SURVIVABILITY VERSUS TIME

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AGENDA

Overview of the Kennedy Space Center (KSC) Independent Assessment Office

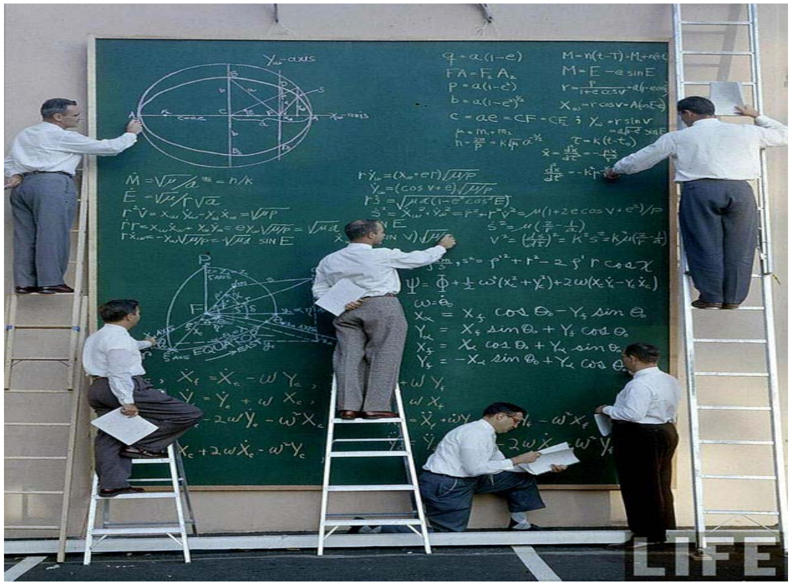
Launch Complex 39B (LC 39B) Overview of Assessment

- Methodology
  - Hazard Scenario Development
  - Likelihood of Initiating Event
  - Error Factor and Uncertainty Distribution
  - Survivability Estimate
  - Survivability Estimate Uncertainty
- Calculations
- Results

Vehicle Assembly Building (VAB) Overview of Assessment

- Methodology
- Calculations
- Results

Summary



Calculations before Palisade @RISK

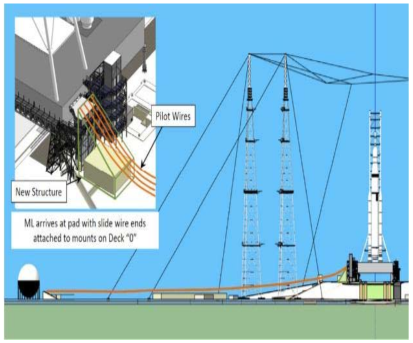
KSC INDEPENDENT ASSESSMENT OFFICE
WHO ARE WE? WHAT DO WE DO?

KSC Independent Assessment (IA) Office

- Perform assessments for Customers.
  - An assessment is an evaluation of a problem or situation based on good practice, reasonableness, and/or situational requirements.
- Provide the Customer with objective non-advocacy recommendations and solutions.

Assessments triggered by multiple Customers

- Office of Safety & Mission Assurance (SMA) Associate Administrator
- KSC SMA Director
- Program/Project Managers/Chief Safety Officers
- KSC Directors



Wide variety of subjects

- Systemic processes (e.g. Mission Assurance)
- Facilities (e.g. Personnel Safety)
- Technical (e.g. LC 39B Emergency Egress Assessment)

Assessments exclude criminal involvement

ASSESSMENT OVERVIEW

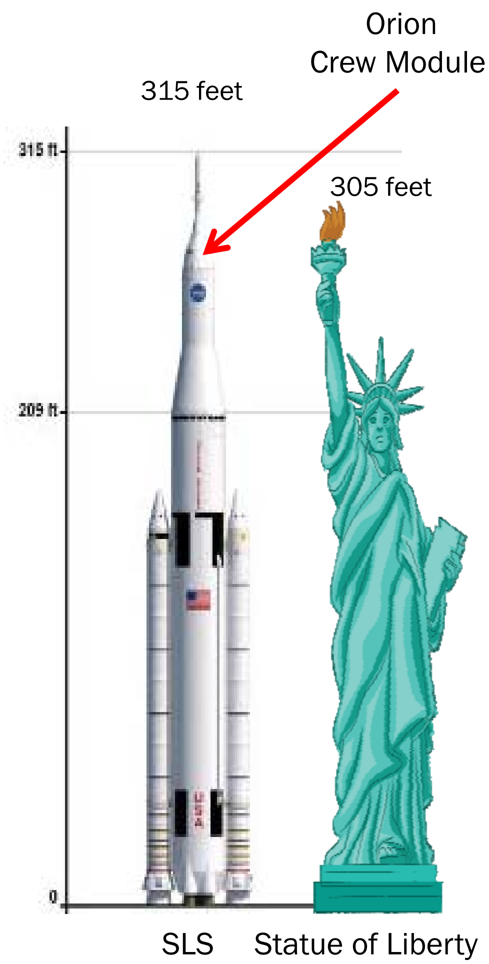
LC 39B EMERGENCY EGRESS ASSESSMENT

OVERVIEW OF LC 39B ASSESSMENTS

LC 39B Assessment

In 2012, a Customer requested the KSC IA Office perform assessments of the Launch Complex (LC) 39B Emergency Egress Methods.

- Modernizing KSC's spaceport with capabilities to launch the Orion Crew Module and Space Launch System (SLS)
    - Orion Crew Module will taking humans to multiple deep space destinations extending beyond our Moon, to Mars, and across our solar system.
    - SLS will carry the Orion Crew Module, as well as cargo, equipment and scientific payloads into deep space.
- The SLS will be launched from LC 39B and SLS will be comprised of approximately:
    - 2,772,100 pounds of solid propellant
    - 527,400 gallons of Liquid Hydrogen
    - 197,000 gallons of Liquid Oxygen
    - 9,700 gallons of Monomethylhydrazine
    - 300 gallons of Nitrogen Tetroxide



OVERVIEW OF LC 39B ASSESSMENTS (CONT.)

If an emergency situation (fire, imminent explosion, etc.) developed with Orion or SLS during launch countdown,

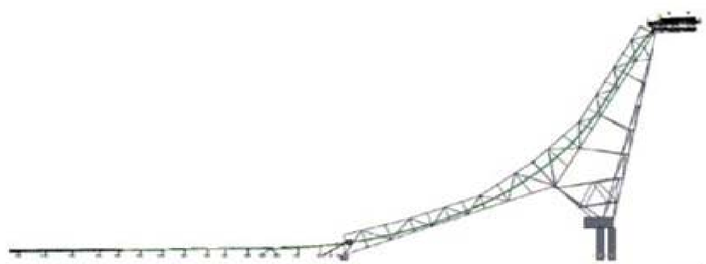
- LC 39B Emergency Egress System quickly transports four astronauts inside the Orion Crew Module to safety located:
  - Apollo era heritage bunker ~ 1,200 feet west of LC 39B, or
  - Any location outside the blast danger area radius ~ 6,000 feet.

Several emergency egress systems were under consideration (rail, slidewire, elevator, etc.)

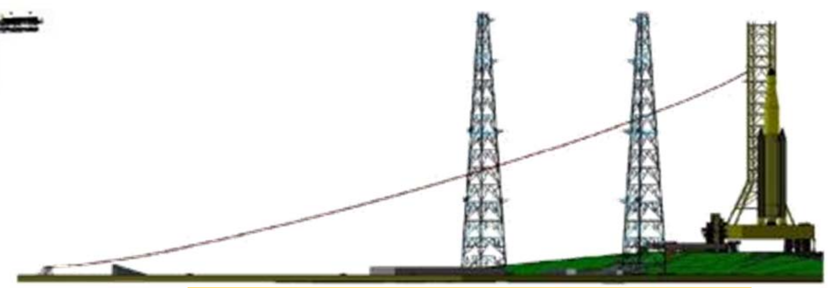
- How can each system be compared other than cost?

Assessment to evaluate astronaut survivability as a function of time.

- Assumed four astronauts moving together using a single egress method.



Rail System Egress Method



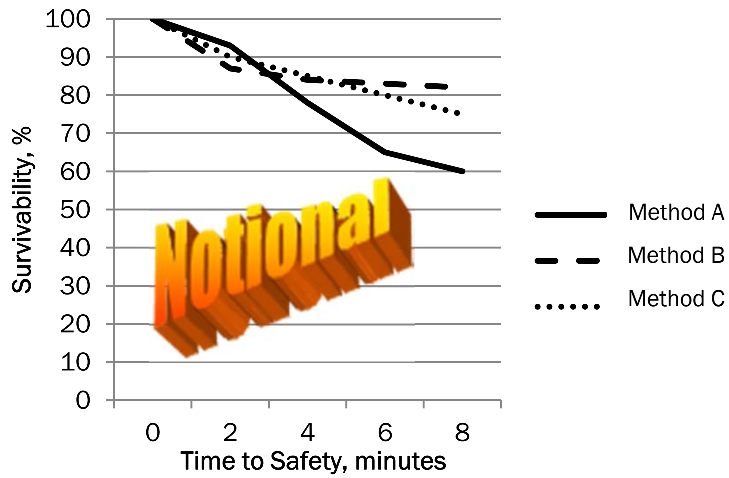
Slidewire System Egress Method

OVERVIEW OF LC 39B ASSESSMENTS (CONT.)

LC 39B Assessment

IA Team generated figures of merit for survivability versus time to reach safety to determine if:

- Do one or more of the egress methods produced a "knee" on the curve at some point in time?
  - A "knee" is a point on the curve which survivability decreased more rapidly than the others methods.
- Figures of merit could be used as criteria to make a final selection on which egress method would be built.



A Figure of Merit

METHODOLOGY

GROUND RULES AND ASSUMPTIONS - DEFINE

METHODOLOGY
Hazard Scenario Development

Key terms. For example:

- Is survival no death, or is survival no death or injuries?
  - Death defined as 0% survival
- What is the timeframe when the event starts and stops?
  - Two minutes for astronauts to unbuckle and egress out of the Orion Crew Module.
  - Time intervals to reach a safe location were estimated at 0 min, 2 min, 4 min, 6 min, 8 min, 10 min, 13 min, and 15 min.

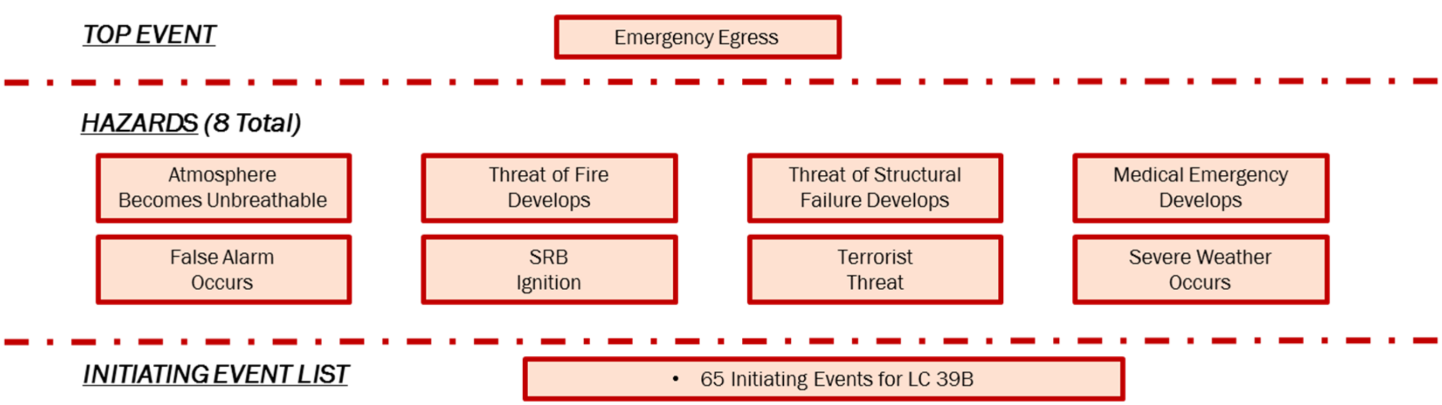
Credible or non-credible event? For example:

- Likelihood of dying from a single object colliding with Earth is 1.6 x 10^{-9}/year. Given that, should the assessment included survivability from an asteroid strike?

WHEN DO YOU NEED TO USE THE SYSTEM?

The Fault Tree Analysis (FTA) Method was used to determine which Hazard Scenario would require an emergency egress. FTA Method resulted in the simplified Fault Tree below which enabled the IA Team to examine all paths from the Initiating Event List to the Top Event to establish credible scenarios.

- Top Event: - is the undesirable event
  - Example: Conduct an emergency egress
- Hazard Causes
  - Hazard – A threat, internal or external to a system, that has the potential to cause harm. The threat is usually a state or set of conditions, but in some circumstances, can be an event or activity
  - Examples: Fire, Unbreathable Atmosphere (Toxic or Smoke), Structural Failure (Explosion), or Other traumatic event (health, weather, terrorist treat, etc.)
- Initiating Events
  - Initiating Event – Some anomalous occurrence that would eventually lead to a hazard that would require an emergency evacuation
  - Examples: Spacecraft Propellant Leak, Launch Vehicle Electrical Fire Starts, Premature Stage Separation Occurs, Ordnance Activation

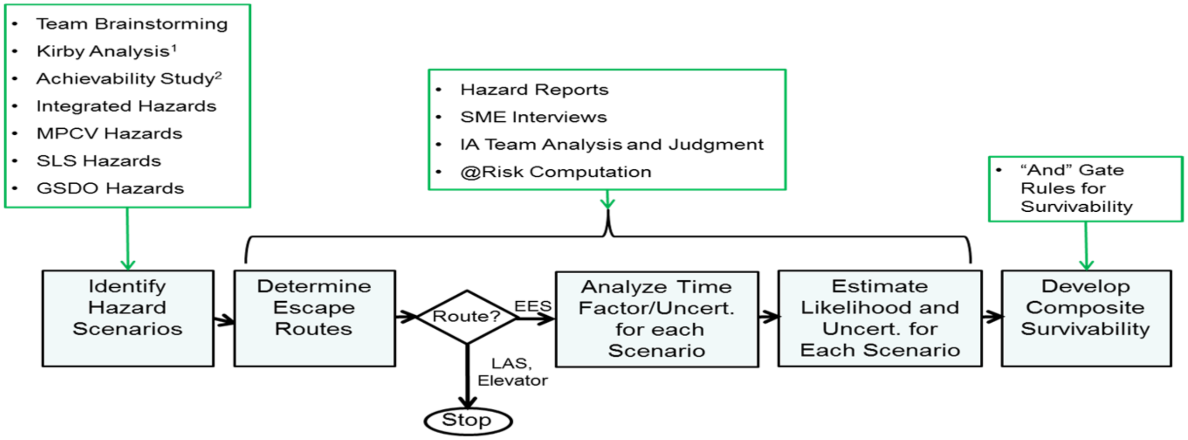


LIKELIHOOD OF OCCURRENCE OF AN INITIATING EVENT

METHODOLOGY

Determine the probability of an Initiating Event occurring:

- Conducted data analysis and reviewed historical documentation
  - Define the likelihood of something failing over time
  - Assigned a probability or likelihood of occurrence for each credible Initiating Event developed from the fault tree
- If no numerical data existed, the likelihood of occurrence was characterized by expert elicitation
  - Adjective rating such as medium or very low likelihood can be converted to a median numerical score
- Median value (50th percentile) is the Initiating Event likelihood of occurrence in Failure Space
  - Failure Space describes events or outcomes management does not want to occur.



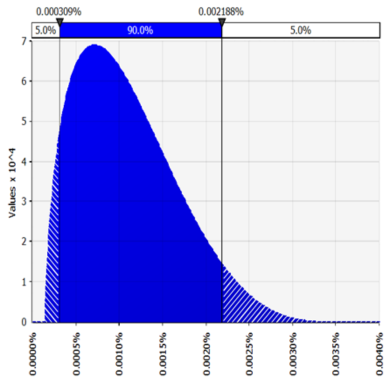
ERROR FACTOR AND UNCERTAINTY DISTRIBUTION DEVELOPMENT

Determine the interval of values or uncertainty distribution for the likelihood of occurrence of the Initiating Event

- Error Factor was used as a measure of dispersion around the median.
- IA Team's rule of thumb for selecting an Error Factor:
  - Error factor 0 - 5 : mature system
  - Error factor 5 – 15: little information available or first application
  - Error Factor > 15: large uncertainties or no information or data

Error Factor established Upper and Lower bounds for the uncertainty distribution

- Lower Bound = Median Value/Error Factor
- Upper Bound = Median Value* Error Factor
- Combined the Upper and Lower Bounds with the median value in @RISK with a PERT Distribution.
  - Error factors are to be used with the lognormal distribution to describe the 5th and 95th percentiles.
  - With the PERT distribution, these lower and upper values generated by the error factor method provide end points and not percentiles.



Sample Likelihood and PERT Distribution Input

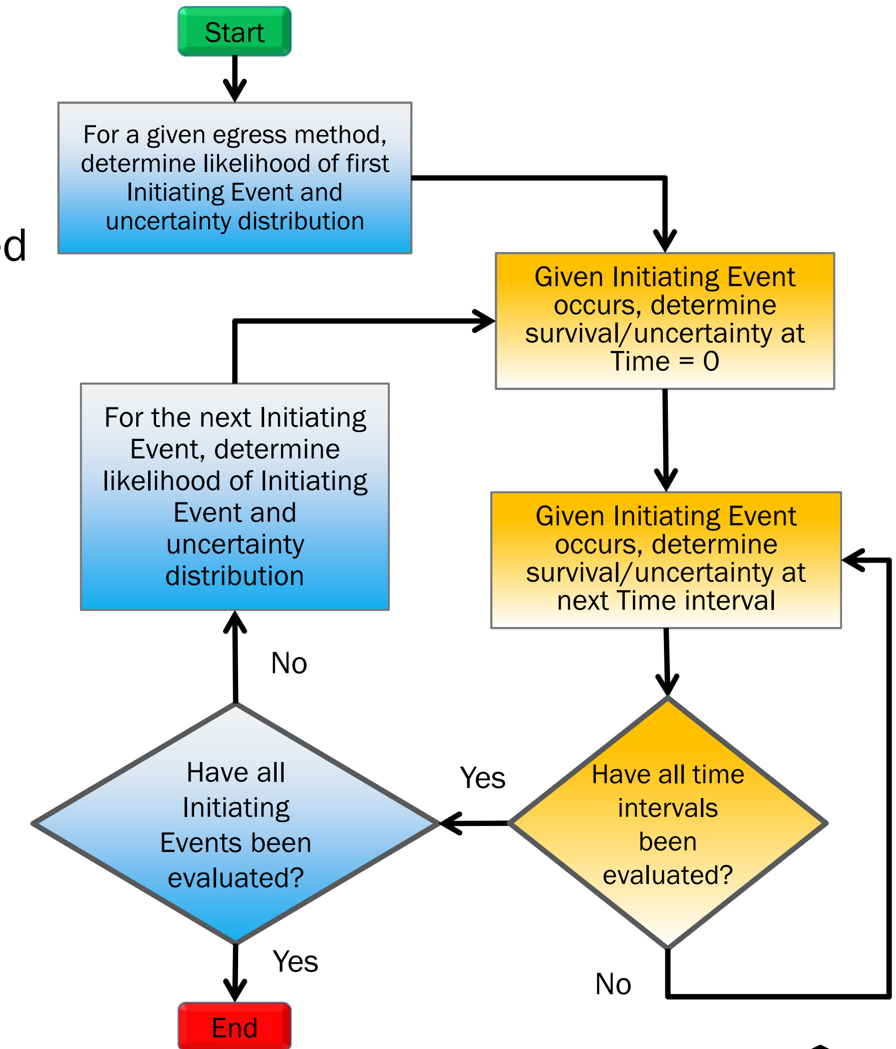
SURVIVABILITY ESTIMATE

Groundrules

- Assumed the initiating event occurs (set the likelihood to 1)
- Determine astronaut survival at each time interval assuming they all reached a safe haven (a location were they are no longer exposed to the hazard).
- The longer the astronauts were exposed to a hazard, the lower their survival was scored.

Basis of Estimate for Survival to determine the survival score

- IA Team consensus
- Interviews
- Consequence rating from hazard reports
- Combination of all these methods



SURVIVABILITY UNCERTAINTY DISTRIBUTION

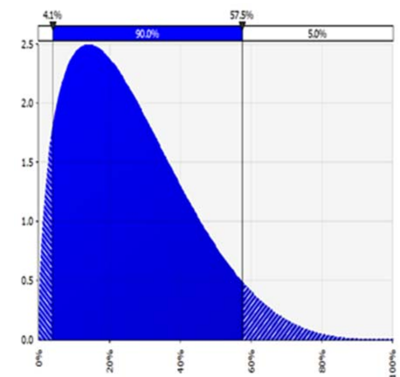
Survival score was the median value or what the Team thought most likely (or 50th percentile) would happen if the Initiating Event occurred.

- So a Most Likely 80% survival score equates to:
  - Any one of the four astronauts had a 20% chance of death while attempting to reach a safe location
- The Maximum or “Good Day” conditions were optimal or the event was not a severe as expected. This set the upper bound of the distribution.
- In the Minimum or “Bad Day” conditions, everything worked against the personnel surviving the hazard. This set the lower bound of the distribution.

Resulted in an interval of values to determine the uncertainty PERT distributions in @RISK.

Survival score given the event has occurred was defined in Success Space.

- Success Space (e.g., mission success) describes events or outcomes management does want to occur.



Sample Survivability and PERT Distribution Input

CALCULATIONS

P_E = likelihood of event occurring. [input in Failure Space]

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

Since Failure Space Distribution should not be multiple by a Success Space Distribution, we need to develop the $P_{D|E}$ = probability of dying if event occurs which is calculated by:

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

P_D = probability of dying due to this event which is calculated by:

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

P_S = probability of surviving due to this event which is calculated by:

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

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

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

LC 39B Assessment

CALCULATIONS (CONT.)

Used @RISK and the Latin Hypercube sampling method when running probabilistic simulations at 50,000 iterations to calculate the output for each time interval

- Given the Excel formula is:

$$1 - (P_E * (1 - P_{S|E})) = P_S$$

- For one time interval and one Initiating Event, then the Excel formula with the @RISK add-in software makes:

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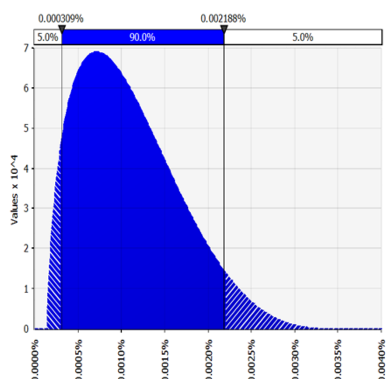

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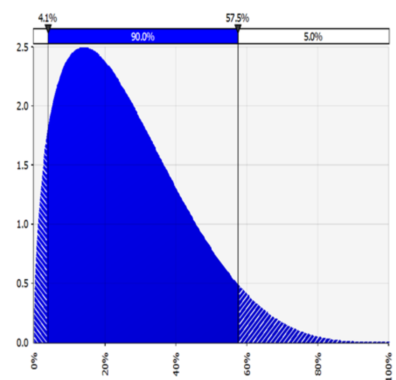

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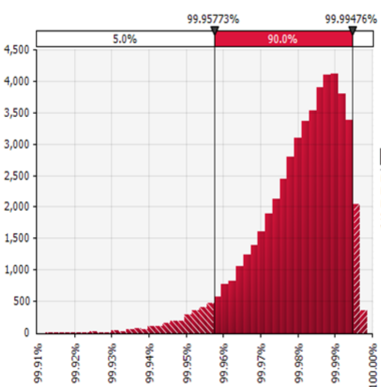


CALCULATIONS (CONT.)

This probabilistic simulation of the Excel formula produces a PERT distribution with results at the lower bound, most likely/median, and upper bound at a specific time.

- Generated the graphs the Customer requested was accomplish by exporting these three values (lower bound, most likely, and upper bound) from the output histogram at each specific time interval in to MS Excel.

The @RISK software could have been used to generate the same graph. However,

- Eliminating the @RISK graphs for each hazard and time interval speeds up @RISK processing time
- Final graphs generated in MS Excel were visually appealing to the Customer

RESULTS

LC 39B EMERGENCY EGRESS ASSESSMENT

LC 39B Assessment

RESULTS

IA Team created five MS Excel files to illustrate/compare Astronaut survival by group or by individual credible hazards identified in the FTA These files were:

- All Scenarios, Fire Only Scenarios, Fire and Structural Failure Scenarios, Structural Failure Scenario, Unbreathable Atmosphere Scenarios

The largest MS Excel file (All Scenarios) contained:

- 1,786 data entries per method of egress of Input Data
- 2,337 data points generated per method of egress of Output Data

Below is an example from a single MS Excel file for one time interval, one Initiating Event, and one egress method.

Initiating Event (E)		Event Likelihood (P_E) [Input Data]				% Survivability @ 2 Minutes					
Event No.	Description	Lower Bound	50th Percentile (Median)	Upper Bound	Error Factor	Minimum $P_{S\|E}$	Most Likely $P_{S\|E}$	Maximum $P_{S\|E}$	P_S at 5.00%	P_S at 50.00%	P_S at 95.00%
70	Engine Explosion at Startup Results in Structural Failure	6.00E-04	1.20E-04	2.40E-05	5.0	1.00%	93.00%	100.00%	99.99%	100.00%	100.00%

Figure of Notional Output Data

Output (P_S) generated from @RISK histogram. These points are then plotted in MS Excel.

RESULTS (CONT.)

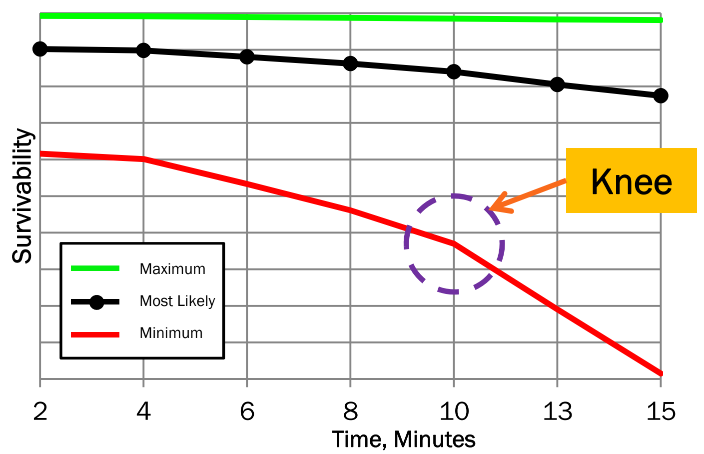
A "knee" in the top graph can be seen at 10 minutes regardless of egress method.

- Each astronaut has 10 minutes of breathable air in their spacesuits.
- Decrease in crew survivability was attributed to no pre-staging of supplemental portable breathing air units.

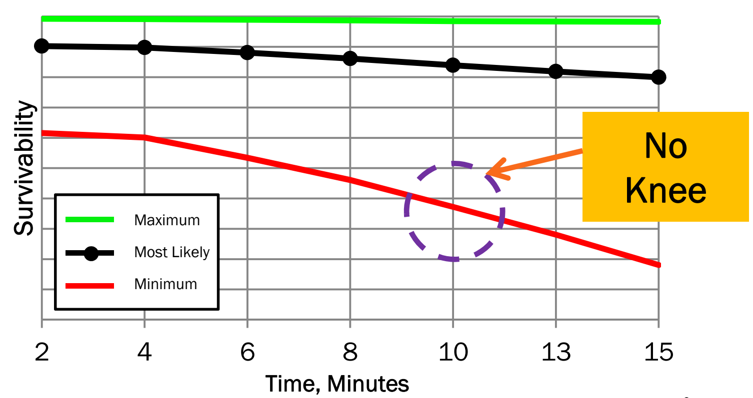
Customer stated mitigation steps will be implemented to eliminate the knee after reviewing top graph.

- Breathing air unit will be pre-stage to allow astronauts to exchange units.
- With mitigation steps in place, knee at 10 minutes disappears in bottom graph.

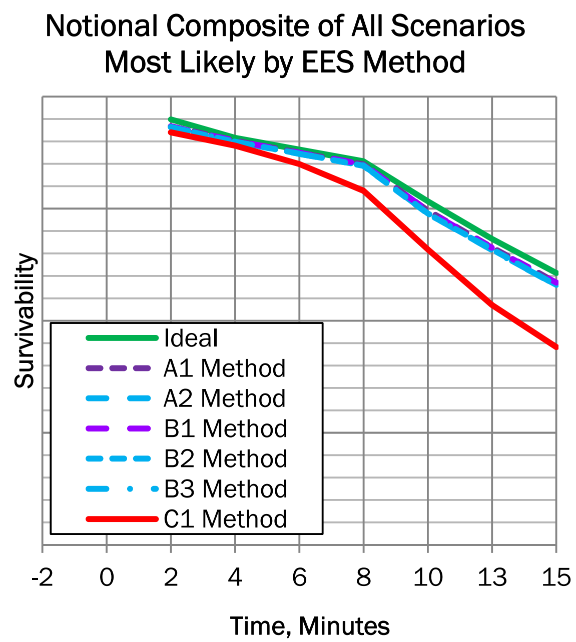
Notional LC 39B Emergency Egress
Unbreathable Scenarios Not Mitigated

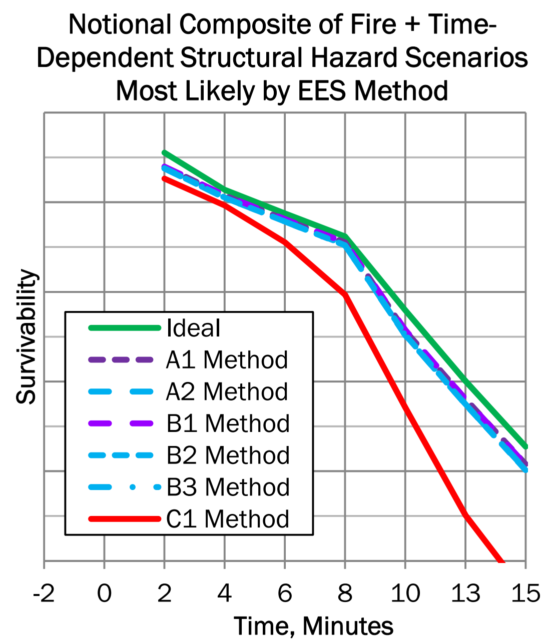


Notional LC 39B Emergency Egress
Unbreathable Atmosphere Scenarios Mitigated



RESULTS *(CONT.)*





Various graphs of the Most Likely values for the seven methods assessed.

- Methods A1, A2, B1, B2, and B3 are roughly the same percentage survivability.
  - Methods A1 and A2 transported Astronauts inside the blast danger zone.
  - All other methods transported Astronauts outside the blast danger zone (~6000 feet).
- However, cost estimates to build Methods A1, B1, and B3 were ~$40 million more than Methods A2, B2, and C1.

ASSESSMENT OVERVIEW

VAB EMERGENCY EGRESS ASSESSMENT

OVERVIEW VAB ASSESSMENT

VAB Assessment

In 2013, same Customer requested an assessment the VAB egress routes using the methodology developed for the LC 39B Assessment.

- For the VAB Assessment,
  - IA Team was asked to determine if an Initiating Event(s) produce a “knee” on the curve indicating that survivability decreased more rapidly than the other event(s).
  - Evaluated multiple workers (~14 - 90 people) egressing from multiple locations compared to the LC 39B Assessment which assumed four astronauts moving together using a single egress method
- SLS processing occurs in VAB Highbay 3. There are four highbays in the VAB. Each bay measures:
  - 450 feet high, 209 feet wide, and 228 feet long

VAB at KSC

OVERVIEW VAB ASSESSMENT (CONT.)

Assemble and testing in VAB occurs over several months.

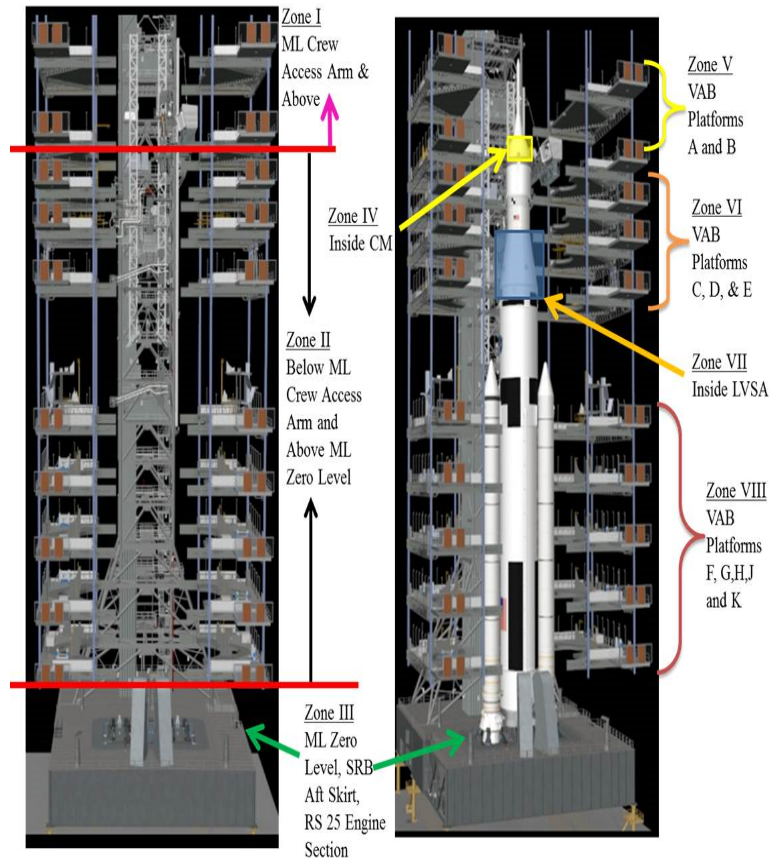
- Created eight different processing phases from the start of solid rocket motor erection to SLS/Orion roll out to the LC 39B.
- Each processing phase had different number of workers in these work locations, and duration of each phase also varied.

Multiple workers located in eight different zones.

- Each worker could take separate paths to reach an exit located ~30 – 180 feet.

Customer requested each work zone/phase assessed at eight different time intervals to reach an exit.

- Time to reach an exit was estimated at eight time intervals of: 0 sec, 10 sec, 20 sec, 30 sec, 1 min, 2 min, 3 min, and 5 min



VAB Zones

METHODOLOGY AND CALCULATIONS

VAB EMERGENCY EGRESS ASSESSMENT

METHODOLOGY AND CALCULATIONS

VAB Assessment

Methodology developed for LC 39B assessment (hazard scenario development, likelihood, survivability estimates, and probability distribution) was used for the VAB assessment.

- FTA for VAB assessment produced 78 Initiating Events

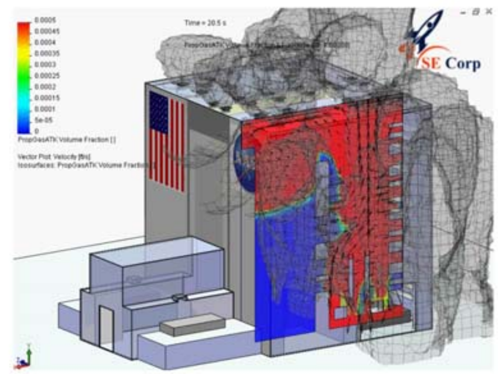
To determine survivability for multiple personnel at multiple locations for a specific time, an Aggregate Survival Level was calculated as a weighted average based on manloading and Survival Level assigned to each Zone.

- Aggregate survival level formula for an individual Initiating Event during one Phase and at one time interval is:

$$P(S_{Aggregate|E}) = \sum_{i=1}^{8}\left[\left(\frac{\text{Headcount}_{\text{Zone i}}}{\text{Total Headcount}}\right) * P(S_{\text{Zone i}}|E)\right]$$

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

$$P_S = 1 - P_D = (1 - (P_E * (1 - P_{S_{Aggregate|E}}))$$ [output]



Computation Fluid Dynamic Analysis of a Solid Rocket Motor Fire in VAB

RESULTS

VAB EMERGENCY EGRESS ASSESSMENT

RESULTS

One MS Excel File with eight MS Excel Workbooks

- Each Workbook captured the results from a single phase.

The largest MS Excel file contained:

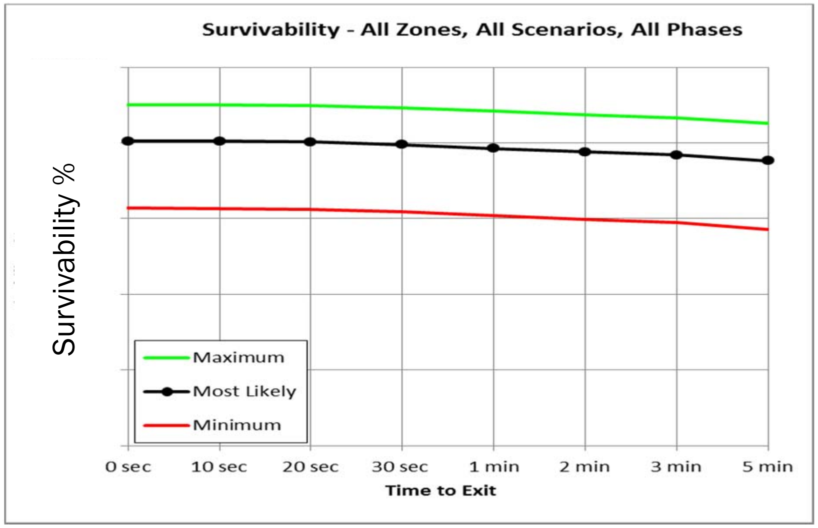
- Eight workbooks (or tabs)
- Each workbook populated rows and columns with data that was:
  - 96 columns wide
  - 715 rows deep
- Processing time was between four to six hours for this large file using a dedicated laptop.
  - Laptop was comprised of:
    - Eight i7 Intel, 64 bit Processors
    - 16 GB RAM
    - MS Excel 64 bit software
  - Palisade's help desk, user manual, and technical bullets were most beneficial in resolving computational errors and speeding up processing time.

RESULTS (CONT.)

A composite scenario was developed, denoted $P(S_{All})$, which is the probability of surviving all initiating events for a given Phase, each time interval, and for all (aggregated) Zones.

A joint probability that contains 78 probabilities occurring at the same time mark. Thus, the VAB Emergency Egress Analysis formula for the probability of surviving all individual 78 Initiating Events at the same time is calculated in success space by:

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



Notional Composite Survivability vs Time Plot

RESULTS *(CONT.)*

VAB Assessment

Pareto Analysis of all the hazard scenarios and all phases revealed slope of the survivability curve is dominated by eight Instant Scenarios.

- Instant Scenarios were defined as: Survivability rapidly decreases within the first few seconds and remains constant thereafter. These instant scenarios were five flight hardware stacking mishaps, arc flash, SRB fire, and propellant tank rupture.
- Degrading scenarios survivability estimates were within industry norms
  - Degrading Scenarios were defined as: Survivability gradually decreases with time required to reach an Exit

Customer accepted risk for survivability estimates

- Egress strategies (build enclosed egress paths, more egress paths, etc.) do not mitigate Instant Scenarios
- $6 - $8 million cost avoidance

SUMMARY

LC 39B AND VAB EMERGENCY EGRESS ASSESSMENTS

LC 39B and VAB Assessments

SUMMARY

Graphs developed from these assessments are a decision-informing tool for Project Managers which roll up multiple factors:

- The whole population of the LC 39B/VAB
- A specific time period
- A spectrum of potential events
- Weighted by the likelihood of occurrence of the event

Both assessments were conducted early in the design process and resulted in cost savings, including $40 million cost savings in LC 39B emergency egress design.