000

This paper presents information on the size, duration and thermal output of fireballs produced on ignition of 1, 5 and 25 kg quantities of a range of propellants. Propellants studied were: FNH 014 and FNH 014 (Graphited), FNH 024, DX/S 56-14, EX03, Hodgdon H4198, Vectan AO and AS 24, Vihtavuori N320 and N340, Alliant Bullseye, Red Dot, Green Dot, Unique, Blue Dot, 2400, and Reloader 7, Hodgdon HS7 and H110. Data linking flame diameter and charge mass are presented from the experiments performed for this paper plus from data published elsewhere including a number of liquid propellants (from the reference above).

AFRPL TR-68-89 Heat Transfer Hazards of Liquid Rocket Propellant Explosions, Final Report, Mansfield, J. A., February 1969.

This report is a summary of the thermal or heat transfer measurements from the Project PYRO. This experimental program was conducted in order to improve the definition of hazards associated with liquid rocket propellant explosions. Tests using propellant quantities ranging from 200 to approximately 100,000 lbs of LO2/RP-1, LO2/LH2 and up to 1000 lbs for the hypergolic propellant combination of N_2O_4/50% UDMH-50% N_2H_4 were conducted. From measurements within the fireball, data are given for the total (convective plus radiant) heat flux density, radiant flux density, and fireball temperature – from remote measurements for the fireball temperature (photo-pyrometric) and radiant flux density. The PYRO program was composed of more than 300 propellant tests.

AFRPL TR-68-92 Volumes 1, 2 and 3 Liquid Propellant Explosive Hazards, Final Report, Willoughby, A. B., Witton, C, Mansfield, J., December 1968

Volume 1 is a comprehensive technical report to the basic Project PYRO program.

Volume 2 is the test data. Volume 3 is the prediction methods.

AFRL-PR-ED-TR-1999-0006 Propellant Sensitivity Program, Merrill, C., Air Force Research Laboratory, June 2003

The Propellant Sensitivity program investigated explosive and fire safety of solid rocket booster propellants and how safety/hazards are influenced by composition, propellant combustion at pressures outside normal motor operating pressures, and high temperature environment. The effort did not often work with more costly rocket motors since rocket motor safety is largely governed by innate properties of the propellants. Propellants tested were HTPB/Al/AP (hydroxy terminated polybutadiene/aluminum/ ammonium perchlorate) and CTPB/Al/AP (carboxy terminated polybutadiene /aluminum /ammonium perchlorate) compositions.

Additional Resources Identified But Not Reviewed

<u>For Liquid Propellants:</u>

Liquid Propellant Explosion Modeling - Steven L. Hancock, Foils Engineering - September 8, 2006

NSA3-19231 : Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels - W. E. Baker [et al.] - September 1977

Characteristics of Liquid Propellant Explosions - R. F. Fletcher - Annals of the New York Academy of Sciences, vol. 152, pp 432-440 - October 28, 1968

WSTF-TR-0985-001-01-02: Correlation of Liquid Propellants, NASA Headquarters RTOP, Test Report - Johnson Space Center - January 23, 2003

NASA TN D-5382: Some Liquid Oxygen/Liquid Hydrogen Explosive Effects in Controlled Failure-Mode Tests - Richard W. High - September 1969

NASA CR-134538 : Assembly and Analysis of Fragmentation Data for Liquid Propellant Vessels - W. E. Baker, V. B. Parr, R. L. Bessey, and P. A. Cox - January 1974

NASA-CS-187872 : Prediction of Explosive Yield and Other Characteristics of Liquid Rocket Propellant Explosions, Final Report - E. A. Farber, J. H. Smith, E.H. Watts - June 30, 1973

Explosive Equivalence of Liquid Propellants - E. J. Tomei - 1996

Delta II (NAVSTAR GPS IIR-1) - Patrick Air Force Base - January 17, 1997

NASA TN D-563: Investigation of S-IV All Systems Vehicle Explosion - J. B. Gayle - September 1, 1964

GDC-BTD66-034: Range Safety Aerodynamics Data for Atlas/Centaur/Surveyor Direct Ascent Flights - T. Chacon - May 4, 1966

Fire and Explosion Hazards of Liquid Propellants - Jim Cochiaro - CPIA Bulletin, vol. 24, no. 1, pp. 4-7 - January 1998

NASA SP-2000-4408: Challenge to Apollo: the Soviet Union and the Space Race, 1945-1974 - Asif A. Siddiqi - 2000

Explosive Shocks in Air, 2nd ed. - G. Kinney and K. Graham - Springer Verlag, 1985

Detonation of Cryogenic Gaseous Hydrogen-Oxygen Mixtures - M. Plaster, F. J. Benz, J. E. Shepherd, J. H. S. Lee - International Colloquium on Dynamics of Explosions and Reactive Systems, Ann Arbor, MI, United States, July 23-28, 1989

Explosions in Air - V. E. Baker - University of Texas Press, 1973

Propellant Explosions in Cargo Bay: Presented at Patrick AFB - D. Lehto - November 20, 1985

FSC-ESD-217-88-435: Centaur in-Tank Explosion Flow Fields within STS and Titan IV Payload Spaces - M. Eck, M. Mukunda - December 1988

CWO 28 : On the Analytical Methods Used to Establish the Cassini Abort Environments, Final Report to JPL Contract 959658 - Marshall B. Eck, Steven L. Hancock - November 1996

Fragment Data from Selected Space Vehicle Explosions - Hazards of Chemical Rockets and Propellants Handbook, vol. 1, General Safety Engineering Design Criteria, p. 2-61 - May 1972

Photo instrumentation for Warhead Characterization - R. Campbell and C. R. Wilkinson - Proceedings of the 19th International Symposium of Ballistics, 7-11 May 2001, Interlaken, Switzerland, pp. 867-874 - 200

NAS 3-00031: Cassini Titan IV/Centaur RTG Safety Databook, Rev. B - Lockheed Martin - March 1997

New Horizons SAR Databook - JPL - September 2005

Linear and Nonlinear Waves - G. B. Whitham - John Wiley and Sons, Inc., 1974

<u>For Solid Propellants:</u>

Solid Propellant Blast Modeling - Steven L. Hancock - February 7, 2007

Technical Report No. 99-400/11.1-02: FY99 BLASTX/C Development Activities - Paul Wilde, Shaw Kang, Mark Anderson - September 1999

UCRD-ID-130077: Propellant Impact Risk Assessment Team Report: PERMS Model to Describe Propellant Energetic Response to Mechanical Stimuli - Jon L. Maienschein, John E. Reaugh, Edward L. Lee - February 27, 1998

Risk Assessments with Various TNT Equivalency Models - J. D. Collins - JANNAF Safety and Hazard Classification Panel Meeting, Huntsville, Alabama, April 29, 1997

Titan IV SRMU Failure Modes and Explosive Yield of Impacting Propellant: TRW Support to Propellant Impact Risk Assessment Team (PIART) - Paul K. Salzman - February 18, 1998

Development of a Yield Histogram for Space Shuttle Blast Risks Analyses - Paul Wilde and Mark Anderson - 1999 JANNAF Safety and Environmental Protection Subcommittee, San Diego, CA 26-30 April

Titan IV SRMU Solid Propellant Impact Hazards Analysis in Support of the Cassini Mission, Final Report - Robert L. Geisler, Edward L. Lee, William G. Nance, Richard T. Rauch - September 30, 1995

ESCM/SEM Report #84-1: Detonability of Large Solid Rocket Motors - Louis J. Ullian - August 10, 1984

On the Nature of Impact-Induced HTPB Explosions, Final Report for RIT P.O. 00089959S - Steven L. Hancock, Marshall B. Eck - April 1998

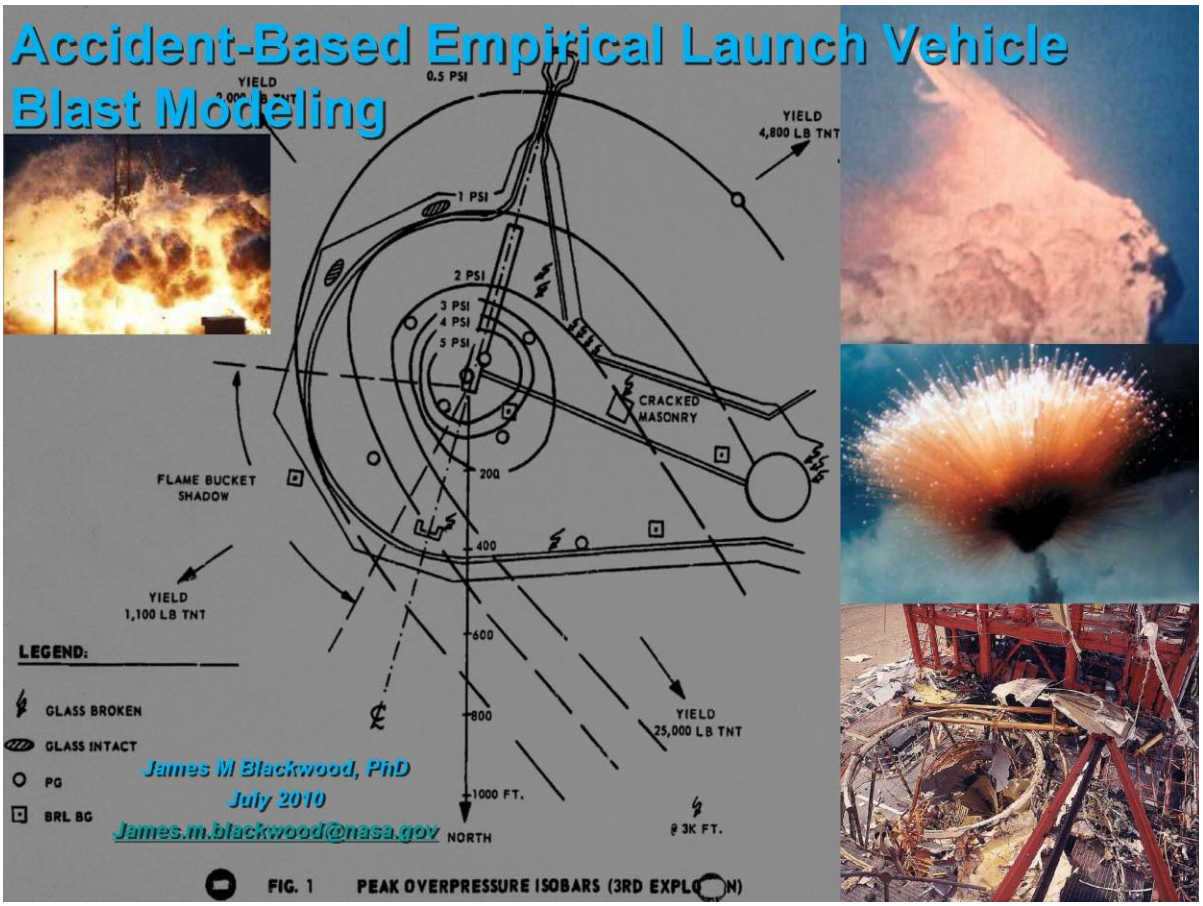
CTH: A Software Family for Multi-Dimensional Shock Physics Analysis - E. S. Hertel, Jr., R. L. Bell, M. G. Elrick, A. V. Farnsworth, G. I. Kerley, J. M. McGlaun, S. V. Petney, S. A. Silling, P. A. Taylor, and L. Yarrington - Sandia National Laboratories - Proceedings of the 19th International Symposium on Shock Waves, Marseille , France 26-30 July 1993, Volume I, pp. 377-382

ARBRL-TR-02555: Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst - Charles N. Kingery, Gerald Bulmash - April 1984

New Horizons SAR Databook - JPL - September 2005

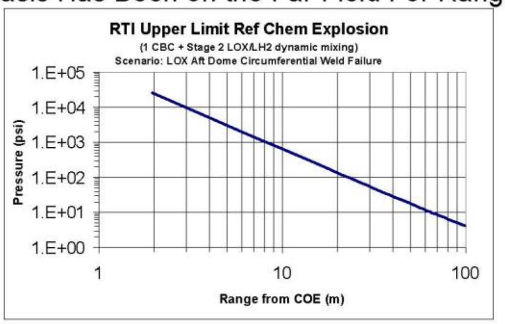
Investigation of USAF Launch Vehicle Accident, Delta II-241/G.P.S. IIR-1, 17 January 1997 - Cape Canaveral Air Station

Appendix B. Bangham Presentation



Bangham Engineering Inc. — Launch Vehicle Blast Modeling Overview

- **1950s to 1990s**
  - Has Almost Exclusively Used the TNT Equivalence Method
    - A Certain Percentage of the Propellant is Considered to React as an Equal Amount of TNT
    - Model is a Point Source
  - Emphasis Has Been on the Far Field For Range Safety

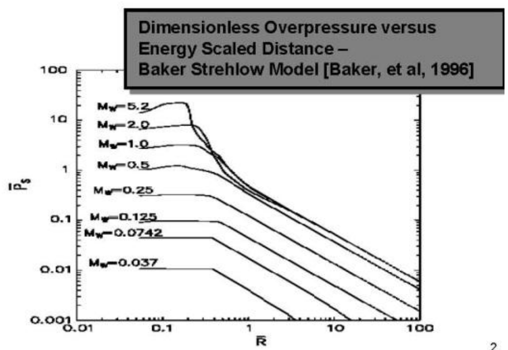


TNT Equivalence Prediction for Probable* Delta IV Explosion

P(3m) = 10183 psi
P(10m) = 678 psi

***Delta IV EELV Explosive Equivalence Study Research Triangle Institute, 3 November 1998**

- **1980s to Present**
  - Better analytical/phenomenological models like VCE (but still insufficient for LVs)
  - Combing various CFD codes (mixing, phase change, FSI, aero, shock, combustion)
  - Still significant use of TNT equivalence



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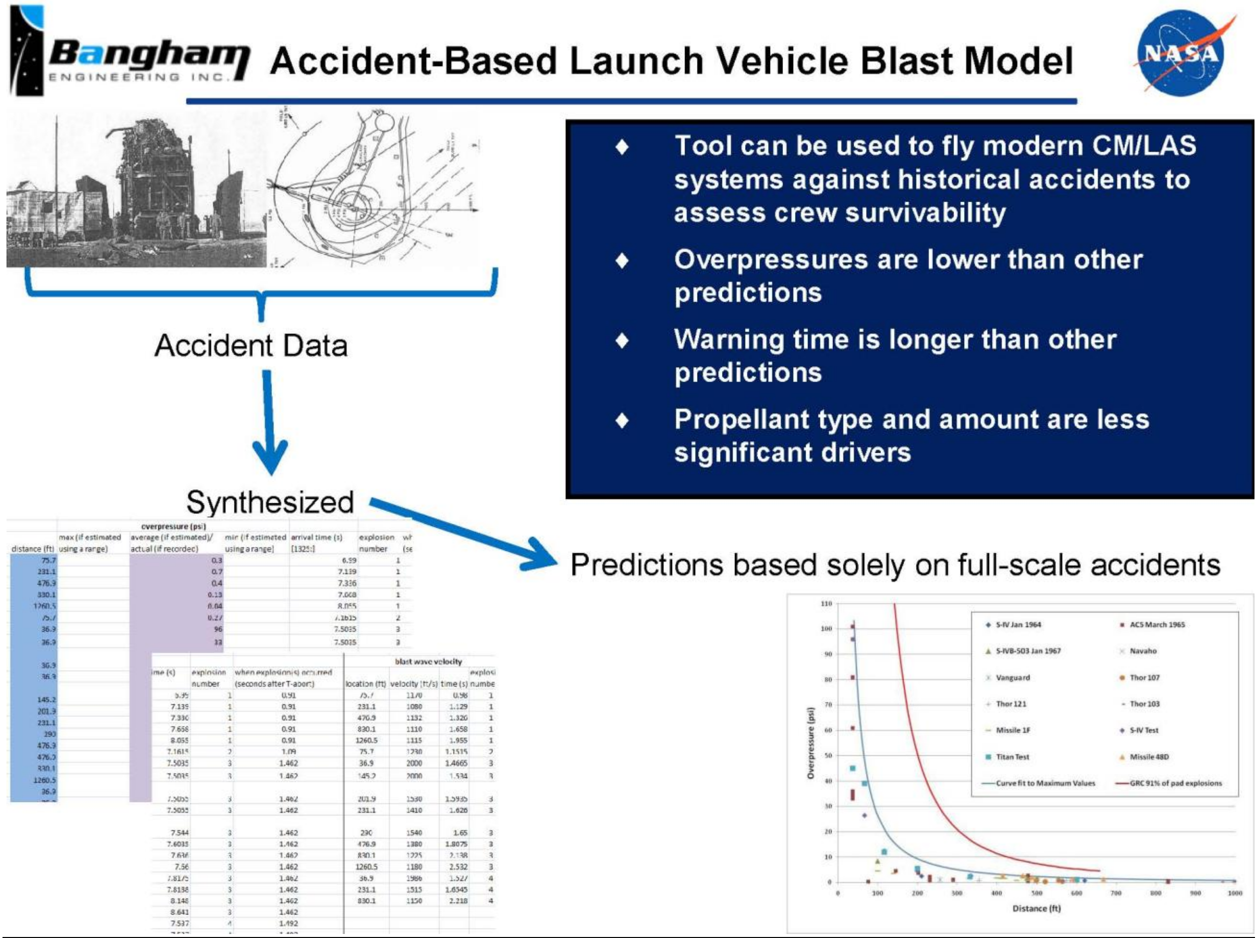


Bangham ENGINEERING INC.
Accident-Based Launch Vehicle Blast Model
Accident Data
Synthesized
Tool can be used to fly modern CM/LAS systems against historical accidents to assess crew survivability
Overpressures are lower than other predictions
Warning time is longer than other predictions
Propellant type and amount are less significant drivers
Predictions based solely on full-scale accidents
Overpressure (psi)
Distance (ft)
S-IV Jan 1964
ACS March 1965
S-IVB-503 Jan 1967
Navaho
Vanguard
Thor 107
Thor 121
Thor 103
Missile 1F
S-IV Test
Titan Test
Missile 48D
Curve fit to Maximum Values
GRC 91% of pad explosions

Liquid Launch Vehicles

LOX/RP and LOX/LH2

with hypergolics encompassed

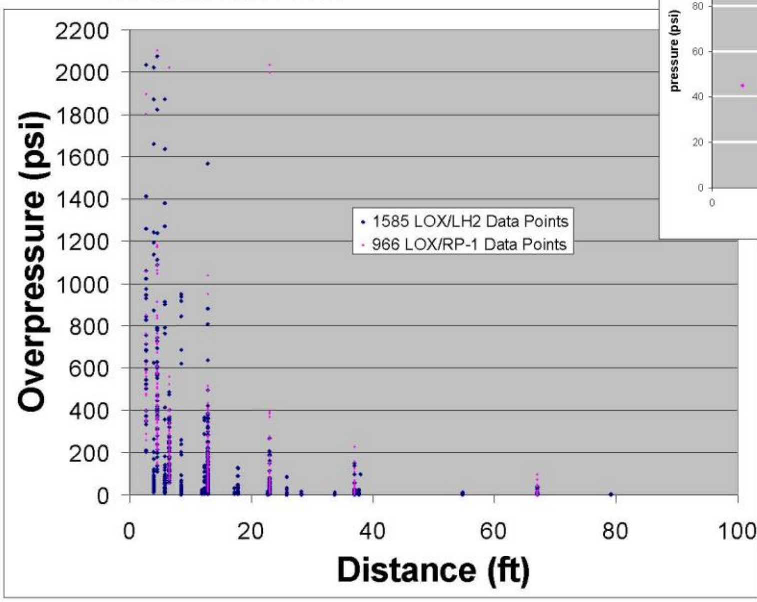
Accident-Based Model Data Summary

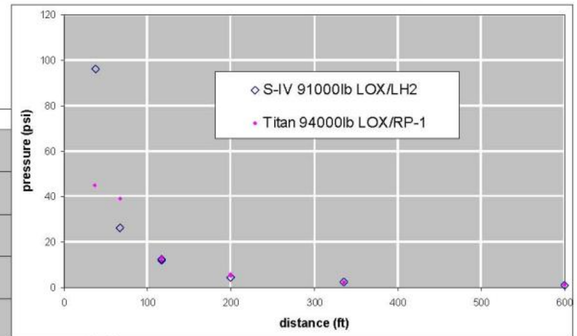
Type of Data	Number of Accidents Found to Date
Overpressure	13
Wave Speed	2
Abort Time	17
Fireball Size/Duration	15
Fragmentation	Not yet assessed
Video	~30

- **20 total pad accidents have useable data**
- **It appears accident database could more than double in size given time and resources**
- **All videos assessed to date are pad failures**
- **Data from a few hundred tests also collected and analyzed, but not included in this presentation**

Similitude of LOX/RP and LOX/LH2

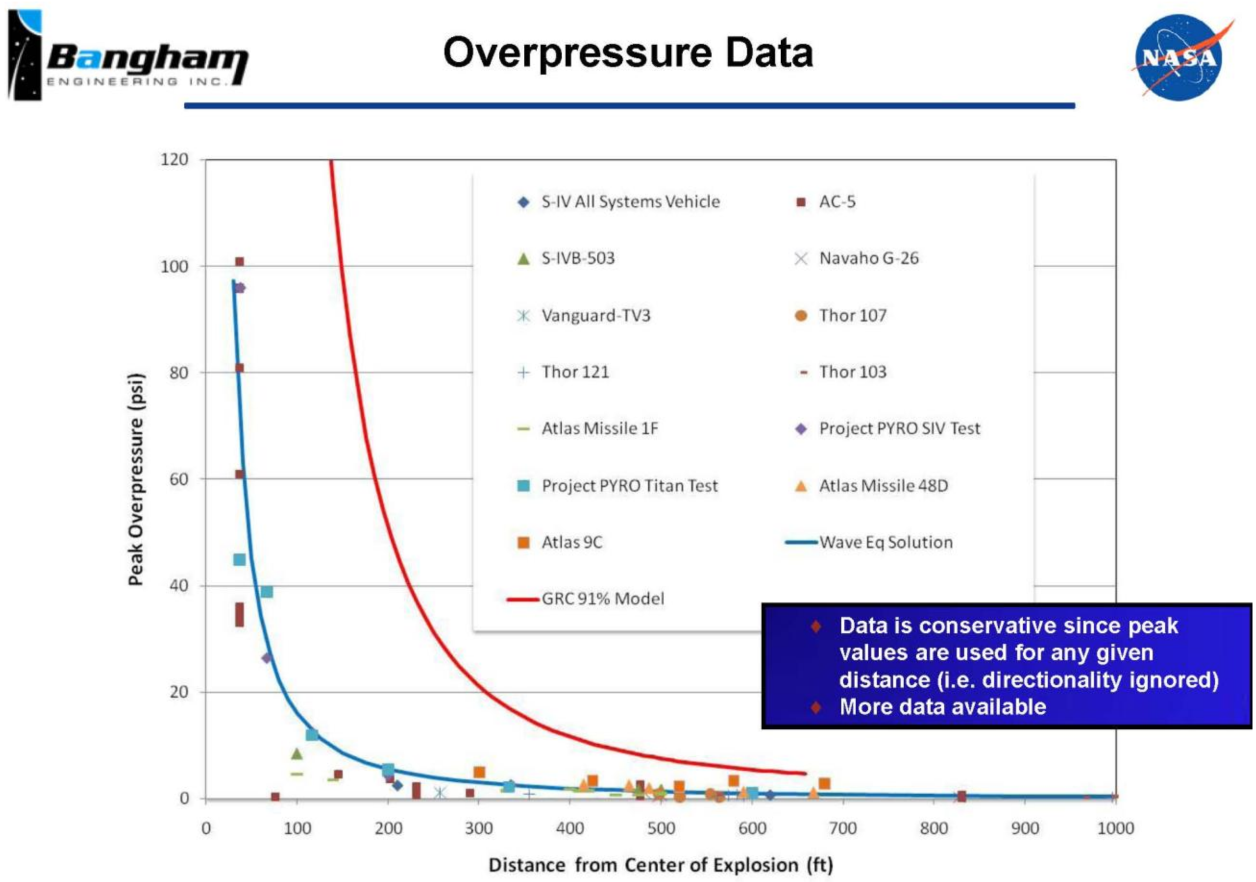
- Statistically same with 95% confidence level





"it is established experimentally that for a given A_c [contact area], the explosive yield of LOX/LH2 is similar to that of LOX/RP-1" - R. High

This allows limited accident data to be statistically relevant for both LOX/RP and LOX/LH2



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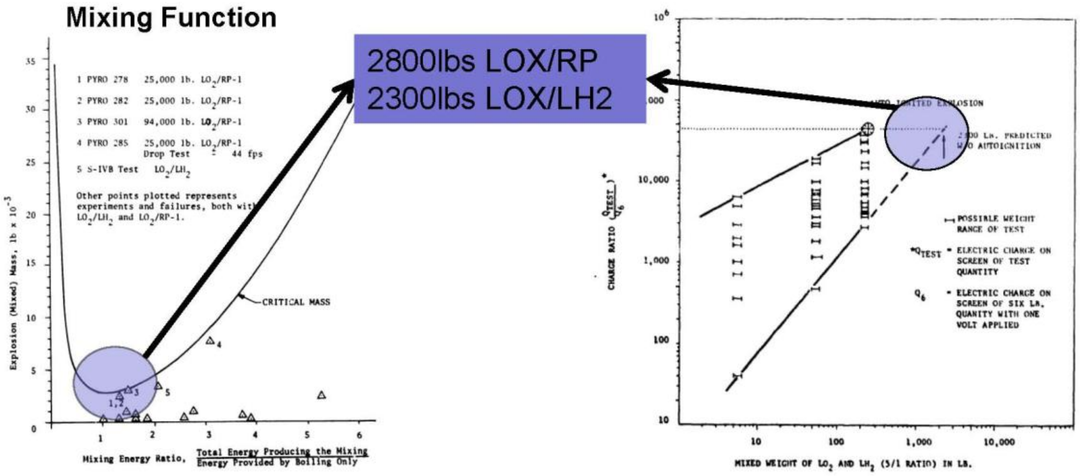
Overpressure Data
NASA
Peak Overpressure (psi)
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Distance from Center of Explosion (ft)
S-IV All Systems Vehicle
AC-5
S-IVB-503
Navaho G-26
Vanguard-TV3
Thor 107
Thor 121
Thor 103
Atlas Missile 1F
Project PYRO SIV Test
Project PYRO Titan Test
Atlas Missile 48D
Atlas 9C
Wave Eq Solution
GRC 91% Model
Data is conservative since peak values are used for any given distance (i.e. directionality ignored)
More data available

Why is LV Blast Overpressure so Low? The Forgotten Auto-Ignition Phenomenon

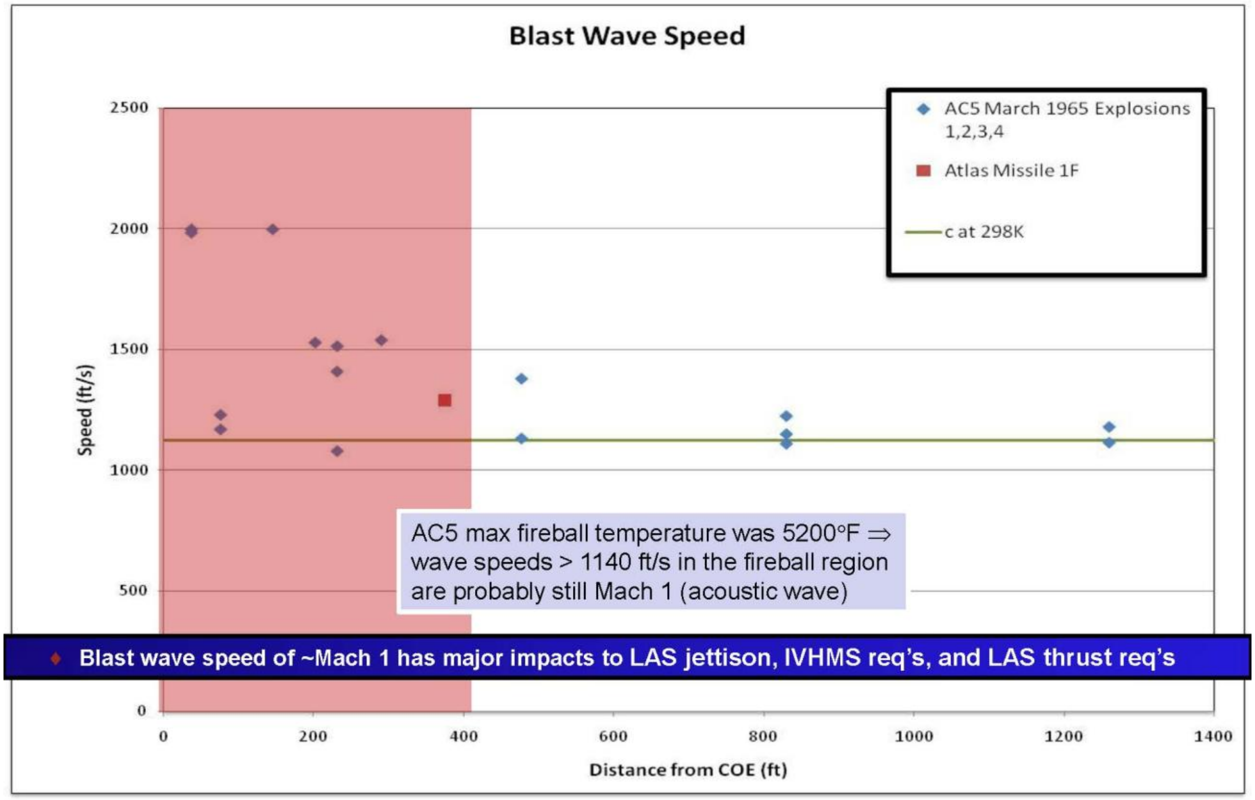
- Auto-Ignition has been theoretically and experimentally studied by Dr Farber of University of FL (~70 publications)
- Auto-Ignition is a function of temperature difference, dielectric constant and strength, bubble size, heat of vaporization
- Critical mass for both LOX/RP and LOX/LH2 is ~1 ton and breaks any scaling laws at this point
- Major physical driver for low overpressure

Charge Ratio

Mixing Function



Blast Wave Speed (Accident)



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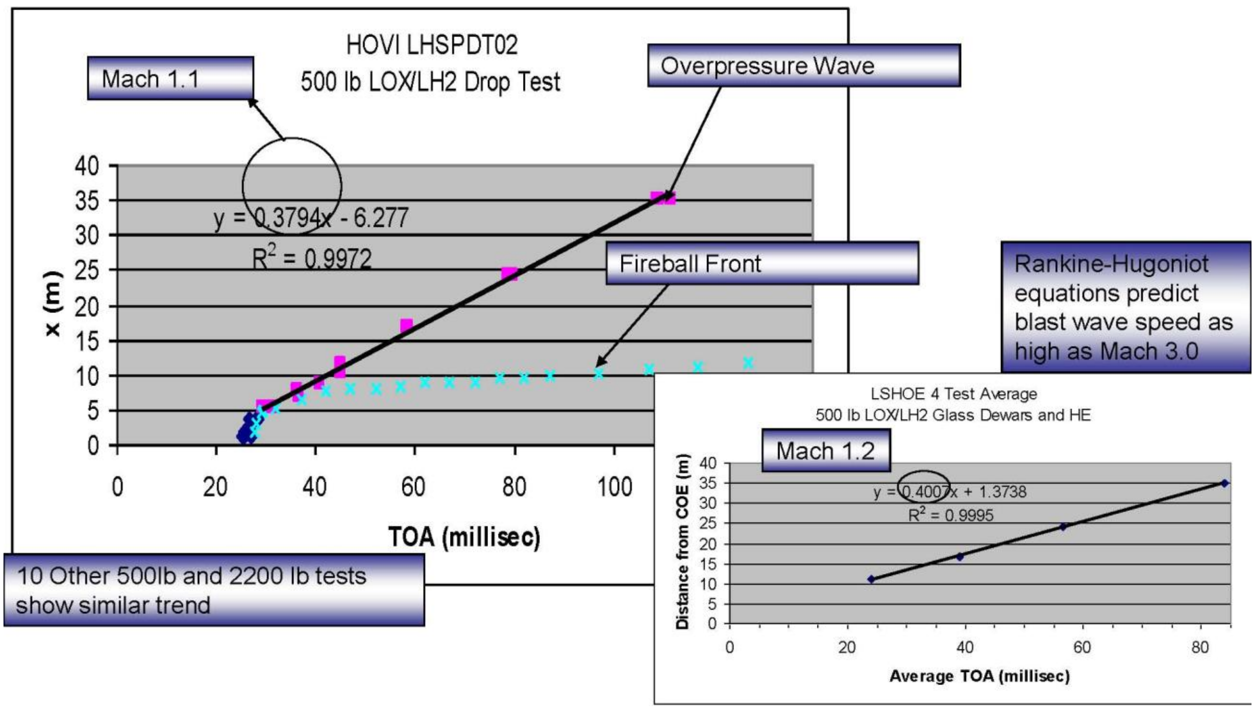
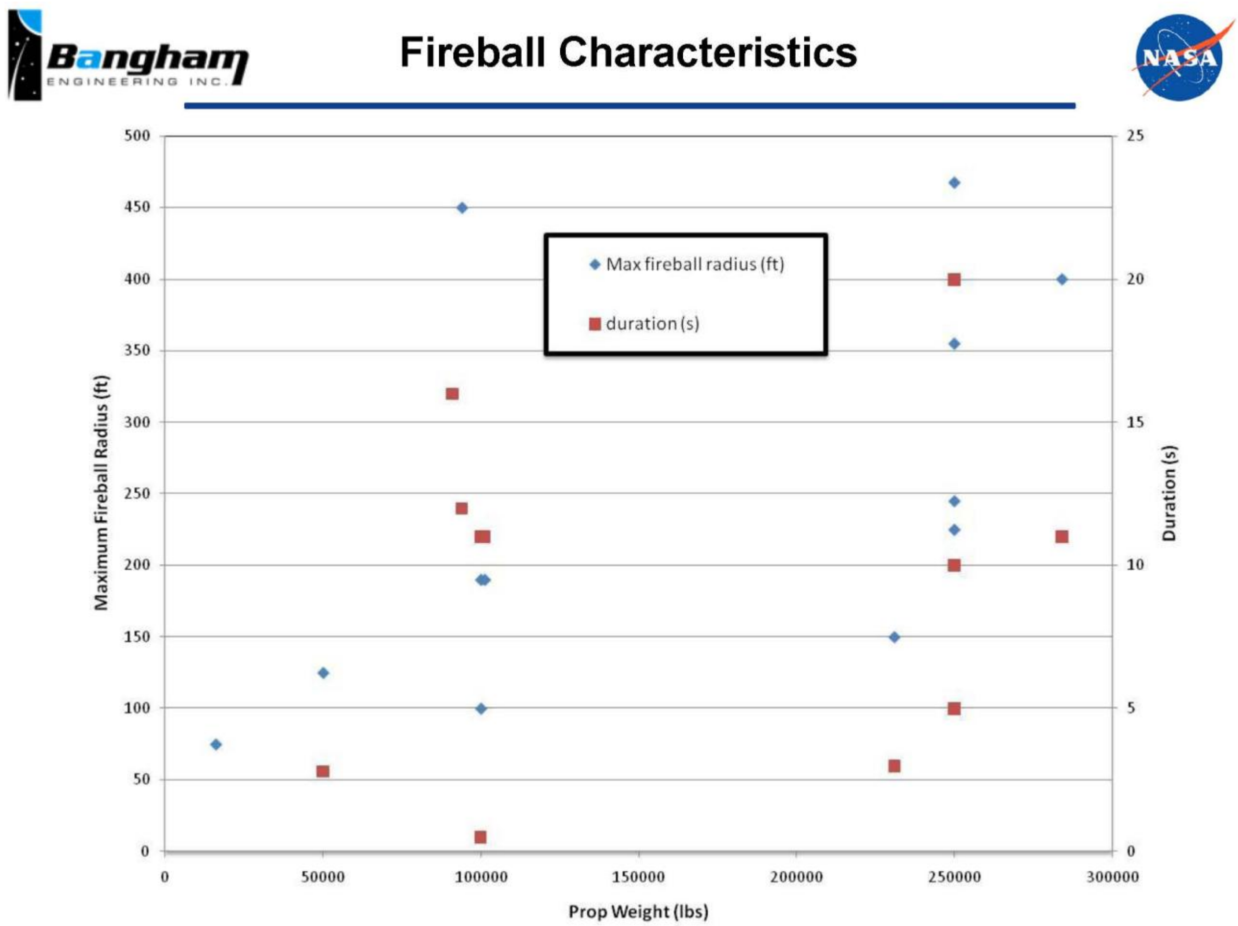
Blast Wave Speed (Test)



So far, test and accident agree that wave speed is ~ Mach 1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Fireball Characteristics
Max fireball radius (ft)
duration (s)
Maximum Fireball Radius (ft)
Duration (s)
Prop Weight (lbs)
0
50000
100000
150000
200000
250000
300000

Abort Warning Time

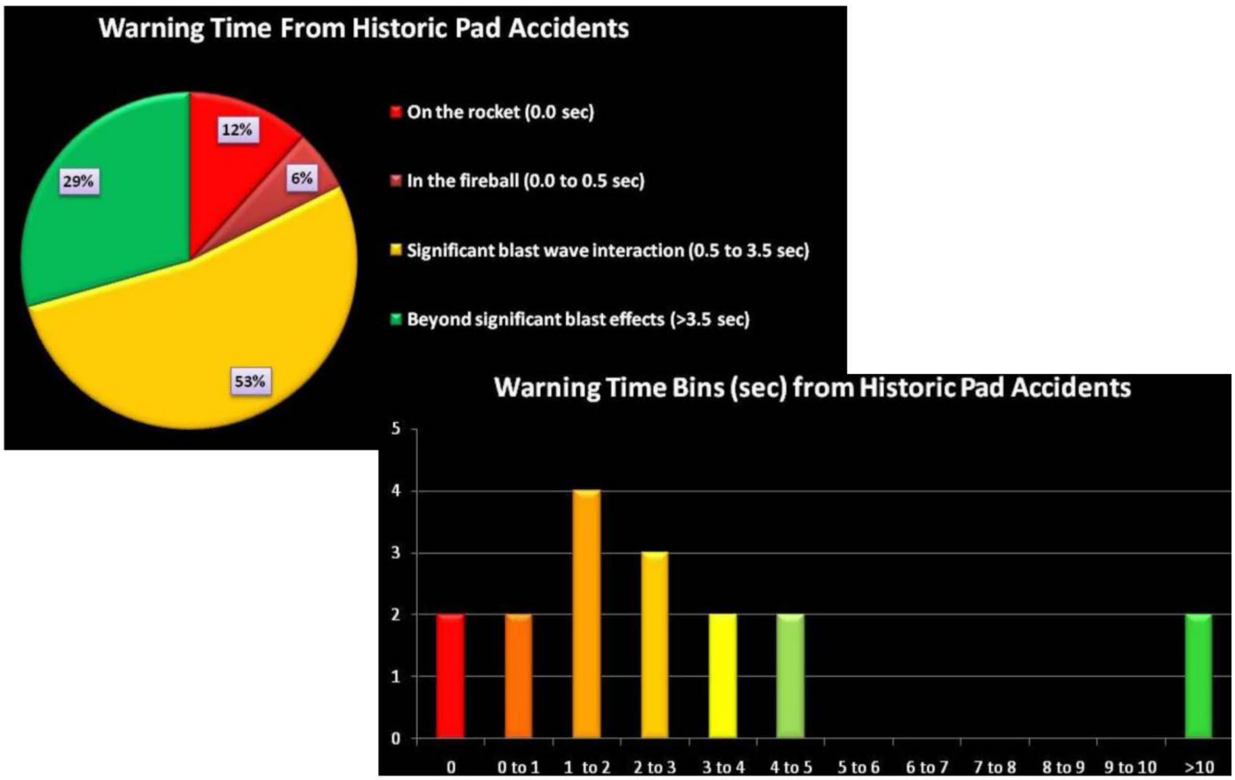
Accident	T-Abort Definition*	T-abort** (sec)
Project PYRO SIV Test	N/A, test	N/A, test
Project PYRO Titan Test	N/A, test	N/A, test
S-IV All Systems Vehicle	Since there was no warning of the explosions, T-abort is defined as the time of the explosion	0.00
AC-5	start of negative velocity	1.462
S-IVB-503	High pressure helium tank catastrophic rupture	0
Navaho	0	
Vanguard-TV3	start of negative velocity	3
Thor 107	start of negative velocity	4.1
Thor 121	start of negative velocity	5
Thor 103	When the tank ruptured	2
Atlas 9C	Significant propellent fire at base of rocket	18
Atlas Missile 1F	Time of the first minor explosion	4
Atlas Missile 11F	initial explosion	0.281
Atlas Missile 48D	at 1.8 seconds-explosion in thrust section	58.49
Sea Launch 2007	start of negative velocity	2
Thor 101	start of negative velocity	2.5
Titan I	0	
Juno II	Rocket pitch >15°	3.4
Atlas 27E	start of neg velocity and significant pitch and roll	2.2
Titan I B5	start of negative velocity	1.5
Atlas Agena-B	start of negative velocity	0.8

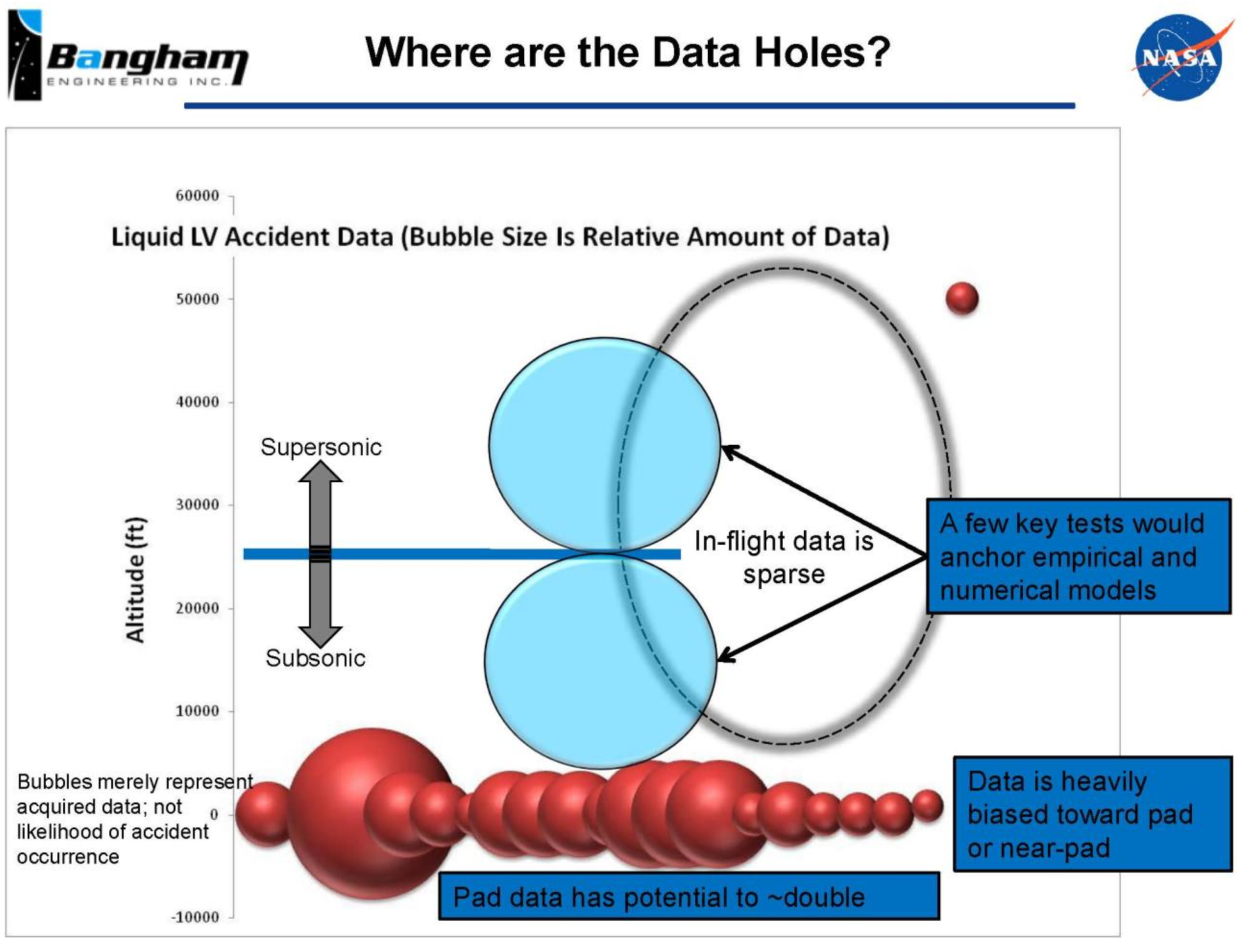
	mean	stdev
	6.40	14.03608
excluding Atlas 48D	3.14	4.233155

*Point in time where need for abort can be recognized even without instrumentation; examples include rocket going backwards, engine explosion, vehicle breakup, etc

**Time of first OP wave >1.0psi

Abort Warning Time




Bangham ENGINEERING INC.
Where are the Data Holes?
NASA
Liquid LV Accident Data (Bubble Size Is Relative Amount of Data)
Altitude (ft)
60000
50000
40000
30000
20000
10000
0
-10000
Supersonic
Subsonic
In-flight data is sparse
A few key tests would anchor empirical and numerical models
Bubbles merely represent acquired data; not likelihood of accident occurrence
Data is heavily biased toward pad or near-pad
Pad data has potential to ~double

Solid Rockets

tests or accidents with >10,000lb propellant

Accident-Based Model Data Summary

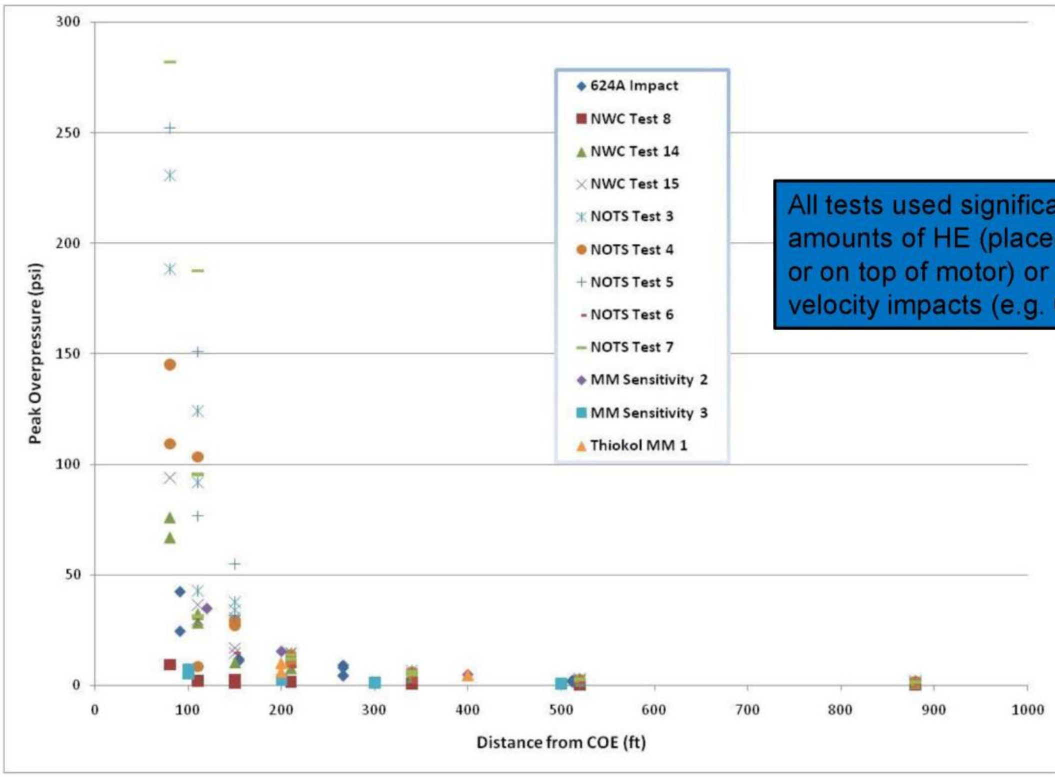
Type of Data	Non-Applicable (acquired / potential)	Applicable (acquired / potential)
Overpressure	12 / 38	7 / ~15
Wave Speed	1 / 38	4 / ~15
Abort Time	0 / 38	0 / ~15
Fireball Size/Duration	0 / 38	0 / ~15
Fragmentation	0 / 38	0 / ~15
Video	0 / 38	0 / ~15

- **Limited search to 10,000 propellant weight or greater**
- **Class 1.3 and 1.1**
- **Unrealistic cases include HE donors or high velocity impact (100s of ft/s)**
- **Both acquired data and potential tests/accidents will increase**

Top-Level Evolving Trends

- **Most tests focused on how to make SRM detonate; not on most likely failure case or even realistic worst case**
- **No accident or range safety destruct test found to date has produced large overpressures**
- Solid propellant explosions have been characterized as "explosions", "violent burns", "sub detonations", "detonations", "deflagrations", "fast deflagrations", "fast reactions"
- Regardless of underlying physics, solid propellant can produce an extreme environment of blast overpressure, thermal, fragmentation **if**:
  - Critical dimension (many feet for 1.3) and…
  - High pressures (100,000s of psi)
    - High explosives or…
    - High velocity impact
- E.g. Titan 34D-9 secondary explosion from large part of SRB hitting ground threw fragments further than both the original SRB failure and other auto-destructed SRB at 800ft altitude
- Case burst overpressure is the minimum for hot SRM failure

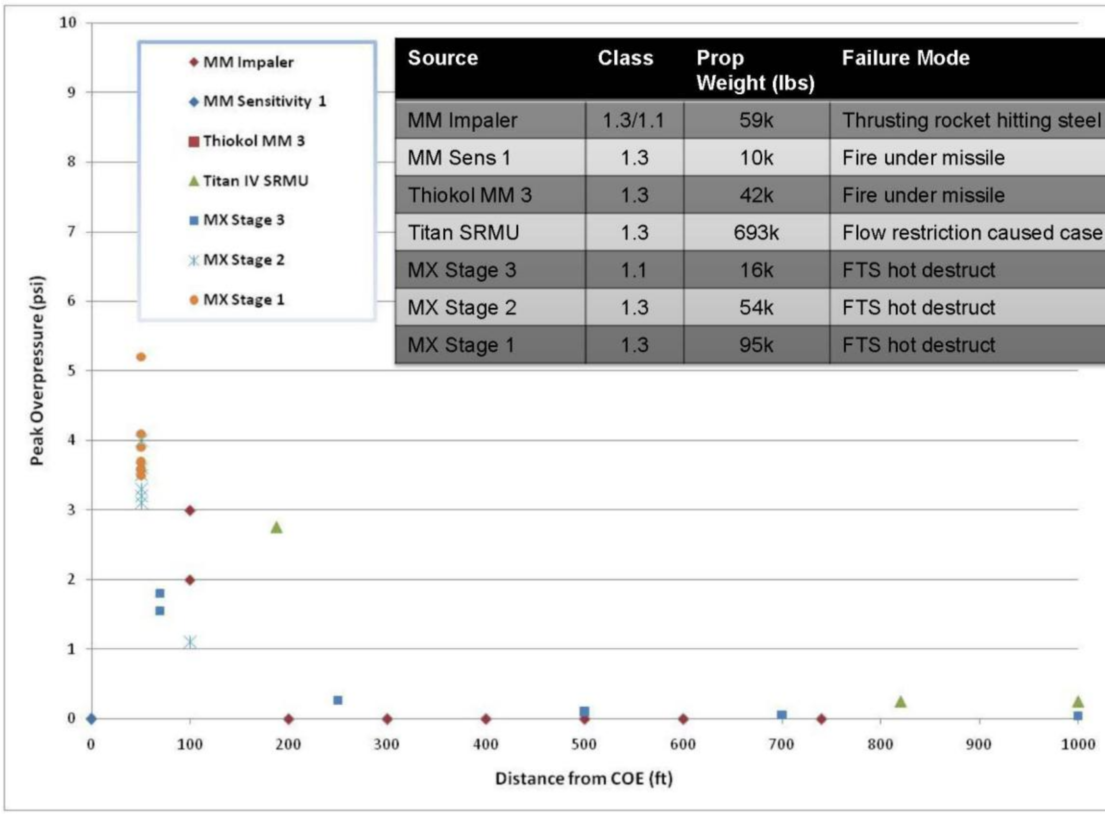
Bangham Engineering Inc. Non-Applicable SRM Explosion Tests



All tests used significant amounts of HE (placed inside or on top of motor) or high velocity impacts (e.g. 667 ft/s)

Accidents and Applicable Tests

Source	Class	Prop Weight (lbs)	Failure Mode
MM Impaler	1.3/1.1	59k	Thrusting rocket hitting steel impaler
MM Sens 1	1.3	10k	Fire under missile
Thiokol MM 3	1.3	42k	Fire under missile
Titan SRMU	1.3	693k	Flow restriction caused case burst
MX Stage 3	1.1	16k	FTS hot destruct
MX Stage 2	1.3	54k	FTS hot destruct
MX Stage 1	1.3	95k	FTS hot destruct



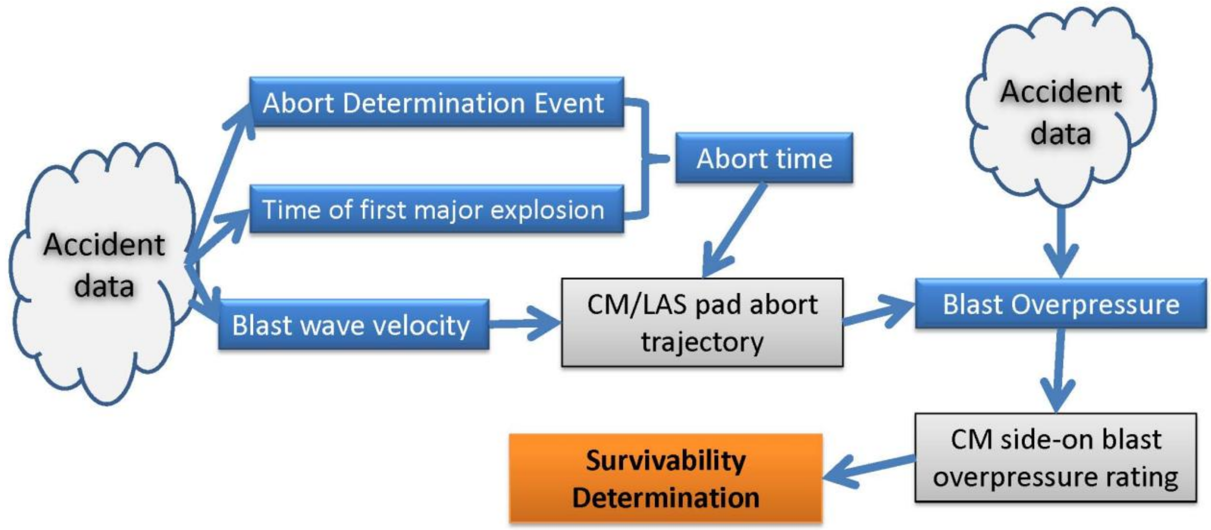
Analysis Work To Be Completed

Work Remaining For Complete Model

Type	Variable	Description	Completion	
			Liquids	Solids
Mechanical	P(x)	Overpressure as a function of distance	50%	25%
	I(x)	Impulse as a function of distance	40%	10%
	v(x,t)	Blast wave speed as a function of distance and time	50%	25%
Fragmentation	m	Fragmentation mass distribution	10%	10%
	v_0	Initial fragmentation velocity distribution	10%	10%
	A	Cross-sectional fragmentation area distribution	10%	10%
	#	Number of fragments as a function of volume	10%	10%
Thermal	r(t)	Fireball radius as a function of time	40%	10%
	T(t)	Fireball temperature as a function of time	40%	10%
Temporal	t_a	Time of abort trigger till first blast wave	50%	10%

In-flight data collection, analysis and **testing** also required

Independent Assessment Tool



- Gives NASA the tools to be able to assess and compare the safety of commercially provided launch systems accurately and independently
- Allows NASA to independently verify prime contractor's safety analysis of heavy lift vehicle

Backup

Potential Implications

In February 2010, the Aerospace Safety Advisory Panel (ASAP) found that,
"For years, the aerospace world has been using the same fault-tree analyses, risk matrix assessments, preliminary hazard analyses, etc., that were developed in the Apollo era to identify and assess hazards and risks. There has rarely been enough time or funds to develop the new tools needed to identify and control hazards inherent in modern technologies such as software, firmware, and robotics, to name a few. A potential NASA shift away from Program support to technology development may provide an opportunity to develop the tools needed to ensure the safety of these modern technologies."

Accident –based empirical blast modeling study needs to be completed, then…

1. A more accurate characterization of the catastrophic LV environment can be made,
2. And if the environment is truly more benign than previously estimated,
3. It could lead to an increase in crew survivability w/o decreasing LV performance

- Could significantly influence architecture of the LV system including LAS, CM, IVHMS, LV trajectory
- Can be used as a crew survivability assessment tool on NASA and commercial launch systems
- Need to involve vehicle system level designers and architects

- Models based on actual data would allow:

1. Benchmarking of other analytical and numerical models describing launch vehicle failures
2. A more accurate assessment of crew survivability on current launch vehicle systems
3. Crew survivability to be maximized on new designs by accurately assessing benefits of launch vehicle, IVHMS, LAS, and crew module designs
4. Human rating assessments of future COTS launch vehicles
5. A centralized database for access by the user community.

Empirical vs. Analytical or Numerical

- **Simple analytical Methods Do a Poor Job of Capturing Very Complicated Physics of Non-Condensed Explosions**

"there are dramatic differences between explosions involving vapor clouds and high explosives at close distances; for the same amount of energy, the high explosive [TNT] blast overpressure is much higher"

- M.J. Tang and Q.A. Baker, *A New Set of Blast Curves from Vapor Cloud Explosions*, Process Safety Progress (Vol. 18, No.3)

- **Analytical models are typically focused on far field (range safety) not near field (crew survivability)**
- **The few numerical (CFD) codes that exist to predict launch vehicle explosions are alterations and/or combinations of various other codes**
- **They typically have 10s to 100s of inputs**
- **Benchmarking against full-scale data seems non-existent at this time**

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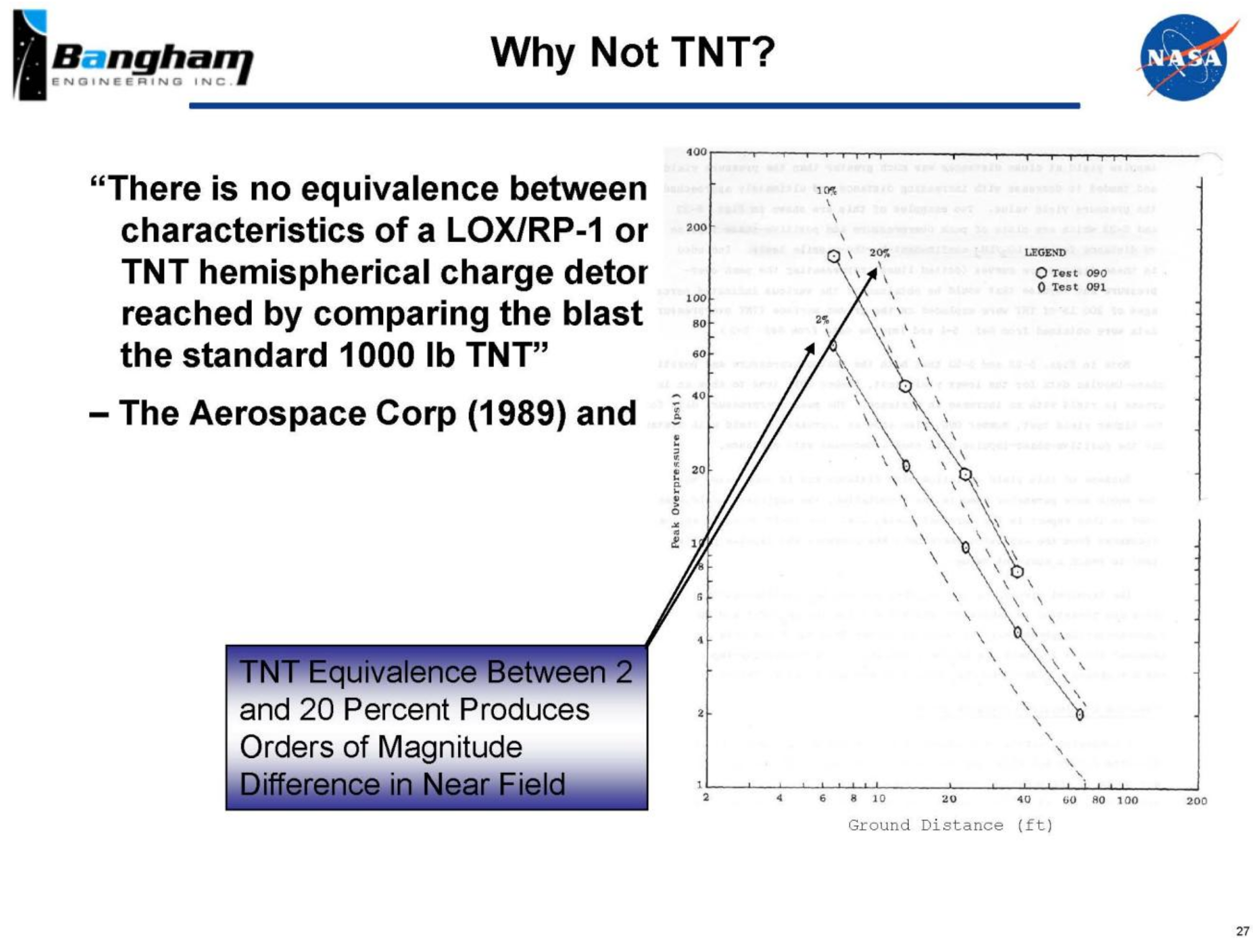
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Why Not TNT?
NASA
“There is no equivalence between
characteristics of a LOX/RP-1 or
TNT hemispherical charge detor
reached by comparing the blast
the standard 1000 lb TNT”
– The Aerospace Corp (1989) and
TNT Equivalence Between 2 and 20 Percent Produces Orders of Magnitude Difference in Near Field
10%
20%
2%
LEGEND
Test 090
Test 091
Peak Overpressure (psi)
Ground Distance (ft)
27

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Why Empirical vs. Analytical/Phenomenological?

- **Analytical Methods Do a Poor Job of Capturing Very Complicated Physics of Non-Condensed Explosions**

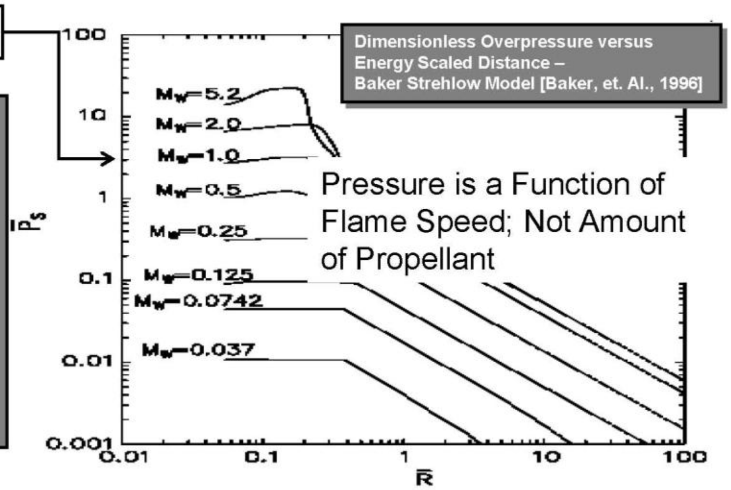
"there are dramatic differences between explosions involving vapor clouds and high explosives at close distances; for the same amount of energy, the high explosive [TNT] blast overpressure is much higher"

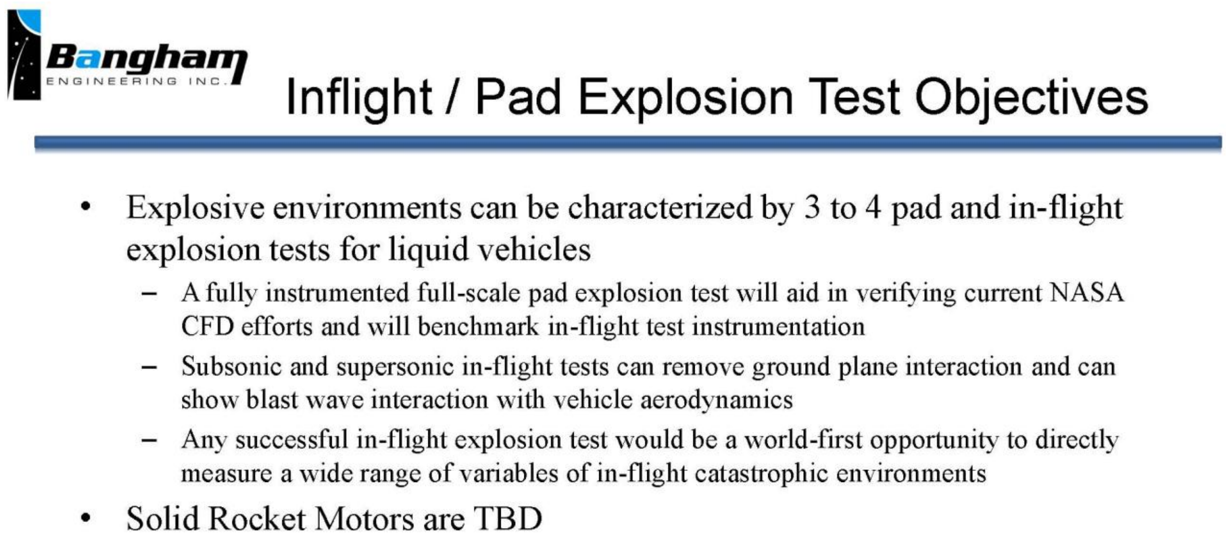
- M.J. Tang and Q.A. Baker, *A New Set of Blast Curves from Vapor Cloud Explosions*, Process Safety Progress (Vol. 18, No.3)

P(Mach 1) ≅ 3atm or 44psi

Vapor Cloud Explosion (VCE):

- A Thermodynamic Model Solved Numerically
- Validation by Experimental Data
  - J. Brossard, S. Hendrickx, J.L. Garnier, A. Lannoy and J.L. Perrot, *Air Blast From Unconfined Gaseous Detonations*
  - Dorofeev, S.B., *Blast Effects Of Confined And Unconfined Explosions*

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Inflight / Pad Explosion Test Objectives
• Explosive environments can be characterized by 3 to 4 pad and in-flight explosion tests for liquid vehicles
– A fully instrumented full-scale pad explosion test will aid in verifying current NASA CFD efforts and will benchmark in-flight test instrumentation
– Subsonic and supersonic in-flight tests can remove ground plane interaction and can show blast wave interaction with vehicle aerodynamics
– Any successful in-flight explosion test would be a world-first opportunity to directly measure a wide range of variables of in-flight catastrophic environments
• Solid Rocket Motors are TBD

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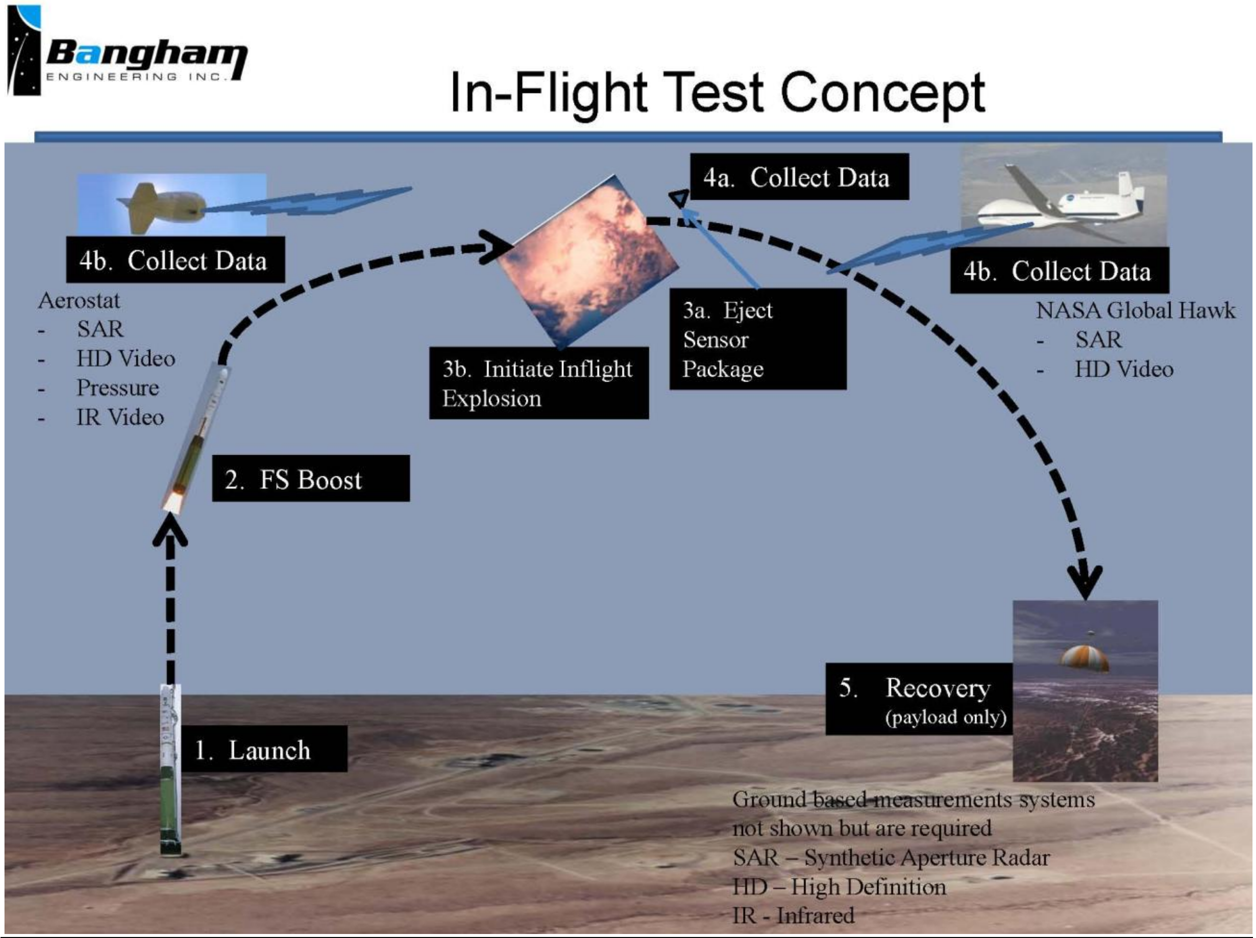
Test Approach

- Tests must establish the underlying physics of the in-flight and pad explosions
  - Generic test data applicable to **<u>any</u>** current launch vehicles under consideration (NASA and Commercial)
  - Test data to be used to confirm findings from empirical and CFD studies now underway
- Notional Test Series
  - On Pad and/or near Pad (Test 1)
  - Subsonic ~0.5M (Test 2)
  - Supersonic ~1.2M (Test 3)
- Need to complete analytical/empirical assessments ASAP
  - Results are guiding test approach
  - Need to work with ARC on CFD aspects


Bangham ENGINEERING INC.
In-Flight Test Concept
4a. Collect Data
4b. Collect Data
Aerostat
- SAR
- HD Video
- Pressure
- IR Video
4b. Collect Data
NASA Global Hawk
- SAR
- HD Video
3a. Eject Sensor Package
3b. Initiate Inflight Explosion
2. FS Boost
1. Launch
5. Recovery (payload only)
Ground based measurements systems not shown but are required
SAR – Synthetic Aperture Radar
HD – High Definition
IR - Infrared

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In-Flight Test Article and Sensor

- First stage boosts LV to appropriate altitude and velocity
  - Test 1 – On Pad or near Pad
  - Test 2 – $0.5<Ma<0.9$, 10,000 to 20,000 ft
  - Test 3 – $1.1<Ma<1.5$, 25,000 to 35,000 ft
- Second stage consists of at least 75,000lb LOX/RP tanks and FTS
  - Rocket is intentionally destroyed via auto destruct or FTS at appropriate altitude
  - Vehicle avionics are relocated with support structure to envelope qualification environments
- Payload is recoverable sensor package
  - May be ejected prior to or during LV destruction
  - Payload is recovered via parachutes
  - Will consider small low cost sensor packages ejected from payload prior / during explosion
- External Sensors are carried by UAVs or Balloons
  - Sensor suite will include high speed video, SAR
  - Airborne sensors may be placed on tethered balloons (Aerostat) strategically located near the planned vehicle trajectory to monitor environments for the planned destruction
- Debris may be collected / mapped to correlate with radar data

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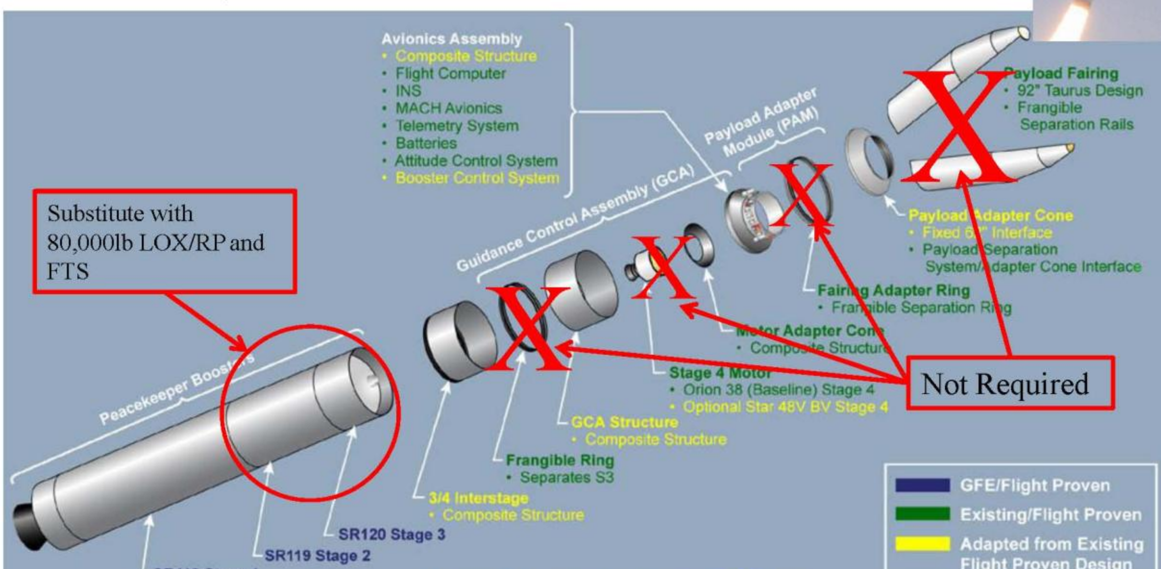
In-Flight LV Concept

- Minotaur IV possible match to requirements, others possible
- Will require First Stage, selected structures, and avionics
- Unique sensor package carries primary instrument platform with "LAS" like tower to acquire critical data in front of payload / nose cone (extends data collection zones)



Minotaur IV diagram taken from www.orbital.com

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Data Collection Systems

- Measurement requirements focused on blast overpressure, blast wave speed, fragmentation, and fireball
  - High frequency pressure, microphones, accelerometers, surface strain gauges,
- Sensors might include blast gauges, synthetic aperture radar, radiometers, high speed / high definition video
- Primary data sources are on surface of launch vehicle and deployed sensor package
- Small probes ejected in sequence prior and during test
  - Option for consideration only if low cost, elegant mechanisms found
- Off-vehicle data acquisition uses NASA, DOD or leased assets
  - Multiple platforms under consideration but might consist of:
    - Balloon, aerostat
    - Global Hawk (NASA or DoD)
    - DOD aircraft (MDA)
    - Commercial leased platform
    - Ground based systems such as long range cameras, debris radar, others
  - Ground survey of debris fields

Ares I 2nd Stage Best Candidate Accident

- 20 January 1967 S-IVB-503 Sacramento Static Test Stand Explosion
- 231,000 lb LOX/LH2
- Cause by Titanium High Pressure Helium Tank Rupture

Points to Note From Video:

1. All Light Bulbs In The Middle Of The Test Stand Went Out
2. One Light Bulb At The Bottom Of The Test Stand Remained On
3. A Flashing Light At The Top Of The Test Stand Remained On
4. The Wooden-sided, Tin-roofed Shed At The Base Of The Test Stand Lost All Windows And One Sheet Of Tin

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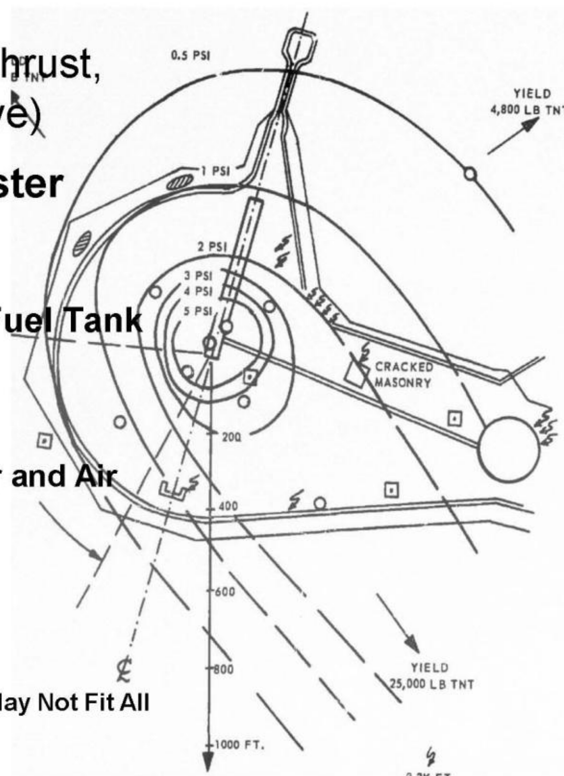
Bangham Engineering Inc. Accident-Based Model Data Selection

I. Minor Failure (e.g. Loss of Thrust, Tank Rupture w/o Blast Wave)

II. Catastrophic Failure (Booster Disintegrates)

- A. Single Tank Failure
- **B. Simultaneous Oxidizer and Fuel Tank Failure**
  1. Case Rupture Only
  2. Ignition of Fuel with Air
  3. **Ignition of Fuel with Oxidizer and Air**
     - a. Slow Burn
     - **b. Deflagration / Detonation**
       - i. Symmetric
       - **ii. Asymmetric**
         - 1) Test
         - **2) Accident (Some Data May Not Fit All Selections)**



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Classes of Explosive LV Failures

A. Ideal – Maximum mixing, vaporization, initiation, etc

1. Only seen in tests
2. Still less than most TNT equivalence estimations

B. Strong – Substantial Mixing

1. Typically pad or near pad explosions
    i. Low or zero velocity
    ii. Physical stop
    iii. Ground reflection
2. Abortable due to significant time (~3 sec) required for mixing and/or energy input
3. Example: 1965 Atlas Centaur AC-5 *{video 2}*

C. Weak – Little Mixing

1. Most common type
2. Usually Multiple weak explosions per failure
3. Most non-abortable (no warning time) explosions are weak
4. Example: Challenger, SIV-B-503 *{video 1}*

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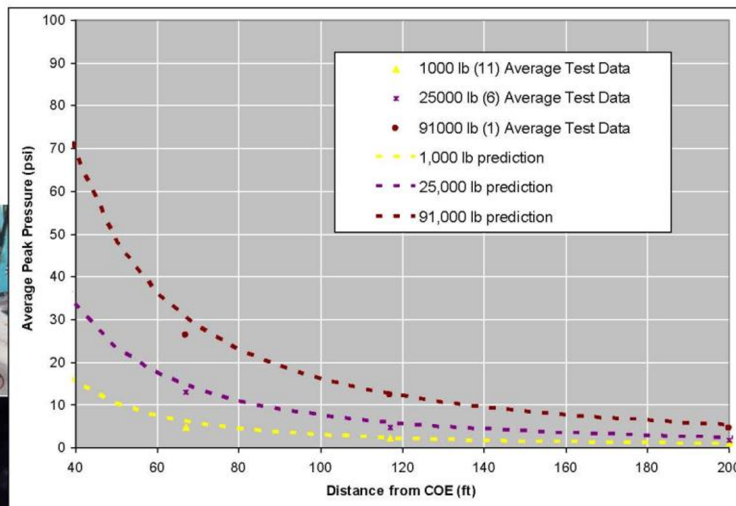
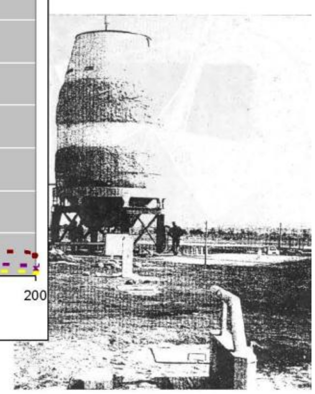
Test-Based (Ideal) Model

- \+ Variety of cases can be modeled
- \+ Easier to model
- \- Usually small-scale
- \- Doesn't fit "real world" data well





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Realistic Hypergolic Catastrophic LV Tests and Accidents Found To Date

Test/Accident Name	No. of Tests	Propellant Weight (lb)	Maximum* Overpressure (psi)	Distance from Explosion (ft)	Notes
Titan II First Stage Destruct Test	1	32,700	10	20	Two tanks completely ruptured by shaped charges
Rocketdyne Small Scale Spill Tests	14	50 and 300	2.5	25	Two tanks completely emptied into a steel silo or steel plate
Rocketdyne Pressurized Spill Test A	1	1600	~0	25	Water deluge system activated 0.5 seconds after both tanks were empty
Rocketdyne Pressurized Spill Test B	1	1300	2.2	25	
Aerojet Common Bulkhead Failure Tests A	2	300	17	10	Dropped from 15 ft with glass common bulkhead and cutter
Aerojet Common Bulkhead Failure Tests B	2	300	<1	10	Aluminum common bulkhead removed by explosive charge
PYRO Command Destruct	2	200	1.5	23	Linear shaped charges along length of tanks
PYRO Common Bulkhead Failure	3	200	1.2	23	Glass common bulkhead rupture by explosive charge
PYRO Low Velocity Fall Back	9	200 and 1000	3.1	15	Dropped from 100 ft tower
Challenger Accident	1	~28,000	0-10†	~0	Hypergolic explosion occurs directly under nose of shuttle with crew cabin seen descending intact after explosion

*This value represents the single greatest overpressure reading by any sensor at any time during all tests. Average overpressures are much lower in all cases.

†Estimation from Challenger vertical accelerations during explosion of hypergolic and cryogenic propellants

CEV SM: 20.5k lb NTO/MMH

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Unrealistic Hypergolic Catastrophic LV Tests and Accidents Found To Date

Test Name	No. of Tests	Propellant Weight (lb)	Maximum* Overpressure (psi)	Distance from Explosion (ft)	Notes
Aerojet Maximum Surface Contact Tests	9	300	104	10	Multiple glass Dewars of oxidizer placed in pan of fuel and dropped from 15 ft
Aerojet External Explosive Tests	11	130	237	15	45 lb of Composition B used to initiate explosion
PYRO High Velocity Impact Tests	15	200 and 1000	53.5	15	Propellants accelerated to 340 to 580 ft/s via sled and impacted upon various walls
Titan II Silo Explosion	1	200,000	Restricted	Restricted	Two servicemen within 150 to 200 ft survived the explosion. One later died in the hospital.

*This value represents the single greatest overpressure reading by any sensor at any time during all tests. Average overpressures are much lower in all cases.

Blast Wave From the CEV SM Is A Secondary Concern for LAS

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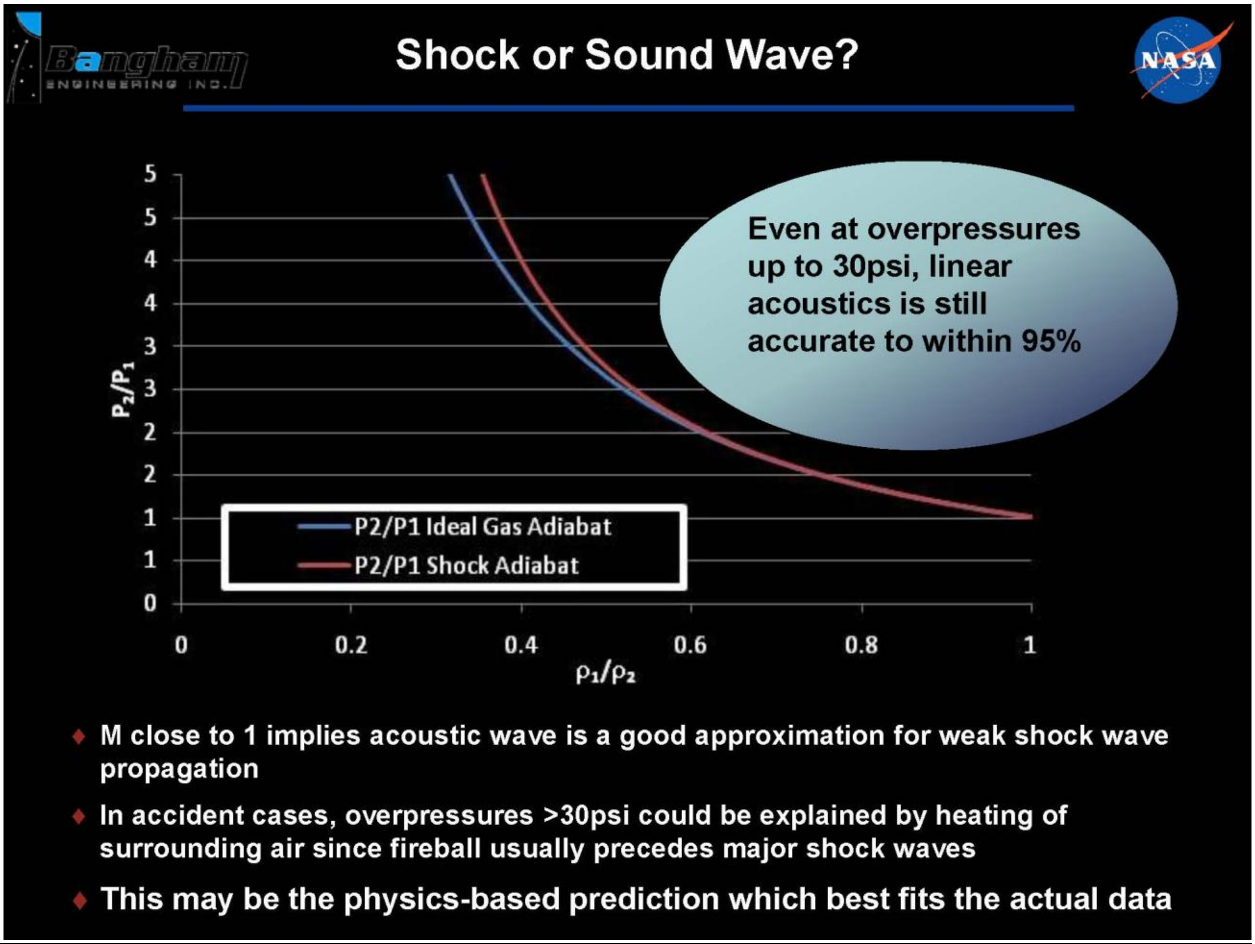
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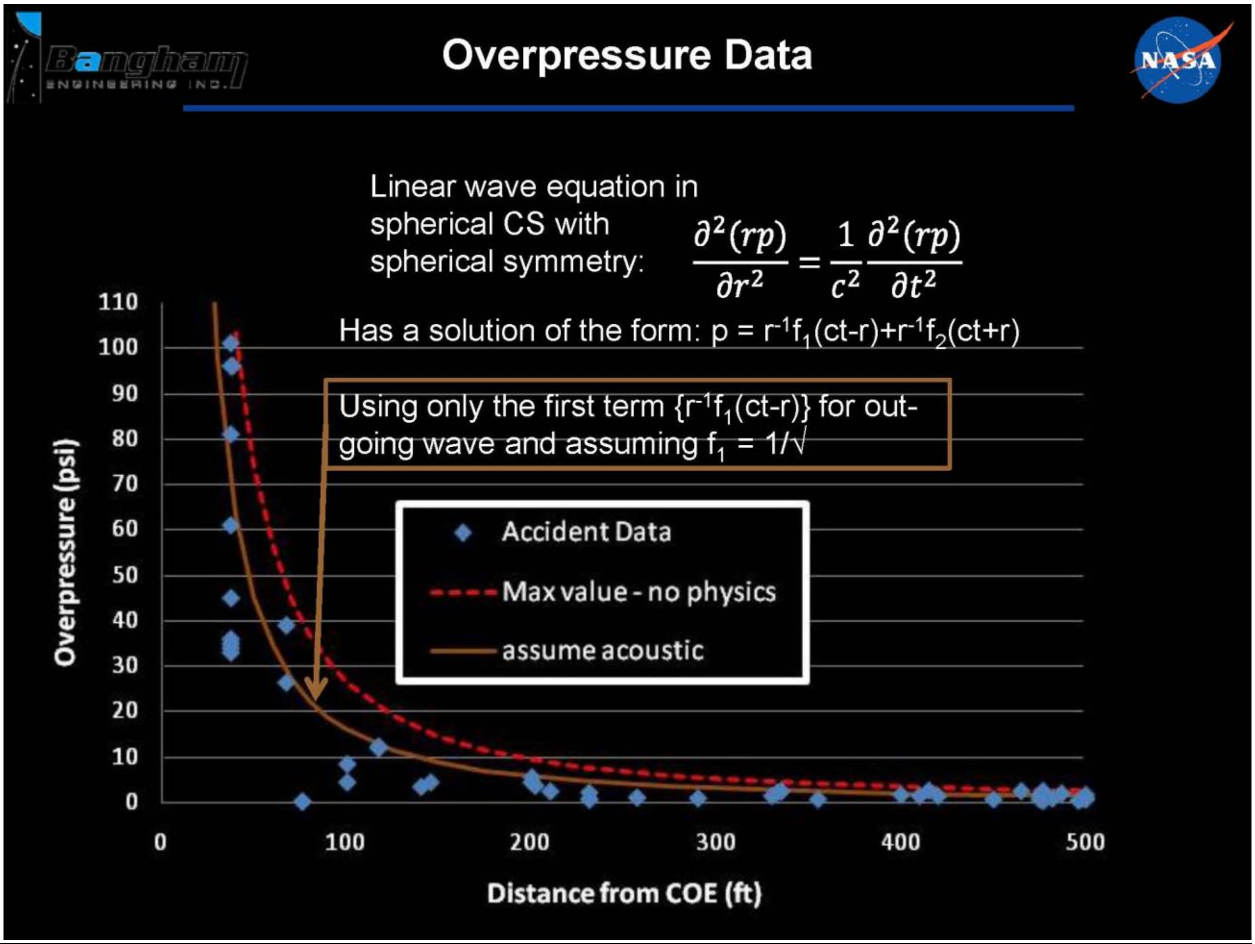
Shock or Sound Wave?
NASA
Even at overpressures up to 30psi, linear acoustics is still accurate to within 95%
P2/P1 Ideal Gas Adiabat
P2/P1 Shock Adiabat
P2/P1
ρ1/ρ2
5
5
4
4
3
3
2
2
1
1
0
0
0.2
0.4
0.6
0.8
1
M close to 1 implies acoustic wave is a good approximation for weak shock wave propagation
In accident cases, overpressures >30psi could be explained by heating of surrounding air since fireball usually precedes major shock waves
This may be the physics-based prediction which best fits the actual data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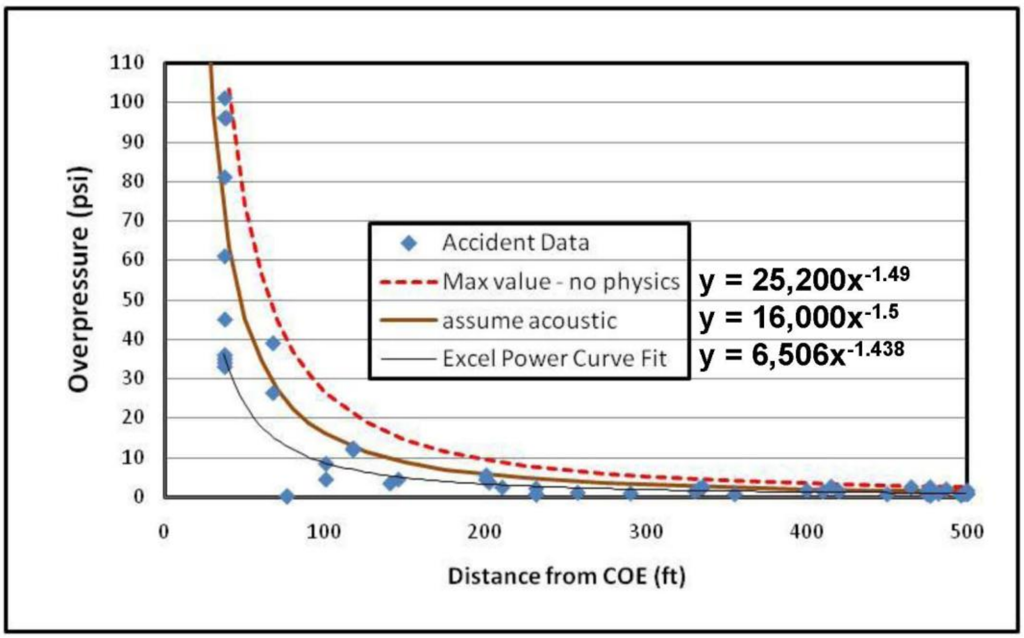
Overpressure Data
NASA
Linear wave equation in spherical CS with spherical symmetry:
$\frac{\partial^2 (rp)}{\partial r^2} = \frac{1}{c^2}\frac{\partial^2 (rp)}{\partial t^2}$
Has a solution of the form: $p = r^{-1}f_1(ct-r)+r^{-1}f_2(ct+r)$
Using only the first term $\{r^{-1}f_1(ct-r)\}$ for out-going wave and assuming $f_1 = 1/\surd$
Accident Data
Max value - no physics
assume acoustic
Overpressure (psi)
0
10
20
30
40
50
60
70
80
90
100
110
Distance from COE (ft)
0
100
200
300
400
500



Overpressure (psi)
110
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
Distance from COE (ft)
Accident Data
Max value - no physics
assume acoustic
Excel Power Curve Fit
y = 25,200x^-1.49
y = 16,000x^-1.5
y = 6,506x^-1.438

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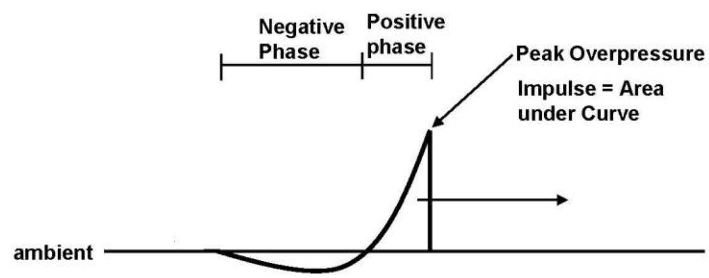
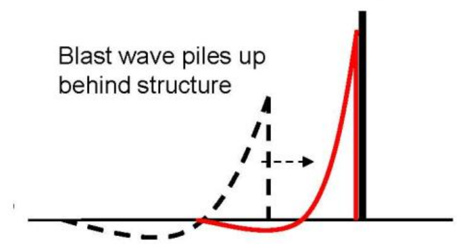
Side-on Vs. Reflective

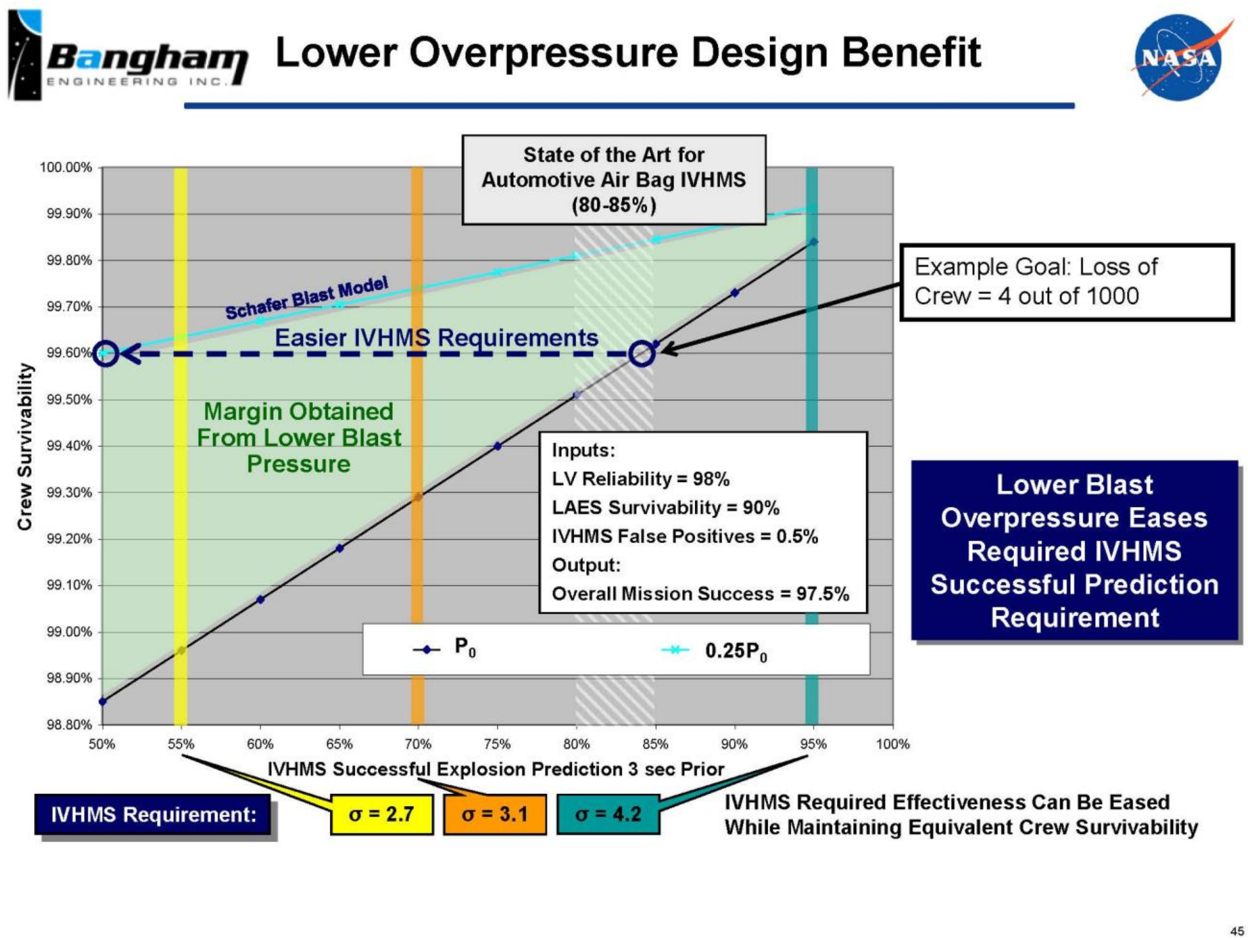
- **Side-on**
  - "The peak overpressure of the undisturbed wave as it travels through the atmosphere"
  - Overpressure measurement devices employ side-on schemes
- **Reflective**
  - "The peak overpressure of the wave as it interacts with a rigid structure"
  - A function of wave speed, impulse, peak overpressure, geometry, medium, angle of incidence, etc
  - Typically ×2 for acoustic waves with infinite solids
  - Can be many times higher than side-on for blast waves

Typical Blast Wave



Interaction With Solid Surface

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Lower Overpressure Design Benefit
State of the Art for Automotive Air Bag IVHMS (80-85%)
Example Goal: Loss of Crew = 4 out of 1000
Schafer Blast Model
Easier IVHMS Requirements
Margin Obtained From Lower Blast Pressure
Inputs:
LV Reliability = 98%
LAES Survivability = 90%
IVHMS False Positives = 0.5%
Output:
Overall Mission Success = 97.5%
P0
0.25P0
Crew Survivability
IVHMS Successful Explosion Prediction 3 sec Prior
Lower Blast Overpressure Eases Required IVHMS Successful Prediction Requirement
IVHMS Requirement:
σ = 2.7
σ = 3.1
σ = 4.2
IVHMS Required Effectiveness Can Be Eased While Maintaining Equivalent Crew Survivability
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14. ABSTRACT
Catastrophic failures of launch vehicles during launch and ascent are currently modeled using equivalent trinitrotoluene (TNT) estimates. This approach tends to over-predict the blast effect with subsequent impact to launch vehicle and crew escape requirements. Bangham Engineering, located in Huntsville, Alabama, assembled a less-conservative model based on historical failure and test data coupled with physical models and estimates. This white paper summarizes NESC's peer review of the Bangham analytical work completed to date.

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