A Failure Propagation Modeling Method for Launch Vehicle Safety Assessment

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Applied Modeling and Simulation Series
NASA Ames Research Center, November 4, 2014

Presented at the 12th Probabilistic Safety Assessment and Management (PSAM12), June 24, 2014
Outline

• Introduction
  − Role of failure propagation in abort effectiveness assessment

• Method Description and Sample Problem
  − Propagation Process
  − Implementation Enhancements
  − Developing Transition Probabilities
  − Some Example Analyses

• Conclusions and Future Work
Abort Effectiveness In a Nutshell (Avocado?)

- All Failures (Loss of Mission)
  - L-V Loss of Crew
  - Uncontained Failures
  - Stage-Level Explosions
- S-C LOC
Abort Effectiveness In a Nutshell (Avocado?)

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Failure Propagation
Abort Effectiveness In a Nutshell (Avocado?)

Failure Environments

S-C LOC

All Failures (Loss of Mission)

L-V Loss of Crew

Stage-Level Explosions

Uncontained Failures
Reality: There are flavors of uncontained, each with its own character

LOC fraction will depend on:
- Mission time (flight conditions, etc.)
- Failure detection (warning time)
• **ESAS**
  - $\text{LOC} = 0.15\times\text{LOM}$

• **Ares 1 Upper Stage Engine**
  - Early: All uncontained $\rightarrow$ Stage Explosion
    - Focus was on environment characterization (blast, fragments)
  - Late: 30% uncontained $\rightarrow$ Stage Explosion
    - Based on analysis by Ken Gee

• **SLS Complexity**
  - Liquid first stage
    - Multiple engines
    - Confined volume
  - Strap-on boosters

• **SLS Core Stage Engine**
  - Early: 50% $\rightarrow$ Stage Explosion (weaker)
  - Current: Why we’re here
Abortability Example

- What is likelihood that, given a main engine turbo-pump burst failure, there will serious injury or death of one or more crew members?
  - What is the likelihood that there will be a “large” explosion (explosion of full stage)?
  - What is the likelihood that a large explosion will critically damage the crew module?

- How does it vary with mission time?
- How does it vary with warning time?

Note: importance of propagation depends on proximity of crew module.
Failure Propagation Model Overview

[Diagram showing the process of failure propagation, including stages, event trees, and binned end-states.]
Selected initiator: Stage 1 turbopump failure
Paths go horizontally and then vertically

<table>
<thead>
<tr>
<th>Initiators</th>
<th>Stage 1 TurboPump</th>
<th>0%</th>
<th>50%</th>
<th>15%</th>
<th>Transition Probabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 MCC Expl</td>
<td>70%</td>
<td>0%</td>
<td>5%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Aft Skirt Explosion</td>
<td>10%</td>
<td>80%</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HE Tank Explosion</td>
<td>20%</td>
<td>10%</td>
<td>5%</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Intermediate Environments</th>
<th>Stage 1 Tank Rupture</th>
<th>50%</th>
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</thead>
<tbody>
<tr>
<td>Stage 1 Intertank CBM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure Environments</th>
<th>Stage 2 Tank Rupture</th>
</tr>
</thead>
</table>

Event Tree: Stage 1 TP
Stage 1 TP burst causes (leakage) aft skirt explosion
Stage 1 TP burst causes (fragment strike) He tank explosion
Aft skirt explosion causes (overpressure) Stage 1 tank rupture
He tank explosion causes (fragment) Stage 1 inter-tank CBM
Simple Propagation Matrix Example

### Event Tree

**Stage 1 inter-tank CBM causes (overpressure) Stage 1 tank rupture**

<table>
<thead>
<tr>
<th>Stage 1 TurboPump</th>
<th>0%</th>
<th>50%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 MCC Expl</td>
<td>70%</td>
<td>0%</td>
<td>5%</td>
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<td></td>
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<td>Stage 1 Tank Rupture</td>
<td>50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1 Intertank CBM</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 2 Tank Rupture</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Stage 1 TP**

- Aft Skirt Expl
- He Tank Expl

**Stage 1 Tank Rupture**

- Stage 1 Intertank CBM

**Stage 1 Tank Rupture**
Transition times introduced to enable chronology-based pruning
Monte Carlo results are binned to produce the desired mapping (branch splits) between the initial manifestation and the explosion(s).

Sample Monte Carlo Results

Pruned Event Tree
# Transition Data Table Snippet

<table>
<thead>
<tr>
<th>ID</th>
<th>PL</th>
<th>Pre-Launch w/ LAS</th>
<th>First Stage Burn</th>
<th>Staging</th>
<th>Upper Stage Burn, w/ LAS</th>
<th>Upper Stage Burn, no LAS</th>
<th>Spacecraft Staging</th>
<th>Source</th>
<th>Target</th>
<th>Timing</th>
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</thead>
<tbody>
<tr>
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<td>0/ 0/ 0</td>
<td>0/ 0/ 0</td>
<td>0/</td>
<td>0/</td>
<td>0/</td>
<td>Stage 1 TurboPump</td>
<td>Stage 1 MCC Expl</td>
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<td></td>
</tr>
<tr>
<td>F6</td>
<td>90/50/15</td>
<td>90/50/15</td>
<td>90/50/15</td>
<td>0/</td>
<td>0/</td>
<td>0/</td>
<td>Stage 1 TurboPump</td>
<td>Aft Skirt Expl</td>
<td>0.1/0.1</td>
<td></td>
</tr>
<tr>
<td>G6</td>
<td>25/15/5</td>
<td>25/15/5</td>
<td>25/15/5</td>
<td>0/</td>
<td>0/</td>
<td>0/</td>
<td>Stage 1 TurboPump</td>
<td>HE Tank Explosion</td>
<td>0.1/0.1</td>
<td></td>
</tr>
<tr>
<td>F7</td>
<td>100/70/20</td>
<td>100/70/20</td>
<td>100/70/20</td>
<td>0/</td>
<td>0/</td>
<td>0/</td>
<td>Stage 1 MCC Expl</td>
<td>Aft Skirt Expl</td>
<td>0.1/0.1</td>
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<tr>
<td>G7</td>
<td>5/0/0</td>
<td>5/0/0</td>
<td>5/0/0</td>
<td>0/</td>
<td>0/</td>
<td>0/</td>
<td>Stage 1 MCC Expl</td>
<td>HE Tank Explosion</td>
<td>0.01/0.01</td>
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</tr>
<tr>
<td>H7</td>
<td>100/15/0</td>
<td>15/5/0</td>
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<td>I7</td>
<td>0/</td>
<td>0/</td>
<td>0/</td>
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## Mapping: Dependence on Phase

**Stage 1 Shutdown/ Separation**

**Stage 1 Boost**

**Pre-Launch**
Initiators/Initial Manifestations (Tables)

Intermediate Environments (Facilitate propagation)

Element-Level Environments (Direct threat to Crew/CM)

Transition Probabilities (Points to table)

Summary
15 phases
3 options (Best/Worst/Base)
15 Initiators
9 ELEs
5 IEs
32 Total Envs
90 Trans Probs
5-stage process
11 triggered environments (not including initiator)
4 triggered explosion types
Transition Analysis Thought Process

- Energy Transfer Mode(s)
  - Overpressure
  - Kinetic Energy (Fragments)
  - Shock & Vibration
  - Environment (pressure, temperature)
  - Etc.

- Source Severity
  - Energy type: \([KE]\)
  - Magnitude: \([\text{Velocity and density}]\)
  - Uncertainties: \([\text{Velocity and density}]\)

- Target Vulnerability
  - Energy type: \([KE]\)
  - Magnitude: \([\text{Size, Location, Limit velocity}]\)
  - Uncertainties: \([\text{Limit velocity}]\)

- Energy Decay
  - Natural decay with distance: \([1/d^2]\)
  - Obstructions: \([\%]\)

Example: TP Burst \(\rightarrow\) He tank burst
Engine Section Propagation

- **Modes**
  - **Fragments**
    - Uncontained engine failures
    - COPV bursts (subsequent to being struck), assumed uniform in all directions
  - **Overpressure**
    - MCC explosion
    - COPV burst
  - **Leaks**
    - Propellant
    - Hot Gas
      - TP pre-burners
      - MCC
    - COPV burst

- **Primary Outcomes**
  - LH2 Tank Rupture
    - Core nonCBM
  - ES Burst (rupture)
    - Damage to nozzle propellant lines → multiple engines uncontained or loss of thrust
  - Multiple engines uncontained
    - Many consequences
  - Core loss of thrust
    - LH2 tank rupture (when boosters on and burning)
Conclusions and Future Work

Status

- Propagation model has been implemented
  - Complex interactive process modeled with a number of simpler interactions
  - Automatically generates potentially complex failure event sequences

- Advantages
  - Facilitate communication with engineers regarding consequences of failure
  - Enables complex mission phase behavior to be captured
  - Tracks and accumulates failure evolution times (where available)
  - Easy to set up easy problems but can be expanded to more complex problems

- Currently being used in support of the Space Launch System (SLS) and Commercial Crew programs

Potential Enhancements

- More automated transition probability evaluation
- Integration with CAD-based simulation methodology
Antares Failure: October 28, 2014

T+14.7s

Plume changes color (ΔMR)

+ <1 s

R.U.D.

FTS @ T+20s

Orbital Sciences Antares Rocket

**Payload Fairing**
- Diameter: 3.9 meters (154 in.)
- Height: 9.9 meters (390 in.)
- Structure: Honeycomb Core. Composite Face
- Separation: Non-Contaminating Frangible Ring

**Stage 1**
- Two Aerojet AJ26 engines with independent thrust vectoring
- Liquid oxygen/RP fueled
- System development and integration by Orbital
- Core tank design and verification by KB Yuzhnoye (Zenit-derived heritage)
- Core tank production by Yuzhmash
- Avionics Stage Controller uses flight-proven Orbital MACH components

**Stage 2**
- ATK CASTOR® 30B Solid Motor with Thrust Vectoring
- Orbital MACH Avionics
- 3-Axis ACS

Duel AJ-26 Engines
Fuel (RP) Tank
LOX Tank
AJ-26 Engines

- Antares powered by dual AJ-26 engines
  - LOX-Kerosene
  - Staged combustion
- Both engines on this flight were manufactured for the Soviet N1 rocket in the 1960s and 1970s
- Conversion to AJ-26 involved:
  - Updated electronics for new electromechanical valve actuators
  - Modifications to fuel systems
  - Added hydraulic TVC system
- Acceptance tests were performed for each engine
  - One minute burn
  - Failure in May during one of these acceptance tests
    - Described as an explosion
  - Failure in 2011
    - Kerosene leak leading to fire
    - Traced to stress corrosion cracks in metal