REDUCING BLAST DISTANT FOCUSED OVERPRESSURE EFFECTS

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ABSTRACT

Many factors are considered when evaluating hazards posed by large launch vehicles during takeoff and early stages of flight. These factors include, but are not limited to: atmospheric conditions, possible failure scenarios, launch vehicle mass, propellant type and classification, accident-induced overpressure, grain geometries and burn back profiles, debris generated during a failed launch, local terrain, permanent and transient population, and so forth. To provide guidance for launch availability of a new all solid propellant launch vehicle, a preliminary analysis was performed. This analysis predicted the window to safely launch would be unacceptably low and formed the impetus for additional work to improve product safety and enlarge the launch window.

The product improvement study described in this paper includes modeling and simulation, piecewise full-scale experimental work, and full-scale validation testing. These efforts culminated in improved product safety and a substantially increased launch window for the subject vehicle. Comparisons of initial and revised launch availability predictions provide system-level guidance designed to minimize hazards associated with launch vehicles using large solid rocket motors (SRM).

INTRODUCTION

Prior to launching rocket-powered launch vehicles, range safety officers perform a careful assessment of the possible hazards associated with the specific vehicle. This assessment involves consideration of several different types of hazards including toxicity, debris, and overpressure. Work described in this paper focuses on the overpressure aspect of launch availability associated with large solid rocket motors (SRM) that are powered using hazard classification 1.3 solid rocket propellants.

During the past several decades, researchers have carefully studied and characterized the energy released when hazard class 1.3 propellants are subjected to various insults. The most comprehensive study with the greatest relevance to SRM fallback was the PIRAT study.[1.] This study was performed by a number of organizations in response to concerns over launch accidents that resulted in SRM fallback events.

One of the important findings of this study was that hazard classification 1.3 propellants do not detonate on impact, rather they release their energy through a rapid combustion/deflagration event as flame propagates through fractured propellant. Even though this reaction is markedly slower than classical shock-to-detonation events, the energy can be released rapidly enough to generate a shock wave. A depiction of such an event is shown in Figure 1.

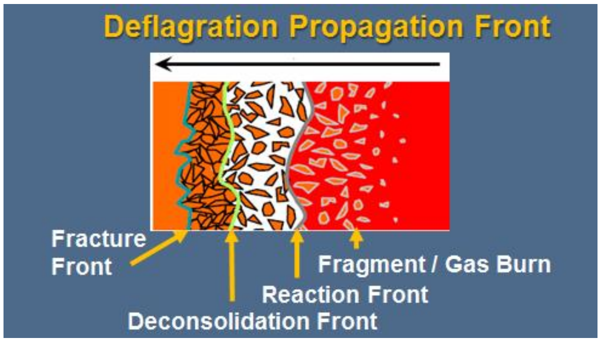

Figure 1. Depiction of Combustion-driven Deflagration That Can Occur Through Damaged Propellant During Solid Rocket Motor Fallback

Researchers working on the PIRAT program expressed reaction violence for fallback events involving hazard class 1.3 solid rocket propellants as a percentage of trinitrotoluene (TNT) yield. Describing the energy released during these events as a fraction of TNT yield made it possible to leverage actual detonation testing of very large TNT charges. Correlations between impact velocity, motor geometry, and the impacted substrate (i.e., earth, sand, water, etc.) were made in the PIRAT program. In general, these correlations predicted that higher impact velocities produced higher relative yields for the same motor geometry. Further, these models predicted that impacts into water would generate less overpressure and impulse than similar impacts on sand.

In 2011, A-P-T Research, Inc. released a report prepared for the U.S. Air Force that updated many of the initial relationships[2]. Figure 2 shows a graph generated using the A-P-T correlations for overpressure when rocket motor segments of varying sizes impact sand in a side-on manner. Similar graphs and correlations are found in the A-P-T report for both impulse and overpressure for different propellant geometries and impact conditions.

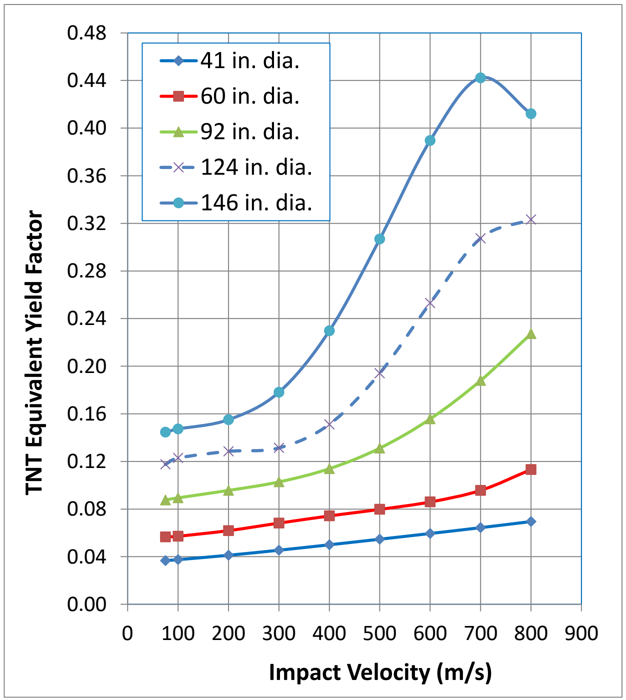

Figure 2. Influence on Predicted Pressure Released, Described as a Function of TNT Equivalence, for Solid Propellant Segments of Different Diameters Impacting Sand Side-on

Northrop Grumman recently performed an initial design study of a new multi-stage, all solid propellant launch vehicle. As part of a viability assessment for this vehicle, a range safety analysis was performed to determine if this vehicle would be judged safe to launch. This analysis indicated that distant-focused overpressure (DFO) would significantly restrict launch availability for this class of vehicle at the desired launch site. Specifically, large diameter unlit upper stage rocket motors were identified as major blast DFO generators for this vehicle. This low launch availability was a major driver for the product improvement work described in this paper.

DEVELOPMENT OF A ROBUST NEW FLIGHT TERMINATION SYSTEM

The launch vehicle that was the catalyst for work described in this paper used four different SRMs of varying sizes and a total solid propellant weight of over 500,000 lbs. The product improvement study undertaken as a result of the initial launch availability analysis considered several different options. After evaluating these potential areas of improvement, the bulk of this work focused on development of a new flight termination system (FTS).

The overall strategy adopted by the product improvement team is summarized in the flow diagram shown in Figure 3. It was recognized that current FTS are very effective in breaking large motors into relatively small pieces; their use on actual failed launches has demonstrated this capability. However, it was also recognized that for realistic failure scenarios, these same systems could not guarantee that unignited and unpressurized rocket motors would be broken into small pieces before the subject rocket motors impacted the earth.

The strategy devised to effect the desired breakup of previously unignited and unpressurized motors was to require that the new FTS accomplish four distinct functions: 1) provide a reliable path to the bore, 2) reliably ignite the motor, 3) ensure that reliable and predictable flame spread and ignition occur, and 4) reliably break up the motor into relatively small pieces. (The initial targeted breakup scenario had 40,000 lbs. as the upper limit for any one piece.)

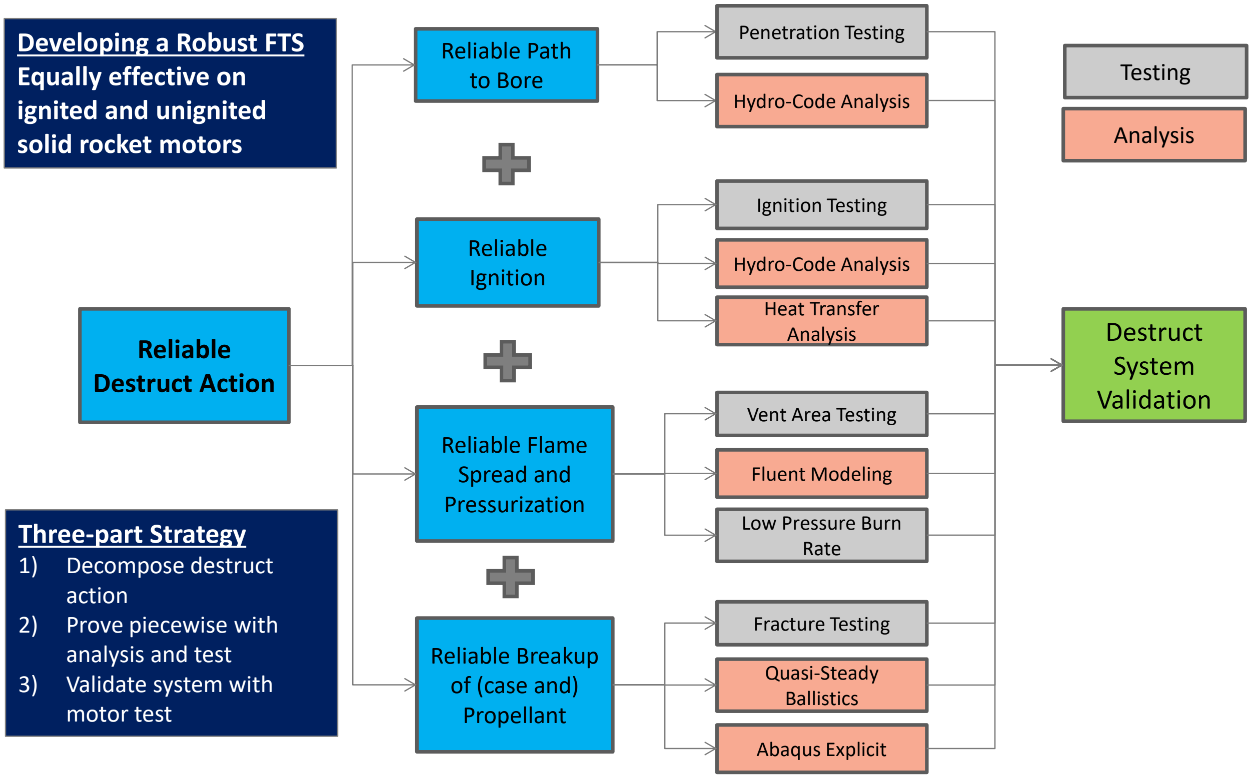

Figure 3. Overall Strategy to Develop of a New Flight Termination System Capable of Destroying any Large Solid Rocket Motor into Relatively Small Pieces

The team's strategy coupled modeling, simulation, and testing and culminated in a validation test using a several thousand pound production motor. Modeling and simulations tools utilized in this study included the CTH hydrocode as a means of ensuring shaped charges would provide a reliable path to the bore, heat transfer and CTH analysis to evaluate the ignition capability of those same shaped charges, Fluent modeling to predict flame spread and pressurization rates, and quasi-steady ballistic and Abaqus Explicit structural analysis to predict the extent of breakup for different FTS designs.

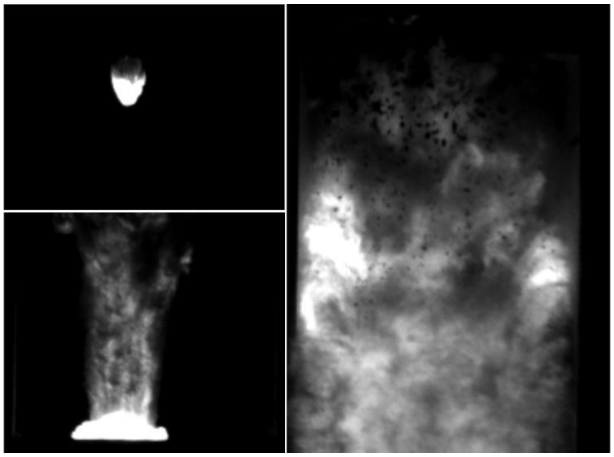

Figure 4. Images From High-speed Camera From Test Designed to Characterize a Small Conical-shaped Charge

Upper left photo shows initial perforation of top propellant, lower left photo shows impact of lower propellant section and right photo shows burning spall

Experimental validation began with the use of existing structural and ballistic test data that had previously been used to anchor and refine several of these models. Special testing developed and conducted for this project involved testing conical- and linear-shaped charges (LSC) against specially designed targets. For example, Figure 4 shows images from high-speed video taken during a test designed to understand the penetration capability and to determine time to ignition when a small conical-shaped charge perforated an initial section of case, insulation, and propellant; traveled across a realistic gap; and penetrated into a large bulk propellant sample. This test provided valuable information regarding penetration capability of a specific shaped charge, time to ignition, and the extent of spall produced during the penetration event. Other special targets were designed to provide information regarding the impact of changes in LSC size and standoff on penetration, case and insulation damage, and so forth.

Information gained from the combination of analysis and testing was used to design a FTS for a several thousand pound motor. This system used a strategically positioned small conical-shaped charge to perforate the case and ignite the bore and a very small LSC to weaken the case. Placement of both the conical and LSCs was determined through analysis. The actual destruct test matched modeling with regard to time to ignition, pressurization rate, and pressure at failure and finally case and propellant breakup. Images of the actual high-speed video of the test are compared with structural analysis in Figure 5.

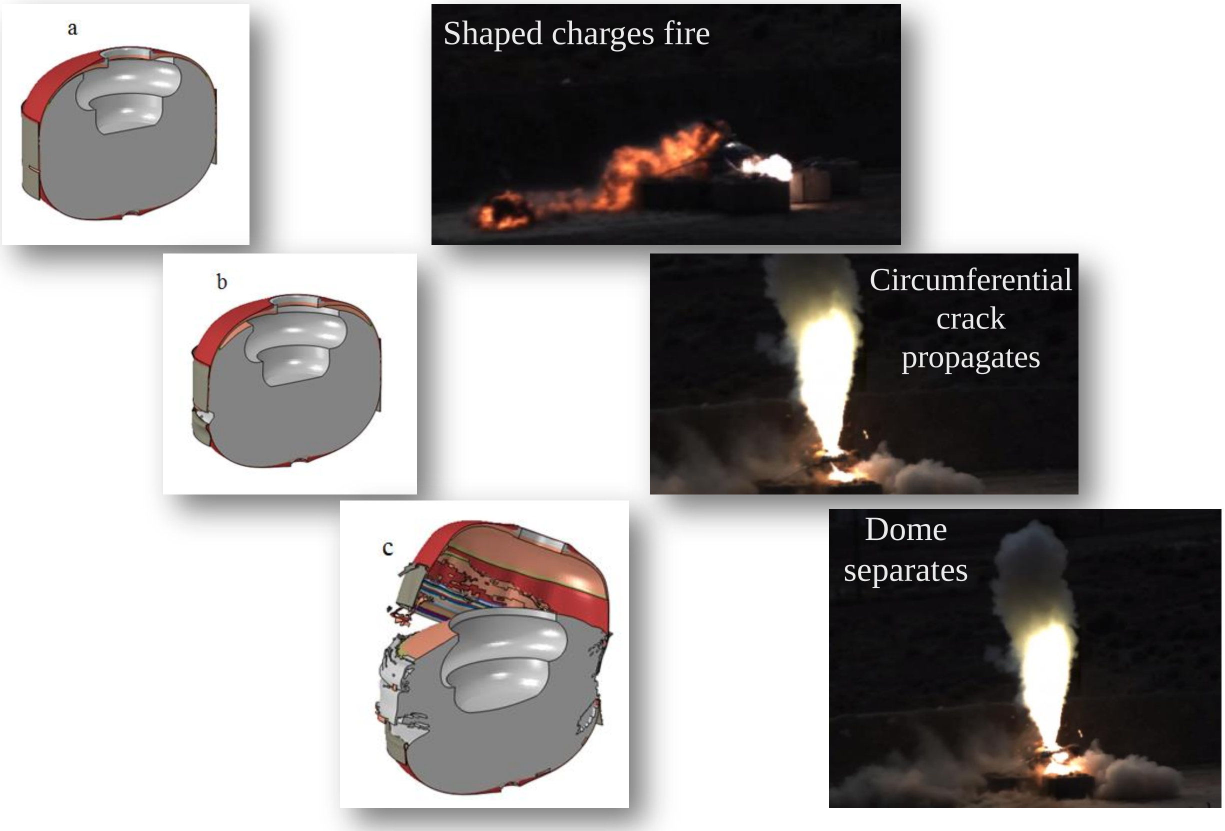

Figure 5. Comparison of Images from an Actual Destruct Test and Structural Analysis Verifying That Case Failure Matched Analysis

BRIEF SUMMARY OF DISTANT FOCUSED OVERPRESSURE AND ASSOCIATED HAZARDS

As discussed briefly in this paper and in greater detail in references 1 and 2, the impact of a SRM or large section of a motor may generate a significant pressure wave. As these pressure waves expand and propagate outward from the source, it is possible for them to be bent and focused by local weather conditions (inversion, wind, and caustic atmospheric conditions). As these focused waves return to earth, they can potentially break windows and cause injuries^3. A graphical representation of such an event is shown in Figure 6.

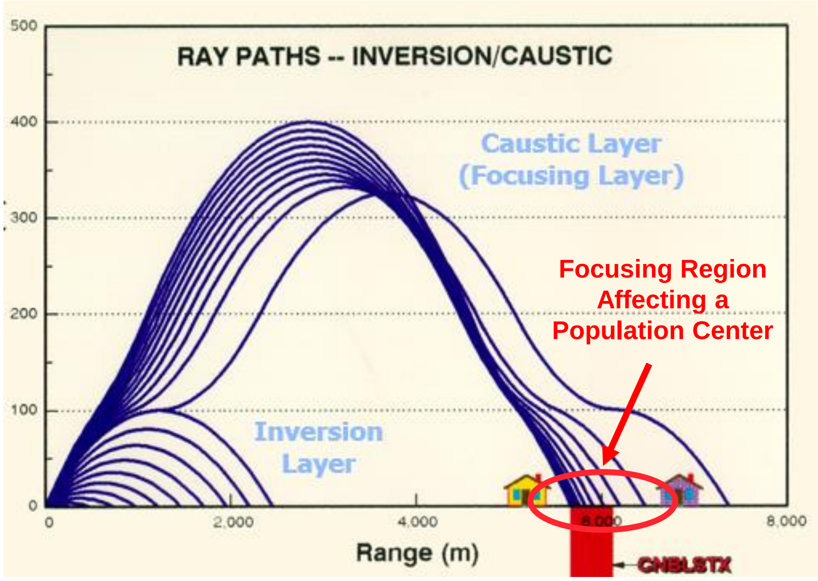

Figure 6. Graphical Representation of a Blast DFO Event

ORIGINAL BLAST DFO RISK ANALYSIS

When the initial blast DFO analysis of the notional all SRM launch vehicle was performed for Northrop Grumman by subject matter experts from ACTA, Inc., this analysis determined the following factors were important and should be considered:

- The nearest off-base population centers are within 3 km of the launch pad
- Large SRMs have potentially high TNT yields
- There was no breakup of the unpressurized upper stages

During the risk analysis, two different scenarios were used to bound the situation where an intact impact of the entire vehicle occurred. The first scenario treated propellant in all stages as a single source. This option was considered a worst case scenario and was thought to be the bounding condition. The second scenario treated each stage as an independent explosive source. This scenario was considered to be the most likely given the orientation of the vehicle stack at impact.

The actual analysis followed a proven pattern that included the following steps:

- Model the vehicle failure modes and resultant vehicle breakup conditions
- Calculate explosive yield based on largest fragment size and impact velocity
    - Utilize the PIRAT curves in these calculations
    - Take into account land versus water impacts
- Construct TNT yield and probability pairs and develop a yield histogram
- Perform blast DFO Monte Carlo simulations for 9,000 archived weather balloon soundings for the proposed launch site and compare predicted risk with launch “Go” threshold for Ec of 80 X 10^{-6}.
    - Perform uncertainty sampling on weather covariance
    - Loop over all yields
    - Loop over discrete azimuth directions

This analysis showed that launch availability varied somewhat with the time of year, time of day, and anticipated transient population in the launch area. However, the overwhelming conclusion was that the launch availability for the all SRM launch vehicle would be very limited, particularly during summer months. A summary of calculations performed in this study is shown in Table1.

Table 1. Summary of Initial Launch Availability Calculations for all Solid Rocket Motor Vehicle at Desired Launch Site

Case	Population	#Cases	#Red	#Grey	#Green	Off Base Max Ec x10^{-6}	Off Base Median Ec x10^{-6}	Launch Availability
JanDay	Winter	428	170	197	61	1845	218	14.25%
JanNit	Winter	243	60	137	46	998	124	18.93%
FebDay	Winter	502	214	229	59	4578	231	11.75%
FebNit	Winter	231	49	132	50	1712	143	21.65%
MarDay	Winter	551	288	212	51	3333	321	9.26%
MarNit	Winter	252	61	149	42	813	154	16.67%
AprDay	Winter	535	259	230	46	2143	290	8.60%
AprNit	Winter	228	58	139	31	971	189	13.60%
MayDay	Winter	548	270	249	29	2043	295	5.29%
MayNit	Winter	248	54	177	17	921	178	6.85%
JunDay	Summer	542	403	133	6	4202	582	1.11%
JunNit	Summer	231	13	203	15	1020	126	6.49%
JulDay	Summer	529	423	105	1	3114	648	0.19%
JulNit	Summer	223	21	195	7	720	127	3.14%
AugDay	Summer	327	275	52	0	4823	847	0.00%
AugNit	Summer	252	38	204	10	787	138	3.97%
SepDay	Winter	553	357	188	8	14412	438	1.45%
SepNit	Winter	256	66	179	11	1148	199	4.30%
OctDay	Winter	521	305	189	27	2437	376	5.18%
OctNit	Winter	282	85	173	24	934	183	8.51%
NovDay	Winter	496	262	193	41	1844	329	8.27%
NovNit	Winter	260	81	153	26	980	201	10.00%
DecDay	Winter	522	234	204	84	1748	251	16.09%
DecNit	Winter	276	91	144	41	7332	183	14.86%

UPDATED BLAST DFO RISK ANALYSIS

Using the same methodology that was proven successful in the full-scale motor destruct tests, a new set of structural breakup calculations were performed for the rocket motors used in the notional launch vehicle. These calculations indicated that the new FTS would successfully break each of the large upper stage motors into several pieces. These calculations indicated that the largest pieces of propellant would be on the order of 35,000 pounds (Table 2).

Northrop Grumman then contracted with ACTA, Inc. to update the launch availability analysis. ACTA used the same methodology for this work as discussed earlier. The improvement in launch availability from the updated analysis was striking and rose to essentially 100%. Figure 7 compares the baseline launch availability results with those obtained using the new FTS.

Table 2. Largest Fragments from Notional All Solid Propellant Vehicle Using Advanced FTS

Mass (lbm)	Number	Volume (in^2)	Cube Dimensions (in)	Area (ft^2)	Beta (lb/ft^2)	Delta-V (ft/s)	Grp Wt (lbm)	Stage
35,087	1	551,185	81.99	68.53	602.3	36	35,087	2
33,964	1	533,544	81.11	66.34	602.3	112	33,964	3
24,548	8	385,627	72.79	47.95	602.3	36	196,384	2
7,320	1	114,991	48.63	14.3	602.3	187	7,320	3
4,894	14	76,880	42.52	12.56	519.7	112	68,516	3
1,329	2	20,877	27.54	5.27	336.5	185	2,658	2

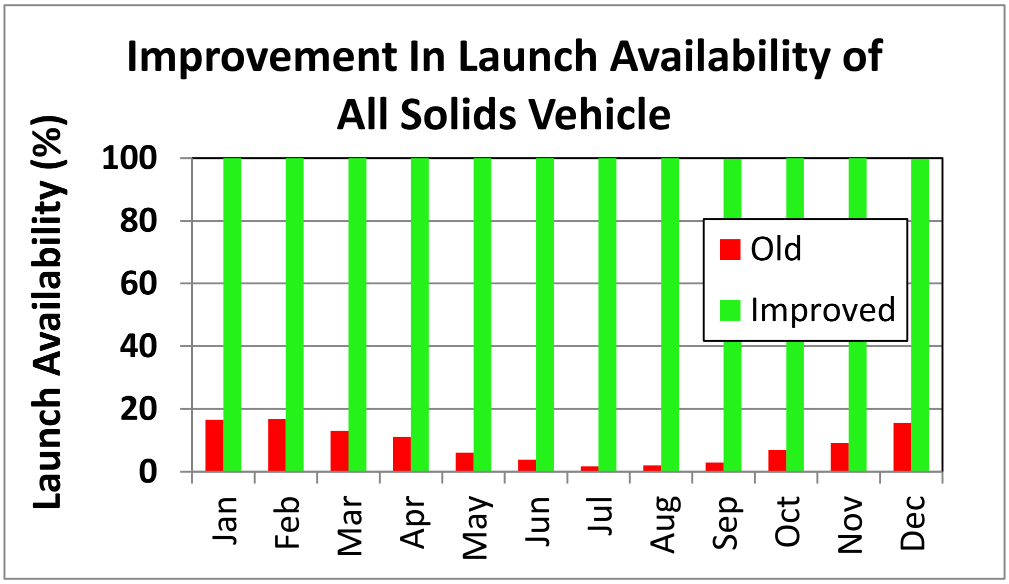

Figure 7. Launch Availability Before and After Improvements to Charlie E FTS

A sensitivity analysis of the all SRM vehicle was performed by systematically increasing the largest fragment size predicted after breakup. The first case assumed that the largest fragments were 52,600 lbs (a 50% increase over the actual analysis). Calculations performed with these assumptions did not change the launch availability, which remained at 100%. These calculations were followed by a second set of calculations where the largest fragment sizes were increased by 100% (70,000 lb). Again no changes in launch availability were noted if the fragments were defined as annular segments of cubes. Careful examination of the results indicated that the TNT yields were dominated by the fourth stage rocket motor, which contained 55,000 lbs of propellant.

A third set of sensitivity calculations were performed where the effect of changes in fragment shape were considered. In this study, the large fragments (70,000 lb) were treated as full cylindrical segments. In the PIRAT tables and correlations, segments have a higher TNT yield than cubes or annular segments of the same weight. This change in the method used to treat the fragments did reduce launch availability to around 80%. While rocket motors that use the new FTS are not likely to fail in this manner, the study was instructive and further supported the use of a FTS that encourages motor breakup.

SUMMARY

Preliminary analyses indicated that the launch of large all solid propellant launch vehicles from a United States launch flight facility would be hampered by potential glass breakage associated with blast DFO. This finding drove a study focused on understanding and mitigating generation of overpressure and energy release associated with the failed launches of these systems. By combining experimental work with modeling and simulation, a new FTS was devised and developed. The new FTS approach works equally well on ignited and pressurized rockets and unignited motors. This FTS and the associated design methodology were validated by destructing an actual production rocket motor.

The methodology developed in this study was subsequently used to predict the extent of breakup for the unignited second and third stages in the candidate launch vehicle. Information from these predictions was used to determine the change in launch availability achievable if the new FTS methodology were adopted. The results of the updated launch availability studies were very promising and indicated launch availability would be increased to virtually 100%, even when conservative factors were applied to the initially predicted breakup models.

RECOMMENDATIONS FOR FUTURE WORK

During the course of this project, several items were identified as candidates for future work that merit consideration for future study. One of the areas is the refinement and improvement of the glass breakup models used in current codes. A suggested approach for this research is to generate experimental glass breakage data for new and legacy windows by subjecting these windows to overpressure in the range observed during blast DFO events. Results of this experimental work could be used to update, refine, and anchor modern hydrocodes and other engineering codes.

A second important area is focused on the need to continue generating data that correlates energy release for hazard class 1.3 propellants against relevant substrates in the velocity range of interest. Much of the data used to guide models in the PIRAT study involved impacting propellant against rigid materials, particularly steel. It is recommended that studies be performed where energy release rates are determined when propellant impacts other media such as sand or water that cover the vast majority of launch sites.

REFERENCES

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