A Failure Propagation Modeling Method for Launch Vehicle Safety Assessment

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Abstract: A method has been developed with the objective of making the potentially intractable problem of launch vehicle failure propagation somewhat less intractable. The approach taken is to essentially decouple the potentially multi-stepped propagation process into a series of bi-component transition probabilities. These probabilities are then used within a simple Monte Carlo simulation process through which the more complex behavior evolves. The process is described using a simple model problem and some discussion of enhancements for real-world applications is included. The role of the model within a broader analysis process for assessing abort effectiveness from launch vehicle failure modes is also described.

Keywords: Launch vehicles, Crew Safety, Failure Propagation, Explosions, Abort Effectiveness.

1 INTRODUCTION

Crewed launch vehicle ascent risk assessment requires consideration of two primary elements: the reliability of the launch vehicle and the effectiveness of the abort process should a failure of the launch vehicle occur. The reliability of the launch vehicle is typically provided in the form of failure scenario types with quantified probabilities. Characterization of launch system safety then builds upon the characterization of the system's reliability by developing an understanding of the consequences of the system's failure modes. Three factors that contribute significantly to crew safety in the face of a launch vehicle failure are: 1) the type of end state resulting from progression of the vehicle failure (e.g., confined explosion, vehicle breakup, vehicle dynamics, etc.), 2) the time required to reach that end state with respect to the time at which the failure is detected (i.e., the warning time), and 3) the severity of the resulting environments. The environment severity might, for example, be represented in terms of the time required for the crew module to reach a distance at which it can endure the environment created. The relative importance of each factor depends on the system's capabilities with respect to the other factors. For example, if failures are contained such that severe environments are rarely developed, then warning time and/or strong abort acceleration are less important. Conversely, if failures are detected early relative to the generation of severe environments, detailed knowledge regarding the failure propagation becomes less essential. The ability to detect catastrophic failures early enough to provide significant warning time is typically difficult to guarantee and, therefore, it is important to understand the potential failure propagation paths of the given launch vehicle when assessing the potential for successful abort.

Previous work within the Engineering Risk Assessment (ERA) team at NASA Ames Research Center [1,2] has focused on characterizing the end-state environments. Specifically, this work has integrated blast overpressure and debris modeling with abort system capabilities to provide failure probabilities as functions of mission time and warning time. The present work represents an effort to address the failure propagation aspect of the problem, i.e., determining the probability that failure environments will be created at all, given the occurrence of a specific launch vehicle failure mode. In the past, this propagation has been represented by relatively simple mappings, e.g., the probability of a stage explosion given an uncontained engine failure. These mappings have been based to a large extent on engineering judgment and expert opinion, supported occasionally with physics-based analysis. The ultimate objective of this work is to obtain this quantitative mapping information through a more systematic application of physics-based modeling and simulation. Further, it is envisioned that the

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inherent complexity involved in the failure propagation process would be "automatically" reflected as the result of capturing relatively simple interactions between pairs of many components. Clearly, the failure propagation process is one with large uncertainties attached and, at some level, engineering judgment will be necessary in performing the analysis. Ideally, however, the analyses will be framed such that the judgment required pertains to parameters with which engineers are more familiar. For example, the question of the probability that stage explosion follows engine explosion is replaced with questions such as the speed and number of fragments generated by an uncontained engine event.

This paper will describe a process that the ERA team has developed to address the failure propagation problem, which is thought to represent a step toward the objectives described above. The process has been applied in support of NASA's Space Launch System (SLS) Program. For the SLS analysis, the propagation process is coupled with a characterization of the failure environments to produce data tables, which are then used to assess launch vehicle failure-related loss-of-crew (LOC) probabilities.

1.1 Definitions

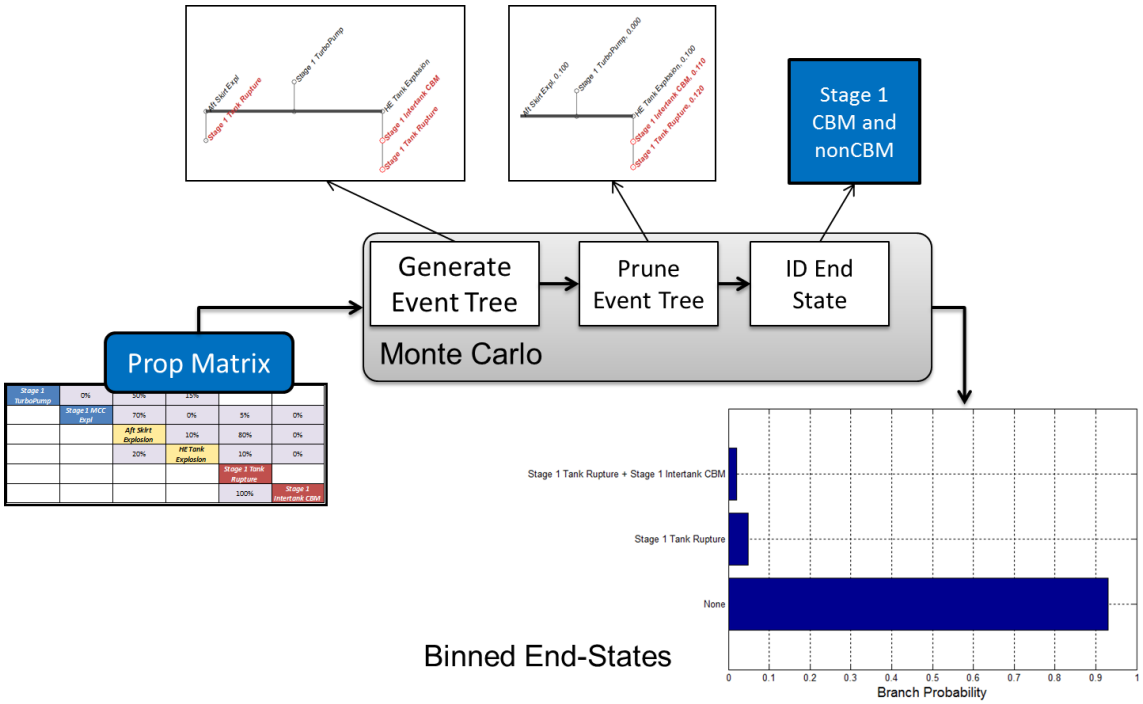
Some critical components of the analysis process are defined below.

- **Loss-of-Mission Environments (LOMEs)** – Local conditions existing at the time of loss of mission, i.e., loss of critical functionality. These are the starting conditions for the analysis described in this document and are, therefore, occasionally referred to as "initiators." LOMEs generally do not pose a direct threat to the crew or crew module, but have the potential to propagate in such a way that larger energy releases are produced, either in the initiating element or adjacent elements of the architecture.
- **Element-Level Environments (ELEs)** – Environments generated by a single vehicle architecture element (stage) that have the potential to directly threaten the crew or crew module. For example, an ELE can be either a solid rocket booster (SRB) case burst or a liquid stage confined-by-missile (CBM) explosion. These are composed of one or more sub-environments, such as blast overpressure, explosion-generated debris or shrapnel, and/or radiant heating from a fireball.
- **Vehicle-Level Environments (VLEs)** – The complete environment resulting from the initial failure. The set of VLEs includes the null case in which no ELEs are created and generally are composed of zero or more ELEs occurring nearly simultaneously. These may result from the initiator generating multiple ELEs simultaneously or from propagation of one ELE to another.
- **Abortability** – The probability of successfully surviving the environments produced given a launch vehicle failure. Abortability can be assessed with respect to a specific failure type (e.g., LOME), or in an integrated sense, given a characterization of the relative likelihoods of various types of launch vehicle failures (failure probabilities). Because the analysis in this study is performed independently of the failure probabilities, it is only capable of providing abortability with respect to a specific failure type. Given the conditional loss-of-crew probability, P_{LOC}, for a specific failure type, abortability is given simply as $(1-P_{LOC})$
- **Warning Time** – The time interval between the moment that the abort vehicle has begun to separate from the launch vehicle and the moment that the explosive event is initiated. Note that other definitions of warning time exist in other contexts, but this is the definition used for the abortability table development.
- **Aft Skirt** – This term has been used to refer to an enclosed engine section between the aft propellant tank dome and a close-out located somewhere along the engine nozzle, aft of the engine combustion chamber and turbopumps.

2 PROPAGATION PROCESS

A schematic of the propagation process is shown in Figure 1. At the center of the process is a recursive algorithm that traverses what is called the propagation matrix (discussed below) and, in the process, creates a tree of failure events. The initial event tree generated through this process will then be "pruned" to ensure that the events in the tree are all compatible with one another such that the propagation is, in fact, realizable. Finally, end-state, or element-level, environments are identified. These steps are applied repetitively within a Monte Carlo process during which the results are binned according to the combination of end-state environments encountered.

Figure 1. Failure propagation process schematic.



2.1 Propagation Matrix

The propagation matrix serves as the primary input to the propagation evolution algorithm, with diagonal cells representing the various environments that have been identified as potentially contributing to the failure propagation process and off-diagonal elements capturing the potential for transition between these environments. A simple example of a propagation matrix is shown in Figure 2.

The diagonal elements can be classified according to whether they are initial states (blue in Figure 2), intermediate states (yellow), or end states (red). Initial states in the context of propagation are the Loss-of-Mission Environments, i.e., the conditions that exist at the time the mission is lost (e.g., engine turbopump burst). Intermediate states are environments that are not considered to occur naturally without the occurrence of another failure environment, but that may contribute to the propagation process. For example, high-pressure tanks in the engine section may be thought to be so reliable that spontaneous explosion is not considered, but they may burst if struck by other failure-generated debris. Finally, the element-level environments described above are also included along the diagonal of the propagation matrix.

Figure 2. Example of a simple propagation matrix.

Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	***HE Tank Explosion***	10%	0%	
				Stage 1 Tank Rupture		50%
				100%	***Stage 1 Intertank CBM***	
						Stage 2 Tank Rupture

One requirement of the propagation algorithm is that the results should be independent of the order in which the environments are placed along the diagonal. The result of re-ordering these elements should only be to cause some off-diagonal probabilities to be shifted from above the diagonal to below, or vice versa.

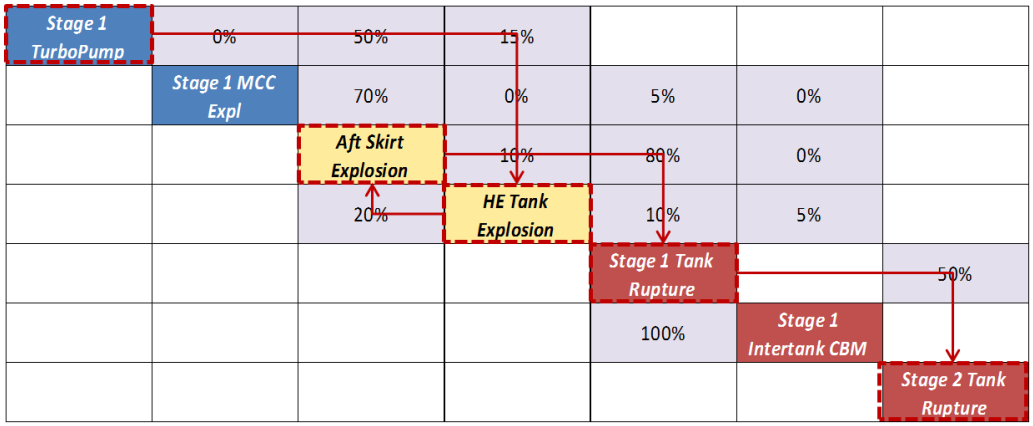
The transition probability in a given off-diagonal cell represents the probability that the environment lying horizontally at the diagonal (source environment) will generate the environment lying vertically at the diagonal (target environment). For example, the 15% transition probability in the 4th column of the 1st row indicates a 15% probability that the turbopump burst will cause a rupture of the high-pressure helium tank. Likewise, the 20% probability in the 3rd column of the 4th row indicates a 20% probability that a helium tank explosion will cause explosion of the aft skirt. Typically,engineering judgment is applied initially to rule out many of the potential transitions (blank cells). In other cases, the transitions are not initially ruled out, but may ultimately be set to zero because analysis shows the transition is either not ever credible or is not possible under certain conditions. For example, in early mission phases for which the aft propellant tank is relatively full, the possibility for fragments from aft explosions to penetrate the intertank walls enabling a confined explosion is considered virtually zero.

2.2 Propagation Simulation

The data in the propagation matrix is used to flesh out a particular propagation scenario by starting at a user-specified initial condition (one of the blue boxes) and "rolling the dice" against each of the transition probabilities in the associated row of the propagation matrix. Here, rolling the dice consists of generating a random number in Matlab [3] and evaluating it against the transition probability to determine whether a "hit" is observed. Given a hit, the same process is applied to the target environment, i.e., the target becomes the source for the next step. An environment is not allowed to recur along a given propagation path.

Figure 3 shows an illustration of one such path that might be generated in response to the inputs of Figure 2, starting with stage 1 turbopump burst. In this case, the turbopump burst releases shrapnel that impacts and ruptures the high-pressure helium tanks. Overpressure and/or shrapnel from the helium tank rupture then causes leakage of propellant, from either the fuel tank or feed-line or both, into the aft skirt volume. This flammable mass is assumed to be ignited, causing an explosion that ruptures the aft propellant tank, which is then driven into the upper stage causing rupture of the upper stage tanks.

Figure 3. Sample failure propagation path.



This propagation scenario is somewhat unique in the sense that it is a single path. In fact, the nature of the propagation matrix shown allows for much more complexity because multiple hits could be observed from a given source environment. For example, shrapnel from the turbopump may create leakage as well as impact the helium tank. Each of those triggered target environments would then be used as source environments for subsequent propagation, and so on, with the final result being a potentially complex tree structure of environments. In the present model, each of the non-zero transition probabilities in the row associated with a given environment is queried independently. If no transitions are triggered, then the process ends for that path. The algorithm makes use of tree data structures and is coded in Matlab.

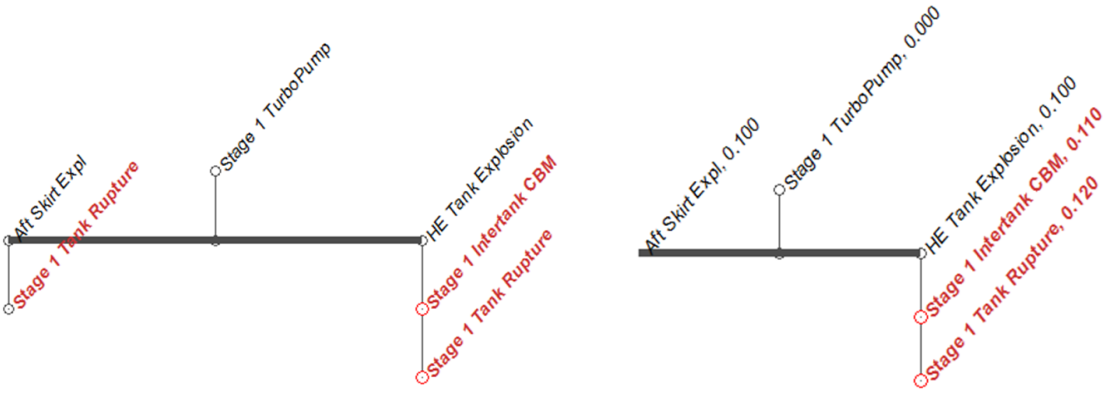
This approach is not dynamic in the sense that transition probabilities at a given point in the process might be influenced by preceding events. The present implementation assumes transition probabilities from a given state are independent of how that state was reached. This is a recognized limitation and is being studied to determine whether it can be removed or whether a substantially different approach is required.

2.3 Event Trees and Pruning

An example of an event tree that might be produced with this model is shown in Figure 4a. The simplicity of the example propagation matrix leads to relatively simple trees. However, one still observes branching in this case. In these plots, element-level environments are highlighted in red. One can also observe that, while no environments are repeated along either branch, stage 1 tank rupture occurs on both branches. In a sense, the branches are incompatible with each other. Furthermore, if the tank is ruptured by the aft skirt explosion, one might question whether the confined explosion (CBM) in the intertank region is possible.

In order to address these issues, a pruning process is applied to these raw event trees. The pruning depends on the introduction of some timing information, which may be physical time associated with the transition process if available, but in the simplest case may be a fixed time increment analogous to a computer clock cycle. All that is needed is to be able to identify which event happened first. The present model allows the user to specify an uncertain range of transition times, which are sampled and accumulated during the development of the raw trees. Then, all the events in a given propagation are sorted in chronological order of their occurrence, and repeat environments are removed along with any subsequent events on that "branch" of the tree.

Figure 4. Propagation event trees.



a) Unpruned tree b) After pruning

The model also allows the user to specify groups of environments for which, if the first environment in the group has been triggered, all other subsequent environments in the group are thought to be impossible and are removed from the tree. In the present case, an example of an "exclusion group" would be {stage 1 tank rupture, stage 1 intertank CBM}. That is, rupture of the tanks precludes subsequent confined explosions. The reverse is not true, however; occurrence of a confined explosion does not prevent a subsequent unconfined explosion. In fact, it is highly likely that non-confined explosion(s) will follow a confined explosion. Thus, the exclusion is based only on the first environment in the group.

Figure 4b shows the effect of applying such a pruning process to the tree shown in Figure 4a. For clarity, two fixed time intervals are used in this case: 0.01 seconds and 0.1 seconds. The resulting tree indicates that, in this case, the intertank CBM occurs earlier than the tank rupture caused by the aft skirt explosion, and so the latter has been removed.

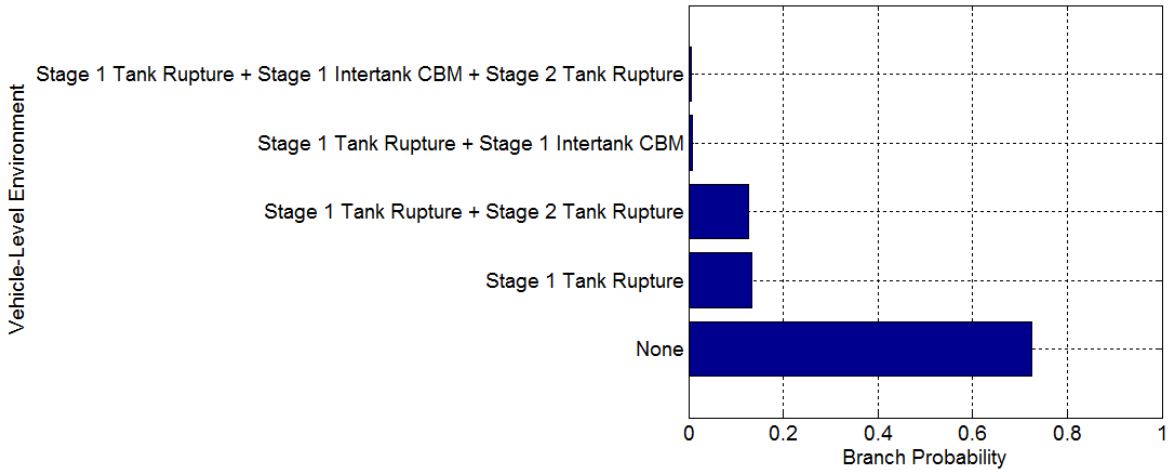
2.4 End States and Monte Carlo

The final step in analyzing a single instance of the propagation is to identify and log the final state. This simply involves collecting all of the element-level environments that have been triggered, e.g., the red environments in Figure 4. Since each of the N possible ELEs can be triggered or not, there are 2^N possible outcomes. These combinations of ELEs have been termed vehicle-level environments (VLEs). Note, one of the VLEs is the null environment, which is the case where none of the ELEs are generated.

The probabilities in the propagation matrix are effectively integrated using a Monte Carlo approach with the outcome of each instance categorized in terms of the particular combination (of the 2^N possible) of ELEs observed. The end result of the Monte Carlo process is a distribution among the possible VLEs, such as the example shown in
Figure 5. Note that only 3 of the 8 possible VLEs have been encountered, with the null environment the most likely in the current example.

This mapping information can be used directly within an integrated safety model such as that described in [4]. In this model, the VLEs are characterized using tables in which the conditional loss-of-crew probability is expressed in terms of functions of mission time and warning time. The integrated model then uses the mapping to determine which of these tables will be queried, and relative frequency with which they will be queried, given the occurrence of the initial failure type.

Figure 5. Example of Monte Carlo result for mapping Stage 1 turbopump failure.



3 COMBINING PROPAGATION AND ENVIRONMENT CHARACTERIZATION: ABORTABILITY AND LOSS-OF-CREW

The mapping information resulting from the Monte Carlo simulations provides the probabilities of different classes of outcomes given the initial failure manifestation. What is ultimately needed is the probability of the crew surviving the environments generated as a result of the initial failure manifestation. To obtain these probabilities, the mapping information of the type shown above must be coupled with the failure environment information. Blast overpressure and debris environment characterization are discussed in [1] and [2], respectively. These environments have historically been produced in terms of tables of conditional failure probability as functions of mission time and warning time.

The ERA team characterizes failure environment severity using tables containing probabilities of failure from overpressure or debris as functions of mission time and available warning time. These tables include effects of the environment initiation, environment propagation and decay, abort trajectories, and crew module vulnerability to overpressure and debris. The environments can be generated using different assumptions regarding the initiation (blast location, blast yield, debris catalogs, etc.) to represent effects from explosions of different parts of the vehicle. The individual tables for overpressure and debris may be convolved into tables for the element-level environments, for example, stage 1 CBM. Under the assumption that the ELEs involved in a given VLE are triggered simultaneously, tables for each possible VLE can then be generated using a similar convolution of the associated ELE tables.

As mentioned in the previous section, the coupling of the propagation mapping with the environment characterization can be performed within an integrated mission safety model (see [4], for example). Alternatively, it can be performed outside such a model by generating what have been termed abortability tables. In this approach, tables for loss-of-crew probability given the occurrence of the initial failure manifestation type (LOME) are generated by combining the set of VLE tables using a simple weighted average in which the weightings are the mapping probabilities generated through the propagation analysis, e.g., those shown in
Figure 5. The results are expressed in terms of abortability by simply subtracting the failure probabilities from unity.

In this model, abortability for a specific failure scenario and mission time is obtained, given its initial manifestation (LOME), by querying the appropriate table at the appropriate mission time with an estimated warning time. The present form of the propagation modeling does not address the important problem of warning time estimations, but could potentially be extended to do so. In the SLS program,

warning times are determined by the SLS Mission and Fault Management (M&FM) group based on knowledge of the available abort trigger sensor design information. See [5] for discussion of abort trigger assessment and selection.

4 IMPLEMENTATION ENHANCEMENTS

The approach used in the preceding sections is somewhat limited in the sense that maintaining the propagation matrices can quickly become unwieldy if one wants to account for variations of the transition probabilities with mission time or phase. This can be important if the transitions are effected through blast overpressure, for example, or another mechanism that depends upon ambient pressure. Further, these transition probabilities are often subject to large uncertainties, either because they are, at least initially, based on engineering judgment or because the process itself is inherently sensitive to small differences in the failure initiation. One may want to investigate and capture the effect of these uncertainties on the propagation. These issues have been addressed using a relatively compact input data format, maintained in an Excel spreadsheet, and a Matlab script that queries the Excel data and generates the propagation matrix on-the-fly.

A section of a sample input data table is shown in Figure 6. Each row represents one potentially non-zero element of the propagation matrix. In the present implementation, a static, qualitative propagation matrix is maintained in which transition probabilities in the off-diagonals are replaced by pointers to the appropriate row of the data table (the ID column in Figure 6 gives the cell index of the associated propagation matrix cell). The table allows the transition probabilities to be varied with mission phase, with each column representing a different phase. Within each cell, a range of values may be captured, separated by slashes, with different values capturing different parts of an uncertain distribution. Typically, the left-most value is considered a lower bound, the right-most is the upper bound, and the middle value is a "baseline" value. Higher values tend to allow the propagation to more easily reach the explosion outcomes so the left-most values are typically referred to as the pessimistic or worst-case set and the right-most values are then the optimistic or best-case set. Colors can be used to represent the level of confidence in the quantitative transition probabilities provided.

This format also allows for convenient documentation (not shown) for specific information regarding the source of the data and any other pertinent information. Also, with this data format, it is relatively easy to implement additional features that may require additional supporting data (e.g., the timing information, shown in the far right column as minimum/maximum ranges).

Figure 6. Sample input data for the propagation analysis.

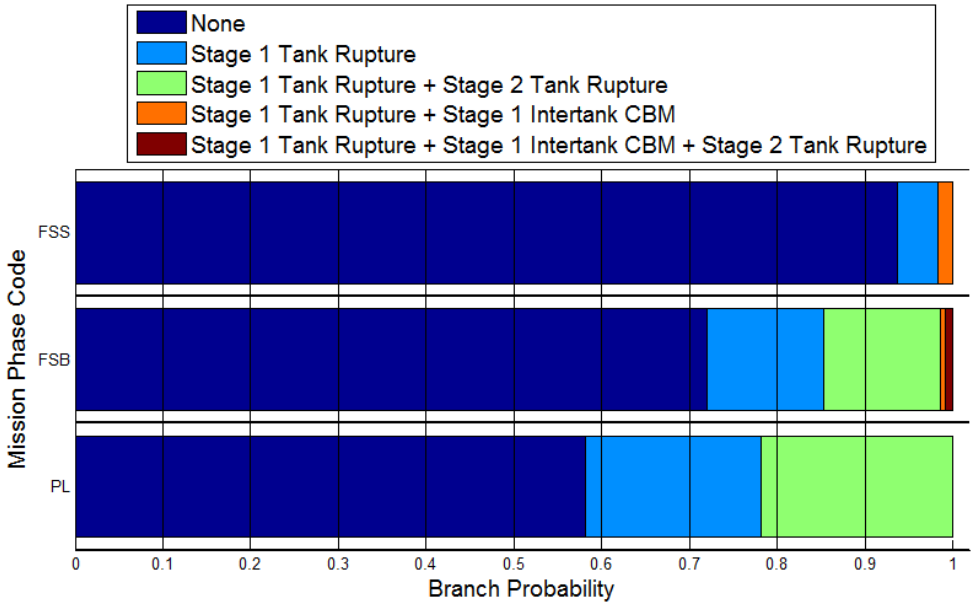
	Pre-Launch w/ LAS	*First Stage Burn*	*Staging*	*Upper Stage Burn, w/ LAS*	*Upper Stage Burn, no LAS*	*Spacecraft Staging*			
ID	*PL*	*FSB*	*FSS*	*USL*	*USN*	*USS*	*Source*	*Target*	*Timing*
E6	0/ 0/ 0	0/ 0/ 0	0/ 0/ 0	0//	0//	0//	Stage 1 TurboPump	Stage 1 MCC Expl	0.01/0.01
F6	90/50/15	90/50/15	90/50/15	0//	0//	0//	Stage 1 TurboPump	Aft Skirt Expl	0.1/0.1
G6	25/15/5	25/15/5	25/15/5	0//	0//	0//	Stage 1 TurboPump	HE Tank Explosion	0.1/0.1
F7	100/70/20	100/70/20	100/70/20	0//	0//	0//	Stage 1 MCC Expl	Aft Skirt Expl	0.1/0.1
G7	5/0/0	5/0/0	5/0/0	0//	0//	0//	Stage 1 MCC Expl	HE Tank Explosion	0.01/0.01
H7	100/15/0	15/5/0	0//	0//	0//	0//	Stage 1 MCC Expl	Stage 1 Tank Rupture	0.01/0.01
I7	0//	0//	0//	0//	0//	0//	Stage 1 MCC Expl	Stage 1 Intertank CBM	0.1/0.1

Figure 7 shows an example of the effect of the launch phase-dependent transition probabilities on the VLE mappings. The launch phases are abbreviated as follows: PL is pre-launch, FSB is first stage boost, and FSS is first stage staging. In this case, the probability of an aft skirt explosion to cause

rupture of the 1st stage propellant tank diminishes with altitude resulting in the trend toward fewer tank ruptures in later mission phases.

The most recent analysis of the SLS vehicle involves 24 environments, including 13 initiating environments and 10 ELEs. The analysis is further complicated by the need to divide the ascent trajectory into 15 separate mission phases. The present data format and pre-processing scripts allow relatively straightforward implementation of this complexity as well as a way to track progress in the maturation of the transition probability data.

Figure 7. Phase-dependent mapping results: Stage 1 turbopump failure.



5 TRANSITION PROBABILITY SPECIFICATION

One feature of the current propagation model is that a simple representation can be created and applied relatively quickly. As the vehicle design matures and/or more detailed questions are asked, additional elements/environments can be introduced. The transition data upon which the analysis is based can also mature, starting with a set of transition probabilities that may be largely based on engineering judgment and evolving into a set that is supported predominantly by analysis and, possibly, test data. Even analysis-based transition probabilities will have uncertainties associated with them, but in general, the transition from judgment-based probabilities to analysis-based probabilities would be accompanied by a reduction in the data spread.

The current thought process for specifying the transition probabilities begins, for a given source and target environment, with an effort to identify the mode by which the source effects the failure of the target. Five general classifications have been identified for these modes:

1) energy transfer from the source, either by blast overpressure, kinetic energy (fragments), or heat transfer,
2) structural shock or vibration from failure of the source causes the failure of the target,
3) an environment created by a source failure, such as a flammable mass or pressure environment, cannot be withstood by the target,
4) the ability of the target to contain its energy may depend on the source functionality, e.g., loss of fuel to the engine combustion chamber caused by turbopump failure leads to combustion chamber failure, and
5) direct transfer.

Direct transfer captures cases in which the LOM environment presents a direct threat to the crew. For algorithmic convenience, these situations have been treated with a separate LOME and ELE within the propagation matrix, but with a direct transition between them (100% always). Solid rocket booster burst is an example of such a case.

Relatively simple analyses may be sufficient to provide significant insight into reasonable settings for transition probabilities. Figure 8 shows an example of a simple geometric assessment of the likelihood of debris from a given turbopump burst impacting a high-pressure pneumatic support tank. Here, the debris pattern is expected to disperse within a limited azimuthal range perpendicular to the rotation axis of the pump. The figure indicates a fragment probability distribution with respect to this angle, and the target tank lies within one tail of the distribution. A rough estimate of the debris strike probability would be given by:

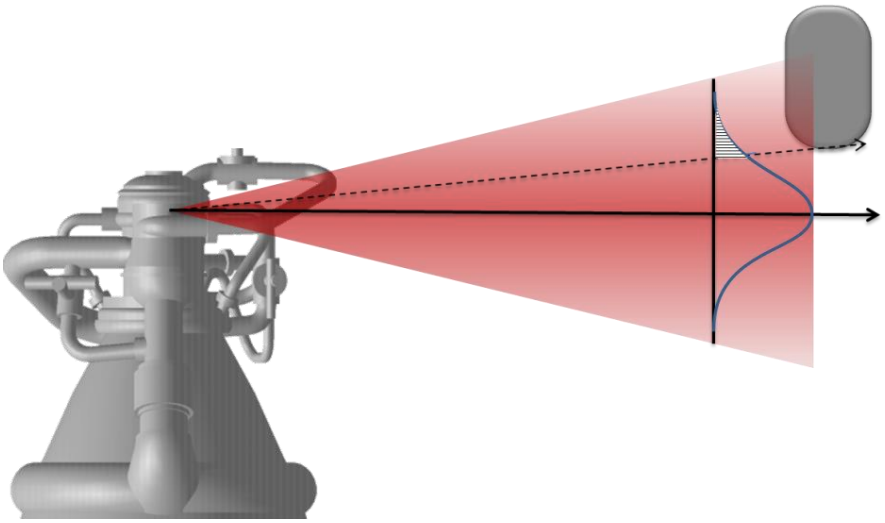
$$P_{strike} = 1 - e^{-\lambda N}$$

where N is the number of fragments released and λ is given by

$$\lambda = FR / \pi d$$

Here, F represents the shaded area under the curve in Figure 8, R is the radius of the target tank, and d is the distance from the source to the target. This accounts for the distributed dispersion shown in Figure 8 as well as uniform dispersion in the circumferential direction.

Figure 8. Example of simple geometric strike probability analysis.



The failure probability given a strike would depend on the likely velocities of the debris, e.g., the spin velocity of the pump (likely conservative), as well as the vulnerability of the target tank, e.g., the ballistic limit velocity based on the material of the tank and some estimate of the fragment sizes. The transition probability from turbopump burst to high-pressure tank burst would then be set to the strike probability if the debris velocity exceeds the limit velocity for puncture, or would be set to zero otherwise.

The threat posed by the main combustion chamber could be similarly analyzed, except that the angular distribution and initial velocities of the debris would be different (see [6] for a discussion of modeling pressure vessel burst velocities). This simple example illustrates how analysis methods do not necessarily eliminate uncertainty—many unanswered questions remain regarding the number of fragments released, the initial velocity after escape from the pump walls, the true vulnerability of the

tanks to debris, etc. However, the nature of the uncertainty is such that engineering judgment can perhaps be more reliable. Further, these questions are more amenable to engineering analysis and testing than is the question of the probability of stage explosion given an engine failure.

6 CONCLUSIONS AND FUTURE WORK

A relatively simple method to address the complex problem of failure propagation following launch vehicle failure has been presented. The method is extensible in the sense that one can generate a simple model for a given scenario and evolve it to account for additional factors as the vehicle design, or the need to understand the behavior, matures. Presently, the model is used only to capture the propagation of one energy-containing component to another in the cascade of events that might connect a local vehicle failure manifestation to crew-threatening explosion. The analysis has to date, therefore, been limited to determining the probability of explosion given various classes of vehicle failures.

Extension of the model to include realistic transition timing information as well as detection elements that might be activated in response to triggering certain environments, is currently under consideration. In this way, the model could potentially be applied to the problem of estimating abort warning time.

Ultimately, the approach envisioned is a system in which the components identified as potential contributors to the propagation process are defined in terms of engineering parameters such as contained pressure and temperature, wall thickness and material, etc. These engineering parameters would then be used to determine both potential threat of the components as sources (e.g., burst overpressure, fragment environments) as well as their vulnerabilities as targets. The off-diagonal terms in the propagation matrix would capture the relationships between the diagonal components: the distances, view factors, obstructions, etc. Given that these component and relationship properties are defined, transition probabilities could be generated automatically. This is in work by the present authors.

A separate effort is underway to apply the Monte Carlo process directly to uncertain elements in the component properties: the number of thrown fragments, the burst yield, component vulnerabilities, etc. Relationships in this model would be evaluated automatically through the direct use of CAD design data. This approach, while more complex to implement, would potentially provide a fully coupled simulation and would therefore relieve any limitations introduced by decoupling.

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