SOLID ROCKET LAUNCH VEHICLE EXPLOSION ENVIRONMENTS

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ABSTRACT

Empirical explosion data from full scale solid rocket launch vehicle accidents and tests were collected from all available literature from the 1950s to the present. In general data included peak blast overpressure, blast impulse, fragment size, fragment speed, and fragment dispersion. Most propellants were 1.1 explosives but a few were 1.3. Oftentimes the data from a single accident was disjointed and/or missing key aspects. Despite this fact, once the data as a whole was digitized, categorized, and plotted clear trends appeared. Particular emphasis was placed on tests or accidents that would be applicable to scenarios from which a crew might need to escape. Therefore, such tests where a large quantity of high explosive was used to initiate the solid rocket explosion were differentiated. Also, high speed ground impacts or tests used to simulate such were also culled.   It was found that the explosions from all accidents and applicable tests could be described using only the pressurized gas energy stored in the chamber at the time of failure. Additionally, fragmentation trends were produced. Only one accident mentioned the elusive "small" propellant fragments, but upon further analysis it was found that these were most likely produced as secondary fragments when larger primary fragments impacted the ground. Finally, a brief discussion of how this data is used in a new launch vehicle explosion model for improving crew/payload survival is presented.

INTRODUCTION

In order to assess crew survivability during an abort from an exploding rocket, the Launch Vehicle (LV) explosion environment must be accurately described. This is also true for the assessment of particularly dangerous payloads such as those containing radioactive material. The LV explosion environment can be broken down into three broad categories: blast wave, fragmentation, and thermal effects. For many years the typical approach to modeling a LV explosion has been to equate a particular percentage of the onboard propellant to high explosive and use the well-known high explosive curves [1] to predict such aspects as overpressure, impulse, and wave speed. Although this method is simple and can be useful in certain circumstances, it is known that it does not accurately capture the physics of rocket propellant explosions [2]. This is especially true in the near field where crew and sensitive payload survivability needs to be assessed. Since high explosives are by definition point-source supersonic combustion events, they predict extremely high overpressures in the near field, whereas Solid Rocket Booster (SRB) explosions can contain large volumes of pressurized gas as well as solid propellant that may or may not detonate. Therefore, empirical SRB explosion data was sought to clarify near field effects for these unique type of explosions.

As an initial step, a literature review was conducted in an effort to locate data from full-scale LV explosion accidents and tests. This effort sought data on all types of LVs, not just those with SRBs. Trips were taken to several libraries and launch sites to collect data. The goal of the data collection was to build empirical models of LV explosions so that a more accurate model could be used for survivability assessments, and to aid in developing improved analytical and numerical models. Most of the empirical data were found in declassified LV accident reports. This search was limited to SRBs of at least 10,000lbs of propellant, with the exception of one STAR 48 destruct test. The arbitrary weight limitation was used to both make the study

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manageable and to reduce the possibility of unknown scale effects. Currently, 25 accidents or tests [3 - 23] met the criteria and had applicable documented SRB explosion data such as overpressure measurement, heat flux, fragment size, etc.

A key distinction was made in the acquired test data between those tests that aimed to simulate a potential explosion scenario versus those that aimed to determine if an SRB could be made to detonate. The latter category all contained significant amounts of High Explosive (HE), ranging from 10's to 100's of pounds, in an attempt to cause the propellant to detonate. The former category only included Solid Rocket Motors (SRMs) that failed by case burst, linear shape charge destruct, impaling, or over-pressurization. This HE-boosted category was deemed not applicable to the task at hand since crewed LVs do not typically fly with large amounts of high explosive. However, data from this category was insightful and is included herein for comparison. A third category was defined as high velocity impacts. To date, only data from this type of explosion has been collected. Analysis on these high velocity impact explosions has yet to be performed since the focus of this study was crew survivability.

A total of 12 accidents or applicable tests (not HE boosted) were found and shown in Table 1. This paper specifically discusses the blast waves from these SRM explosions and a potential physical model to represent them. SRM fragmentation data and a semi-empirical model generated from such is in a forthcoming report. Also, a detailed description of cryogenic blast wave data and modeling efforts was produced in Blackwood [24]. For comparison, the data from HE initiated SRM explosion is included in Table 2.

Table 1 List of Applicable SRM Tests and Accidents

SRM	Date	Reference
Minute Man Missile	12 April 1966	7
Minute Man 2nd Stage	4 May 1960	9
Minute Man	15 May 1961	8
Titan IV SRMU	1 April 1991	11, 19
MX Stage 3	19 March 1982	10
MX Stage 2	30 June 1982	10
MX Stage 1	4 May 1982	10
Titan III 1202-1	28 March 1964	18
STS-51L	28 Jan 1986	12
Titan 34D-9	18 April 1986	12, 25
Delta II	17 Jan 1997	17, 21, 23
STAR 48	15 Feb 2002	22, 26

Table 2 List of Non-applicable (HE Initiated) SRM Tests and Accidents

SRM	Date	Reference
Titan III C 624A	Oct 1964	14
Polaris (X2)	June 1965 – Feb 1968	16
Minuteman Missile	June 1965 – Feb 1968	16
Minuteman Missile	June 1965 – Feb 1968	16
Bureau of Naval Weapons SRM (X2)	18 Nov 1964	6
Bureau of Naval Weapons SRM (X2)	20 Nov 1964	6
Bureau of Naval Weapons SRM (X2)	8 Jan 1965	6

Bureau of Naval Weapons SRM (X2)	16 Mar 1965	6
Bureau of Naval Weapons SRM (X2)	17 Mar 1965	6
Minute Man 2nd Stage	13 April 1960	8, 9
Minute Man 2nd Stage	12 Jan 1961	8, 9
Thiokol Minuteman Subscale	13 Sept 1960	8, 9

RESULTS AND DISCUSSION

OVERPRESSURE

When the peak overpressure measurements are plotted from the tests that used significant portions of HE (those in Table 2) a clear trend is shown as seen in Figure 1. The black line in Figure 1 represents the peak overpressure from a theoretical 20,000lbs of TNT. It has the same general trend as the HE-initiated SRMs and follows many of them in the near field. TNT equivalencies for these tests vary greatly depending on distance chosen for equivalency, but several tests can have more than 100% equivalency. Peak measured overpressures are in the 100's of psi.

Impulse — the area under the overpressure curve — for the same HE-initiated SRM explosions is plotted in Figure 2. The black line is the impulse from a theoretical 20,000lb TNT surface explosion. As with the peak overpressure, this line follows the trend of the impulse data. And as before, any TNT equivalence can be picked to match each test given a particular distance from the center of explosion. Most would range from 10% to over 100% equivalence.
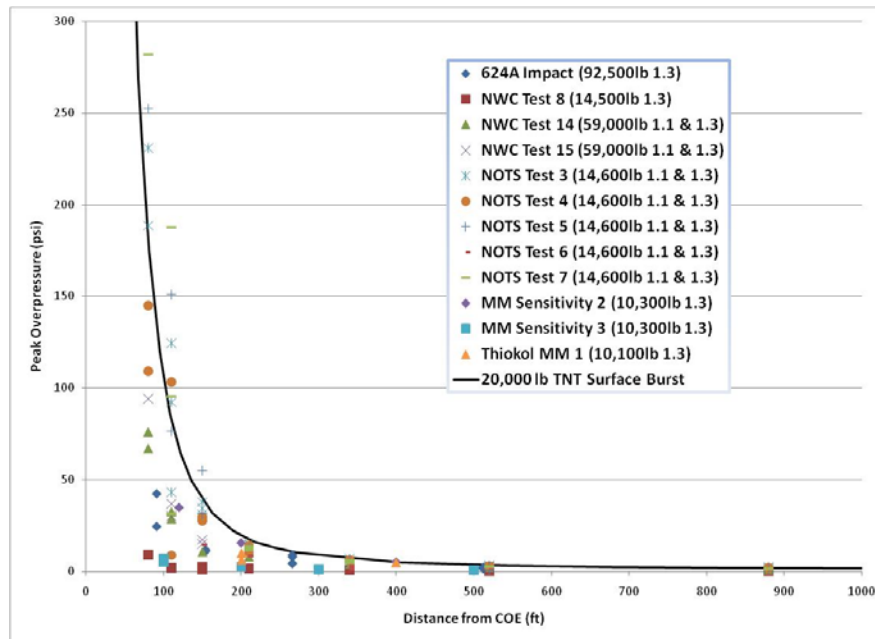

Figure 1 Peak Overpressure from SRMs initiated by High Explosives
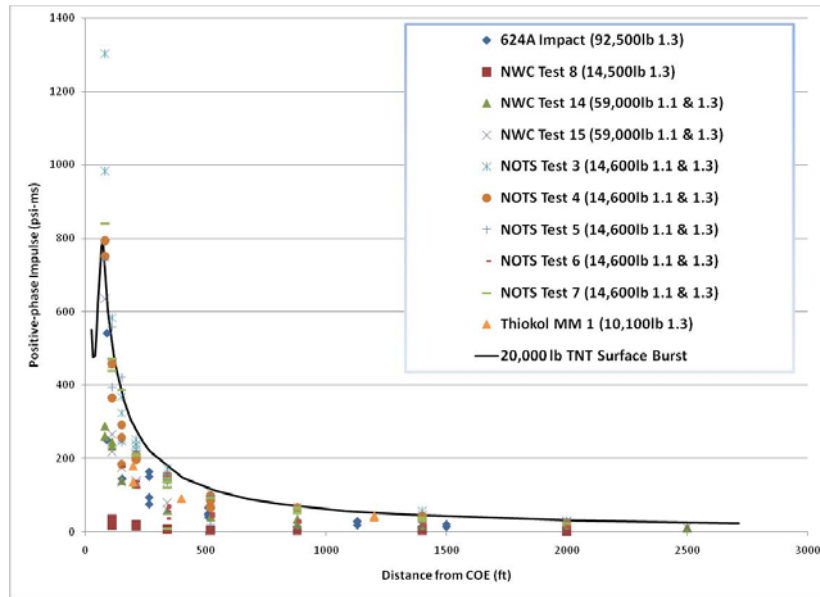
Figure 2 Impulse from SRMs initiated by High Explosives

As opposed to Figure 1, SRMs shown in Figure 3 contain rockets that were either over-pressurized to the point of failure, impaled on cutters while firing, or destroyed with linear shaped charges while firing. The only HE used in these tests or accidents was that of the normal destruct system. When the peak overpressures measurements for these "normally" exploding SRMs are compared to those that were initiated with HE a different trend appears. For reference, the black line in Figure 3 is the same theoretical 20,000lbs of TNT. If calculated, the TNT equivalencies for this class of SRM explosion would be extremely small, suggesting that a high explosive model for these explosions is a poor fit to the data.
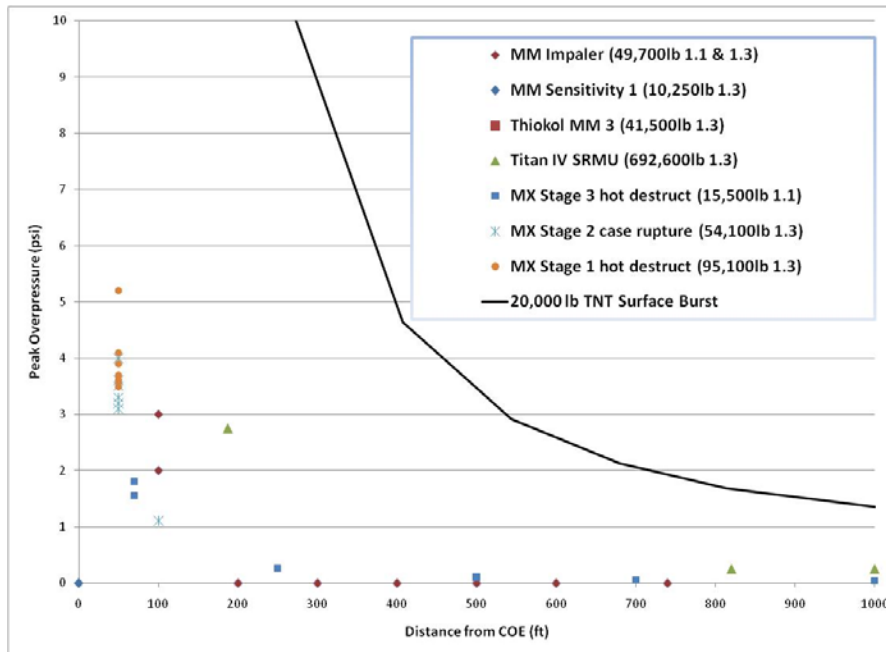

Figure 3 Peak Overpressure for "Normally" Exploding SRMs

Figure 4 compares the two classes of SRM explosions. The grey overpressure measurements contain SRMs that used a significant amount (typically between 50 and 100lbs) of HE to initiate the explosion. The blue measurements are for SRM explosions that contained no HE other than the amount contained in the range destruct devices. When compared on the same scale these two classes of SRM explosions appear to produce very different magnitudes of explosions.
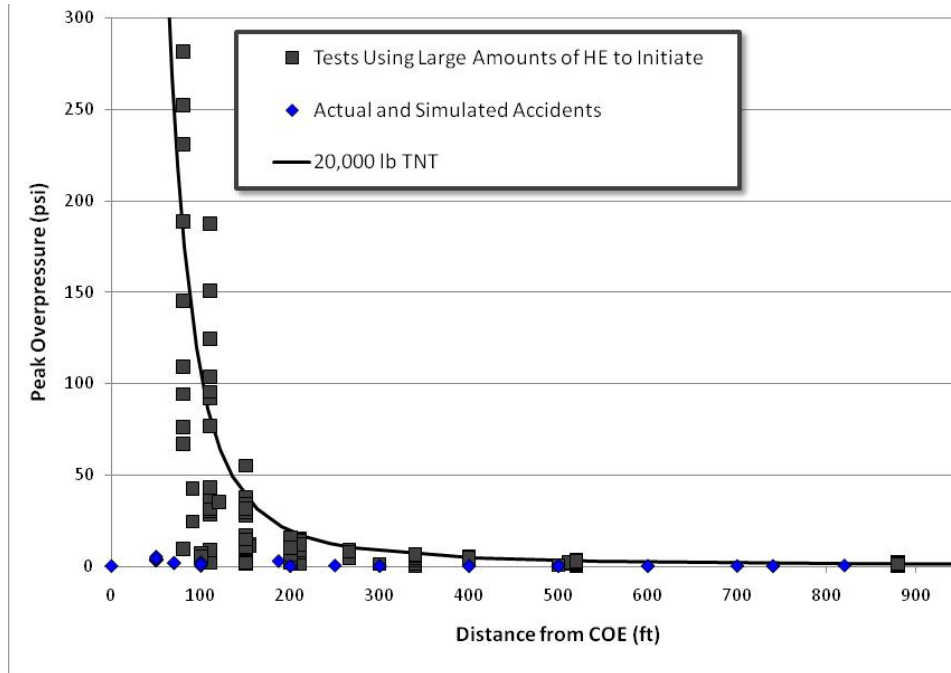

Figure 4 HE-initiated vs. "Normal" SRM Explosions

WAVE SPEED

A limited amount of wave speed data was found for SRM explosions above 10,000lbs of propellant, as seen in Figure 5. Out of the five cases with wave speed data, four fit into the "normal" explosion category. One, the Titan III C 624A test impacted the burning motor into a concrete wall at 667 feet per second. Unfortunately, no wave speed data was found for any of the HE-initiated SRM explosions. The black line in Figure 5 is the speed of sound in ambient temperature.

The "normal" explosions can be seen to be slightly subsonic in the near field and then form into an acoustic wave. The Titan IV SRMU that failed at approximately 1800psi [11] is slightly supersonic in the near field, although the hot gases produced in the near field may have affected the sound speed. The one test that shows a clear trend beyond sonic is the 624A case. As with all blast waves it eventually decays to a sonic wave. This wave speed data seems to indicate that "normal" SRM explosions do not act like high explosives with their supersonic wave speeds, but are rather sonic events. This suggests that a non-TNT model might be a better fit for this class of SRM explosions.
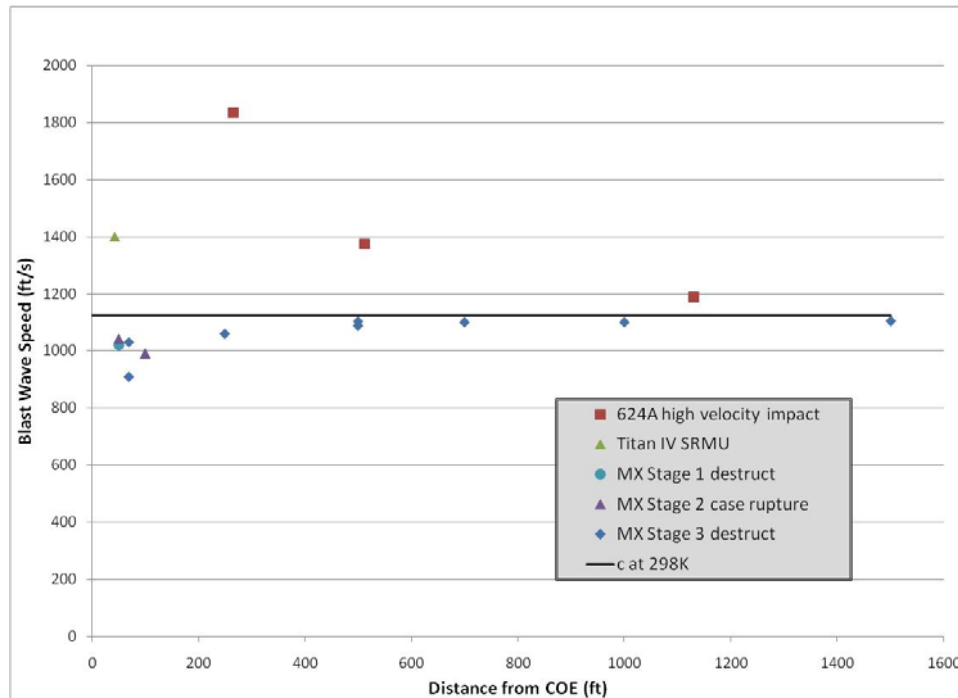
Figure 5 Measured Blast Wave Speed for a Few SRM explosions

FRAGMENTS

Speeds were calculated for 64 individual fragments emanating from the Titan IV SRMU explosion via video analysis [19]. For most of these fragments a two-dimensional (2D) speed was calculated, but for 22 of these fragments enough video imaging was available to calculate a three-dimensional (3D) speed. These speeds are shown in Figure 6. The average speed difference between the 2D estimation and the 3D measurement is less than 10%, therefore the 2D speeds are deemed sufficient for analysis. As can be seen in Figure 6 all the measured speeds are at or below Mach 1, with the average speed at 235 ft/s. These relatively low fragment speeds seem to be in good agreement with the relatively low overpressure measurements (Figure 3) and Mach 1 blast wave speeds (Figure 5). The data trends indicate range destruct or case burst failures of a solid rocket motor are an acoustic or thermodynamic type event and not a HE or supersonic detonation. It should be noted that even though these fragments are going relatively slow they still can have a large amount of kinetic energy – a key factor in conducting loss of crew or structure calculations. Using the estimated and measured masses of the fragments shown in Figure 6 and their individual speeds, the average kinetic energy is 5 MJ. This is several orders of magnitude greater than even the highest power rifles.
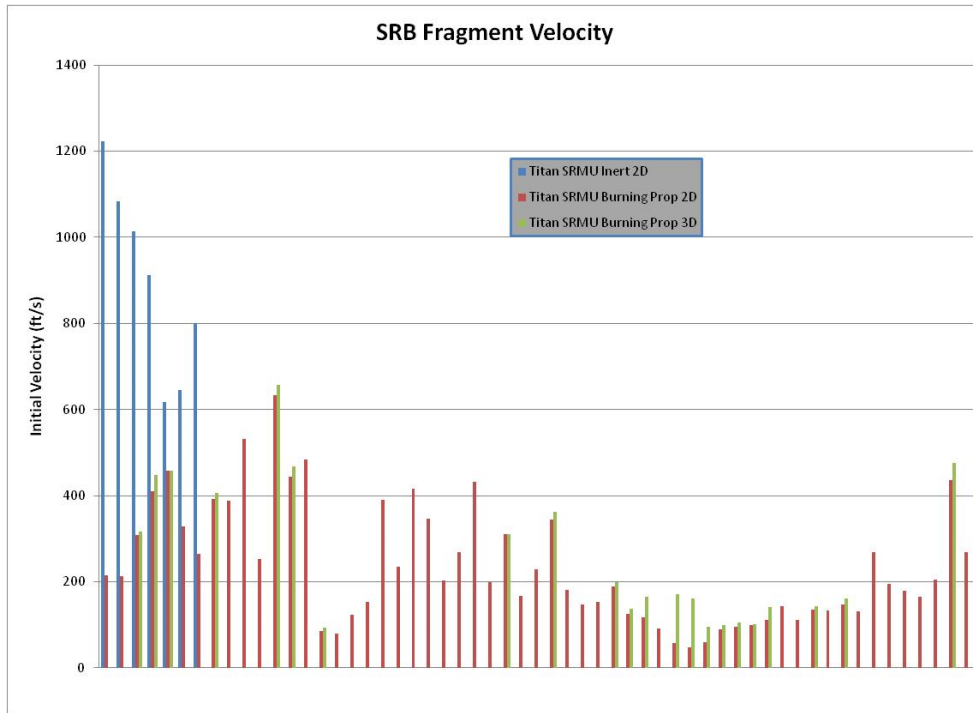
SRB Fragment Velocity

Figure 6 Titan SRMU Fragment Speeds

PRESSURE BURST MODEL

Given that all the data found for "normal" SRM explosions appears to be a non-HE-type event, a different theory is proposed. Since the detonation of the solid propellant does not seem to be the source of the blast energy, the stored gas energy (U = PdV) in the pressurized chamber was modeled to determine if there is enough energy to produce the magnitude of overpressures that have been measured during "normal" SRM explosions. The model used is one proposed by Baker [27] for spherical and cylindrical pressure vessel bursts. Calculations and estimations are made for various inputs for each of the "normal" SRM explosions at the appropriate burn time for their respective explosions, such as bore volume, chamber pressure, and heat capacity ratio. Given the uncertainties in these input values for these SRMs at the time of explosion, error bars are calculated for 10 of the measured overpressure values. These are represented in Figure 7. The error bars cover every one of the 10 measured overpressure values. This indicates that a pressure vessel burst model can accurately predict the blast wave properties of an exploding SRM assuming the SRM failed from over-pressurizing, range destruct, or case wall defects. This model is not appropriate for SRM explosions resulting from high velocity impacts or those initiated by significant (10's or more pounds) amounts of high explosives.

If the pressure vessel burst model is correct for "normal" SRM explosions then several ramifications are immediately apparent. First, propellant weight is not a primary driver of the blast wave properties, thereby eliminating the ability to use TNT equivalency. Second, since the hot gas volume inside an SRM increases with time, then the blast energy is at a minimum at launch and increases during flight. This assumes the pressure inside the SRM remains somewhat constant. At some point near burnout, the pressure does decrease enough to overcome the increased effect of volume. Finally, shock wave formation occurs more rapidly as the SRM increases in altitude. Again, assuming the pressure inside the SRM stays somewhat constant, the relative pressure from inside the SRM to the ambient pressure increase and can approach infinity if atmospheric pressure approaches zero.
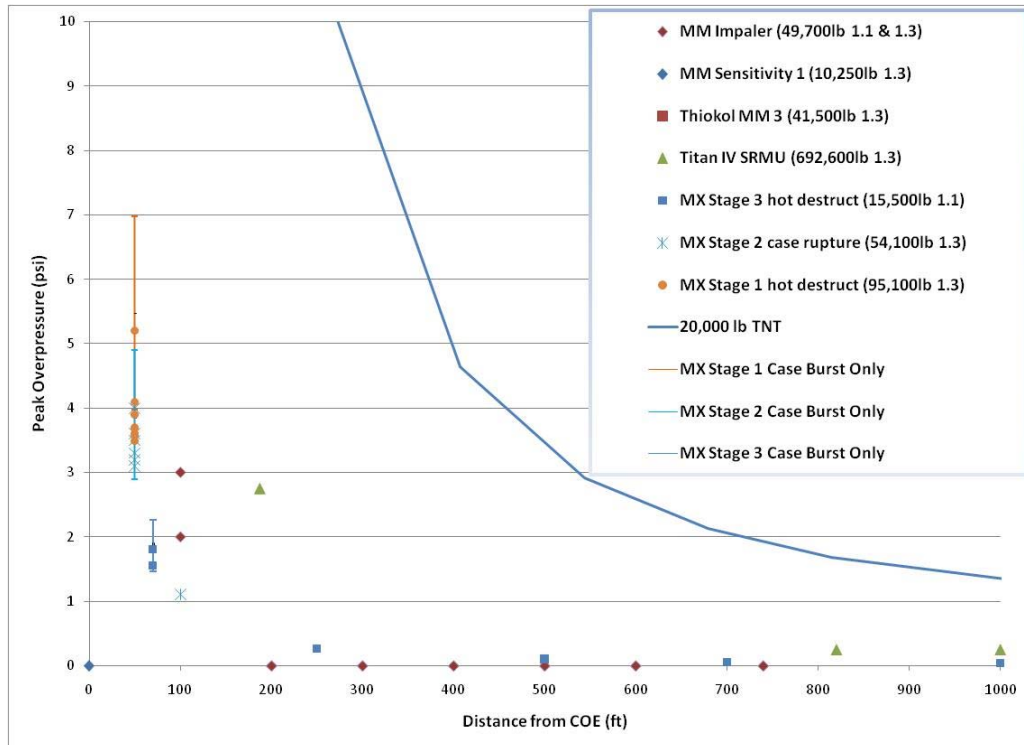
Figure 7 Peak Overpressure Predictions Using Pressure Vessel Burst Model

SUMMARY AND CONCLUSIONS

A literature review for large SRM explosion environments was conducted. Measurements of peak overpressure, blast wave speed, and fragment speed were found. All data suggests that typical SRM explosions are not similar to high explosives. Peak overpressures are low, wave speeds are near sonic and fragments tend to go much slower than Mach 1. Only when 10's to 100's of pounds of HE were used to initiate the SRM explosion did the explosions start to look similar to a high explosive event.

A pressure vessel burst model, which is independent of the amount of solid propellant, has been employed that reproduces the measured peak overpressure data. This model can be used to make assessment of crew, payload, or pad structure survival, in the event of a catastrophic SRM explosion.

FUTURE WORK

Since this work was only focused on SRMs that were initiated by typical failure modes, a similar process could be undertaken for high velocity impact cases. This scenario may be of particular interest to range personnel. Preliminary analysis shows the high velocity impact case to be significantly different than the normal failure modes assessed here.

Additional work by the authors has produced a semi-empirical model for SRM explosion fragment generation. This fragment model can be coupled with the pressure vessel burst model to accelerate each individual fragment, for a complete SRM explosion model.

If a pressure vessel burst is indeed the correct physical impetus for these types of explosions then this opens up the opportunity for inert propellant testing. An inert SRM can be fabricated, plugged, pressurized, and failed in order to measure the number, size, mass, and speed of the fragments. In the past, this type of test has used burning propellant. The combustion products have obscured much of the area where fragment speed data needs to be

collected. Also, the burning propellant fragments leave no way to measure the initial mass or size of the fragments. These issues could potentially be eliminated by conducting this type of test, without sacrificing accuracy.

ACKNOWLEDGMENTS

REFERENCES

1. Kingery, C. N., Bulmash, G., *Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst*, ARBRL-TR-02555 (April 1984).
2. Strehlow, R. A., Baker, W., E., *The Characterization and Evaluation of Accidental Explosions*, NASA CR 134779 (June 1975).
3. Salzman, P., Morgan, G., **TRW Solid Rocket Motor and Detonation Handbook**, TRW, (June 1992).
4. Allman, R. M., **Titan 34D-9 Failure Investigation and Recovery**, AAS 88-055, (1988).
5. Elwell, R. B., Irwin, O. R., Vail, R. W., **Project SOPHY – Solid Propellant Hazards Program**, Aerojet AFRPL-TR-67-211, Volumes I and II, (Aug 1967).
6. Weals, F. H., Wilson, C. H., **High Explosive Equivalency Tests of Rocket Motors**, China Lake, NOTS TP 3910, (Nov 1965).
7. Woods, D. F., Scambia, J. K., **Minuteman (LGM-30) Impaler Test Report**, 2705th Airmunitions Wing OOY-TR-66-509, (May 1966).
8. Dykstra, P. R., Thurston, J., **Weapon System 133A (Minuteman) Explosive Classification Tests Final Report**, Thiokol TW-543-5-61 (15 May 1961).
9. Anon, **Weapon System 133A Final Summary Report Minuteman Detonation Sensitivity Test Program**, Aerojet-General 0162-01DR-10, AF 33(600)-36610, (28 Feb 1961).
10. Bridges, S. F., **MX Stage Destruct Tests**, AFRPL-TR-82-068, (Dec 1982).
11. Nance, W., et al, **Titan IV SRMU Failure Investigation Final Report**, RDA-TR-1690001-001, (Sept 1991).
12. Reynolds, J. R., et al, **Final Report of the NASA/DOE/INSRP STS 51-L and titan 34D-9 Explosion Working Group**, Vols. I and II, NASA KSC, (16 Jun 1989).
13. Brown, B., **Explosive Hazards of Composite Solid Propellants**, 3rd ICRPG/AIAA Solid Propulsion Conference, Vol II, AD389859, (Mar 1968).
14. Vorwerk, R. F., Weals, F. H., **624A Solid Propellant Motor Impact Test**, Naval Ordnance Test Station, China Lake TPR 381, (1 Oct 1964).
15. Anon, **Determination of the TNT Equivalency of a Typical Class 1.1 Solid Rocket Propellant**, AFRPL-TR-80, (1 Apr 1980).
16. Anon, **High Explosive Equivalency Tests of Large Solid Propellant Motors**, Naval Weapons Center, China Lake NWC TP 464, (1 Sep 1968).
17. Weaver, J. R., Ward, Jr, J. A., **Delta II Fragmentation Model Final Report**, RTI/6762/06-12F, (30 Sep 1998).
18. Anon, **Test Evaluation Report (Ground Test) 1202-1**, ER-UTC 64-116, (8 May 1964).
19. Weaver, J. R., Bieringer, G. F., **Titan IV SRMU Failure Debris Analysis**, RTI/5180/26-14F (5 May 1993).
20. Parker, L. C., Ward, Jr, J. A., **Solid Propellant Size Distribution Model for Large Solid Rockets**, 30SPW-TR-93-07, (5 May 1993).
21. Deal, D., **Investigation of USAF Launch Vehicle Delta II-GPS IIR-1**, (17 Jan 1997).
22. Eck M. B., **ST48 Breakup System Demonstration Test**, Foils Engineering, (Apr 2002).
23. Deal, D. W., **Investigation of USAF Launch Vehicle Accident Delta II-241 GPS- IIR-1, 17 January 1997**, Sections 1 and 2, Accident Investigation Board, (Apr 1997).

24. Blackwood, J. M., Skinner, T., Richardson, E. H., **An Empirical Non-TNT Approach to Launch Vehicle Explosion Modeling**, AIAA SciTech 2015 Conference, (5-9 Jan 2015).
25. Garnholz, L., Nance, W., DiPol, J., **Project Galileo and Ulysses Booster Fragment Data Analysis Flights STS 51-L and Titan 34D-9**, RDA-TR-OI13000011-009, (May 1989).
26. NASA White Sand Test Facility, **STAR 48B Full Scale Demonstration Test Special Test Data Report**, WSTF-02-36952, (29 Oct 2002).
27. Baker, W. E., et al, **Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels**, NASA-CR-134906, (Sep 1977).