



# PSAM 14

**PROBABILISTIC SAFETY ASSESSMENT  
AND MANAGEMENT CONFERENCE  
September 16-21, 2018**

**AERONAUTICS AND AEROSPACE SESSION II**

**Synthesizing a New Launch Vehicle Failure Probability  
Based on Historical Flight Data**

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- New launch vehicles have historically had significantly higher failure probabilities in early flights than what has been predicted using Probabilistic Risk Assessment
- Work on a new methodology originally started with ARES I-X and Common Standards Working Group (CSWG) for range safety applications
  - CSWG consists of the Federal Aviation Administration (FAA), Air Force, and NASA
- Historical launch vehicle data was viewed as the best predictor of success/failure for launches of new vehicles.

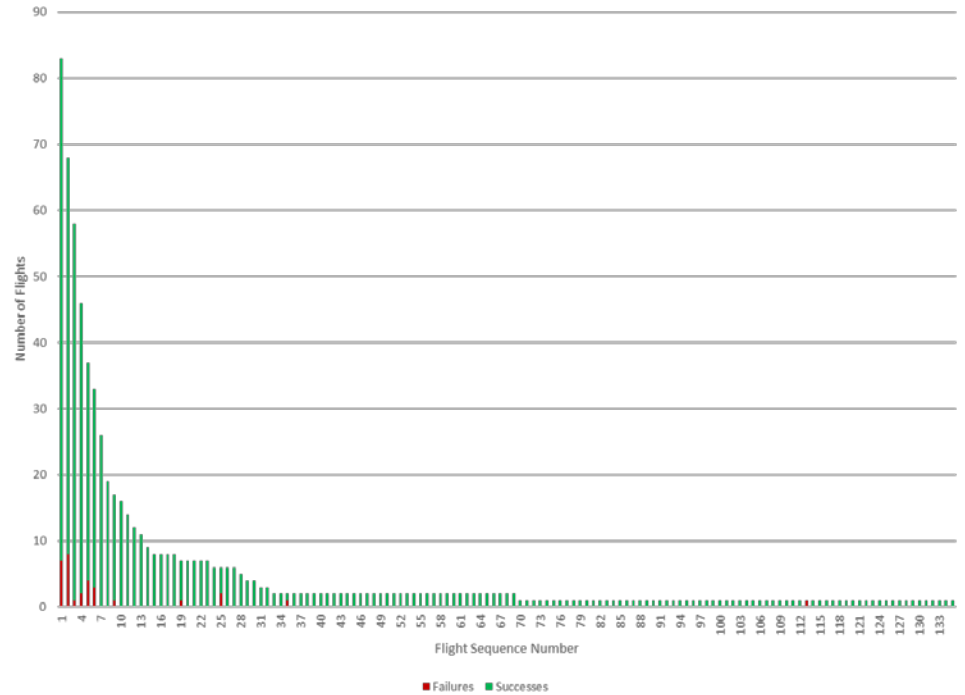


- A launch vehicle database was developed that includes all launches from 1980 - 2017 (both US and foreign)
- Entries to the database include:
  - Vehicle by model type
  - Launch dates
  - Failure description
  - Failure Result (Loss Of Vehicle (LOV)/Loss Of Mission (LOM))
  - Failure cause (when available)
  - Vehicle designs (stages/engines/etc.)

# Historical Launch Vehicle First Flight Risk



- Database was reviewed to determine launch outcomes by flight sequence number for each launch vehicle model



Launch Vehicle Model	1st Flight	2nd Flight
Antares 110	Success	Success
Antares 120	Success	Success
Antares 130	Success	Success
Athena I	Success	Success
Athena II	Success	Success
Atlas 1	Success	Success
Atlas 2	Success	Success
Atlas 2A	Success	Success
Atlas 2AS	Success	Success
Atlas 3A	Success	Success
Atlas 3B-SEC	Success	Success
Atlas 3B-DEC	Success	Success
Atlas 5 (A01)	Success	Success
Atlas 5 (A011)	Success	Success
Atlas 5 (A21)	Success	Success
Atlas 5 (A31)	Success	Success
Atlas 5 (A01)	Success	Success
Atlas 5 (A21)	Success	Success
Atlas 5 (A31)	Success	Success
Atlas 5 (A41)	Success	Success
Atlas 5 (A51)	Success	Success
Atlas Allair-3A	Success	Success
Atlas E/F S65-2	Success	Success
Atlas H-MSD	Success	Success
Atlas G Centaur	Success	Success
Delta 4M	Success	Success
Delta 4M+(4,2)	Success	Success
Delta 4M+(4,2)upg	Success	Success
Delta 4M+(5,2)	Success	Success
Delta 4M+(5,2)upg	Success	Success
Delta 4M+(5,4)	Success	Success
Delta 4M+(5,4)upg	Success	Success
Delta 4H	Success	Success
Delta 4Upg	Success	Success
Delta 3910	Success	Success
Delta 3910 PAM-D	Success	Success
Delta 3920	Success	Success
Delta 3920 PAM-D	Success	Success
Delta 3913	Success	Success
Delta 3924	Success	Success
Delta 4925	Success	Success
Delta 5920	Success	Success
Delta 6920	Success	Success
Delta 6925	Success	Success
Delta 7320	Success	Success
Delta 7326	Success	Success
Delta 7420	Success	Success
Delta 7425	Success	Success
Delta 7436	Success	Success
Delta 7520	Success	Success
Delta 7520H	Success	Success
Delta 7925	Success	Success
Delta 7925H	Success	Success
Delta 8930	Success	Success
Falcon 9 v1.1	Success	Success
Falcon 9 v1.1 (ex)	Success	Success
Falcon 9 v1.2	Success	Success
Minotaur 4 HAPS	Success	Success
Minotaur 4	Success	Success
Minotaur 4+	Success	Success
Minotaur 4-Lite	Success	Success
Minotaur 1	Success	Success
Minotaur 2	Success	Success
Minotaur 5 (1)	Success	Success
Pegasus Hybrid	Success	Success
Pegasus XL	Success	Success
Pegasus XL HAPS	Success	Success
Scout G1	Success	Success
Space Shuttle	Success	Success
Taurus 1110	Success	Success
Taurus 2110	Success	Success
Taurus 2210	Success	Success
Taurus 3110	Success	Success
Taurus 3210	Success	Success
Titan 2(2)G Star-37X(1)SS	Success	Success
Titan 34D IUS	Success	Success
Titan 34D Transstage	Success	Success
Titan 4B Centaur-T	Success	Success
Titan 4A IUS	Success	Success
Titan 4A Centaur-T	Success	Success
Titan 4A	Success	Success
Titan 4B IUS	Success	Success
Titan 4B	Success	Success
Titan 2(2)G	Success	Success
Titan 3-Commercial	Success	Success

# Design Element Failure Probability



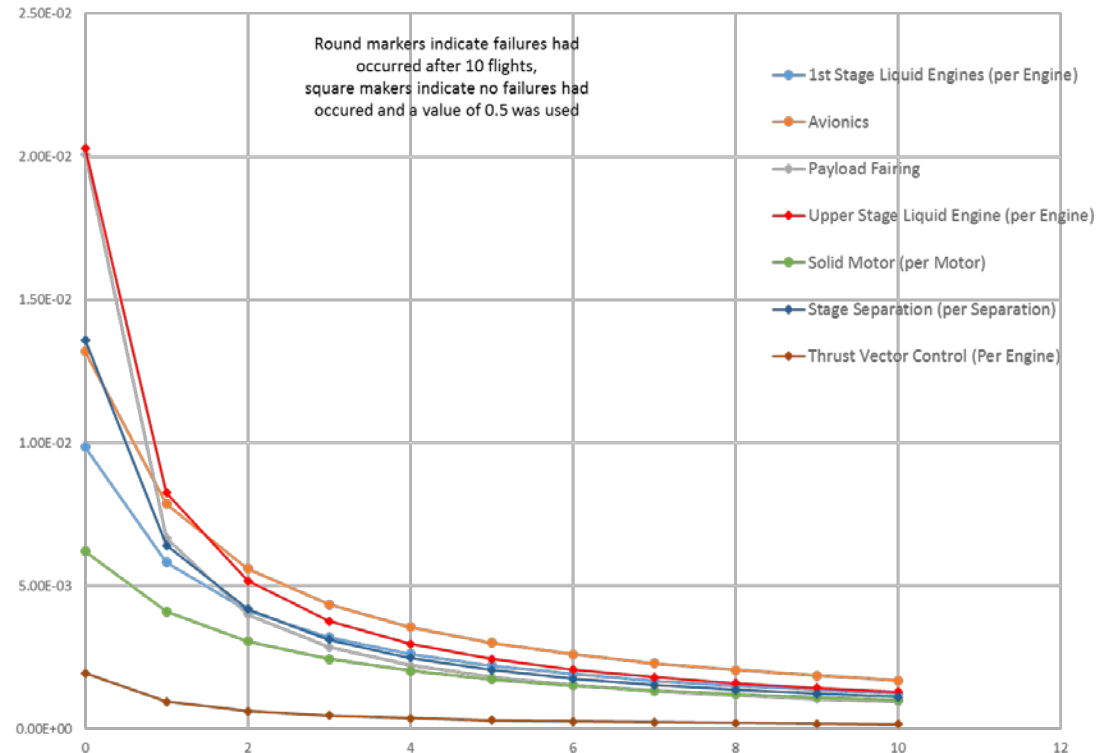
- First two flights had similar, high, failure probabilities
- Table below shows failures by design element based on first two flights
- Number of elements flown is based on vehicle designs from the database

Design Element	Failures	Number of Design Elements Flown	Failure Probability per Design Element per Launch
Avionics	2	151	1.32E-02
1st Stage Liquid Engines	2	203	9.85E-03
Solid Propulsion	1	161	6.21E-03
Upper stage Liquid Engines	3	148	2.03E-02
Stage Separation	3	220	1.36E-02
Fairing Separation	3	149	2.01E-02
Thrust Vector Control	1	512	1.95E-03

# Estimated Design Element Failure Probabilities by Flight Sequence Number



- Starting with the failure probabilities on previous page, the failure probabilities per element per launch by flight sequence number were estimated



# Use of Data on a Hypothetical New Launch Vehicle



- A hypothetical vehicle was evaluated using the data
- The basic design assumed for the new vehicle is shown below

Basic Design Elements	
Number of Stages	2
Fairing Separations	1
1 <sup>st</sup> Stage Design Elements	
Number of Liquid Engines	3
Number of Solid Motors	2
Upper Stage Design Elements	
Number of Liquid Engines	2

# Probability of Failure based on Design and Empirical Estimates



- Based on the assumed design, the design element failure probabilities were found
- The estimated first flight failure probability is 0.134

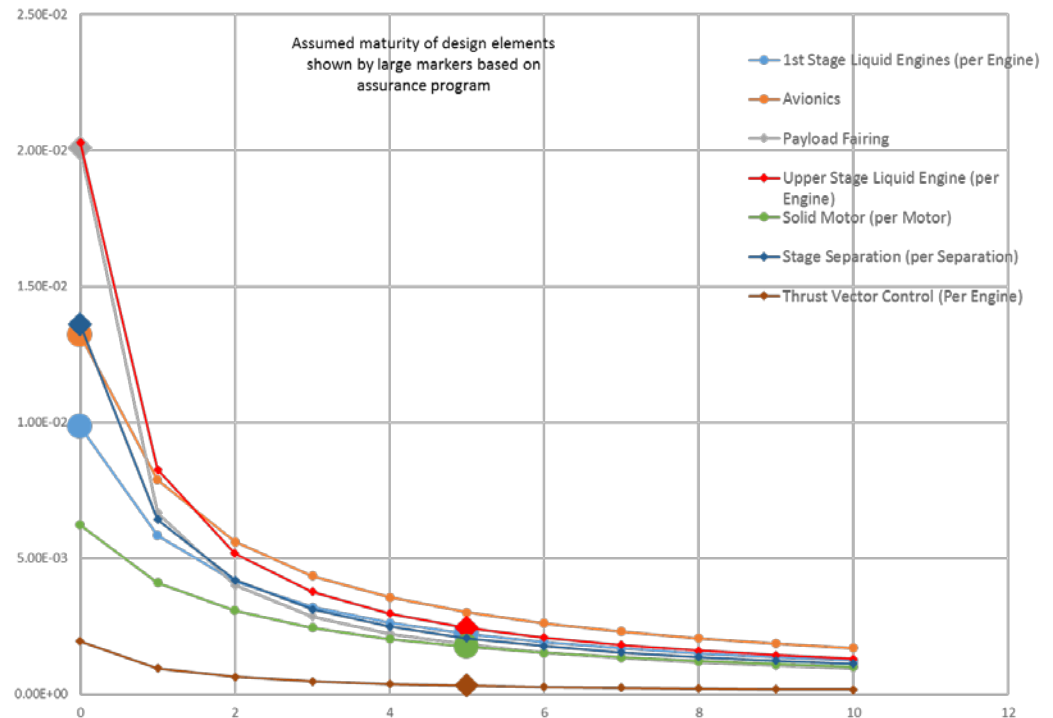
Design Element	Design Element Failure Probability	# of Design Elements	Total Design Element Failure Probability
Avionics	1.32E-02	1	1.32E-02
1st Stage Liquid Engines	9.85E-03	3	2.93E-02
Solid Propulsion	6.21E-03	2	1.24E-02
Upper stage Liquid Engines	2.03E-02	2	4.01E-02
Stage Separation	1.36E-02	1	1.36E-02
Fairing Separation	2.01E-02	1	2.01E-02
Thrust Vector Control	1.95E-03	7	1.36E-02
<b>Total</b>			<b>1.34E-01</b>



# Extending the Example to Account for the Assurance Program



- The previous example was extended to account for the assurance program
- Try to account for heritage hardware, extensive testing, etc.
- In the example assume credit is given to solid rocket motors, 2<sup>nd</sup> stage engines and thrust vector control.
  - Credit assurance equivalent of 5 flights



# Example Result with Assurance Program Credit

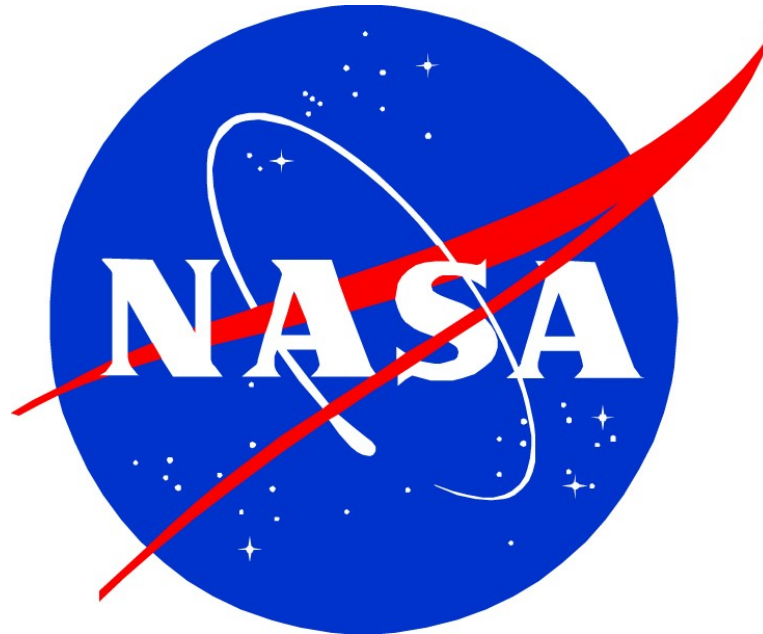


- Crediting the 3 design elements with 5 flights each yields the below result
- The estimated failure probability per launch is reduced by 1/3.

Design Element	Design Element Failure Probability	Design Element Equivalent Experience	Total Design Element Failure Probability
Avionics	1.32E-02	0	1.32E-02
1st Stage Liquid Engines	9.85E-03	0	2.93E-02
Solid Propulsion	6.21E-03	5	3.47E-03
Upper stage Liquid Engines	2.03E-02	5	4.89E-03
Stage Separation	1.36E-02	0	1.36E-02
Fairing Separation	2.01E-02	0	2.01E-02
Thrust Vector Control	1.95E-03	5	8.73E-03
<b>Total</b>			<b>8.98E-02</b>



New launch vehicles have historically had a significantly higher average failure probability than mature launch vehicles, and PRA analyses do not adequately assess their failure probability. Assurance programs for launch vehicles have an impact on the success or failure probability of launch vehicles. By reviewing historical failures against assurance practices, greater confidence can be had for the first flight of a new vehicle and using this methodology can translate into a more accurate estimate of first flight failure probability and can be bridged into an existing PRA model.



*Thank you for your attention!*