A METHODOLOGY FOR EVALUATING THE EXPLOSIVE HAZARDS OF LARGE SOLID ROCKET MOTORS

Paul K. Salzman*, TRW Strategic Systems Division, San Bernardino, CA

ABSTRACT

A new methodology was developed for quantitatively determining the explosive hazards of launch systems that use large rocket motors containing solid propellant. The method is generally applicable to all large military, space, and commercial launch vehicles. In a failed launch, solid propellant ultimately impacts the ground, which can lead to an explosion and production of blast waves that can cause damage to people and property. The extent of the energy release (severity) and the chance of the event (probability) determine if the launch is "safe."

This development was sponsored by an Air Force program for a new TITAN IV vehicle to be launched at both the Eastern and Western Ranges. The goal of the study was to determine propellant ground impact patterns (footprints) for various failure modes and to determine the function, probability of exceeding various levels of blast overpressure, at several vulnerable locations surrounding the launch site. The results of the analysis are presented for a TITAN IV launch from Launch Complex 41 at the Eastern Range (Cape Canaveral Air Force Station) for a nominal Cassini mission. Data are included for each of ten vulnerable locations. It is shown that for all but the launch site itself, such a launch is generally "safe."

INTRODUCTION

An important part of launch operations (vs. test) of a new large military or space vehicle is the evaluation of risk to test range personnel, spectators and facilities. Permission to launch is primarily based on this evaluation, which is required for every system to be launched and may takes several years to complete. Risk is usually defined as the product of the probability of a failure and the consequences of that failure summed over all credible failures.

TRW developed a new general methodology to quantitatively assess the explosive hazards (i.e., risks) of launch of systems that use large rocket motors containing solid propellant. If the system fails, propellant can impact the ground, release explosive energy and produce blast waves that reach people or vulnerable facilities.

The method, generally applicable to all large military, space and commercial launch vehicles, was developed during the evaluation of an Eastern Range launch of the TITAN IV vehicle that uses two Solid Rocket Motor Upgrade (SRMU) boosters. The effort was initiated to develop an alternate, more realistic, methodology because the Air Force TITAN IV SPO (Systems Program Office) was concerned that the currently used methods for evaluating range safety could be unnecessarily conservative making it difficult to achieve launch approval.

The methodology developed used the TITAN IV Cassini mission as a basis because most of the required information was readily available. Whenever possible, failure modes and effects data (discussed below) were taken from Lockheed-Martin Aerospace (the prime contractor for TITAN IV) engineering sources. In a few instances where data were not yet available, engineering experience and judgement were used to complete the data base.

Neither the Air Force nor Lockheed-Martin Aerospace has been asked to validate this representation of the TITAN IV solid rocket motor launch hazards. The method developed, using the stated mission example, has been presented to the Air Force TITAN IV SPO, Lockheed-Martin Aerospace personnel and CCAS (Cape Canaveral Air Station) and VAFB (Vandenberg Air Force Base) range personnel and their contractors. TITAN IV with SRMU is currently going through its launch approval cycle based on currently used modeling techniques. TRW believes that the presented methodology is the approach of the future for launch hazards safety evaluations.

SOLID PROPELLANT HAZARDS

Solid propellants have been used in rocket motors since WW II; remember JATO's (Jet Assisted Take Off). Because of their simplicity, high mass fraction and low cost compared to liquids, solid propellant rocket motors have become standard boosters for liftoff of large military and commercial space systems (consider TITAN, the Shuttle and Ariane). Although the type of solid propellant used in these applications (designated Class 1.3 propellant) has traditionally been considered to burn or deflagrate only (as it does in a rocket motor) we now know that it can also detonate or explode when impacting surfaces at high speed, and that this event will produce blast waves in the surrounding air just as high explosives do. Thus there is justifiable concern every time a system with large solid

* AIAA member

rocket motors is launched in that a failure could lead to the explosion of a significant portion of the solid propellant aboard. For TITAN IV, the total amount of propellant is approximately 1,400,000 pounds while for the Shuttle the total is about 2,200,000 pounds. The hazards associated with such an event are potentially great and warrant an investigation, via appropriate methodology, into the quantification of risk.

GOALS OF THE METHODOLOGY

The overall methodology development described in this paper is based on an update of launch hazards technology previously and successfully developed under various ballistic missile programs. Much of the original methodology was reviewed, evaluated and approved by a committee of national experts.

As indicated above, there is a risk at any vulnerable location at or near the launch site that a system failure could cause casualties or serious damage. For each credible failure mode, we are interested in the product of the probability of that failure and the severity of the event. In terms of the risks with solid propellant rocket motors, the extent of the explosive energy release on ground impact measures "severity" because the impact will generate blast waves that can travel from the ground impact site to the vulnerable location. It is the blast waves that cause damage. Since these kinds of data have been compiled over many years, using TNT as a "standard" explosive material, we can relate severity directly to the amount of propellant hitting the ground.

The "probability of the failure" is measured by a series of probabilistic and deterministic events that precede ground impact (discussed under Event Trees below) but is traced back to the original failure aboard the vehicle that resulted in these particular events. The probability of this failure is usually measured by the system reliability, specifications, or tests available in documents such as the FMEA (Failure Modes and Effects Analyses).

The overall goals of the methodology can be stated as follows:

- Choose vulnerable locations (people/facilities)
- Determine ground impact "footprints" of propellant (how much, how fast, where, and when) for each failure time, for each failure mode
- Determine the function, probability of exceeding blast overpressure vs blast overpressure, at the vulnerable location (the result is in the form of a probability distribution)

Benefits of this developed methodology include the use of analytic probabilistic procedures. Scientific/engineering calculations are used whenever possible to explicitly treat the physics of any particular event; probabilistic calculations are used only when this is not possible. No Monte Carlo techniques are employed.

The results can be used directly by the range to determine risk. If low enough, either due to low probability or low severity, launch hazard risk may be acceptable. If not low enough, the method will help identify and evaluate mitigation approaches.

METHODOLOGY ROADMAP

The methodology consists of the development of a database of salient features of the vehicle to be launched and of the launch site, the determination of the relevant set of failure modes that can lead to propellant/ground impact, the evaluation of the specific spatial trajectories of both uncontrolled (ballistic) propellant (fragments, rocket motor segments) and controlled propellant (full boosters or the entire vehicle) to determine ground impact locations and impact velocities, the determination of explosive energy release and blast overpressure for each propellant item based on a TRW developed yield correlation, and (using probability "chains" for all failure modes and times of failure) appropriate summation of all the individual probabilities (for all propellant items impacting the ground) to give the desired function, the probability of exceeding blast overpressure for each vulnerable location.

Each of these steps is described below in detail. The steps can be matched with the flow diagram in Figure 1. The entire process is a classic example of systems engineering utilizing the skills and capabilities of engineers trained in various technical disciplines such as aerodynamics, guidance and control, rocket motors, propellant technology, structures, detonation physics and probability and statistics.

Database

Before attempting to evaluate the relevant potential failures of the launch process, a substantial database regarding both the system to be launched and the launch site is required.

For TITAN IV SRMU (Figure 2), interest is focused on the SRMU booster systems since that is where the majority of solid propellant is located. For the particular mission being planned, data were gathered on the structural attachments, the three-segment SRMU design including

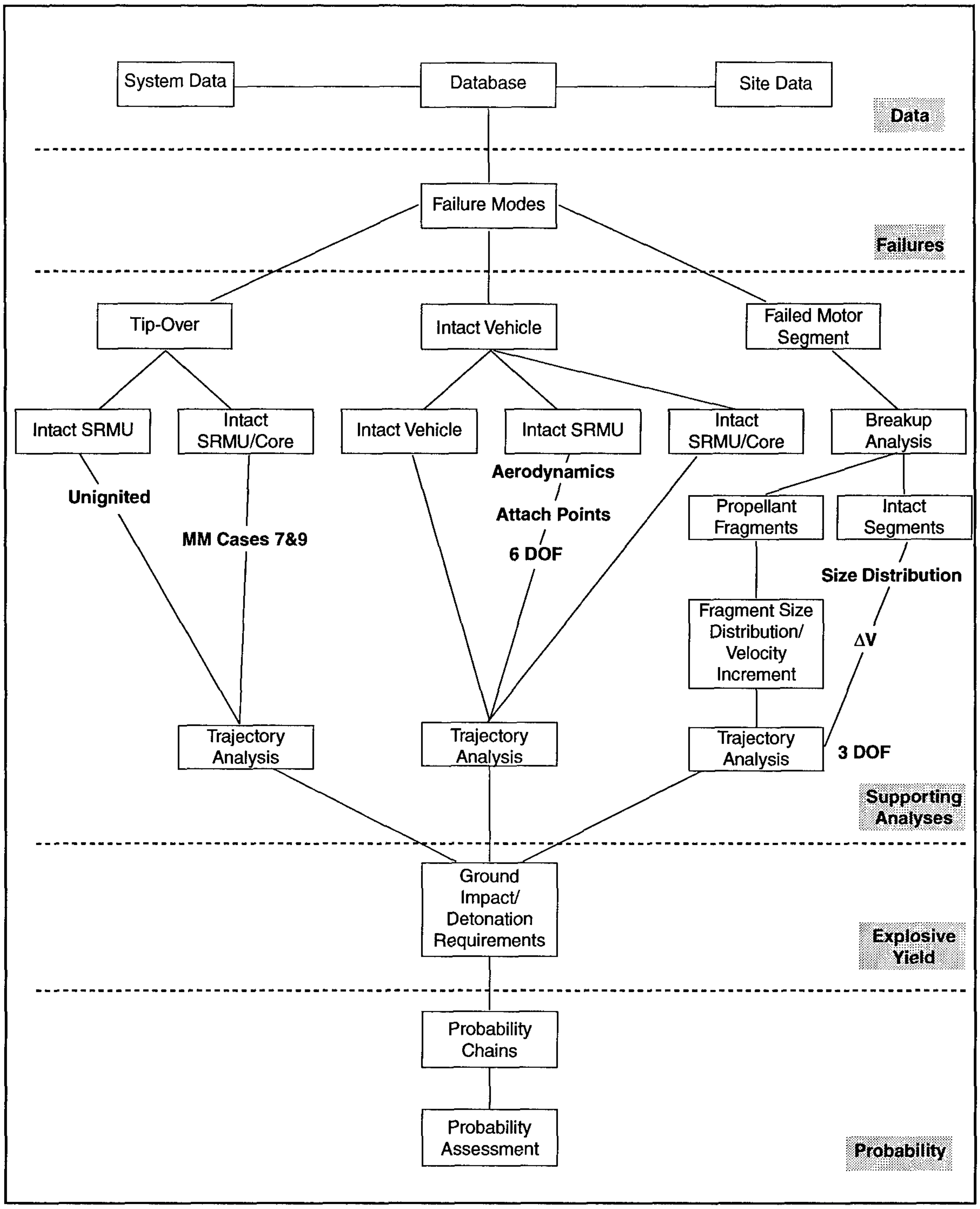


Figure 1. Methodology Roadmap Flow Diagram

motor performance parameters, the Guidance and Control (G&C) characteristics including nominal trajectories and, very importantly, the automatic destruct systems which play a major role in determining the state of the propellant after a system failure. In particular, these systems are designed to "cut" the operating rocket motor case with a device called a linear shaped-charge, such that the graphite-epoxy filament-wound case completely unravels. Thus, removing external restraint on the burning propellant grain will immediately result in fragmentation and radial expulsion of the remaining propellant; this process defines the size distribution of the propellant under these circumstances. The system is designed such that this will occur either 1) by manual command by Range Safety, 2)

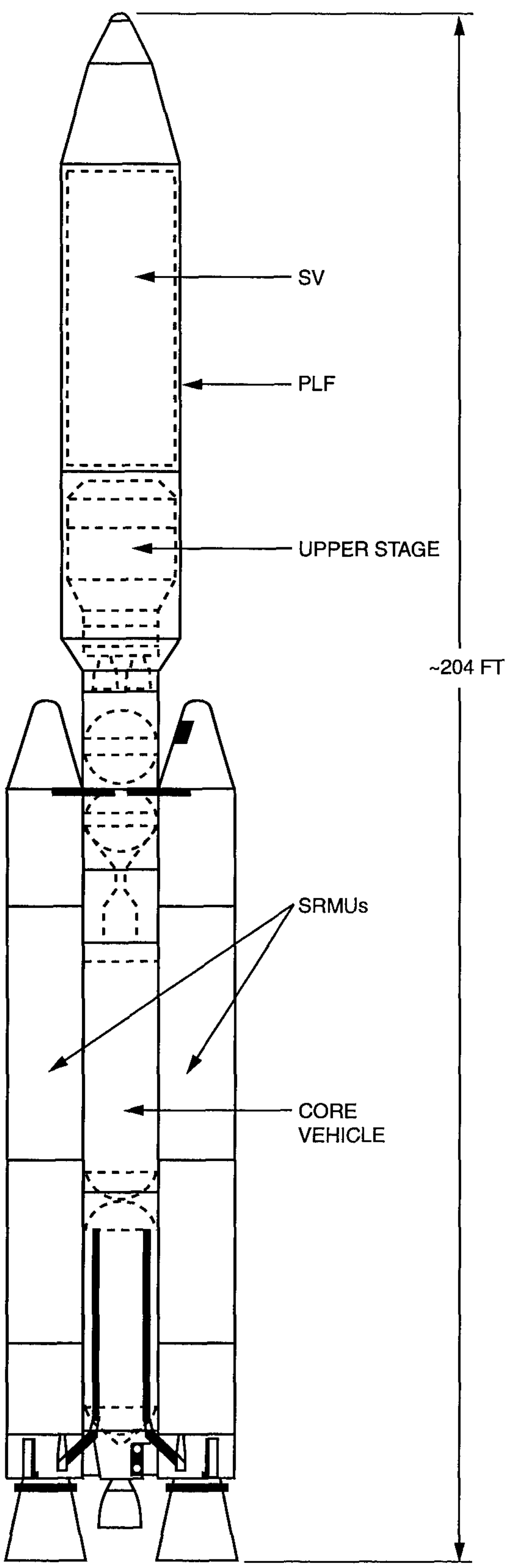


Figure 2. Titan IV SRMU

by sufficient inadvertent physical separation of the SRMU from the central (core) vehicle, or 3) by activation of a "thermal barrier" due to an upper stage explosion. As discussed below, when these destruct systems are not activated, the propellant is generally intact, either as individual segments or as a complete SRMU. This has significant implications for explosive energy release.

The characteristics of the launch site are also of interest. Vulnerable locations at or near the launch pad were identified and precisely located with respect to the launch pad (see Figure 3). Terrain in the vicinity was identified and classified as either water, based on the Eastern Test Range coastline (which was analytically modeled), sand between vulnerable locations or concrete at the launch pad. The characteristics of these surfaces determine the extent of explosive reaction when impacted by propellant.

Another important feature of the site is the reaction time of Range Safety Launch Operations from a failure event to activation of the manual flight termination system. This usually consists of data link and processing time plus reaction and decision time. Since it is known that large propellant pieces are "worse" than smaller propellant pieces and that flight termination will lead to the abovementioned propellant fragmentation, short reaction times are clearly most desirable. Therefore, to make the analysis tractable while being "conservative," a reasonable worst case (i.e., largest) reaction time was determined for two cases: 7 seconds for quick recognition when the failure is obvious and 13 seconds when there is slow recognition.

Failure Modes

The determination of an appropriate list of failure modes is difficult but essential to the fidelity and usefulness of the methodology depicted in Figure 1. On the one hand, it is critical to develop a comprehensive enough list that all the likely cases (that lead to significant consequences) are considered while on the other hand excluding a multiplicity of unlikely or non consequential cases that will make the analysis intractable. For the TITAN IV SRMU study, we organized failures in terms of failure groups: rocket motor failures, G&C failures and structural failures. From these we define specific "single point failure modes" that lead, through "event trees," to specific propellant states that impact the ground.

Failure Groups and Modes

Within the rocket motor failure group, the failure modes considered were non-ignition of one of the two SRMUs

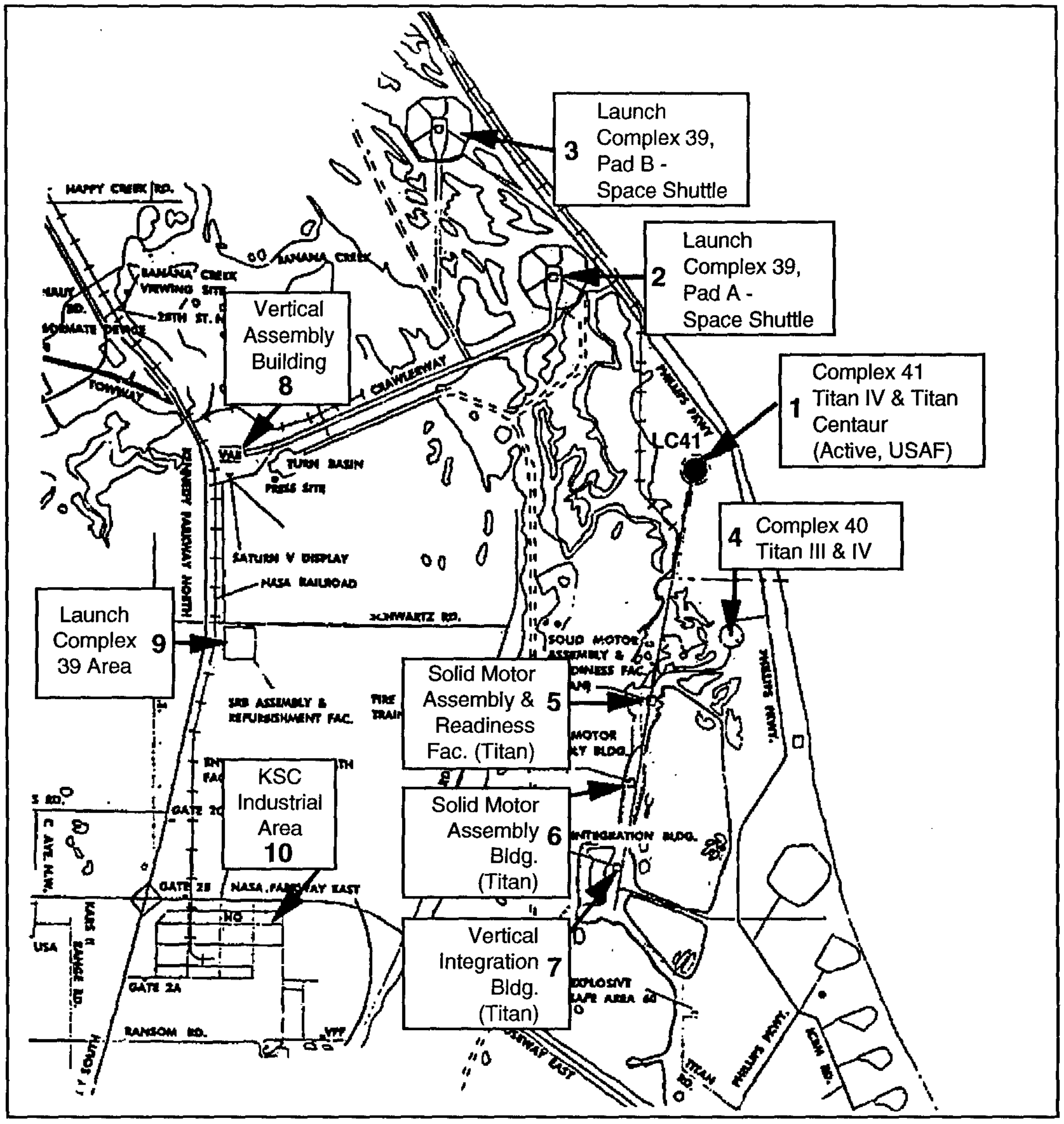


Figure 3. Vulnerable Locations At Launch Site (LC41)

at launch, seal-leakage between segments as in the Shuttle Challenger disaster, rocket motor case failure such as a burn-through, a "blown" (loss of the) throat, loss of the exit cone and a damaged exit cone.

For the G&C failure group, the failure modes considered (all but one) led to abnormal motion of one or both of the TVAs (Thrust Vector Actuators) on the SRMU which steer the entire system during the early part of flight up to 120 seconds. The failure modes are TVA(s) hardover as far as they can go (26 subcases since there are two TVAs per SRMU and two SRMUs), TVAs null, one TVA constant at last position (4 subcases) and all TVAs constant at last position. The final G&C failure mode is inadvertent early separation of the SRMUs which are supposed to separate after burnout.

The structural failure group considered two failure modes, collapse of the core vehicle and Centaur failure which includes the upper stages forward of the core vehicle.

Failure Modes are summarized in Figure 4.

Failure modes are called "single point failure modes" and are specific events that form the starting point of an event tree. They are identifiable in that a numerical probability of the event can be determined either from component/ subsystem/system reliability data, from customer requirements or by actual test.

These data are sometimes compiled in a FMEA (Failure Modes and Effects Analysis) document for the system. Because we are concerned only with those failures that

Group	Mode	Single Point Failure Name - Description
Rocket	FM1	Single SRMU fails to ignite - Tip over - 2 subcases
	FM2	Seal leakage - Segment field joint - 2 subcases
Motor	FM3	Case failure - Burnthrough, burst, etc. - 2 subcases
	FM4	"Blown" throat - Nozzle throat loss - 2 subcases
Failures	FM5	Exit cone loss - Nozzle intact - 2 subcases
	FM6	Damaged exit cone - 2 subcases
	FM7	TVA(s) hardover - 26 subcases
G&C	FM8	TVA(s) null - 2 subcases
	FM9	One TVA constant at last position - 4 subcases
Failures	FM10	All TVAs constant at last position - 2 subcases
	FM11	Inadvertent separation - SRMUs separate from core
Structural	FM12	Centaur failure
Failures	FM13	Core collapse

Figure 4. Failure Modes

lead to propellant impact on the ground, the "book" values of the probabilities (or reliability) must be modified by 1) the proportion of all failures of the type under consideration that will lead to propellant-ground impact and 2) the proportion of time over which the analysis is concerned (i.e., while ground impact is still possible) compared to the time over which the reliability is specified. These two "correction" factors are to be multiplied by the quantity (one minus reliability) to yield the probability of the failure mode.

Event Trees

For each single point failure there is a series of (perhaps many) following, or consequential, events that includes 1) deterministic paths in which following events are known or can be analyzed, 2) alternate paths in which the probability values are fixed by engineering judgement, 3) paths in which a series of alternatives is known to be equally likely (the probability is divided among the number of paths), and 4) alternative paths that are determined by a 6 DOF (Degree-of-Freedom) simulation analysis which shows that these alternate event probabilities change with time-of-failure. Some of the branch points reached after the single point failure may lead to consequential failures including further structural failure of the vehicle.

By definition for this study, each event tree results in propellant impacting the ground or water. Therefore, in every case the end of the branch (last box on the right) is the state of the propellant on impact. Five states are recognized. Propellant impacts either as fragments, intact single segments, intact attached segments, intact SRMUs or as the entire vehicle with two SRMUs.

Technically, there are as many event trees as single point failures (48 in all). For convenience, since many are similar, the study grouped them into 13 failure modes. Example event trees are shown in Figures 5 and 6.

The event tree specifies the probability of each particular path starting from the single point failure, through the various branch probabilities, to the final states.

Also the event trees are to be analyzed in detail to determine what size propellant pieces impact the ground, where they hit and how fast. This is seen in the middle section of Figure 1, which refers to a series of "supporting analyses" that are, for convenience, divided into the Tip-Over, Intact Vehicle and Failed Motor Segment cases. Note that in each instance a trajectory analysis is performed of the solid propellant to the ground in order to determine its fate at impact.

Trajectories

The Tip-Over case is unique in that it is derived directly from the single failure mode; one SRMU fails to ignite. The system barely leaves the ground but the consequences are significant. The Intact Vehicle case occurs when both SRMUs impact the ground intact (either jointly or separately) after the system has become airborne. The Failed Motor case comes about when either SRMU case fails due activation of the Flight Termination System (FTS), a burnthrough, etc., and fragmented propellant is produced (because of the internal pressure) along with intact segments. These are illustrated in Figure 1.

Tip-Over Case

When one SRMU fails to ignite, it can be shown that the "hot" SRMU, still attached core vehicle, will accelerate and break the forward attachments to the "cold" SRMU, leaving it unsupported on the stand. The cold SRMU will tip over and fall to the ground landing on its side. An analysis of this event shows that all segments impact at essentially the same time but with considerably varying impact velocity; approximately 30 ft/sec at the aft segment c.g., 70 ft/sec at the center segment c.g. and 100 ft/sec at the forward segment c.g.

These velocity differences, and the respective weights of the individual will lead to different explosive yields for each segment (see Explosive Yield Correlation below).

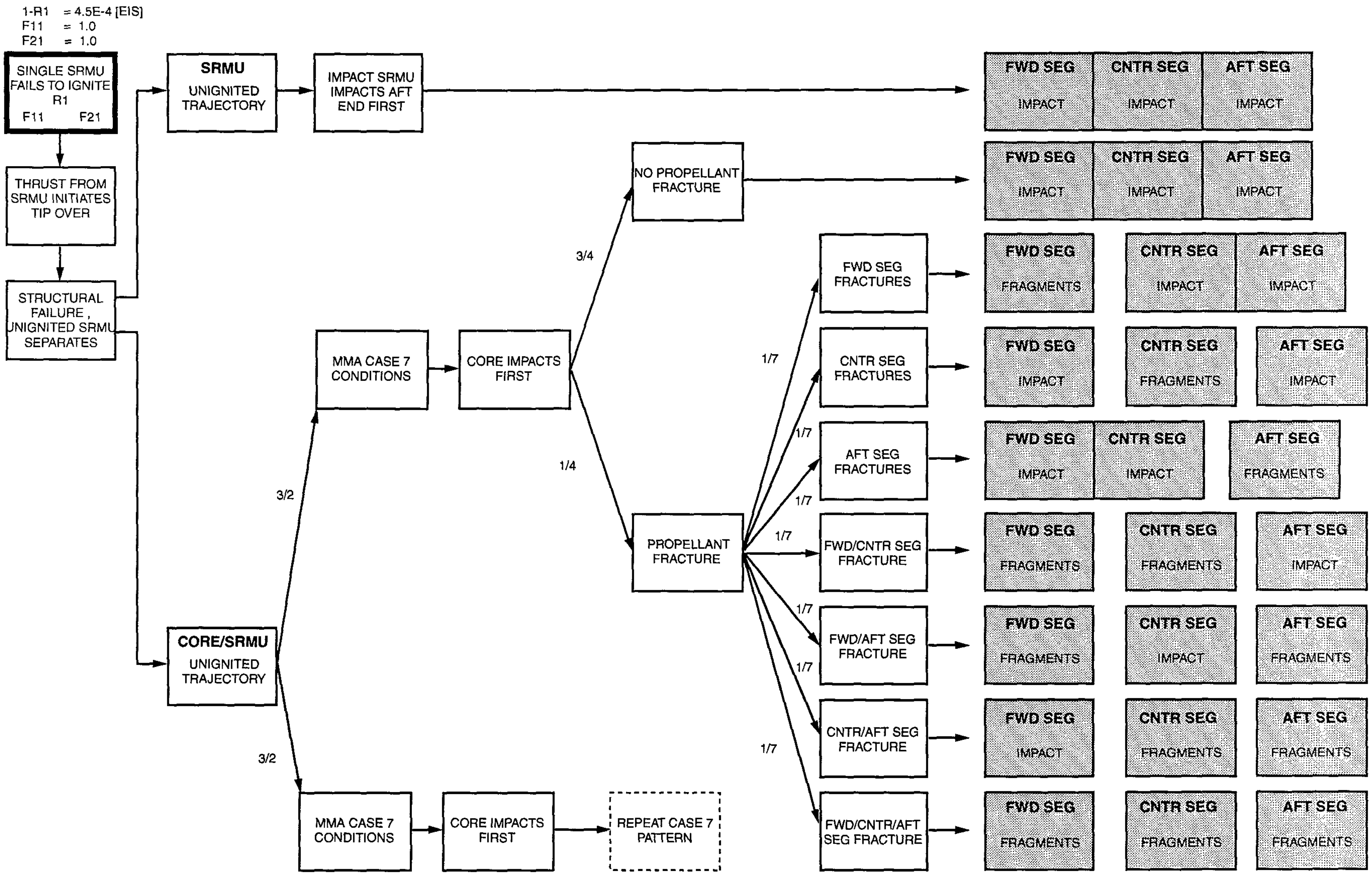
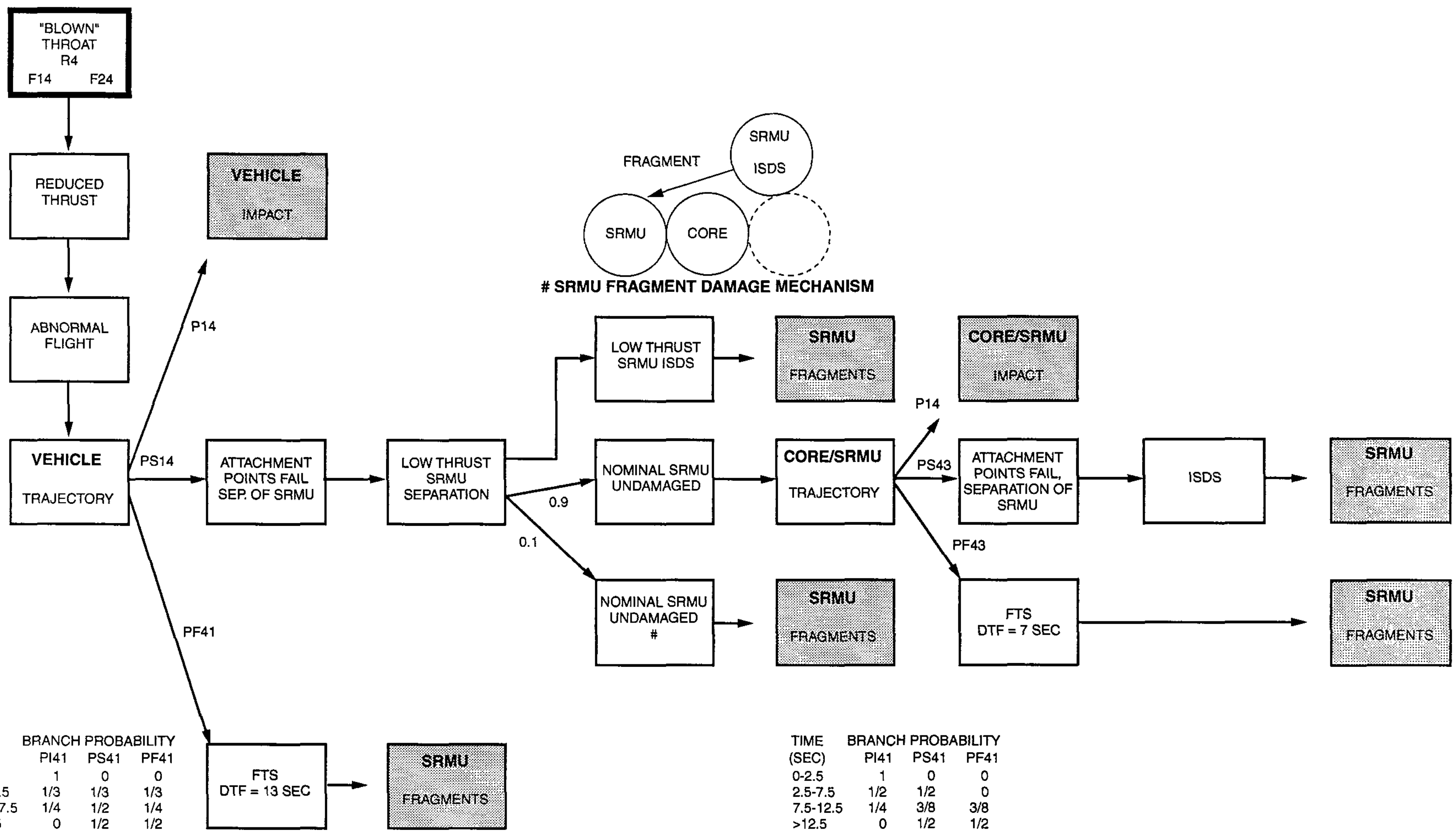


Figure 5. Failure Mode 1: Single SRMU Fails To Ignite

1-R4 = 9.67E-4 [SRMU FMEA]
F14 = 1.0
F24 = DT/TMAX4
TMAX = 140 SEC



TIME (SEC)	BRANCH PROBABILITY PI41	PS41	PF41
0-2.5	1	0	0
2.5-7.5	1/3	1/3	1/3
7.5-17.5	1/4	1/2	1/4
>17.5	0	1/2	1/2

TIME (SEC)	BRANCH PROBABILITY PI41	PS41	PF41
0-2.5	1	0	0
2.5-7.5	1/2	1/2	0
7.5-12.5	1/4	3/8	3/8
>12.5	0	1/2	1/2

Figure 6. Failure Mode 4: "Blown" Throat

Further, the computed yield for each segment is statistically distributed. Because the segments are effectively independent when they land, the yields generated are statistically added, using a procedure which uses a convolution integral, to get the correct distribution of yield for all three segments. As discussed below, the Tip-Over case results in a significant explosion at the launch site.

The hot SRMU/core combination is capable of flying a short distance horizontally but does not have enough thrust to lift off. It will also impact (concrete) in the launch pad vicinity but the hot SRMU will be cushioned by the core vehicle which lands first. The calculated vertical impact velocities ranging from 80-120 ft/sec depending on the degree of damage to the exit cone in the separation of the cold SRMU, will be reduced significantly to 35-50 ft/sec. The corresponding yield is computed as for the cold SRMU.

Intact Vehicle Cases

Within an event tree, various configurations of the vehicle may be generated depending on the consequential failures that might occur after an initial single point failure. As indicated in Figure 1, one possibility is the fully intact vehicle, while another is an intact SRMU and a separate, intact, SRMU/core vehicle combination. The latter configuration(s) may occur because of attach point failure between one or both SRMU(s) and the core. The trajectory for each of these cases can be followed using a 6 DOF (Degree-of-Freedom) simulation (computer code) with the appropriate aerodynamics, guidance information and control authority. The timing of configuration changes (i.e., attachment failures) can be determined by incorporating a structural analysis into the simulation. Generally speaking, attach point failures are precluded only by ground impact or by range safety FTS operation. The relative probabilities of these events usually depend on the time after launch when the initial single point failure, occurs.

Aerodynamics: Examination of the event trees indicates that four vehicle configurations with an intact SRMU* can occur: the original fully intact vehicle with two SRMUs, a core vehicle/SRMU combination, and the same two configurations with the Centaur (upper stage) removed and called the modified core/vehicle and the modified core/SRMU. Each of these has a unique set of aerodynamic coefficients to be used in the 6 DOF simulation. The basic vehicle data were taken from the TITAN IV databook. For the other configurations, at low angles of attack, empirical and DATCOM (a standard Air Force aeroprediction code) methods were used to determine the coefficients. At high angles of attack (up to 180°; some of the vehicles tumble) the low angle-of-attack data were extrapolated using empirical methods.

Attach Points: SRMUs are attached to the core vehicle, forward at a shear fitting and at outriggers and aft at "A" points. For a given failure scenario, the system is subject to significant acceleration, angular rates and thrust; aerodynamic loads and angular accelerations were shown not to be of concern. Resulting moments, derived from statics, were evaluated to determine the vertical, lateral and horizontal reactions at each attach point and shear fitting. Load components were summed and compared to attach point capabilities in their respective directions. A Margin of Safety (MOS) calculation was defined for each direction, for each attach point, by dividing the structural capability by the applied load and subtracting one. This was introduced into the 6 DOF code and computed at each time increment; the first MOS that becomes negative defines an attach point failure leading to SRMU separation.

6 DOF: The 6 DOF simulation is a computer code with subroutines that predict vehicle motion and orientation for all of the above described configurations. The simulation uses flight control equations from the TITAN IV prime contractor software development group and includes features such as autopilot executive, Stage 0 (SRMU) mix and limit function, cant angle logic, segment change logic, and malfunction reset logic. The code inputs are the nominal trajectory, mass properties and aerodynamics of the intact baseline vehicle, propulsion thrust vs time, guidance and control autopilot functions, aerodynamic coefficients of altered configurations as described above, the MOS subroutine just described and meteorological data vs altitude. The code output predicts vehicle motion for each failure mode and determines impact time, location, velocity and orientation including total vector velocity and vertical velocity (to predict explosive energy output), ground-track coordinates, altitude, body angles, inclination, azimuth, pitch and yaw rates and MOSs for all attachments. These are the data necessary to determine the location and magnitude of the explosive yield if the vehicle (two SRMUs) or a single SRMU impacts the ground.

As indicated above, the 6 DOF code was specifically used to determine the probabilities associated with multiple paths when considering attach point failures. Although the simulation is a deterministic tool, probability paths

---

* A separated SRMU alone is not considered since a built-in system automatically fires the FTS in that eventuality; clearly this will result in propellant fragments only, as discussed above.

were estimated by running a single failure mode with various events allowed or inhibited. For example, the attach point failures would be inhibited to obtain a particular logic path or the FTS system would be inhibited and the vehicle allowed to fly to impact. From the relative times of these possible events, the relative probabilities of attach point failure, FTS and ground impact were estimated for each of several failure times for the initiating single point failure.

Failed Motor Segment Cases

When a SRMU case fails by FTS, burnthrough, etc., the graphite-epoxy wrap is expected to unravel very rapidly, leaving full motor pressure within the burning core and no restraining force on the unlit outer periphery. This may occur for all three segments (for an FTS) or for only one of the segments (in a burnthrough). As seen in the third column of the Supporting Analyses portion of Figure 1, this will lead to a fragment size (weight) distribution and a velocity increment radial to the center line of the SRMU which must be vectorially added to the vehicle state-vector velocity obtaining at the time of the breakup. At the same time, any segments not involved in the breakup will be released intact with only state-vector velocities and no velocity increment.

Fragmentation Model: Contrary to our expectations, very little data exists regarding the size distribution of a fragmented rocket motor grain. The major reason is that most propellants will burn at atmospheric pressure and very few pieces are unignited or inadvertently quenched in the failure process. Although many flights and tests are documented with photography we could not obtain realistic data from such sources. Therefore, it was concluded that a plausible theory should be applied. The fragmentation model utilized for this study is based on an empirical relation developed from crushing and grinding theory. Several other models were also considered (probability theory of point/area/volume defects and flaw line and energy density probability, and two- and three-dimensional mechanical breakup theory as in warhead design). But these were considered too complex to justify their use. The chosen model is the simplest of those considered and is consistent with all of them. It is a theoretical exponential distribution and states that the number of fragments greater than a given size divided by the total number of fragments is equal to e (the natural logarithmic base) to the negative power formed by the fragment size divided by the average fragment size. Except for the average fragment size, each of the terms in this expression can be related to total propellant weight at any given failure time. Average size was correlated with web thickness using (scant) available data from ground FTS tests of Peacekeeper Stage III, Small ICBM Stage I and C-4. This correlation and the distribution function then allow a mathematical determination of the statistical weight of every fragment. By dividing all the fragments into a limited number of weight bands, the average weight per band and the number of fragments in that band can be determined. This provides a complete, statistically reasonable weight distribution of fragments for any failure time.

Radial Velocity Increment: As with fragment size distribution, there is virtually no database for the expulsion velocity of propellant on failure of a motor case even though film coverage of this type of event is plentiful. Therefore a new predictive method, known as the "incremental force balance method," was developed to estimate this expulsion velocity. It assumes rigid annular-segment shaped fragments, adiabatic/insentropic expansion of the core gas, sonic (choked) flow between fragments, realistic geometric pressure distribution on fragments and no axial flow (which means that all fragments are expelled radially only).

The method is based on conservation of gas mass, the continuity equation, isentropic flow relationships, the core gas equation-of state and Newton's laws of motion. It accounts for pressure reduction on fragments due to the growth of the central core (gas expansion) as well as leakage from the central core between fragments, and assumes all fragment motion is due only to pressure forces. From a well-documented chamber pressure history for an SRMU, and the applicable set of iterative equations, a unique fragment velocity is predicted for each failure time. The method assumes that, at the time of the burst, for the bulk of the propellant, the fragments are initially similar in size, shape and weight are thus all expelled at the same velocity. Continued fragment breakup is assumed to occur after this initial acceleration because of fragment interaction and crack propagation leading to the above fragment size distribution.

Because of uncertainties associated with fragment shape and surface roughness, non-uniformities in the grain fragmentation and case failure processes, and geometrical variations in web thickness, a ±20% variability in computed velocity increment was assigned.

3 DOF: As discussed above, and indicated in Figure 1, both fragments and possibly intact segments can be released in the failed motor segment case. In both instances, the subsequent trajectory to the ground is calculated with a 3 DOF simulation which computes ballistic trajectories for unguided/uncontrolled/unpropelled objects and depends only on gravitational and aerodynamic (drag) forces and the initial velocity vectors.

Fragments: We assume that the fragments are non-burning cubes, tumbling randomly. The nominal drag is obtained from the literature and a ±20% variability in the coefficient is assumed. At the time of failure, the velocity vector of each fragment (represented by an average fragment for each weight band) is determined by adding the applicable expulsion velocity increment (see above) to the vehicle velocity to vectorially determine the new fragment velocity. Clearly we do not know which position around the circumference of the failed segment a given fragment will come from. We therefore assume the fragments are equally likely to come from any position and arbitrarily choose eight positions at 45° intervals around the circumference; thus each interval has a one-eighth probability of being the source of the fragment. By knowing the vehicle body orientation (inclination and azimuth) from the 6 DOF simulation at the failure time, we compute all eight, 3 DOF trajectories. Each gives the impact time, location relative to the launch site and ground impact velocity. The pattern of eight points per initial condition (failure time and fragment weight) gives an "impact ellipse" on the ground with the probability that the fragment will impact between any two adjacent points equal to one-eighth. This can be viewed as "mapping" the fragments from the SRMU segment to the ground. For nominal drag and expulsion velocity, this is called the nominal impact ellipse.

The process is repeated for the same fragment with a ±20% variation in expulsion velocity and drag thus defining five impact ellipses in total. A portion of each ellipse is fit with a second order, non-linear equation that is used to determine the "center" of the ellipse, the angle of its major and minor axes relative to north and east at the launch site, as well as the magnitude of the major and minor axes.

The ground is divided into square cells the size of which depend on the perimeter of the nominal ellipse. The combination of the five ellipses then determines a PDF (Probability Density Function) for the probability of fragment impact on the cells.

The "thickness" of the combined ellipse is first defined by measuring distances from the nominal ellipse along the major and minor axes and finding the maximum root-mean-square of the averages between the drag and expulsion velocity cases. A rectangular "ellipse area" is then defined by seven times this value from the nominal ellipse, in the major and minor axis directions. This approach assures that this somewhat restricted area will statistically capture all impacts. In any given instance, we need only computationally consider those cells within the ellipse area.

As a check on the procedure, we compute the probability of impact of any fragment in the impact ellipse area and it should be equal to 1.0. We then determine the maximum range consistent with the blast overpressure of interest (chosen in the course of the computations) for the largest (average) fragment from a standard set of tables. Adding this range around a rectangular area enclosing all the vulnerable locations defines a larger area called the "hazard" area.

This complex procedure is made computationally efficient by considering cells only in the "intersection" area defined by the overlap of the hazard area and the impact ellipse area. Sequencing cell-by-cell, the shortest distance to the nominal ellipse and the four others is determined and the local "thickness" calculated along the particular normal to the nominal ellipse; from this the number of "thicknesses" from the cell to the nominal ellipse is determined. Assuming a standard normal (Gaussian) distribution normal to the ellipse, and a uniform distribution along the ellipse, the probability of landing in the cell is computed. Repeating this procedure for all cells in the intersection area produces a map of the distribution functions for the impact ellipse. Figure 7 illustrates the result obtained. The peak probabilities are at mid-point of the thickness and decrease "normally" both away from, and toward, the center of the ellipse. The boundaries of the eight sectors chosen above can be clearly seen. In the figure, the white (A) and red (B) areas denote high probability while the green (C) and purple (D) areas indicate low probability. It is noted that the peak probability is not constant around the perimeter of the ellipse. The southeast quadrant of the ellipse exhibits the highest probability.

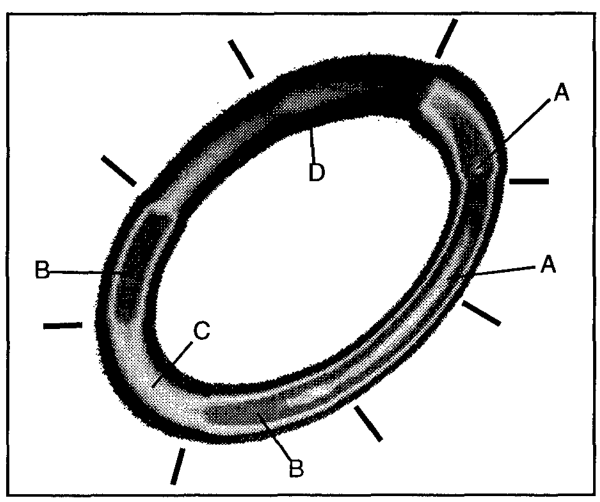


Figure 7. Sample Impact Elipse (1/8th Probability Sectors Marked)

Generally speaking, the cell of interest will not be at (or even near) the nominal ellipse for which fragment impact velocities are defined. Although fragment weight for each of the eight points on the nominal ellipse is the same (by definition), the impact velocity varies somewhat over the ellipse perimeter because of differences in trajectories. The reciprocal of the impact velocity at the cell is assumed proportional to the ratio of the sum of the square of the inverse distances from the cell to the known eight impact points divided by the sum of the respective known eight impact velocities divided by the square of the same distances. Thus the impact velocity for each sized fragment at each cell can be computed.

This new method effectively accounts for all fragments from a segment, or from an entire SRMU, and provides an appropriate statistical description of events on the ground.

Segments: Whenever fragments are produced by a failed motor segment, there may also be intact segments generated. They are assumed to be cylindrical, tumbling randomly and non-burning. Because they are intact, no incremental velocity is applied to segments; their initial velocity vector, with small uncertainty, is the state vector of the vehicle at the time of the failure. The nominal drag, with small uncertainty, is determined from an empirical relationship for tumbling, low fineness ratio cylinders coupled with data at 0° and 90° angle-of-attack. The location and ground impact velocity of the segment(s) are determined from the 3 DOF simulation.

All trajectories evaluated for the supporting analyses seen in Figure 1 lead to ground impact of propellant as fragments, segments, SRMUs or as an intact vehicle. In each case, it is necessary to determine the behavior of the propellant in terms of the production of blast waves that can propagate to the surrounding vulnerable locations.

Explosive Yield Correlation

Because SRMU propellant consists primarily of ammonium perchlorate (AP), powdered aluminum (Al) and a rubbery binder (HTPB = Hydroxy-Terminated-Poly-Butadiene) it is considered a Class 1.3 propellant. It has been traditionally assumed not to be detonable as are other propellants, such as Class 1.1, which usually contain various military high explosives. Recently, it has been accepted that this traditional view is only partly accurate and that these materials are capable of explosive reactions up to and including full detonation given the right circumstances. If even a "partial" or "fading" detonation occurs, blast waves from large propellant samples are potentially damaging. What was needed for this study was a quantitative correlation of the extent of the explosive yield given an impact of a given weight of propellant at a given velocity on a given surface.

Impact Data

Unfortunately, there is only a relatively small body of such impact data; at least for Class 1.3 propellant. While two sources reported scientific findings (SANDIA and Lawrence Livermore National Laboratory), the majority and most relevant data in terms of the weight of the samples are contained in a document describing "fallback" events of failed, live missile firings for which yields were roughly estimated. Nevertheless, the data were transformed to a common steel impact basis using standard impedance-mismatch calculations using the shock-equation-of-state (called the Hugoniot) of the materials involved. The procedure was to determine the shock pressure in the propellant in the actual event and then calculate the equivalent steel impact velocity that would generate the same shock pressure in the propellant. These data directly represent the type of information needed, but the lack of data (22 points total) is of concern if a good statistical correlation is desired.

Donor Data - Impulse Correlation

There are a number of Class 1.3 rocket motors (or propellants) which were tested by "boostering" with high explosive donors, either Class 1.1 rocket motors or military high explosives. Boostering in these tests means that a donor was placed on or near the propellant and the results reported as yield of the Class 1.3 propellant (the acceptor) for the given geometry, shape, weights and separation from the donor. These donor data were converted to an equivalent steel impact velocity by equating the impulse delivered to the acceptor in an impact event with that delivered by the explosive donor. This resulted in a linear expression relating effective steel impact velocity to the ratio of the donor weight to the acceptor weight and several fixed parameters which correct for donor composition and geometry, donor/acceptor separation and motion of acceptor. Using this expression, all of the donor data (31 points) were converted to equivalent impact data.

Correlation

The impact and donor data (53 points) were combined and correlated to obtain the desired relationship of steel impact velocity (V) vs propellant weight (W) vs yield (z), defined as the fraction of the propellant weight that undergoes detonation. Because of the logarithmic nature of the physico-chemical processes involved, and to allow statistical treatment of the data, 100% yield points (i.e., full detonation) were assigned a value of 99% and 0% yield points were assigned a value of 0.1%. Further, each data point was assigned a weighting factor as a measure of the relative reliability of the data based on the original test reports.

The correlation technique adopted (after considering several alternatives) was to assume that the quantity u, one minus yield over yield [(1 - z)/z], is distributed lognormally; i.e., follows the Gaussian distribution of the natural logarithm (ln) of u. This makes sense since z by definition varies from 1 to 0, u varies from 0 to $-\infty$ and therefore lnu varies from $-\infty$ to $+\infty$, which is appropriate for a normal distribution. Of many possible alternatives, it was found that the expression, $\ln V = A + B\ln W + C\ln u + D\ln W\ln u$, was the "best" correlation function, having a correlation coefficient of ≈85%. Using linear regression, the constants A, B, C and D were determined from the compiled data.

The result is shown in Figure 8, which correlates impact velocity vs propellant weight vs yield for steel impact. Because of the nature of the development of the correlation, any point on the plot represents the median of a distribution function of yield, normal to the z direction; this distribution is not shown on the plot, only the midpoints. This simply means that the same weight of propellant impacting at the same velocity would produce a series of statistically varying yields (not the same one every time) of which the given point is the median. The quantity u is distributed lognormally. The "spread" of this distribution, called the variance factor of the yield distribution (k) was also estimated from the raw data.

For purposes of standardization, the correlation in Figure 8 is based on shock pressure generated by steel impact. This does not match the varied and quite different surface materials actually surrounding the launch site. Three surface materials were shown to closely represent all these surfaces: concrete in the vicinity of the pad, sand in the surrounding on-shore land and water in the surrounding off-coast areas. Using impedance mismatch calculations based on the respective average Hugoniots of these materials, the impact velocity on that surface, that will produce the same shock pressure in the propellant as would a given impact velocity on steel, was calculated. The ratio of the impact velocity required for the surface of inter-

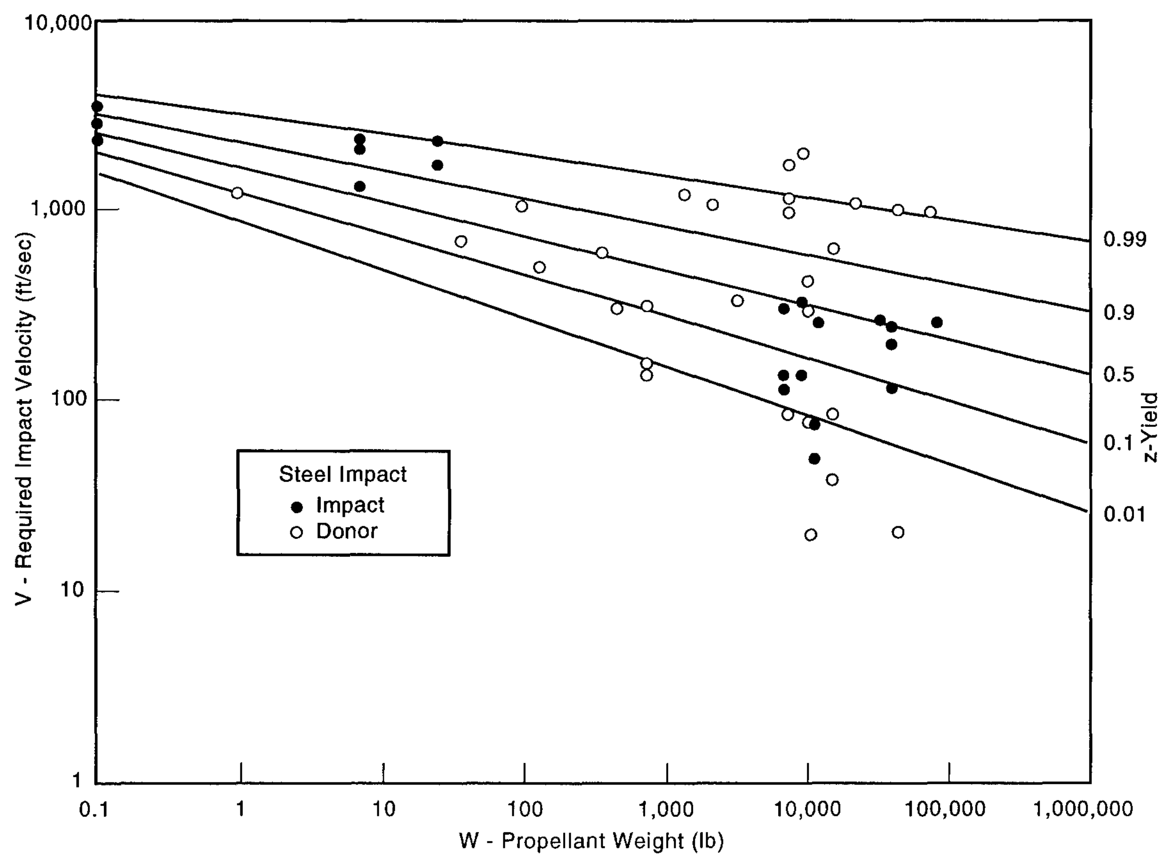


Figure 8. Explosive Yield Correlation (z_{50} - 50% Probability Curves)

est to that determined for steel impact, in this way, is defined as the surface factor (S). For each of the three surfaces it was found that S only varied slightly over the entire W and z range of interest. The average factors, S = 1.41 for concrete, S = 1.81 for sand and S = 2.92 for water, can therefore be used to effectively transform Figure 8 to the applicable impact surface.

Figure 8 is usable for all ground impacts of propellant weight W at velocity V. Assuming a given impact location, the surface material and surface factor S are identified. From this modified velocity V/S, Figure 8 gives the median yield z (usually denoted z_{50}). Therefore the median propellant weight exploded is $z_{50}W$, and the median "TNT equivalent" is $1.2z_{50}W$. Here, the amount exploded is converted to a standard, the amount of TNT which when detonated would produce the same blast; 1.2 is the generally accepted factor for Class 1.3 propellants. The blast overpressure produced by this weight of TNT is computed for a given range from the impact point with a well-known set of equations called the Kingery-Bulmash relationships. Of course, in any given case, this is the "median" value and it can vary in accord with the previously described distribution function.

Probability Assessment

With reference to Figure 1, all the elements of the methodology up to the last are in place. It is now necessary to analyze all the branches of the event trees, for each vulnerable location, to "add up," probabilistically, all the possible events and all the possible consequences to determine the probability of exceeding a given level of blast overpressure vs blast overpressure. This will determine the overall risk of the given launch, to that particular location.

Probability Calculations

For all failure modes which lead to a respective event tree at a given failure time T, the "chain" equation can be written as a sum of product terms. The first is the probability of the failure mode; the second is the probability of exceeding a given (chosen) blast level at T given the failure mode. Since the failure is assumed to be equally likely for all times, the chain equation is integrated from T = 0 sec to T_{max} sec, defined as the time after which significant blast cannot reach any vulnerable location (found to be approximately 25 seconds after launch).

For each vulnerable location, repeat calculations for a series of values of blast overpressure, produce the general result: the function, probability of exceeding blast overpressure vs blast overpressure.

By definition, the probability of a failure mode is uniquely related to the complement (one minus) of the reliability of the component/subsystem/system that is assumed to have failed. These data are usually available as part of the system specifications and published in the FMEA document, or in an EIS (Environmental Impact Statement) or as an engineering estimate. Since these data generally refer to any failure at any time during the launch, the "book" values cited need to be modified for our purposes to represent both the fraction of all failures of the component/subsystem/system that lead to the specific failure mode we are considering, and those failures that could occur within the selected time increment (or at the specified event) that we care about; e.g., failures after T_{max} are of no concern. These modifications represent the correction factors previously cited.

The more difficult issue is to determine, for each failure mode, the probability of exceeding the chosen blast level.

This is accomplished by analysis of the event trees, which arrange failure modes systematically starting with single point failures and developing all possible consequential failures including probabilistic branches. All events eventually lead to one of the five final propellant states. As previously discussed, branch probabilities were determined based on engineering judgement or analyses considering the physical nature of the event. For mechanical failure of attachments, the various probabilities of various paths (ground impact before structural failure or FTS before ground impact, etc.) were found to change significantly with the timing of the initial failure.

General Procedure for Fragments: For each failure time there are six impact ellipse areas (each consisting of five ellipses) which correspond to the six weight bands chosen. Each fragment will impact in an impact ellipse area and contribute blast overpressure to the vulnerable location. The ground surrounding this location is divided into a suitable matrix of cell areas each at a known range. For a chosen blast overpressure, we index through each cell in turn, and determine the probability of a fragment landing in the cell (see Figure 7), and the probability of exceeding the chosen overpressure from its impact velocity and location (see Figure 8 and the Kingery & Bulmash relationships). The product of these is the probability of exceeding the overpressure for the one average weight fragment for the one cell. For multiple fragments in the band, this result is modified to include the sum of product terms of the probability of one (through all) fragments landing in the cell and the probability that these multiple impacts will cause the overpressure chosen. This result is then obtained for each cell and, assuming independent events, evaluated for all cells from "one minus the product of one minus the probability for each cell." Next, having up to six weight bands, the last result is determined for each band and evaluated for all bands using the same product rule just stated, but replacing "cell" with "weight band." This gives the final result for fragments of the "net" probability of exceeding the chosen overpressure at the vulnerable location for the chosen failure mode and failure time.

General Procedure for Segments, SRMUs: Large propellant masses are treated individually. For single or paired segments, the impact velocity and location are known directly from the 3 DOF code since they are ballistic; for SRMUs attached to the core or the entire vehicle, these values are known from the 6 DOF simulation since they are still being "guided." Variability in impact location is modeled as a bivariate normal distribution. Knowing the weight and velocity at impact, the yield is determined from the yield correlation (Figure 8). A "lethal range" (beyond which the chosen overpressure will not be exceeded) is then defined from the Kingery-Bulmash relationships noting that this quantity is a random variable because yield is a random variable (see discussion of Explosive Yield Correlation). The probability of exceeding a chosen level of overpressure at a given vulnerable location is then calculated by the coverage function (for statistically minded readers, a non-central chi squared distribution with 2 DOF) which integrates the bivariate normal distribution over an offset circle with radius equal to the lethal range, centered at the vulnerable location. The expected value of the probability of exceeding the overpressure is found by integrating the coverage function over all values of lethal range up to the maximum value defined at a yield of 100%.

Given an event tree describing one failure mode at one time, a generalized sequence of calculations is used to work through all final states and all branches for all times for each chosen overpressure, for each vulnerable location.

The probability of exceeding the overpressure for any final state is the product of the branch probabilities leading to that state and the probability of exceeding the overpressure given that branch (these are the numbers calculated using the general procedures above). Calculations are repeated for every final state at every time and the results integrated over the time of interest to give the average or expected probability of exceeding the overpressure. This is repeated for a sequence of overpressures, usually 0.1, 0.25, 0.5, 1, 2, 4, and 8 psi, and then for each location.

Since all failure modes can affect each vulnerable location, the individual results are combined by summing all the products of the probability of the failure mode (as discussed earlier) and the probability of exceeding the overpressures (the function just described). This yields the final result of the probability of exceeding the overpressure vs overpressure for all failure modes at the location. It is this function that is to be used by the Range to decide how safe or how risky the launch is for that vulnerable location; i.e., is this (now quantified) risk acceptable?

Example results are shown in Figures 9 and 10 for the launch site and one other location.

CONCLUSIONS

The results in Figure 9 show how the individual failure modes stack up to yield the upper line, which is the overall result for vulnerable location 1, the launch site. Note that the vertical scale is "logarithmic" so that each major division is a factor of 10 less (or more) than the next. The upper failure modes therefore contribute most heavily to the overall result. For this case the probabilities do not diminish significantly over the range of overpressures considered. The analysis shows that a large explosive yield is possible at the launch site, which is at risk for considerable damage. The chance of these overpressures is about one in a thousand, most of this due to the Tip-Over case (FM1 in Figure 9) discussed above. However, assuming no personnel are present at the launch site, this may still be acceptable for the somewhat risky business of launching large solid rocket motors.

A different result is seen in Figure 10, which shows a rapid drop in probability with overpressure for the individual modes and the total in the upper line; the probability of exceeding relatively modest blast) is less than three chances in a hundred thousand. This is an example of much safer vulnerable location.

The summary results for ten vulnerable locations are shown in Figure 11. Other than the launch site, all the locations appear safe and one might conclude that, overall, the launch risk is acceptable.

One important feature of this methodology is that the results can be used not only to assess risk, but also to mitigate it by suggesting ways to reduce the probability of the occurrence (perhaps a minor design change to the vehicle) or to reduce the severity of an occurrence (perhaps by changing the surface properties of the ground in the launch pad area if tip-over is the dominant issue).

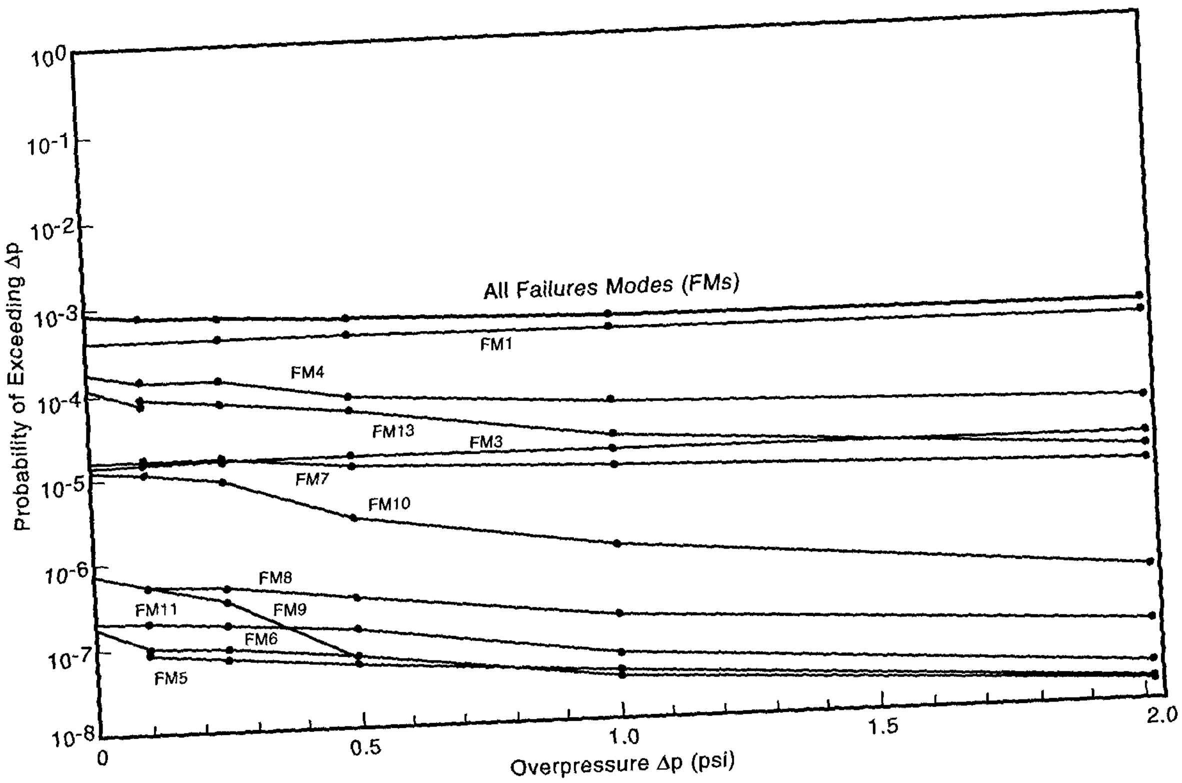


Figure 9. Probability of Exceeding Δp for Vulnerable Location 1 (Complex 41 - Primary Pad)

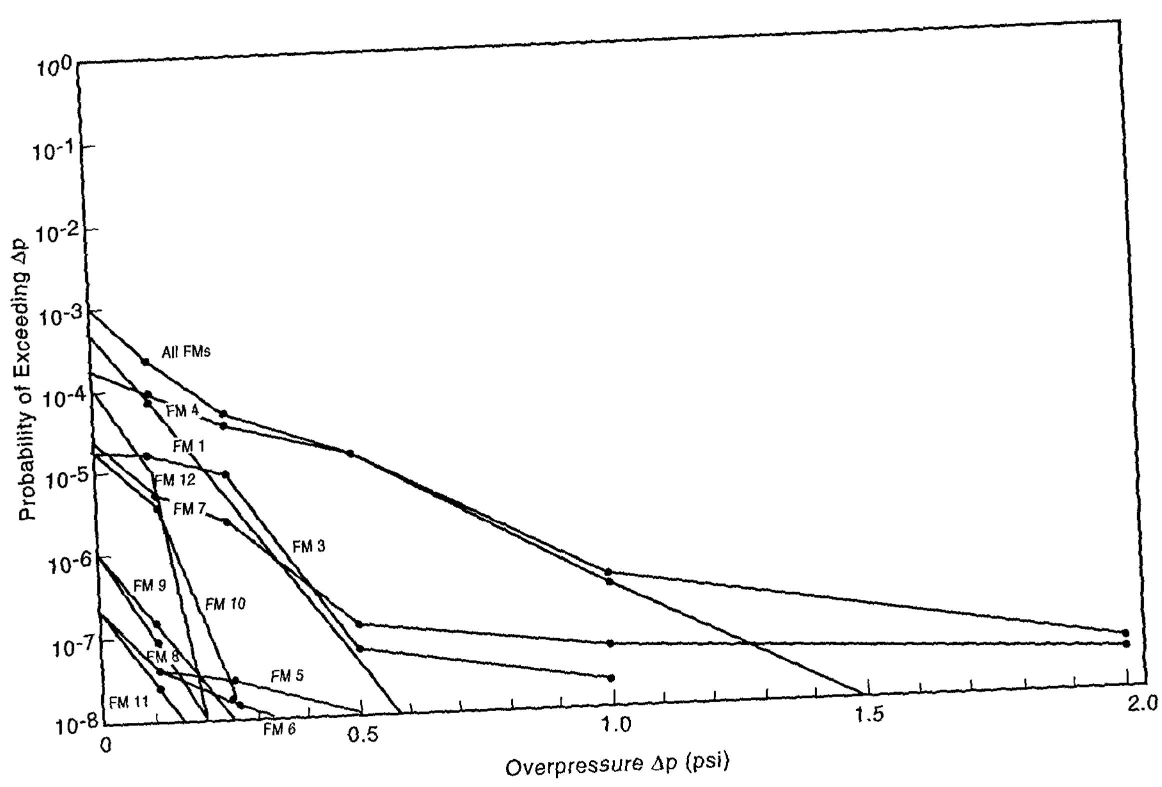


Figure 10. Probability of Exceeding Δp for Vulnerable Location 4 (Complex 40 - Secondary Pad)

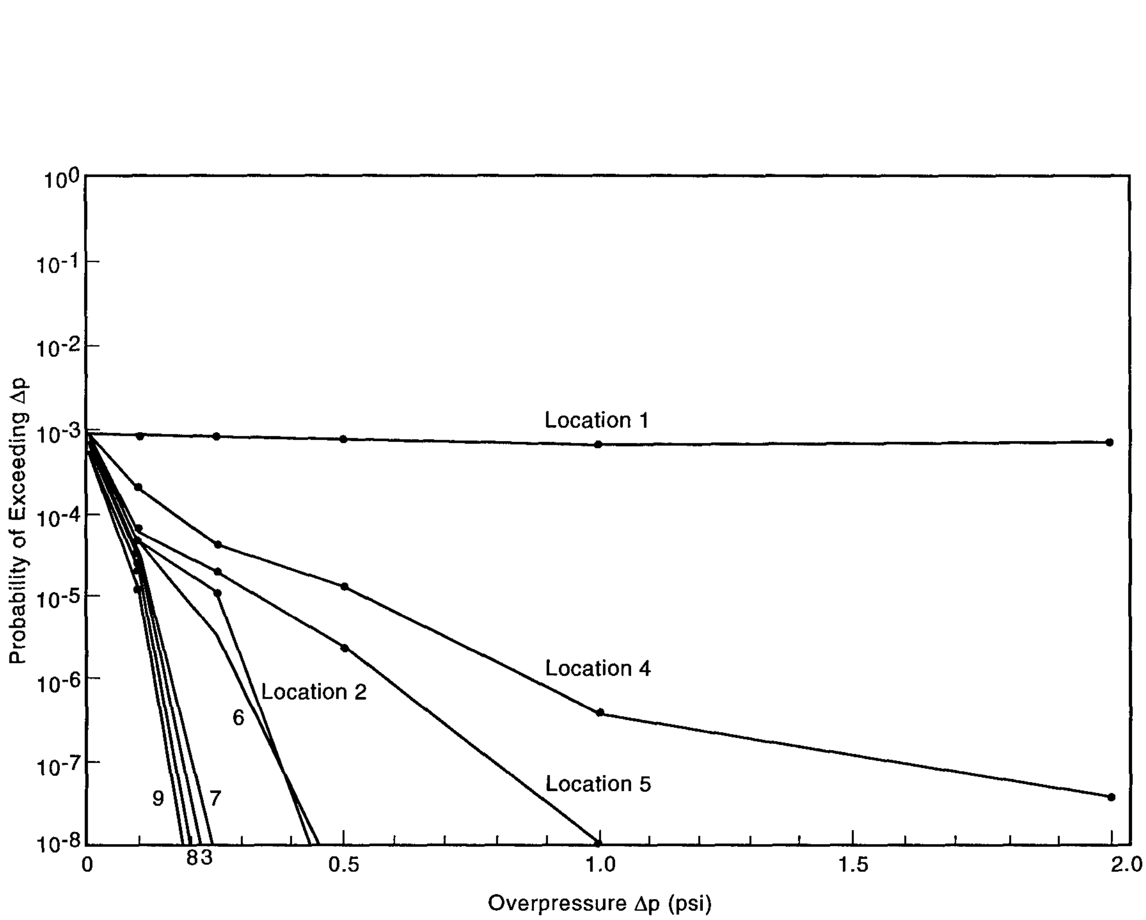


Figure 11. Probability of Exceeding Δp - All Vulnerable Locations

In summary, the methods developed in this study have been used to analyze and evaluate the hazards associated with the launching of a very complex system. They can be used effectively with any similar vehicle, including much smaller and simpler ones, and can be an important tool for evaluating safety at any launch range. Since almost all the effort required is analytical in nature and the method uses data usually available in the design phase of the system, it is possible to make risk determinations in a timely fashion; the payoff to Range Safety in the use of these methods is significant. It is hoped that these and similar methods are adopted by the aerospace community in evaluating the safety of launch systems.

ACKNOWLEDGEMENTS

The writer wishes to thank the persons who did the work on this study. In particular, W. Hoyt Andersen, Graham Morgan, David Ressler and Augusto Soux performed brilliantly in contributing new methods to major portions of the study. Rick Araiza, Brian Snyder and Gary Whitmer also contributed significantly to the effort.

The writer wishes also to thank the TRW management (Dr. James Kliegel) and the TITAN Program Office (Dr. Jerry Mason and Del Voss at TRW and Lt. Col. Doug Van Mullem at HQ SMC/CLTS, AFMC) for their uncompromising support.

Appreciation is also expressed to the reviewers of the manuscript who improved the paper considerably: Lt. Sarah Gabig (USAF), Dr. James Kliegel, Dr. Jerry Mason, Bob Welles, and especially Augusto Soux.

PLEASE CHECK THE APPROPRIATE BLOCK BELOW: M97-03-2028

☐ A copies are being forwarded. Indicate whether Statement A, B, C, D, E, F, or X applies.

☒ DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

☐ DISTRIBUTION STATEMENT B:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES ONLY; (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT C:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTORS; (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT D:
DISTRIBUTION AUTHORIZED TO DOD AND U.S. DOD CONTRACTORS ONLY; (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT E:
DISTRIBUTION AUTHORIZED TO DOD COMPONENTS ONLY; (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT F:
FURTHER DISSEMINATION ONLY AS DIRECTED BY (Indicate Controlling DoD Office and Date) or HIGHER DOD AUTHORITY.

☐ DISTRIBUTION STATEMENT X:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND PRIVATE INDIVIDUALS OR ENTERPRISES ELIGIBLE TO OBTAIN EXPORT-CONTROLLED TECHNICAL DATA IN ACCORDANCE WITH DOD DIRECTIVE 5230.25, WITHHOLDING OF UNCLASSIFIED TECHNICAL DATA FROM PUBLIC DISCLOSURE, 6 Nov 1984 (Indicate date of determination). CONTROLLING DOD OFFICE IS (Indicate Controlling DoD Office).

☐ This document was previously forwarded to DTIC on ____________ (date) and the AD number is ________________.

☐ In accordance with the provisions of DoD instructions, the document requested is not supplied because:

☐ It is TOP SECRET.

☐ It is excepted in accordance with DoD instructions pertaining to communications and electronic intelligence.

☐ It is a registered publication.

☐ It is a contract or grant proposal, or an order.

☐ It will be published at a later date. (Enter approximate date, if known.)

☐ Other. (Give Reason.)

Paul K. Salzman 12/4/96
Authorized Signature Date

Paul K. Salzman
Print or Typed Name

(909) 382 6685
Telephone Number

#.64

A Methodology for Evaluating the Explosive Hazards of Large Solid Rocket Motors 7B