

AN OVERVIEW OF THE LAUNCH VEHICLE BLAST ENVIRONMENTS DEVELOPMENT EFFORTS

Erin Richardson
NASA MSFC EV33
Huntsville, AL

Mike Bangham, James Blackwood, Troy Skinner, Michael Hays, Austin Jackson, Ben Richman
Bangham Engineering, incorporated
Huntsville, AL

ABSTRACT

NASA has been funding an ongoing development program to characterize the explosive environments produced during a catastrophic launch vehicle accident. These studies and small-scale tests are focused on the near field environments that threaten the crew. The results indicate that these environments are unlikely to result in immediate destruction of the crew modules. The effort began as an independent assessment by NASA safety organizations, followed by the Ares program and NASA Engineering and Safety Center and now as a Space Launch Systems (SLS) focused effort. The development effort is using the test and accident data available from public or NASA sources as well as focused scaled tests that are examining the fundamental aspects of uncontained explosions of Hydrogen and air and Hydrogen and Oxygen. The primary risk to the crew appears to be the high-energy fragments and these are being characterized for the SLS. The development efforts will characterize the thermal environment of the explosions as well to ensure that the risk is well understood and to document the overall energy balance of an explosion. The effort is multi-path in that analytical, computational and focused testing is being used to develop the knowledge to understand potential SLS explosions. This is an ongoing program with plans that expand the development from fundamental testing at small-scale levels to large-scale tests that can be used to validate models for commercial programs. The ultimate goal is to develop a knowledge base that can be used by vehicle designers to maximize crew survival in an explosion.

INTRODUCTION

The Launch Vehicle Blast Environments study is an ongoing effort to characterize the environments resulting from catastrophic launch vehicle explosion. The purpose is to develop the data and information required to allow launch vehicle and crew systems designers to develop safer crewed launch systems. This paper is a high level summary of the activities, early results and plans of the project. Detail data is provided in a series of papers that address both the liquid propellant launch vehicles and solid boosters. The more detailed papers address the blast physics, the fragments that are generated and accelerated and the thermal aspects of the explosions that can be produced. The effort is continuing but some early observations can be made about how they might impact future vehicle designs.

This work is focused on the near field effects of the explosions. This is the least studied region and is of direct influence to the crew. Higher fidelity analysis is required to adequately define the risk to the crew and to understand possible impacts to the crew systems involved in protecting and rescuing the crew. All phases of the ascent are being addressed but current efforts have focused on the pad and near pad regions since there is more data available and the magnitude of the blast overpressures is increased due to ground reflections. These results can be used to inform the ground environments but additional work is required to ensure the safety of ground crews due to the susceptibility of unprotected humans to the environments.

This effort has been ongoing for over four years and was started as the result of an independent assessment by the NASA Marshall Space Flight Center (MSFC) to define the blast environments and to assess if the existing requirements were adequate. The Ares program office provided subsequent funding and then a focused study on liquid propellant launch vehicles was assigned to the NASA Engineering and Safety Center (NESC) out of Langley Research Center. The Space Launch System program provides the current funding and is now focused on Hydrogen/Oxygen propellants and the solid rocket boosters. Table 1 provides a summary of the project sponsors and the primary goals and emphasis.

Customer	Time Frame	Focus / Goals
Independent Assessment (MSFC S&MA)	2011	Define requirements for blast environments to assess current program requirements
Ares Program Office	2012	Identify governing physics based on test and accident data for both liquids and solids
NESC NASA Engineering and Safety Center	2013	Focus on liquids and develop a test program, small scale testing was funded
SLS Space Launch Systems	2014	Focus narrowed to Hydrogen/Oxygen propellants and added Solids to assessment

Table 1 - Project Funding / Customer that have Sponsored this Effort

The program so far has relied on prior work and some small scale testing. There have been some excellent test programs conducted in the past including: Project PYRO [1], Hydrogen / Oxygen Vertical Impact Test (HOVI) [2], Large Scale Hydrogen Oxygen Experiment and several others. Accident data was a good source of information but is limited due to the sparse data recovered. The emphasis on accident investigation to date has been on the root failure cause of the accidents and not the results of the blast and fragment dispersions. Even today the accident investigations focus on the failure causes and tend to overlook data that can be easily obtained from the resulting fragment populations and blast effects. While individual accidents provide data to support insight, a collection of accidents can indicate trends.

One of the findings from the NESC reviews determined that efforts going forward should integrate testing and engineering analysis with computational efforts that are already underway. As a result the SLS program integrated computational/test/analysis efforts. Computational efforts here include both Computational Fluid Dynamics (CFD) as well as Fluid Structure Interaction (FSI) simulations. FSI solutions are coupled CFD and Finite Element Method (FEM) solutions that can provide insight as to how the structures will react under dynamic loads. Current efforts involve both CFD and FSI solutions that are being used to develop in-depth understanding of the test results that are being obtained.

Early investigations indicated that all of the data available was very inconsistent and that there were significant variations within a given test program and between different test programs. Some of this is expected in that the test programs targeted different aspects of the explosions and involved very different configurations. These test programs were well conceived for their specific purpose and executed with proper test practices but the configuration of the tests involved multiple test factors that complicate the detailed analysis of the results. When the tests were examined as a single body of work the variances between test configurations and the variances within the test programs themselves create a challenge for data interpretation efforts. One insight gained from the narratives within the test reports was that the magnitudes of blast overpressures were inconsistent with TNT explosions, which were used to define the explosions at that time. Some of these insights provided guidance for our team to expand on the work that was performed.

All of the publically available data was examined in-depth to develop a model for the launch vehicle blasts. A large number of tests and some accident data were analyzed and a clear trend was discovered and documented in 2011. This led the team to develop some path-finding small-scale tests where weakly contained hydrogen/oxygen and hydrogen/air mixtures could be ignited at various mixture ratios. These tests were needed to validate the trends that were extracted from the test and accident data. A second series of path-finding tests were done to examine aspects of the fragmentation process —

including generation and acceleration of the fragments. These early path-finding tests led to more formal and rigorous testing.

The SLS program revived the work on the solid rocket motor blast environments. This resulted in the development of a model that is based on the chamber pressure and volume. Research indicates that the solid propellant does not participate in the blast event for situations involving crew survivability. This excludes high-speed impacts and ignitions by high-energy charges. This finding is consistent with DOD experience with both small and large solid rocket motors. The SRB's operate at pressures that can exceed 1000 psia at ignition. Catastrophic failures or case bursts can approach pressures close to 2000 psia. Comparisons with solid rocket motor tests of FTS events compare well to a pressure –volume gas rapid release. Solid Rocket Motors of large enough size can produce fragments with much higher kinetic energies than the liquid systems. This makes the SLS SRB a key part of the risk assessment.

There is a significant difference in the philosophy, objectives and approach of this work from the Air Force Range Group. Highly conservative assumptions in the Range assessments provide for superior protection for the public and facilities near launch sites. These same highly conservatism assumptions will not serve the crew well because it can overemphasize risks that are not, in fact, risks to the crew. This approach will predict that it is unlikely for the crew to survive even minor explosions. This hides risks that may ultimately put the crew in danger when the crew modules does survive and the crew safety systems are unprepared for the consequences. It is these kinds of differences that led NASA and this team to investigate the near field blast environment in more detail.

RESULTS AND DISCUSSION

This paper is organized in four subsections below, beginning with the anatomy of an explosion. That section provides a summary of the work and findings for defining hydrogen/oxygen explosions along with some data provided for RP fuels. The next section addresses the generation of fragments and provides some overview of the velocities of the fragments produced. The section on thermal aspects of fireballs is relatively shallow at this time due to lower maturity of the work to date. The final discussion section provides an overview of the near term plans as well as some look ahead to larger scale testing that is highly desired but not yet funded.

For the work herein there are four aspects of an explosion that are being investigated to describe the explosions. The variables are described in Table 2 [1] below and consist of mechanical (blast), fragmentation, thermal (fireball), and time. These variables are used to describe the effects on the vehicle and crew systems but are insufficient to describe the physics of the explosions.

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

Table 2 - Variables used to Describe Launch Vehicle Explosions

This work is being done to define the environments that can be produced. System models such as Ames Research Center (ARC) Engineering Risk Assessment (ERA) models are required to apply the possible environments to the vehicle configuration, state, and potential failure modes. This effort is to obtain the data to improve and validate these simulations and to provide future vehicle designers with the knowledge to eliminate conditions that prevent the crew safety systems from functioning as designed. The trends being demonstrated for the SLS program indicate that the blast waves are not the primary threat from explosions to crew safety due to lower overpressures now being predicted and the distance between the center of any possible SLS explosion and the crew module. Highly unlikely scenarios are being assumed that do present a risk when detonations occur near the crew module. However, the high-speed fragments generated by a segment or booster explosion represent a risk that influences the loss of crew predications. Efforts described herein are to integrate fragment production and acceleration with the blast mechanical aspects including the overpressures, flame/wave speeds, radius and timing.

Significant work has gone into developing an approach for defining the fragments that are produced and how they are accelerated. The process uses a set of heuristics or rules to define how the various structures will breakup based on prior accidents and tests. This is done for each major structural segment. Examples of a segment include the aft skirt with the major propulsion elements, the hydrogen tank, the oxygen tank, the inter-stage, and so on. The nature of each unique structure is accounted for in the generation of the fragments using this approach.

The study of the long duration fireball represents the thermal efforts now underway. The fireballs are the large fires that may last 10's of seconds. The team differentiates between the initial blast, sometime referred to as the luminous boundary and the fireball that follows the initial blast event. The crew capsules are designed for high-speed reentry and therefore get exposed to very high heat rates. The fireball temperatures are actually less than what most capsules are designed to accommodate and the durations are less than the reentry periods. Therefore this work was considered secondary as a threat to the crew but is beginning to mature.

Timing is a very important consideration in any launch vehicle accident. Today's abort systems are designed to sense and recommend or initiate an abort in milliseconds. The actual timing of the onset of the blast and production of the blast waves and fragments will influence the amount of risk to the crew. If sufficient time exists then the crew or on-board systems can activate the escape sequence and propel the crew modules some distance away from the vehicle, increasing the safety of the crew. Therefore, understanding the timing of these accidents is a key aspect and is being undertaken to provide vehicle designers benchmarks to design abort logic/recommendations.

One aspect that the team discovered early in the research was that the community used vehicle accidents and tests that consisted of events or configurations that were designed to produce high energy explosions as part of the databases used to characterize the launch vehicle explosions. Solid Rocket Motors were tested to assess the consequences of being destroyed by high-energy explosions that may come from an incoming weapons system. These events were not considered to represent a survivable accident. Solid rocket motors can detonate from high-speed impacts. The kinetic energy required is a function of the grain/chemistry-of the particular motor which will define a characteristic depth when a detonation can occur. This scenario was ruled out of consideration since it is highly likely that the crew or the onboard abort logic would initiate an escape well before the vehicle turned around and accelerated toward the ground. Therefore tests or accidents that involved high-speed impacts with the ground were not considered. Other cases not considered included destruct demonstrations that used large quantities of high energy explosives that were designed to detonate the propellants. These kinds of filters were applied to all of the accidents and tests that were used in developing the models and algorithms that were created. In addition, the team uses the SLS vehicle Probability Risk Assessments (PRA) to eliminate cases, which are so improbable that they do not justify the investment to address in detail.

ANATOMY OF AN EXPLOSION

Explosions are a complex multidisciplinary problem that involves combustion, fluid dynamics, thermodynamics, structures / fluid interaction, and shock physics for high-speed flows. Adding to that complexity is that the areas of concern are accidents. Accidents, by their very nature, make it difficult to predict when and where the failures occur that generate an explosion. The launch vehicle makes this even more complex in that the vehicle is accelerating upward with the atmospheric conditions changing with altitude and vehicle velocities. In the past, the designers of the crew safety systems and launch vehicle designers have used worst-case assumptions to define the potential explosions and fragment risk in an attempt to envelope the environments. These assumptions tend to use similarity to well-known phenomena, such as TNT blasts, where there is a very large knowledge base on the blast generation and effects.

This body of [3] work clearly shows that the use of TNT as the basis of the blast does not represent the actual physics of launch vehicle explosions. The TNT event is a high-energy explosion that produces huge overpressures that are measured in thousands of psia. The TNT representation can match the blast overpressure at a single distance but the impulse will be different at that distance. The data shows that the peak overpressure for hydrogen and oxygen mixture will be limited to no more than 482 psia. This value is for highly constrained environments and has only been produced in shock tubes. This data matches the Zeldovich-von Neumann-Doring [4] theory. Such high magnitudes of overpressures are highly unlikely to occur on a launch vehicle but the upper limit here is clearly several orders of magnitude lower than the near field overpressures that are produced by TNT or other high energy explosions. TNT and similar high energy explosions create near field blast overpressures that are not survivable by current launch vehicle/crew module designs or technologies.

Relatively low overpressures can cause launch vehicle destruction. One must recognize that, when the source is large volumes of exploding gas, even small overpressures become major loads on the vehicle. The data in Table 3 provides some insight to the level of damage expected from low overpressures.

Overpressure* (psig)	Expected Damage
0.04	Loud noise (143 db); sonic boom glass failure.
0.15	Typical pressure for glass failure.
0.40	Limited minor structural damage.
0.50-1.0	Windows usually shattered; some window frame damage.
0.70	Minor damage to house structures.
1.0	Partial demolition of houses; made uninhabitable.
1.0-8.0	Range for slight to serious laceration injuries from flying glass and other missiles.
2.0	Partial collapse of walls and roofs of houses.
2.0-3.0	Non-reinforced concrete or cinder block walls shattered.
2.4-12.2	Range for 1-90% eardrum rupture among exposed populations.
2.5	50% destruction of home brickwork.
3.0	Steel frame buildings distorted and pulled away from foundation.
5.0-7.0	Nearly complete destruction of houses.
10.0	Probable total building destruction.
14.5-29.0	Range for 1-99% fatalities among exposed populations due to direct blast effects.

Table 3 - Level of Damage Expected at Specific Overpressures for Terrestrial Structures [5]

Overpressures of 2 to 3 psig will destroy concrete buildings and damage steel structures. The values in the table are derived from high energy explosive loading. Trends for gaseous explosions would be similar or even greater due to the longer duration and resulting higher impulse. Shock loads can be very high when the small overpressures are integrated over the large surface areas of the launch vehicles surfaces. Loads of 200K to 300K pounds of force on the launch vehicle structures would be representative of an explosions of 2 psi over 30 degrees of surface of a single tank. This magnitude of blast load on a lightweight structure in paths/directions that are not designed to accommodate them can easily lead to the destruction of the vehicle.

Crew modules tend to be robust structures that carry large dynamic, static and pressure loads to and from space. Typical capabilities for accommodating overpressures are expected to withstand greater than 10 psig. The capability of any particular crew module to accommodate overpressures is design-specific. Most launch vehicle designs to-date have used other launch vehicle loads such as the hoop stresses, axial loads during ascent, or bending loads due to pitching or wind gusts to drive the design. Design capabilities for overpressures and impulse loads are not a design parameter but a resultant of the capabilities achieved by designing to the vehicle loads. In most cases the capabilities to accommodate overpressures are specified on the crew module to be greater than 10 psia for overpressures but there are no design loads for overpressures for the launch vehicle design.

For this work an explosion is defined as a rapid release of energy and an increase in volume that can generate high temperature gases. Supercritical cryogenic explosions were examined but have been ruled out for hydrogen/oxygen or RP/oxygen mixtures due to the operational temperatures and purity of the propellants used.

Figure 1 shows the basic regions of explosions in the context of an accident. The event is assumed to be chaotic; therefore, the mixing of the propellants will be chaotic as well. We expect to see small regions that may produce stoichiometric mixtures while most regions will be fuel rich or lean or may even fall out of the flammable ranges for the fuels involved. The explosion/blast is produced in the first 1 to 5 milliseconds while the long duration fireball may last 10 or more seconds. The fireball is a slow combustion event that will not produce blast waves but will produce a large amount of thermal energy. Our current models assume homogenous mixtures for a given explosion. The ability to mix well determines the probability of a high overpressure/impulse while the failures that lead to poor mixing will

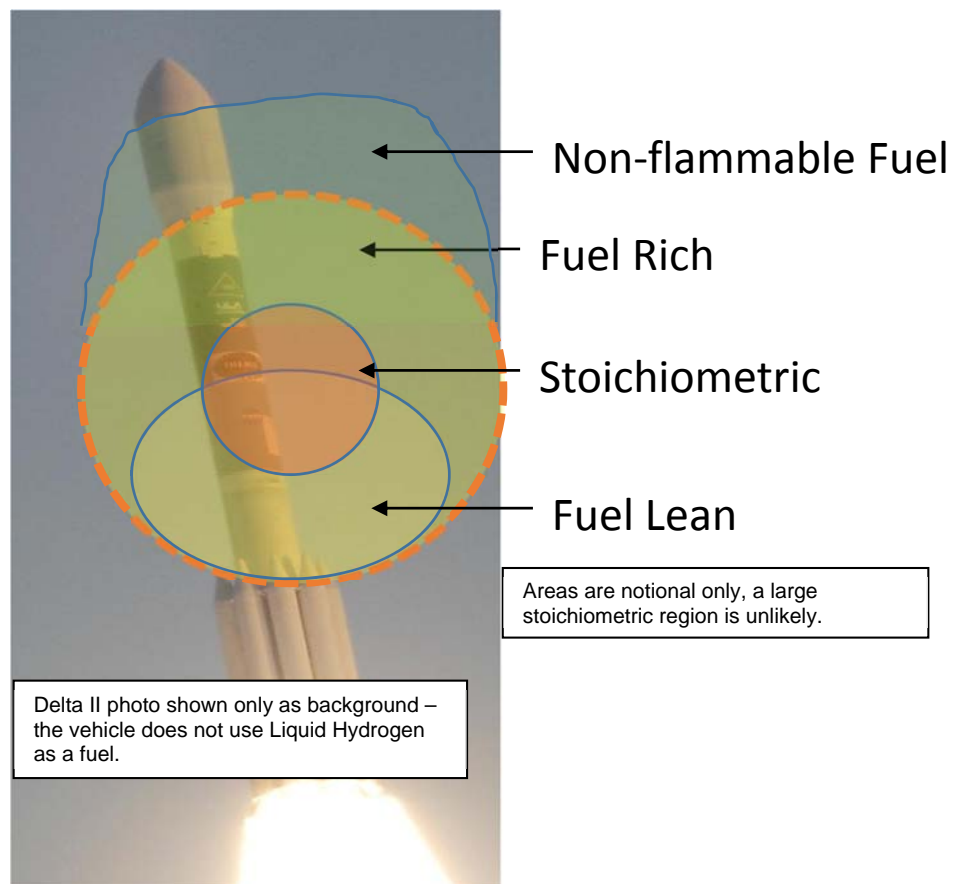


Figure 1 - Notional Regions of a Launch Vehicle Explosion

produce lower overpressures and impulse. This is addressed in the system models by assigning probabilities to the mixing cases by defining the overpressure values. The mixing assumptions can be handled at the system models level as probabilities of occurrence. The goal here is to provide the fundamental inputs to the system models including a basis for the probability distributions of the blast overpressure and impulses.

The typical explosion for liquid propellants is a deflagration or a subsonic combustion of the propellants or the fuel with air. Data obtained from testing and several pad accidents indicates the blast waves are acoustic in nature. Detonations, in this context, are combustions that propagate at supersonic speeds. Close examination of all of the accidents and representative tests indicate that no detonations have ever occurred with hydrogen/oxygen or RP/oxygen for accidents or tests representative of launch vehicles. However, we are defining requirements for crewed vehicles so the lack of any occurrence is insufficient to rule them out. Detonations must be ruled out by other means, such as a detailed understanding of what generates a detonation and what factors can be designed out of the vehicles to ensure that no detonations can occur. The current state of knowledge available to this team is not sufficient to exclude detonations. The current blast overpressure and impulse models assume detonations as the upper limit. The mean or most likely overpressure level used is still very conservative based on data.

The peak pressure used for the hydrogen-oxygen explosions is based on the steady state detonation pressure profile prediction given in the one dimensional Zeldovich-von Neumann-Doring (ZND) theory [4, 6, 7]. This theory, created during the early 1940's, assumes that the detonation wave can be represented by a planar shock wave, an induction region, and a reaction zone. The peak pressure exists only in the induction region while the reaction zone decreases to the Chapman-Jouguet (CJ) pressure. The Chapman-Jouguet theory was a steady state theory developed early in the 20th century and considered only the initial and final states of a detonation wave, at chemical equilibrium, ignoring chemical kinetic processes occurring within the detonation wave. CJ theory may be used to compute the steady state propagation speed of the detonation. The model can be developed algebraically and an example of its use is given in [4]. ZND profiles for Hydrogen-Oxygen detonations may be found in [6,7]. CJ and ZND properties for fuels including Hydrogen, Propane and Ethylene have been tabulated by the Explosion Dynamics Laboratory at the California Institute of Technology [8]. Many researchers have considered hydrogen explosion and the possibility of detonation. Literature reviews covering hydrogen explosion phenomena have been written [9,10,11]. CJ and ZND pressures may be found from

$$P_{CJ}[bar] = \frac{\gamma M^2}{\gamma + 1}$$

$$P_{vN} = \left(\frac{2\gamma M^2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1} \right) P_1$$

In practice the only hydrogen detonations obtained in the literature appears highly constrained in shock tube tests. These are not representative of known launch vehicle explosions.

The current cryogenic blast overpressure model is provided in Figure 2. Detailed discussions of this model can be found in references 12 and 13. Several observations can be made of this model — first the theoretical maximum is defined by the ZND theory at 480 psia for hydrogen/oxygen mixtures. The radius is a key attribute of this model in that it directly influences the effective distance that a fragment could be accelerated. The radius is limited by auto-ignition phenomena as defined by Farber [14] that indicates for hydrogen/oxygen cryogenic propellants the critical mass limit is 2300 lbm of total propellants. Auto-ignition will usually occur well before the critical mass and the 2300 lbm sets an upper limit. The launch vehicle environment provides a wide range of possible ignition sources ranging from electrical sparks, hot surfaces, plumes and pyrotechnic devices. These ignition sources will tend to ignite the propellants before the auto-ignition limit is achieved. After the initial blast event the decay is defined by the model but will be similar in shape to that of a TNT decay for the initial pressure regions. However,

once the pressure decays beyond the knee of the curve the predicted overpressures will actually be higher for the liquid propellant explosions. The magnitude of the overpressures in these regions is very low and the differences are less than 1 psia.

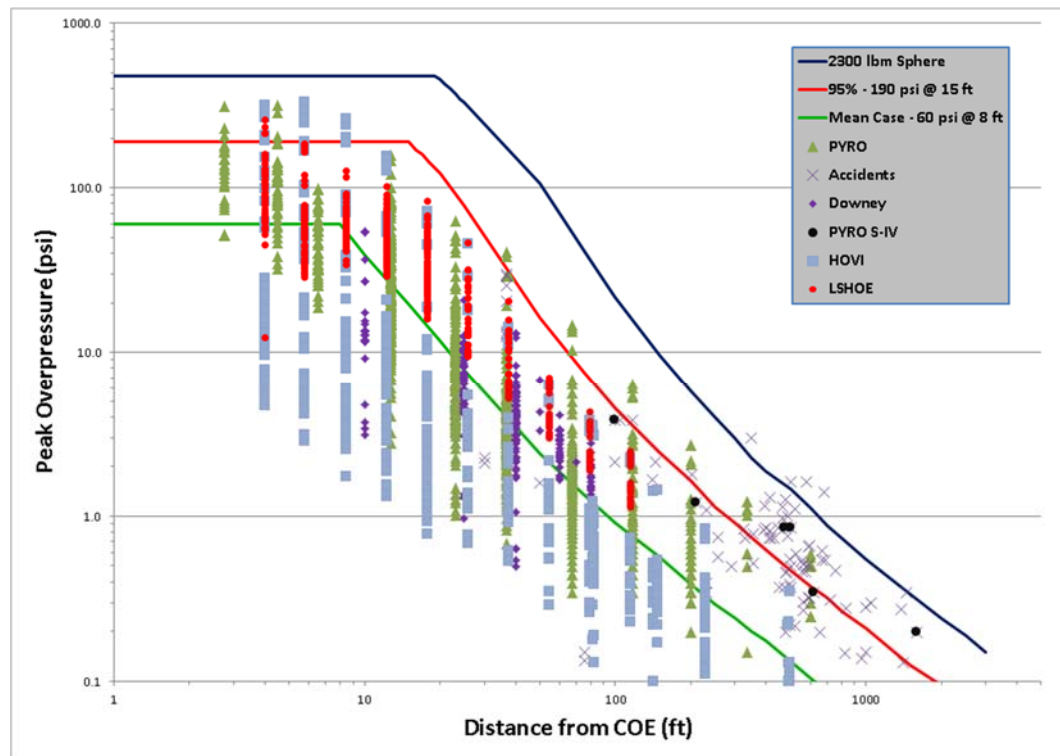


Figure 2 - Hydrogen/Oxygen Launch Vehicle Overpressure Model

Chemical and petroleum industries use a Vapor Cloud Explosions (VCE) model developed by Baker et al [15]. The model has been extensively researched and applied for over 20 years for designing chemical and petroleum processing facilities. The VCE model is designed for hydrocarbon/air mixtures and for near-surface atmospheres. Launch vehicles carry their own oxidizers and in catastrophic failures the fuel and oxidizer are free to mix. VCE uses an obstruction parameter to account for flame acceleration due to the geometry of the containment. The VCE module is a viable model for launch vehicle if applied in the limited areas where the containment is sufficient and atmospheric pressures are near a standard atmosphere. However, VCE does not account for the cryogenic explosion effects and the initial temperatures of the cryogenics involved. Further, the VCE model does not provide for the auto-ignition effect that limits the mixing with most liquid oxygen and fuels.

As density decreases with increasing altitude, two aspects come into consideration. First the lower density reduces the overpressures and can be scaled by Sachs relationships [16]. This has been well described for high-energy explosions and considered sufficient for launch vehicle applications at this point in time. Second, as the atmospheric density decreases it reduces the flammability limits. At some point in altitude the air does not have sufficient oxygen to sustain an explosion and the only source of explosions to produce actual blasts are situations where the oxidizer and fuels can mix or/and an ullage pressure release / flash evaporation occurs. Most upper atmospheric explosions may be the result of flash evaporation of the propellants or the release of the internal ullage pressure and may not produce a meaningful blast wave. Additional work for high altitude explosions is still underway and is using knowledge gained from the orbital debris generation knowledge bases.

Any launch vehicle accident is an unplanned event that will be chaotic in nature. Therefore the propellants' ability to mix will be uncontrolled and a wide range of mixtures will be present in any explosion. Good data exists for ideal mixtures of hydrogen and air from recent testing that provides overpressures, flame speeds and other characteristics of the explosions. The test data comes from an ongoing investment in hydrogen-fueled automobiles and the interest in providing safe hydrogen fueling infrastructures. Hydrogen blast events are a major concern to some nuclear power systems and a large knowledge base was assessed. No relevant data was found for hydrogen/oxygen mixtures. The team elected to conduct small-scale tests to develop the overpressures/flame speed relationships for mixture ratios of hydrogen/oxygen with and without diluents present. The current results of this testing are provided in reference [3, 12] with additional testing still to be conducted.

The testing shows a significant difference for overpressures as a function of the mixture ratios. The overpressures decline rapidly as the mixture becomes either fuel rich or lean. The gases have different viscosities, heat capacities, masses and diffusivities and it can be difficult to maintain the ideal mix without mechanical means. The test uses thin walled plastic bags or balloons to contain the mixture and recirculation pumps to mix the gases until ignition. The balloons are destroyed by either the heat or the expanding gas well before the flame front reaches the material. The effective internal reactant gas pressure prior to ignition is on the order of a 0.1 psig.

Various balloon sizes have been tested as well as configurations with sample materials inside to see the effects of flame acceleration on the overall overpressures. These particular flame acceleration tests were conducted for path finding and more detailed testing is planned.

Flame acceleration is a key aspect of the explosions in that Deflagration to Detonation Transition (DDT) is driven by flame accelerations that start subsonic and accelerate to supersonic. More testing is planned to address diluents, DDT, ignition by a detonating source, ignition by pressure changes, and non-homogenous mixtures. The overall test planning is presented later.

While the early strategy is to envelope detonations, the risks can be further reduced if detonations can be eliminated from consideration. Research indicates that there are only two practical sources of detonations in a launch vehicle accident. The first is obstructions in and around the engines, inter-tanks or system tunnels where there can be a complex geometry of plumbing, structures, pressurant tanks, and avionics. The second is actual detonations as the initiator/igniter of a larger event. The potential sources are the various pyrotechnic devices on the vehicle such as separation systems or the range flight termination systems. The pyrotechnic devices produce high-energy shocks that can be immersed in a flammable mixture in an accident. These issues have not been addressed at this point and therefore the team will continue to use detonations as the upper bounds for the blast event until additional knowledge is gained.

One clear finding of this work is that the use of high-energy blast waves does not represent the physics of cryogenic launch vehicle accidents. This also applies to solid rocket explosions that are relevant to crew safety. While it is common in the industry to use TNT as a measure of the magnitude of an explosion the effect on the vehicle and crew systems are considerably different.

FRAGMENTS

At present the preliminary evidence from the system level assessments performed by Ames Research Center indicates that fragments represent the primary risk to crew survivability from explosions. The magnitude of the risk will be configuration-dependent and changes when staging occurs or propellants are consumed. The SLS is an inline vehicle where the propulsion elements are below the crew modules. Risk to the crew for other configurations of launch vehicles will be different. Prior to this work most risk models used high-energy detonations as the source explosion to drive the fragments. This allowed the simulation to build on a large knowledge base of high-energy weapons systems development.

Once the team established that the blast event, which drives the fragmentation generation and acceleration in launch vehicle explosions, was not a high energy event, then the team began to explore new approaches to simulating the generation of fragments and assessing the risk to the crew.

Obviously launch vehicles accidents are not deterministic. The initiating failure, locations or the magnitude of the explosions occur randomly. Many other parameters come in to consideration when assessing the risk to the crew from fragments. One approach used across many organizations is to use Monte Carlo assessments where the various failure modes are used to determine the location of a blast and then generate the fragments from those initial assumptions. The initial assumptions are driven by the specific vehicle and either the failure modes and effects assessments (FMEA) or the Probability Risk Assessment (PRA). This is still going to be conservative but allows design teams to develop systems or logic to define how and when the crew should abort. The blast event is the fundamental driver in that if one assumes a high-energy event the resulting fragment products will have populations with a larger percent having higher kinetic energies. The efforts herein are an attempt to connect the blast event to the actual fragmentation and produce probability field functions that determine the direction and kinetic energy of the fragments.

The high energy explosive knowledge base is based on a very large collection of empirical data. Very little of this kind of data exists for the weak, acoustic shock type phenomena seen in the launch vehicle blasts. The team elected to establish an initial database by the use of limited empirical data that was available as well as small-scale tests that could replicate the blast wave. This database supported the effort to determine how fragments get formed, the production of small fragments (which none of the empirical databases addressed) and how the fragments get accelerated.

Reference [17] provides a detailed description of the tool developed to address the unique fragmentation generation and acceleration process of cryogenic propellants for launch vehicles. The process can be described at the top level as a heuristic process in that a set of rules and relationships were developed based on the limited data that is available from prior accidents and tests. The majority of the detailed relationships for liquid rockets come from a test performed with a Saturn IVB performed under project PYRO. Since the process is largely empirical and heuristic, the algorithm developed improved dramatically with larger databases and therefore there is a strong desire to obtain detailed data from any related accident or test.

The small-scale tests developed to observe fragmentation consist of a two stage cannon that functions like a shock tube. The first section is used to generate the blast wave that simulates and/or envelopes the blast waves observed in accidents and tests. The resulting blast wave is released into the second section that can be filled with various media to simulate liquid filled and partially filled structures or can be left unfilled to simulate empty structures. Liquid Nitrogen was used in some testing to examine the impact of the flash evaporation and the cold temperatures on the fragmentation process. Fragments were produced and measured for both aluminum alloys and stainless steels. The current database is limited to thin walled samples due to the small bore size (6 inch internal diameter) of the cannon and the need to maintain the blast overpressures within the range that are possible in a launch vehicle accident. Therefore no pressures above 480 psig were used. Future testing will address actual flight thickness materials and samples with a large 12-inch diameter cannon since the fragmentation process is non-linear and must be addressed for actual thicknesses.

Figure 3 presents a view of the 6-inch cannon producing fragments under the influence of a blast wave. The photo shows the fragments being accelerated after the sample breaks apart. Figure 4 shows a summary of the results for accelerating the fragment under various modes. In general the presence of liquids reduces the fragment energies for the test conducted. Extrapolation of these results to large systems is not complete. However the trend does indicate additional investigation is clearly warranted.

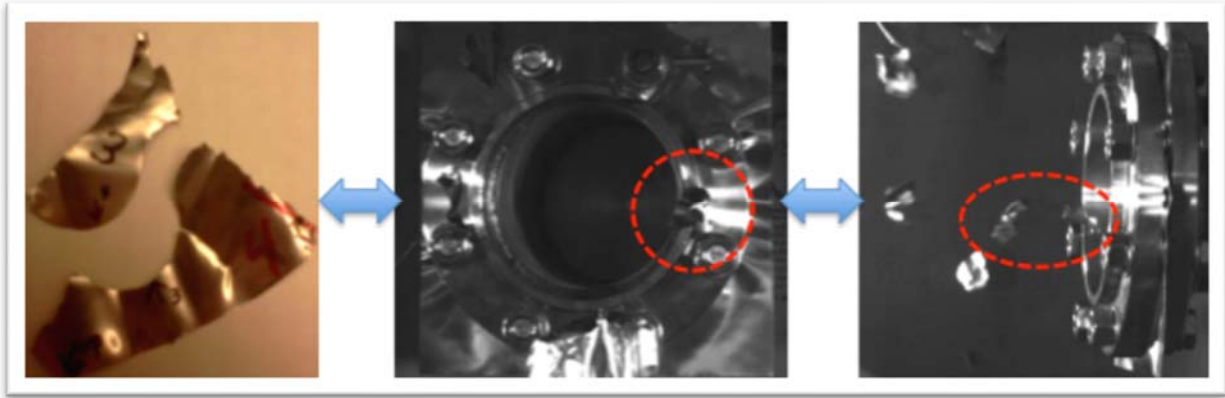


Figure 3 - Photos show Fragments being Accelerated and Recovered for Analysis

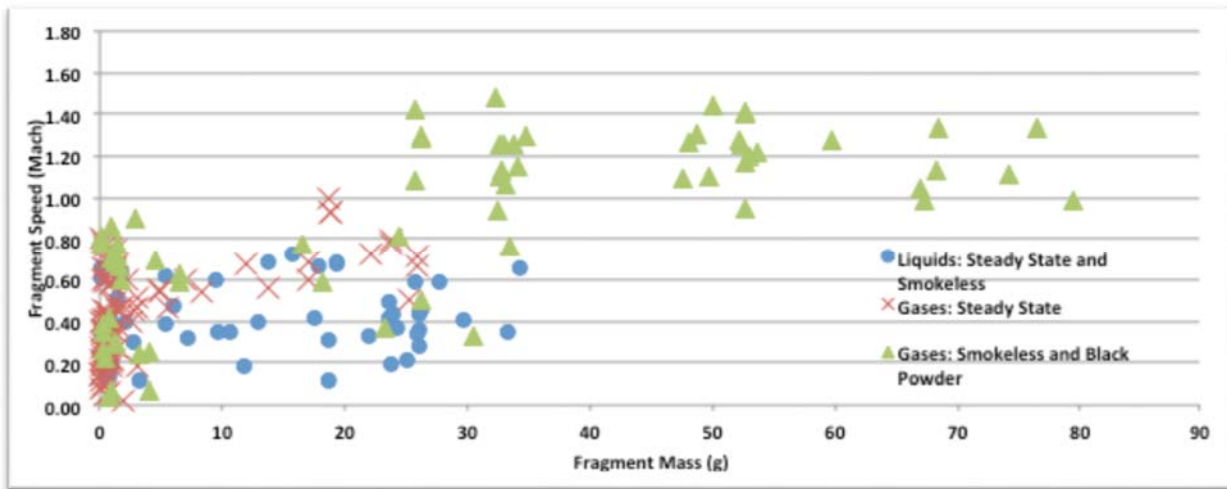


Figure 4 - Fragment Speed/mass Designated by Test Configuration

The early results of the small scale tests were instructive to the heuristic process used based on the empirical data. Some of the key findings to date include:

- Small fragments are unlikely to be produced from these blasts
- Liquids reduced the number of fragments produced with obvious differences showing in samples with half liquid and half ullage gas. The gas side produces considerably more fragments than the liquid side.
- Aluminum alloys tend to produce larger fragments than stainless steels
- Acceleration by blast waves produces the highest energy fragments
- Flash evaporation appears not to be effective at accelerating fragments.

A pair of programs called Liquid Propellant Fragment Overpressure Acceleration Model (L-FOAM) and Solid Rocket Propellant Overpressure Acceleration Model (S-FOAM) have been developed that allow a user to develop a fragment catalog based on the empirical data in the database and the specific design of the launch vehicle. Both versions of the program allow the user to generate fragment catalogs

in the form of probability distribution of fragments with sizes and initial velocities defined. Details of how the program works are found in the discussion in reference [17]. The number of Monte Carlo cases are defined by the users and the distributions of the fragments are based on variances in vehicle state, velocity, altitude and the type of explosions to be considered. Due to wide variances in explosion magnitudes that can occur, the user is allowed to select the mean and upper bounds or they can use those defined by the work discussed above. One should remember that the worst-case liquid rocket explosion assumes a detonation which has never been observed in any test or accident to date. These programs are maturing but still require significant user expertise to utilize appropriately.

Several observations can be made from the early result of this work. First, solid rocket motors can produce fragments with an order of magnitude higher kinetic energy than launch vehicles that use liquid propellants. The simplicity and reliability of solid rocket motors are well established. The solids can be made considerably safer for cases where in flight destruction by the flight termination system is required. This is the most likely catastrophic failure for most solids and there are established mechanisms such as blow out ports/vents that can reduce the work pressures prior to destruction that would reduce the kinetic energy of the fragments. This is counter to well-founded desires by the range to provide for total destruction of the rocket motor to avoid large propellant masses to impact the ground that can lead to secondary detonations that are more energetic than the original destruct event. Additional research is warranted in these areas to reduce the risk to the crew as well as the range.

Other observations have to do with the propellant mass of the vehicle during a catastrophic failure. The system models will need to address propellant mass and ullage areas to determine the fragment generation and acceleration.

THERMODYNAMICS OF FIREBALLS

To reduce the uncertainty of simulations of launch vehicle explosions, a total energy balance is desired. However this is only practical for ideal cases. The explosions are considered an "open system" meaning that there are no boundaries in which to contain all of the products/reactants of the explosion. In any explosion of a launch vehicle there will be considerable losses of the propellant to evaporation, mechanical disbursement and the chaotic nature of the explosion creating regions which will be outside the flammability limits. Where low vapor pressure, high evaporation temperature fuels like RP are used the fuel can pool and produce low rate combustion for long periods (hours). Other losses for these kinds of fuels include absorption of the fuel into the ground, or the fuel can flow out of the combustion zones. However, the team is developing models for ideal explosions to determine where the energy is being consumed to allow the vehicle and pad designers to assess risks outside the immediate area of the crew such as downwind of the pad. In addition, an effective energy balance increases the confidence that all aspects of the combustion /explosion are being addressed in whole.

This work is less mature than any other area but Table 4 provides a first order assessment of the energy consumed in the various HOVI tests. The team used ideal relationships for estimating the energy consumed by the thermal energy release, the energy consumed in the blast wave, and compared that to the available chemical energy in the propellants. This ignores several significant sources including the phase change, and the kinetic energy from the impact. This was not intended to be a total energy balance like that desired for an ideal explosion. HOVI test 9 produced the largest over pressures of any of the tests and consumed more than 20% of the total energy available in the blast wave. All of the remaining tests appear to have less than 2% of the energy consumed by the blast events. It should be noted that HOVI 9 had the longest mix time prior to the ignition of the mixture. This implies the HOVI 9 test had the potential for more of the propellants to mix prior to ignition. The thermal energy is two orders of magnitude greater than the blast energy except for HOVI 9 where the ratio drops to a factor of 3. However the current efforts indicate that a significant percentage of the chemical energy is released as gaseous propellants that escape the blast system without being combusted. Table 4 provides some insight as to where the energy may be going but much of the available chemical energy is probably escaping the explosion system volume. The amount of energy in the blast wave is ~3 orders of

magnitude smaller than the available combustion energy except for the HOVI 9 test where the blast wave consumed 21% of the energy.

Test	Blast Wave E (MJ)	TNT NRG Eq lbs	Ave Thermal E (MJ)	Blast + Th Energy (MJ)	blast energy to Th NRG ratio	Maximum Potential Combustion NRG (MJ)	fraction used in heat and blast	fraction used in blast
2	5.0	2.4	171.7	176.7	2.9%	4,819	3.7%	0.104%
3	0.7	0.3	93.5	94.3	0.8%	4,760	2.0%	0.015%
4	1.3	0.6	284.5	285.8	0.5%	3,510	8.1%	0.037%
5	5.3	2.5	362.9	368.2	1.5%	4,760	7.7%	0.111%
6	59.0	28.2	454.5	513.6	13.0%	4,641	11.1%	1.272%
7	0.6	0.3	77.4	78.0	0.8%	4,760	1.6%	0.012%
8	0.2	0.1	87.9	88.1	0.2%	4,403	2.0%	0.004%
9	900.3	429.7	2629.6	3529.9	34.2%	4,284	82.4%	21.017%
10	0.7	0.3	82.5	83.2	0.8%	4,760	1.7%	0.014%
12	54.1	25.8	505.6	559.7	10.7%	19,753	2.8%	0.274%
13	55.7	26.6	1706.5	1762.2	3.3%	16,957	10.4%	0.329%
14	51.3	24.5	1306.1	1357.4	3.9%	20,229	6.7%	0.253%
15	0.6	0.3	284.5	285.1	0.2%	20,229	1.4%	0.003%

Table 4 - First Order Energy Estimates for HOVI Test Series

Unlike RP-1, hydrogen is highly diffusive and highly buoyant. It rapidly mixes with the ambient air during any accidental release. The diffusion velocity is directly related to the diffusion coefficient which will vary with temperature, T^n , with n in the range of 1.72 to 1.8. The temperature of the hydrogen will vary over a wide range from the initial liquid state and goes through a phase change and rapid expansion while being exposed to a hot radiative environment once a combustion event begins [19].

Besides the rapid diffusion occurring, the hydrogen is driven by buoyancy forces as the hydrogen gas temperature approaches the ambient temperature. The velocity under the influence of (positively) buoyant forces cannot be determined directly, since it is dependent on the density difference between hydrogen and air as well as on drag and friction forces. Mechanical disbursements of the liquids due to the accident, the shape and size of the rising gas volume and atmospheric turbulence have an influence on the final velocity of the rising gases. Both diffusion and buoyancy determine the rate at which the gas mixes with the ambient air. The rapid mixing of hydrogen with the air can quickly dilute the mixture to the non-flammable range. Therefore it is estimated that in a typical unconfined hydrogen explosion, a significant fraction of the gas mixture cloud escapes the blast event system. This further reduces the theoretically available energy.

The fireballs produced for pad or near pad accidents can become very large due to the large amount of propellants that are available for combustion. Figure 5 provides an estimate of the fireball radius as a function of propellant mass based on accident data available. This is a curve fit to the data that is considered appropriate for the launch vehicles under consideration. The initial blast event is a 1 to 5 milliseconds event but the fireballs are a long duration combustion event and can be observed for durations of up to 16 seconds after a vehicle accident. The burn duration is a function of the mass of the propellant and the energetics of the accident. Figure 6 provides an estimate of the burn duration as a function of propellant mass. In cases where the initial explosion is relatively small and the entire vehicle remains somewhat contained the propellant release is slower and the burn durations can be longer. Still the flash evaporation of the uncontained cryogenics is very fast with rates of liquid hydrogen flash-evaporation at 280 kg/second [18] observed in hydrogen spill tests. A statistical approach was used to define a burn duration of the fireballs using the accident database described earlier. These burn durations become important when the vehicle designers and crew systems designers must assess the use of parachutes near the fireball. In the case of the SLS/MPCV program the burn duration is on the same order of time that occurs between the crew escape sequence and parachute deployment. It is unlikely that they overlap but when possible destruct time delays are accounted for, the issue becomes problematic and must be assessed however unlikely.

Future updates of these curves will be made as the entire project matures. Total energy balances will be used to assess how much of the propellants may be escaping by mechanical expulsion, by evaporation and by gravitational flow. At present the team considers the energy balance an open consideration requiring additional investigation.

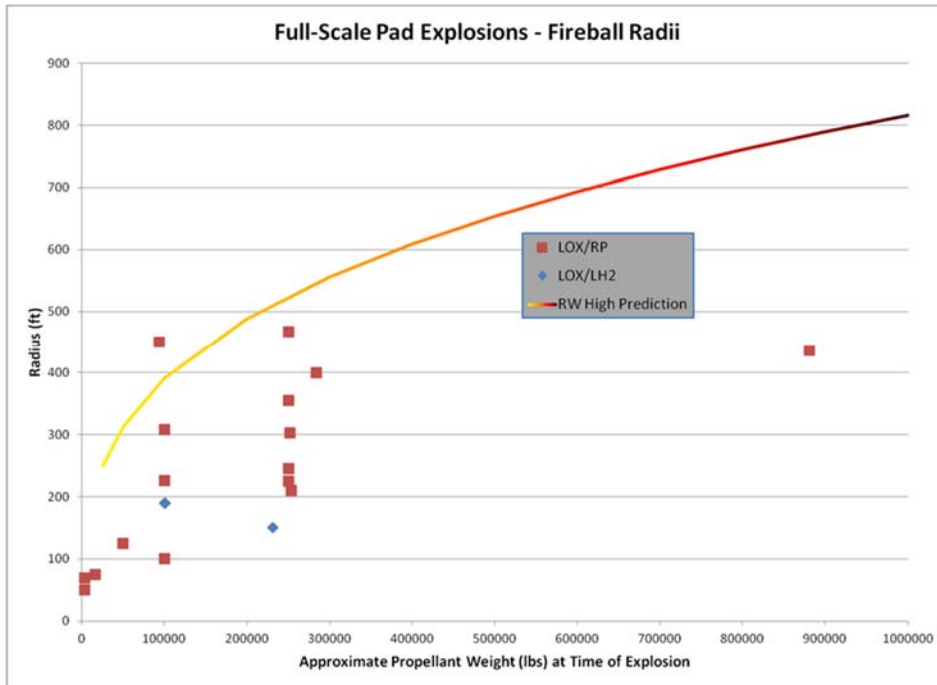


Figure 5 - Radius of the Fireball for Pad or Near Pad Explosions

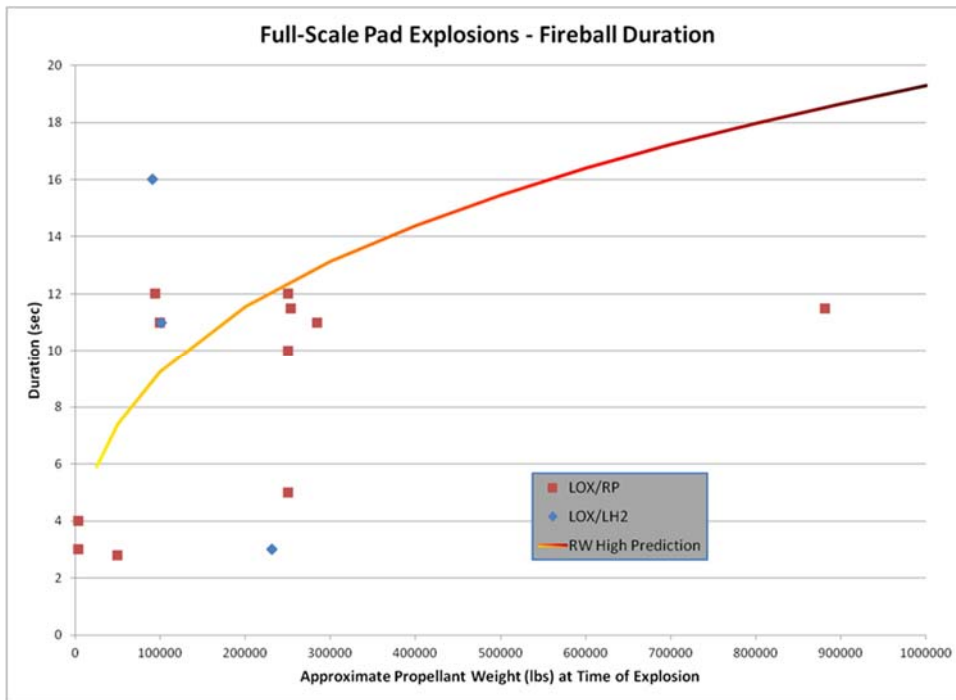


Figure 6 - Fireball Durations for Pad or Near Pad Accidents

TIMING

When one considers an explosion, the initial perception is that the event would occur near instantaneously. A review of historical accidents of launch vehicles indicates a wide range of times between when the initial failure occurs that propagates to the explosion and when the actual explosions occurs. Figure 7 provides a break out of the lead times between the event and the initial indication of the failure. There is some subjective data used to develop the lead times due to the lack of detailed failure data for all of the launch vehicle failures. The data indicates that approximately 18% of the accidents historically provided less than 0.5 seconds of warning or lead-time. The remaining accidents had more time between the initial failure and the explosion including one case where the lead-time approached 1 minute. This database has been expanded to more than 30 accidents but additional work is needed to resolve ambiguity in the warning times. The new database is also being assessed to determine if the current SLS abort logic would have detected the failures. The data is conservative in that in most cases where actual failure reports did not provide the data, then visual indications were used. Due to the low resolution of the video there was a judgment call as to the lead-time and the approach was intended to be conservative so as not to overstate the success of the abort logic. Most solid rocket failures are very rapid with STS-51 Challenger SRB leak/containment failure being an exception.

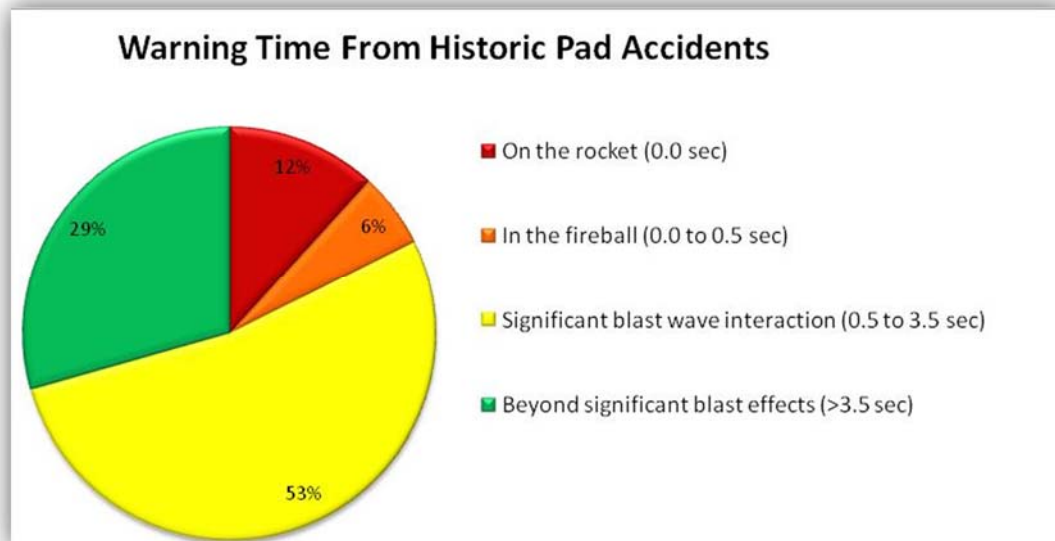


Figure 7 Warning Times from Prior Accidents show a Wide Distribution of Lead-times

The results provide some insight as to the true nature of the launch vehicle explosions. They can be very rapid events. However, the majority of accidents appear to progress at a rate that enables the onboard systems or the crew to make a good decision to abort and escape the launch vehicle. Further, there is some indication that a very rapid event is likely to be a low yield explosion since the ability to effectively produce a high yield mixture is limited. One case of a rapid event is the so called Confined By Missile (CBM) explosion that is used to simulate worst case events but historically have been low yield events due to the auto-ignition phenomena discussed earlier. Prior work assumed that the propellant would mix well leading to very large events. While these results are generalizations and should be interpreted with caution they do indicate a trend that should have some applicability for similar configurations of launch vehicles.

TEST PROGRAM PLANNING

Additional research is planned over the next year including maturing the blast and fragmentation models at vacuum conditions and expanding the small scale testing. Long term larger scale testing is needed to achieve the next level of validation for system level models. Expansion of small-scale testing has been funded and is planned over the current fiscal year. Long-term planning discussions are actively occurring with various agencies and industry representatives. All testing and analytical work is being done in parallel with computational efforts to ensure test plans can validate system-level simulations and provide for the lowest uncertainties.

The three primary objectives for the next phase of testing consist of larger scale balloon testing to assess flame acceleration effects, assess high-energy ignition effects and examine non-homogeneous mixtures. Table 5 presents a preliminary test matrix for the fiscal year 2015 testing. These are categories of tests and the specific tests will be defined in the near future. In general tests are repeated multiple times in random fashion consistent with design of experiments (DOE) practices to minimize random errors, test biases and systematic errors being introduced into the process. The design of experiments practice allows the team to minimize testing in order to reduce costs and minimizes the effects of wear and tear on the test hardware, repetitive tasking errors and so on. Table 5 also presents tests used to assess flame acceleration effects from materials that will be present on the launch vehicle services. Consideration is being given to introducing well-defined obstructions inside the balloon to examine flame acceleration effects due to obstructions. In addition the goal is to increase the data available from regions inside the blast zones /balloon.

Type	Objective	Comments
Larger Volume / Characteristic Length	Flow acceleration as volume increases and investigation of internal pressure dynamics and flame speeds	Addresses length related flame acceleration and internal data provides insight into blast wave development
Alternate Ignition Sources	Test ignition by large pressure increases, high energy spark, high-energy detonations (pyros)	Better define what drives DDT and assess alternate ignition sources
Non-homogenous mixtures	Examine flame speed and overpressures due to non-ideal mixtures	Requires multiple balloons tied together, common volume is impractical due to inability to define actual mixtures by zone.
Blast reflection validation	Provide for a single reflection from wall to validate blast propagation model for hydrogen/oxygen blast	Purpose is to validate blast propagation computational simulations
Material Effects to flame acceleration	Assess flame speeds that would occur near the vehicle surfaces under the influence of the surface insulations.	Provides insight as to what will occur at the surface of the vehicle.
Obstructions	Develop flame acceleration models for simple obstructions	Attempt to better understand the potential for DDT in main engine compartments

Table 5 - Current Blast Physics Test Plans for Fiscal Year 2015

Table 6 presents a preliminary test matrix for the planned fragmentation testing. The initial series of each test series consists of duplicate/replicated tests from the smaller 6-inch cannon testing for benchmarking. These tests will allow direct one-to-one comparison between actual flight thickness materials and the thin material samples from the prior test series. Initial tests will address smooth walled materials followed by materials representative of the typical ortho-grid walls used in propellant tank construction. In addition, tests will be conducted using representative materials with thickness transitions and welds. It is unlikely the team will complete the entire test series in fiscal year 2015 due to limited resources available and longer setup times for the larger components of the 12 inch cannon.

Type	Objective	Comments
Design	<ul style="list-style-type: none"> • Smooth wall panels • Otho-grid at constant thickness • Panels with welds • Panels with material thickness transitions 	explores the impact of the material design on the fragment generation

Working fluids/gases	<ul style="list-style-type: none"> • Gas ullage from ambient to 60 psig • Liquid (water) various fill levels • Liquid Nitrogen various fill levels to assess temperature effects 	Provides additional acceleration effects data with actual flight materials.
Materials	<ul style="list-style-type: none"> • Al-Li • Stainless Steel 	Addresses the two primary tank materials in use for EM-1. Composites desired but not justified for current SLS configuration

Table 6 Current Fragmentation Test Plans for Fiscal Year 2015

The small-scale testing has proven to be a very valuable tool to understand the underlying physics that are occurring during these kinds of explosions. This small-scale testing, when combined with the knowledge obtained from larger scale testing conducted under the PYRO and HOVI programs, allow the team to significantly enhance knowledge of a launch vehicle explosion. However, the small-scale tests require extrapolating results to support large-scale system simulations. Larger scale tests are required to ensure fragmentation models are properly representing the initial velocities and directions of fragments. In addition, the effect of the phase change from the cryogenic propellant is very difficult to address with the small-scale tests and would be easier to address with larger scale tests such as those currently being planned.

SUMMARY AND CONCLUSIONS

While the work is not complete, early trends appear to indicate that most launch vehicle accidents and explosions are survivable for in-line vehicles. There will be some launch vehicle explosions that may not be survivable. The goal here is to define the blast environments and allow vehicle and crew systems designers to eliminate or minimize configurations that can lead to explosions that are not survivable. In addition, this development program is being designed to support engineering risk and probability risk assessment tools to provide more realistic estimates and characterizations of the actual risk to the crew.

The philosophy of the research and test program is to build on the knowledge gained at each step in the program. Engineering models and computational simulations are prepared at each step in order to ensure that the engineering team has a firm understanding of underlying physics. The larger scale tests, similar to those that have been conducted, combine multiple parameters and variables that become difficult to isolate without a firm understanding of the individual parameters involved. It is the integrated computational models, and analyses with small and large scale testing that allows the team to provide the necessary data for the future launch vehicle design industry. Even large-scale testing will have limited validation capabilities since the test must envelope a large number of failure modes. The objective is not to develop high fidelity models to represent a given/specific explosion but to create data and knowledge of launch vehicle explosions, fragmentation generation / acceleration and thermal dynamics of fireballs such that launch vehicle designers can develop robust crew escape systems. An excellent analogy is the crash testing of modern automobiles. The car manufacturers' knowledge of the crash dynamics allows them to design vehicles to reduce occupant injuries. For real world automobile accidents your manufacturers must rely on the safety systems to perform similarly to the way they performed in the crash testing. It will be unrealistic to expect crew safety systems to ensure the crew survives all possible accidents that result in an explosion just as the automobile manufactures do not accommodate all possible accidents. Data collected from this ongoing effort appears to indicate that most (not all) launch vehicles accidents are survivable if the developers design to accommodate the environments. Therefore crew safety systems designers should be addressing other factors that may influence safety and success of crew safety systems.

A review of current vehicle system models indicates that many are using worst case assumptions in the guiding principle that if the crew can survive these worst case assumptions then safety is assured. Of course it is not practical to design for the worst case assumptions for an explosion and the concern is that

the vehicle designers overestimate the crew demise for an accident when evidence indicates that in most cases the crew could survive. This overly conservative approach will hide the real threats to the crew by over predicting their demise due to an explosion and then ignore the aspects that may lead to their actual fatalities. The objective of the work here is to provide the vehicle designers the means to understand the real risks to the crew from explosions and to allow them to design for survivable accidents.

FUTURE WORK

This effort is an ongoing task that will continue to expand the knowledge base for launch vehicle explosions. Development work will continue to expand the knowledge of the mechanics of the blast events including impacts due to size, ignition sources, non-homogenous mixtures and obstructions. Fragmentation development work will explore actual flight materials and attempt to address the mechanisms that are accelerating the fragments. Large scale tests and limited flight tests are being proposed that are cost effective but generic enough to apply to all current configuration of launch vehicles being proposed for human flights.

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