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Probabilistic Survivability versus Time Modeling

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Sabrina Dalo

Chris Nagy

Andrew Stampfel

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Two of these individuals developed products that laid the cornerstone for all three assessments. Mr. Chris Nagy's unique vision developed the methodology and figure of merit used to model the Survivability versus Time. Dr. Tim Adams spent countless hours on the mathematics and documenting the @RISK spreadsheets necessary to produce the graphical results. His efforts were pivotal in withstanding numerous internal and external peer reviews.

This report is available in electronic form at

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Probabilistic Survivability versus Time Modeling

The KSC Independent Assessment (IA) Team conducts assessments as requested by a Customer, providing the Customer with objective, non-advocacy recommendations and solutions. IA Team customers include the Office of Safety and Mission Assurance (OSMA), the KSC Center Director, Program Managers, Chief Safety and Mission Assurance Officers, and other first line Directors at KSC. Assessments performed by the team cover a variety of subjects ranging from systemic process evaluations and technical assessments to process improvement. Assessments exclude any criminal investigation.

This article summarizes three KSC assessments in which Survivability versus Time Models were developed as a decision-evaluation tool. The first assessment developed a mathematical model of Survivability versus Time for an emergency egress system at Launch Complex 39B (LC-39B). The second assessment used the first model to evaluate and compare various emergency egress systems under consideration at LC-39B. The third assessment used a modified LC-39B model to determine if a specific hazard(s) decreased survivability more rapidly than other events in the Vehicle Assembly Building (VAB). Probability distributions were developed for hazard scenarios to address statistical uncertainty, resulting in survivability plots over time. Composite survivability plots encompassing multiple hazard scenarios were also developed. These assessments produced a set of plots that acted as a decision-informing tool for the Ground Systems Development and Operations (GSDO) Chief Safety and Mission Assurance Officer (CSO) and GSDO Program Manager during key programmatic reviews.

In 2012, the GSDO CSO requested that KSC IA perform an assessment of the LC-39B Emergency Egress Systems. If an emergency situation (e.g., fire, imminent explosion) developed with the Orion Crew Module or Space Launch System (SLS) vehicle at LC 39B during launch countdown, an Emergency Egress System (EES) would quickly transport four astronauts to safety. The intent of this first assessment (KSC IA 1207, “Crew Emergency Egress Survivability”) was to determine if survivability as a function of time to reach a safe location could be used to develop a Figure of Merit (see Figure 1) to enlighten EES design trade studies. By-products included a list of scenarios leading to emergency crew egress and initial estimates of the likely crew survivability.

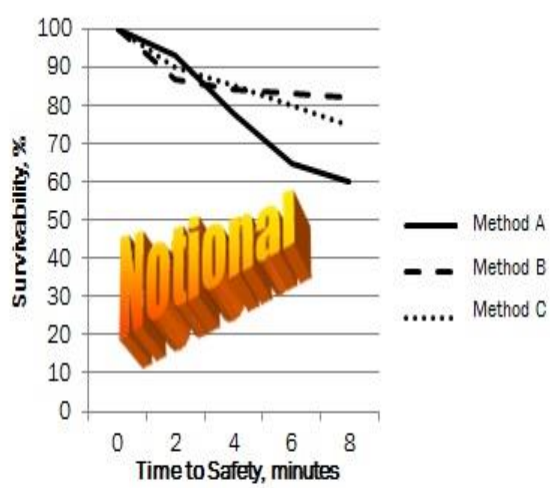

Figure 1 A Figure of Merit

To accomplish this task, the IA Team started by defining terms, groundrules, and assumptions early in the process. Death was defined as 0% survival if any of the crew members died before reaching a safe location. The IA Team made no assumption as to the nature of the Ideal EES (e.g., rail, slidewire, elevator) or a destination of a safe location (an area where the crew are free from the effects of a hazard). The evaluation started once all four crew members were on the Crew Access Arm, noting survivability at specific time intervals until a safe location was reached.

The Fault Tree Analysis (FTA) Method was used to determine which Hazard Scenarios would require an emergency egress. The FTA Method resulted in the simplified Fault Tree (soon in in Figure 2 below) which enabled the IA Team to examine all paths to establish credible scenarios.

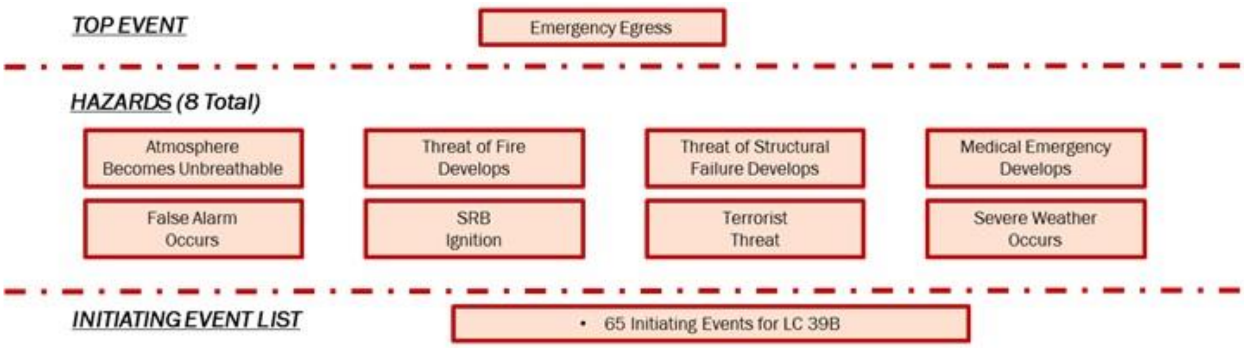

Figure 2 Simplified FTA

For each credible initiating event, the Likelihood of Occurrence and the Probability of Survival (given the initiating event occurred) were determined. The "Most Likely" value for the Likelihood of Occurrence was determined through data analysis and review of historical information or, in the absence of numerical data, via expert elicitation. Uncertainties in the Most Likely value were bound by Maximum and Minimum limits determined using the Error Factor method described in the NASA PRA Guidebook[1].

The "Most Likely" survivability value was bound by Minimum ("Bad Day" or everything working against crew surviving the hazard) and Maximum ("Good Day" or optimal conditions/not severe as expected) limits. These Maximum, Most Likely, and Minimum values establish the survivability distribution. All three survivability values were determined via team consensus, interviews, or consequence rating from hazard reports, or by a combination of these methods.

To calculate the probability of survival for all credible initiating events:

$\mathbf{P_E}$ = likelihood of event occurring. [input in Failure Space]

$\mathbf{P_{S|E}}$ = probability of surviving if event occurs. [input in Success Space]

Since a Failure Space Distribution should not be multiplied by a Success Space Distribution, $\mathbf{P_{S|E}}$ needs to be converted into Failure Space, so **$\mathbf{P_{D|E}}$ = probability of dying, calculated by:**

$$\mathbf{P_{D|E} = 1 - P_{S|E}}$$

$\mathbf{P_D}$ = probability of dying due to this event, which is calculated by:

[1] Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners, NASA/SP-2011-3421, December 2011

$$\mathbf{P_D = P_E * P_{D|E} = P_E * (1 - P_{S|E})}$$

Converting back into Success Space (Survivability):

$\mathbf{P_S}$ = probability of surviving due to this event, which is calculated by:

$$\mathbf{P_S = 1 - P_D = (1 - (P_E * (1 - P_{S|E}))} \text{ [output]}$$

$\mathbf{P_{S\ all}}$ = probability of surviving the occurrence of all Initiating Events (assumes events are independent), which is calculated by:

$$\mathbf{P_{Sall} = \Pi\ (P_{Si}) = P_{S1} * P_{S2} * \ldots * P_{S65}} \text{ [output]}$$

The @RISK software was used calculate the survivability distributions. The Latin Hypercube sampling method was chosen to run probabilistic simulations at 50,000 iterations in order to calculate the output for each time interval. The first assessment produced an Ideal EES model with Most Likely value bounded by a Maximum and Minimum limit. Based on the composite survivability, there is a soft “knee” in the curves at eight minutes (ten minutes after the egress order was given). As a secondary effort, the team also developed survivability estimates assuming the existing launch pad elevator would be used after significant hardening changes. Use of the upgraded launch pad elevator as the EES decreases survivability somewhat compared to the Ideal EES since it involves taking the flight crew past the hazard for some scenarios.

The second LC-39B assessment (KSC IA 1304, “Crew Emergency Egress Comparison”) evaluated each emergency egress system under consideration (e.g., rail, slidewire, elevator) based on the astronauts’ survivability as a function of time to reach a safe location (a bunker inside the blast danger area or outside the blast danger area). The GSDO Program provided the IA Team with a study that outlined each EES route, time, distance, and safe location. For each EES design option, the IA Team considered 65 initiating events, rescored the survivable for each credible initiating event at each time interval to account for the characteristics of that EES transporting the astronauts to the safe location, and then calculated a $\mathbf{P_{Sall}}$ for that EES. .

The @RISK software calculated $\mathbf{P_{Sall}}$ for each EES and produced the curves shown in the figure of merit. Notional composite graphs of the Most Likely values for the seven egress methods assessed are shown in Figure 3 below:

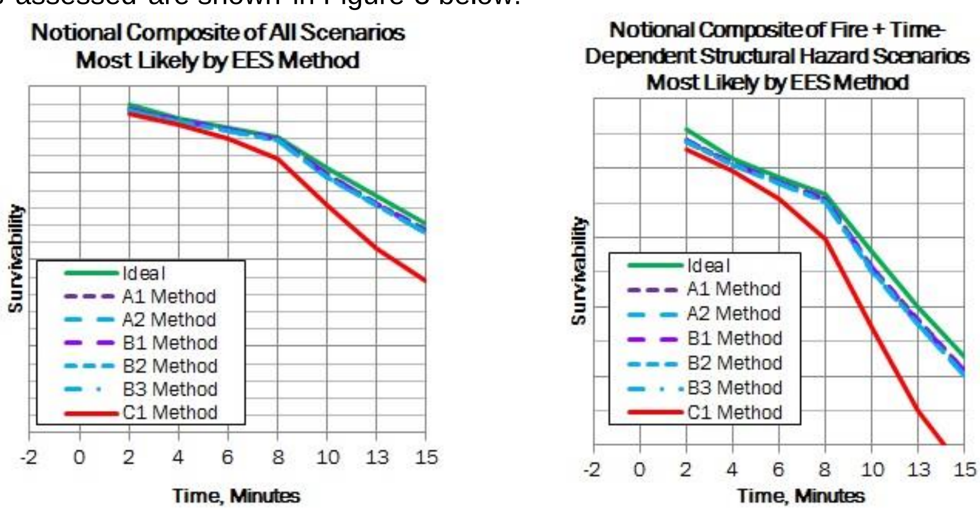

Figure 3 Notional Composite Graphs of Most Likely Values

Results from both assessments were briefed to the stake holders, GSDO CSO and the GSDO Program Manager. The GSDO Program held various check point reviews leading up to an EES design concept down-select at the GSDO Program Control Board. Method B was selected as the EES design for the LC-39B.

The third KSC assessment in which a Survivability versus Time Model was developed started in 2013 (KSC IA 1308, “VAB Emergency Egress Survivability Assessment”). As before, the GSDO CSO requested an assessment of the VAB egress routes using the same methodology developed for the LC 39B Assessment. For the VAB Assessment, the IA Team was asked to determine if specific hazard scenarios encountered in processing the SLS and Orion flight hardware reflected a survivability that decreased more rapidly than the other event(s). The VAB assessment evaluated multiple workers (~14 to 90 people) egressing from multiple locations from VAB High Bay 3, compared to the LC 39B Assessments, which evaluated four astronauts moving as a unit using a single egress route. Assembly and testing in the VAB occurs over several months and was divided into seven different processing phases, each with different time durations, spanning from the start of solid rocket motor stacking operations to SLS/Orion rollout to the LC 39B. Each processing phase has a different number of workers in multiple work locations. Due to the size of High Bay 3 and the distribution of workers, the High Bay was divided into eight different work zones (see Figure 4). Egress paths to reach an exit varied by work zone between approximately 30 to 180 feet. The Customer requested the time to reach an exit from each work zone/processing phase be assessed at eight different time intervals.

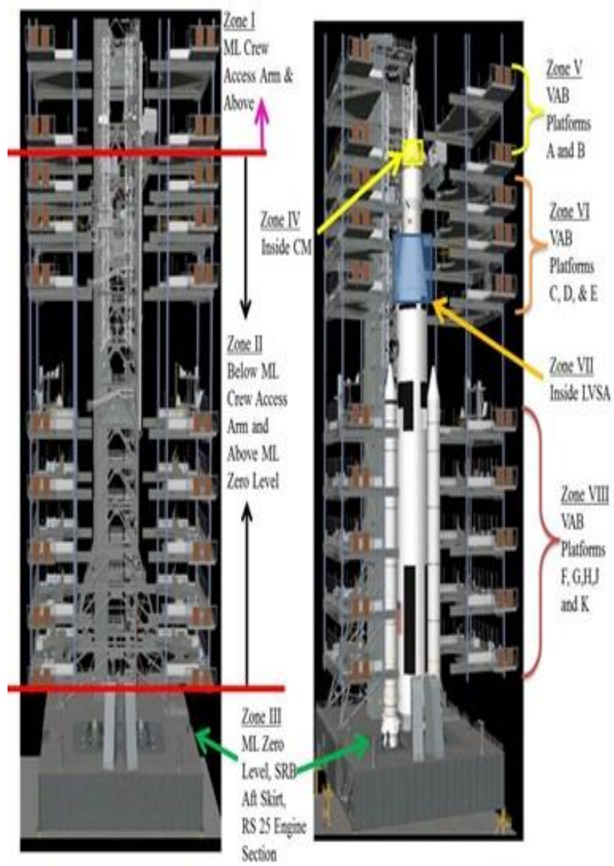

Figure 4 VAB Zones

To determine survivability for multiple personnel at various locations for a specific time, an Aggregate Survival Level was calculated as a weighted average based on manloading and the Survival Level assigned to each Zone.

- The Aggregate Survival Level formula for an individual Initiating Event during one Phase and at one time interval is:

$$\mathbf{P(S_{Aggregate|E})} = \sum_{i=1}^{8}\left[\left(\frac{Headcount_{zone\ i}}{Total\ Headcount}\right) * \mathrm{P}(S_{zone\ i}|\mathbf{E})\right]$$

- As outlined in the LC 39B assessment, then **Ps** for all Zones, one Phase, one time interval and Initiating Event is:

$$\mathbf{P_S = 1 - P_D = (1 - (P_E * (1 - P(S_{Aggregate|E}))}\ \text{[output]}$$

Thus, the VAB Emergency Egress Analysis formula for the probability of surviving all individual Initiating Events at the same time is calculated in success space by:

$$\mathbf{Ps_{All} = \Pi\ (P_{Si}) = P_{S1} * P_{S2} * \ldots * P_{S78}}\ \text{[output]}$$

Thus, a composite scenario was developed, denoted $\mathbf{Ps_{All}}$, which represents the probability of surviving all initiating events for all Phase, each time interval, and for all Zones. The @RISK software calculated $\mathbf{Ps_{All}}$ and produced curves for the Maximum, Most Likely, and Minimum. Figure 5 represents a notational composite survivability versus time graph for the VAB Assessment.

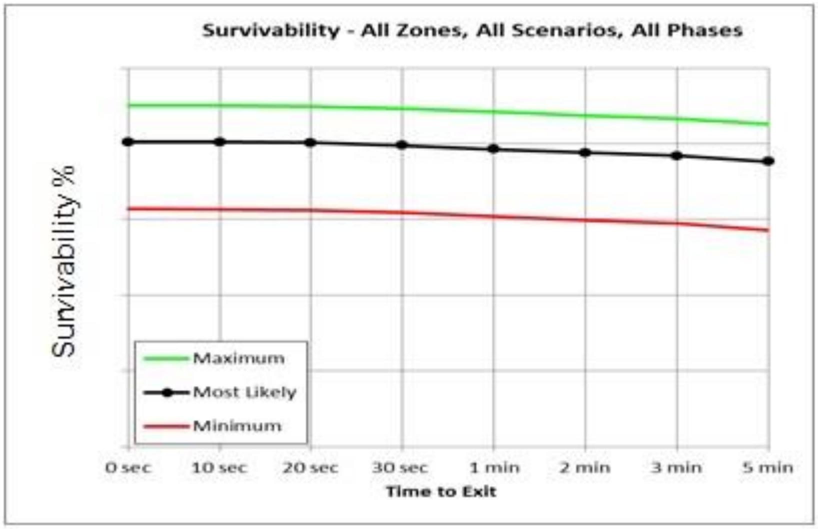

Figure 5 Notional Composite Survivability versus Time Graph

The results of these three independent assessments provided a series of graphs that formed the basis of a decision-informing tool for the GSDO CSO and Program Manager. These plots took into account the workforce population over a specific time period and a spectrum of potential hazard events weighted by the likelihood of occurrence for each event.