Safety & Reliability Assessment of Delta IV EELV Based Crew Launch Options*

Gaspare Maggio & Tony Hall

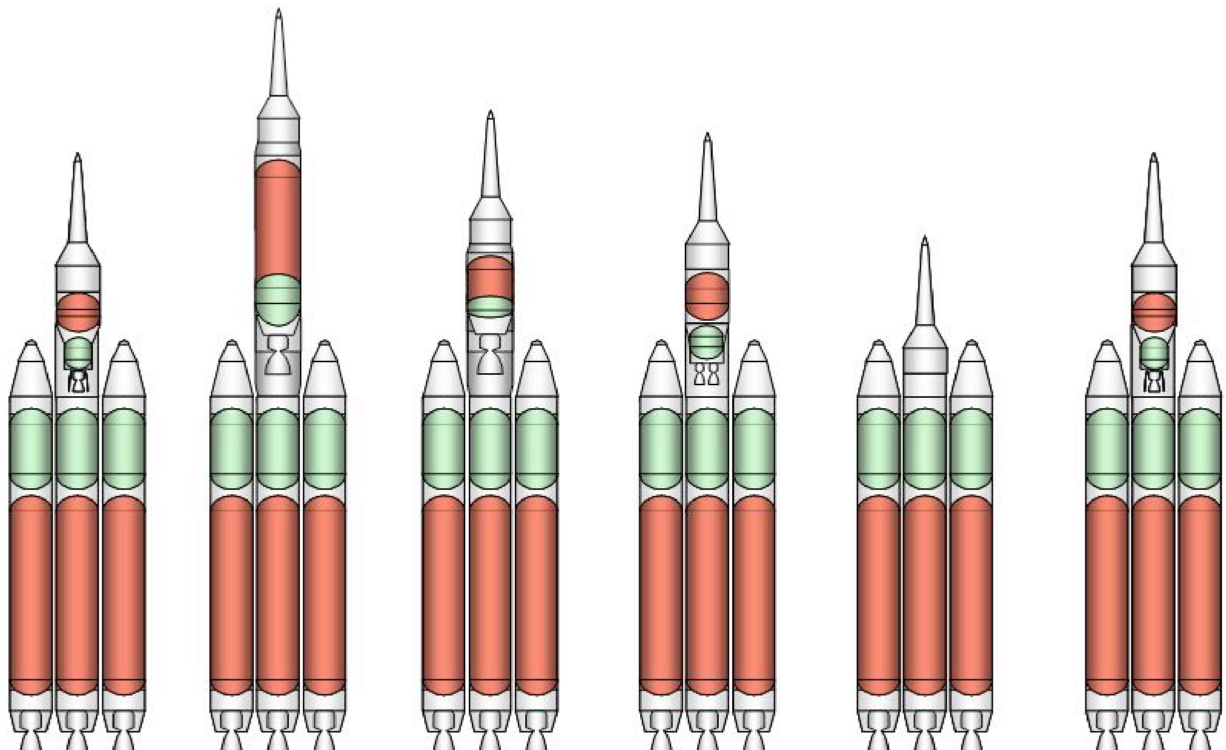
Information Systems Laboratories

Technology Risk Management Operation

June 10, 2009

*Options are as defined in the Aerospace Corp's "ESMD Architecture Strategic Analysis Task Forward Action Study" presentation dated March 31, 2009

Summary of Vehicle Configurations



	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5	Configuration 6
Strap-on	Planned (HUG)	Human-Rated	Human-Rated	Human-Rated	Human-Rated	Human-Rated
Core	Planned (HUG)	Human-Rated	Human-Rated	Human-Rated	Human-Rated	Human-Rated
Core/Strap-on Engine	RS-68A	RS-68B HR	RS-68B HR	RS-68B HR	RS-68B HR	RS-68B HR
Upperstage (US)	Existing	Ares I US	Resized Ares I US	New Human Rated US	No US	Existing with HR
US Engine	1 RL-10 B2	1 J2-X	1 J2-X	4 RL-10-A-4	- - -	1 RL-10-A-4
Engine-Out	No	No	No	Yes	- - -	No

Configuration Performance Assumptions

	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5	Configuration 6
Stage 0						
Engine	2 x RS-68A	2 x RS-68B HR	2 x RS-68B HR	2 x RS-68B HR	2 x RS-68B HR	2 x RS-68B HR
Burn Time (s)	244	180	234	234	234	234
Propellant Mass (lbm - ea)	451,749	349,082	451,749	451,749	451,749	451,749
Percent Prop Off-Loaded	0%	30%	0%	0%	0%	0%
Percent Prop Residual	2%	2%	2%	2%	2%	2%
Powerlevel (%)	102%	108%	108%	108%	108%	108%
Sea-Level Thrust (lbf - ea)	663,000	702,000	702,000	702,000	702,000	702,000
Sea-Level Isp (s)	365	370	370	370	370	370
Stage 1						
Engine	1 x RS-68A	1 x RS-68B HR	1 x RS-68B HR	1 x RS-68B HR	1 x RS-68B HR	1 x RS-68B HR
Burn Time (s)	328	242	315	315	315	315
Propellant Mass (lbm)	451,749	349,082	451,749	451,749	451,749	451,749
Percent Off-Loaded	0%	30%	0%	0%	0%	0%
Percent Residual	2%	2%	2%	2%	2%	2%
Powerlevel (%) (0-50s)	102%	108%	108%	108%	108%	108%
Powerlevel (%) (50-S0 Sep)	57%	60%	60%	60%	60%	60%
Powerlevel (%) (S0 Sep to MECO)	102%	108%	108%	108%	108%	108%
Sea-Level Thrust (lbf)	663,000	702,000	702,000	702,000	702,000	702,000
Vacuum Isp (s)	408.8	415	415	415	415	415
Stage 2						
Engine	1 x RL-10B-2	1 J-2X	1 J-2X	4 x RL-10-A-4-2	n/a	1 x RL-10-A-4-2
Burn Time (s)	1,125	457	147	649	n/a	1,125
Propellant Mass (lbm)	64,210	302,000	97,431	96,209	n/a	64,210
Powerlevel (%)	100%	100%	100%	75%	n/a	100%
Thrust (lbf)	24,740	294,000	294,000	16,725	n/a	22,300
Vacuum Isp (s)	462	449	449	451	n/a	451
LAS Jettison Time (nominal)	358	272	345	345	264	345
Orion Service Module Main Engine Sub-orbital Burn Time					285	

Configuration assumptions are based on data within the Aerospace Corp presentation and engineering assumptions and estimates made by the assessment team.

Note that due to performance limitations Configuration 5 can only be used for ISS missions .

Safety & Reliability Assessment Ground Rules & Assumptions

- **Scope of assessment is from lift-off (T+0) to end of second stage burn or Orion SM engine orbital insertion burn (configuration 5 only)**

- **Reliability Assessment**
  - A margin of 30% has been used to account for possible integrated failures and other unforeseen development/operational difficulties
  - For stages with multiple engines a 10% likelihood is assumed that one engine failing to start may also cause other engines to fail to start
  - For stages with multiple engines a common cause factor of 5% is assumed for engine shutdown
  - Human rating is assumed to improve system reliability by about 4 times but due to changes in design and operation (primarily increasing the RS-68 nominal power level from 102% for the HUG to 108% for the human-rated systems) the overall reliability improvement achieved was actually between 2 to 2.5 times (see results on slide 6)

- **Safety Assessment**
  - LAS jettison occurs 30 seconds after first stage MECO (which also covers upperstage engine start) except for configuration 5 where LAS jettison occurs 30 seconds after booster MECO
  - Orion is assumed to have a blast overpressure tolerance of 1440 psf
  - Launch Abort System (LAS) is assumed to be designed to abort with an acceleration of 10 Gs and burning for 2 seconds
  - Launch abort is assumed to occur simultaneously with the initiation of the failure (no delay, or conversely, warning time is assumed)
  - Uncontained failure on any one EELV CBC is assumed to detonate all CBCs
  - There is a 75% mean likelihood of an uncontained failure of the first stage/booster propagating to the upperstage
  - The g's that the crew is exposed to during a nominal ascent trajectory is not considered in the safety assessment of the configuration s for modeling simplification purposes

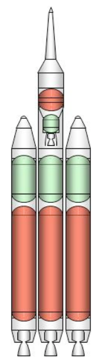
Reliability Assessment Methodology
The Process using SPREAD

The Streamlined Process for Reliability Evaluation of Ares Designs (SPREAD) model was used to support this analysis

Mission Profile

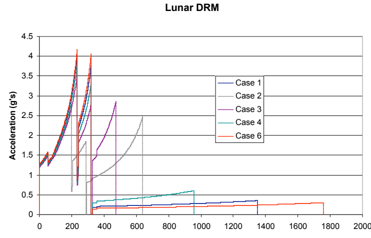
	Configuration 1
Stage 0	
Engine	2 x RS-68A
Burn Time (s)	244
Propellant Mass (lbm - ea)	451,749
Percent Prop Off-Loaded	0%
Percent Prop Residual	2%
Powerlevel (%)	102%
Sea-Level Thrust (lbf - ea)	663,000
Sea-Level Isp (s)	365

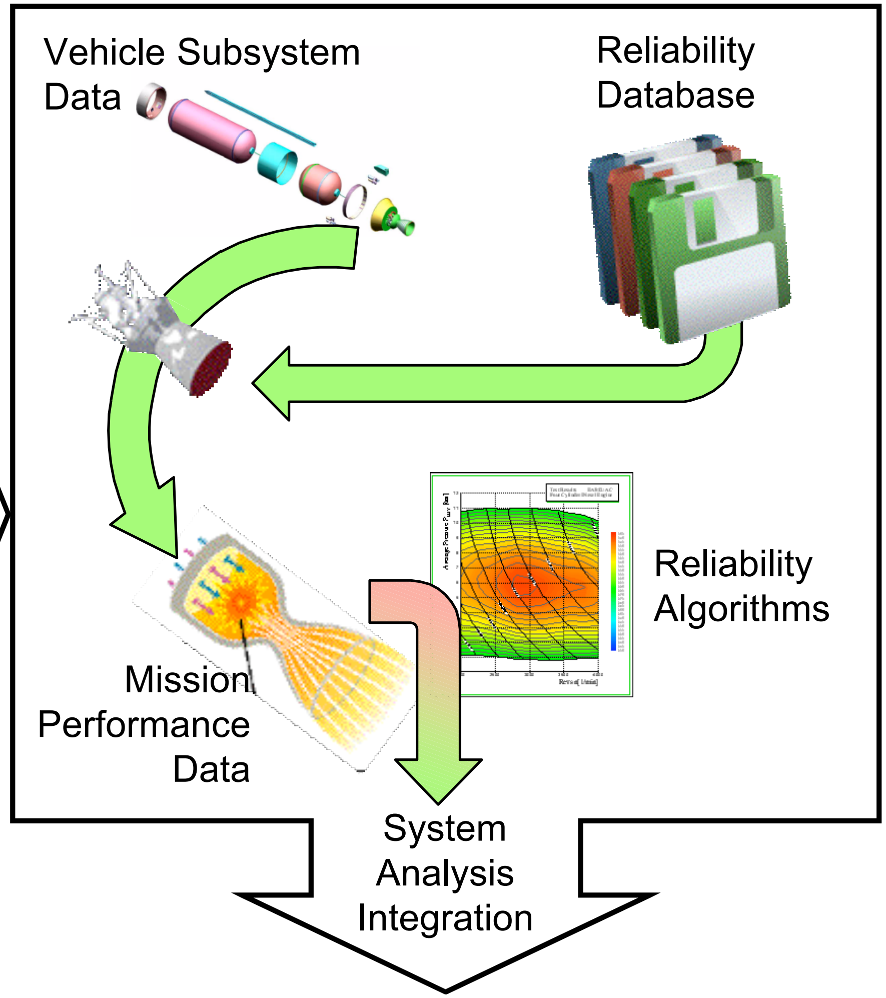
Vehicle Configuration



Configuration Design & Operational Data Input into SPREAD Model

Subsystem Parameters

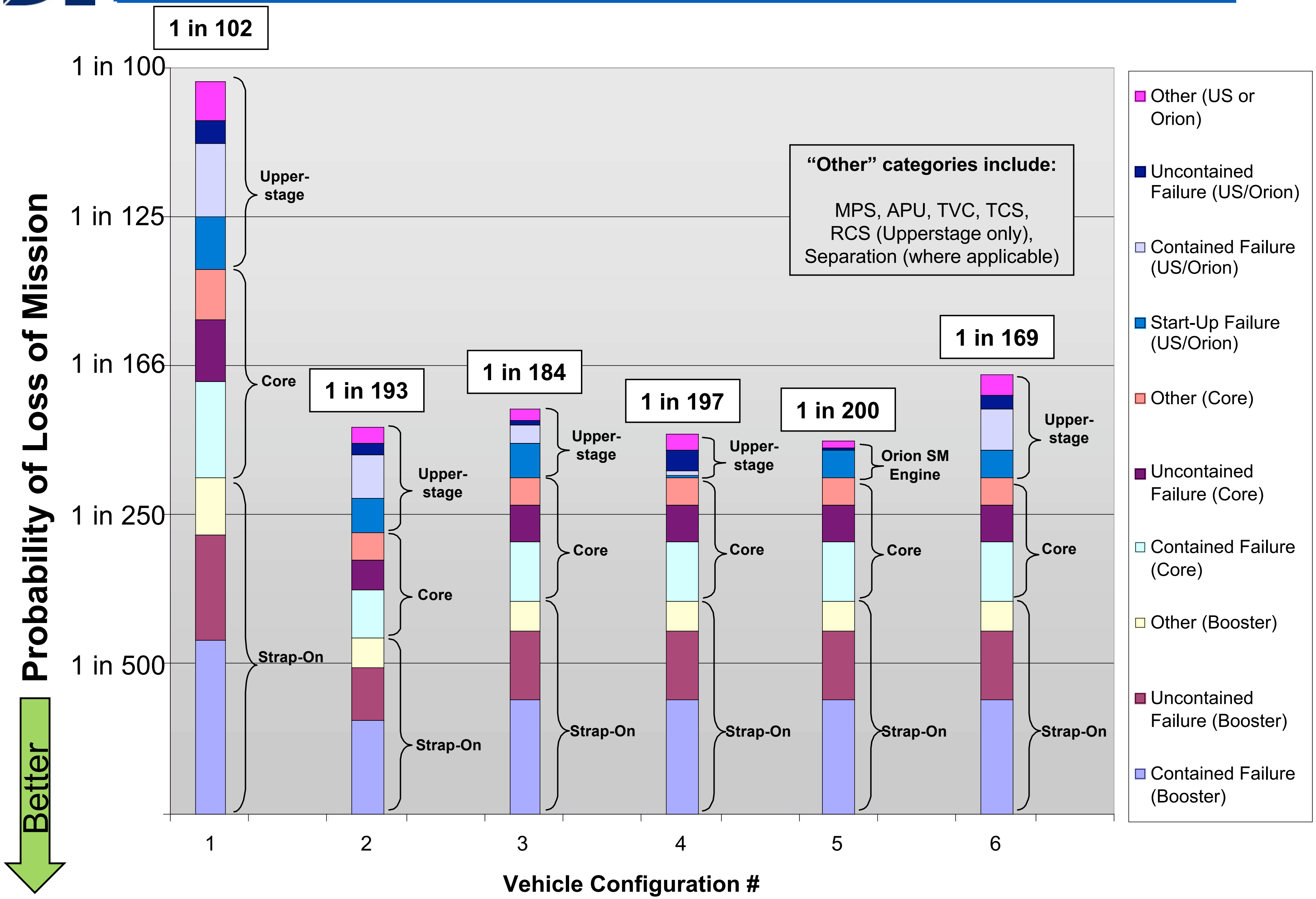




Reliability Evaluation Results

Mission LOM Comparison

all results generated by using SPREAD Model



Loss of Mission – Variation Explanations

RL-10 Based Upperstage

- **Configuration 1**
  - This LOM probability represents the baseline, non-human rated vehicle.
- **Configuration 6**
  - Configuration 6 represents the human-rated analog of Configuration 1. Probability of LOM is lower based almost entirely on human-rating.
- **Configuration 4**
  - Probability of LOM is lower than Configuration 6 due to engine-out capability on the 2^{nd} stage.*

J-2X Based Upperstage

- **Configuration 3**
  - For this configuration, the 4 RL-10's from configuration 4 are replaced by 1 J2-X which eliminates the engine-out capability and therefore increases the LOM probability.
- **Configuration 2**
  - Compared to Configuration 3, 2^{nd} stage performance is increased back to Ares I 2^{nd} stage levels, thus reducing the performance load on the CBC stages. Therefore the lower powered J2-X (compared to the RS-68) is utilized sooner thus lowering the overall LOM probability.

No Upperstage

- **Configuration 5**
  - This configuration has the lowest LOM probability because the upperstage is completely eliminated and the delta-V shortfall is made up by an orbital insertion burn from the simple and reliable, hypergolic Orion SM engine. Note that this configuration cannot support lunar missions however and has marginal ISS capability at best.

*A sensitivity analysis was performed to assess the effect of varying two of the main multiple engine assumptions used in this assessment. The results are shown on slide 8

Sensitivity Assessment on Engine-Out Parameters

- The baseline analysis of Configuration 4 assumes a 10% likelihood that one engine failing to start may also cause another engine to fail to start, as well as a common cause factor of 5% for engine shutdown during mainstage burn.
- A sensitivity analysis was performed varying these parameters from +/- 10% and +/- 5%, respectively

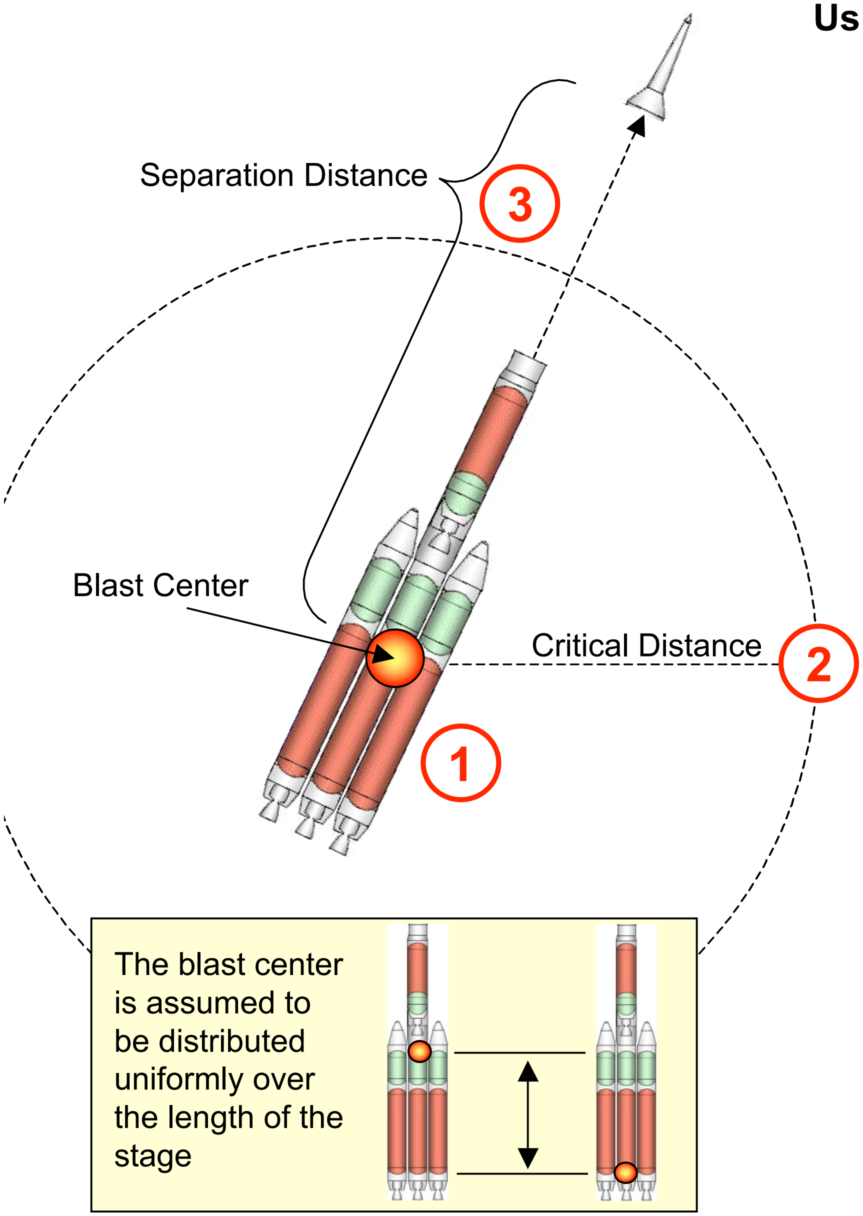
Note: Slightly lower LOM than Config 5 (0% / 0% case)

Note: Same LOM as Config 2 (20% / 10% case)

Common Cause Factor for Shutdown during Mainstage \ Likelihood that one engine failing to start may also cause another engine to fail to start	0%	10%	20%
0%	**LOM: 1 in 201** Start-Up Failure: 1 in 1,424,217 Engine Shutdown: 1 in 954,675	**LOM: 1 in 199** Start-Up Failure: 1 in 25,185 Engine Shutdown: 1 in 954,675	**LOM: 1 in 198** Start-Up Failure: 1 in 12,705 Engine Shutdown: 1 in 954,675
5%	**LOM: 1 in 198** Start-Up Failure: 1 in 1,424,217 Engine Shutdown: 1 in 15,860	**LOM: 1 in 197** Start-Up Failure: 1 in 25,185 Engine Shutdown: 1 in 15,860 ***Baseline Case***	**LOM: 1 in 195** Start-Up Failure: 1 in 12,705 Engine Shutdown: 1 in 15,860
10%	**LOM: 1 in 196** Start-Up Failure: 1 in 1,424,217 Engine Shutdown: 1 in 7,996	**LOM: 1 in 194** Start-Up Failure: 1 in 25,185 Engine Shutdown: 1 in 7,996	**LOM: 1 in 193** Start-Up Failure: 1 in 12,705 Engine Shutdown: 1 in 7,996

Safety Assessment Methodology

Dynamic Abort Risk Evaluator (DARE) Model

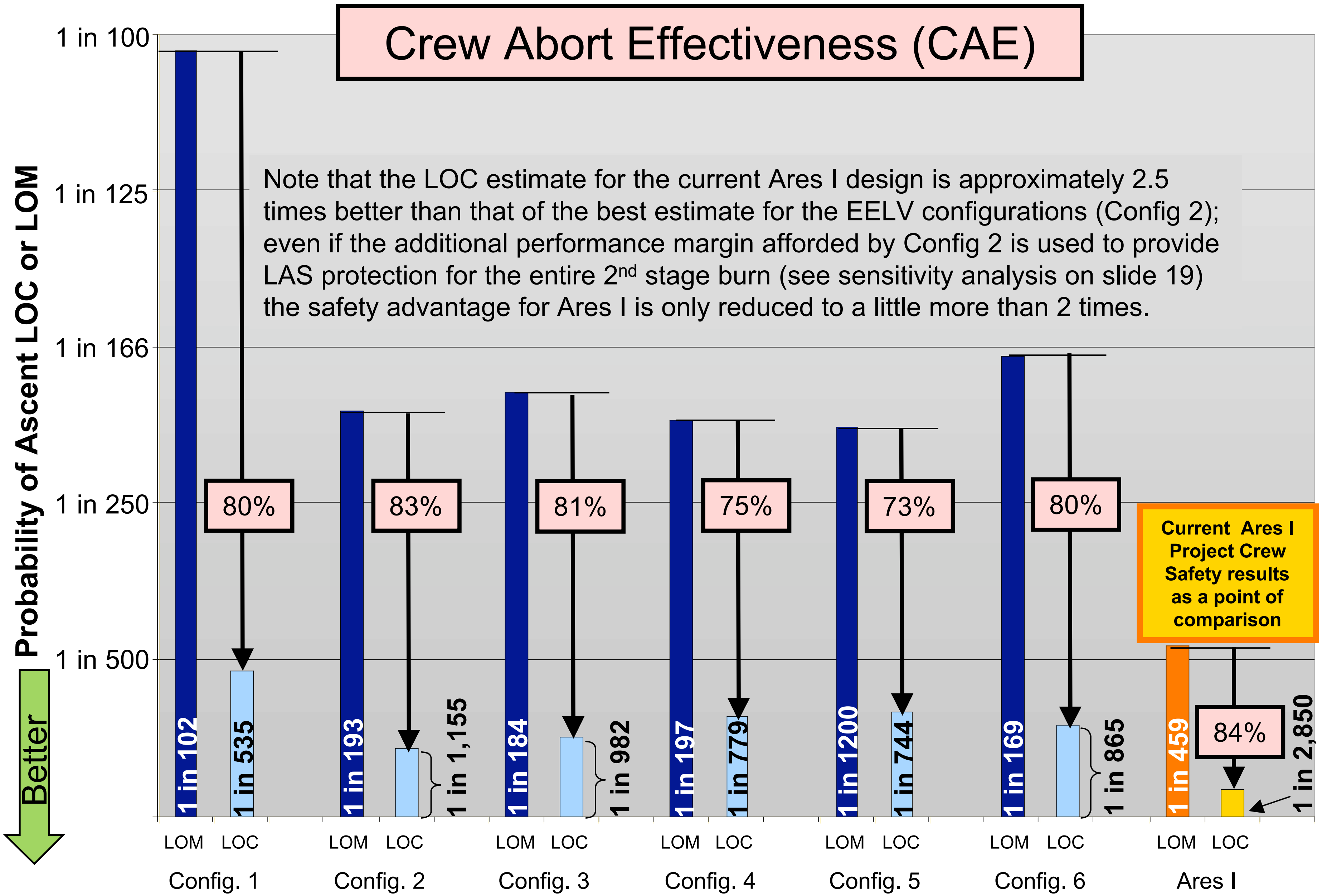


Using first-order equations:

1. **DARE calculates potential blast yield at time of failure**
   - Based on remaining propellant, fuel/oxidizer mixing ratios, stage propagation potential, and atmospheric conditions
2. **DARE determines the critical distance at which the blast pressure wave will no longer cause Orion failure**
   - A function of overpressure tolerance of Orion and atmospheric conditions
3. **DARE calculates the separation distance of Orion relative to the blast center**
   - Based on initial separation distance, LAS acceleration, LAS burn time, launch vehicle acceleration, and atmospheric conditions
4. **If Orion is outside of the critical blast pressure region, then a successful abort from the accident environment is assumed to have occurred**
5. **Potential for safe re-entry and recovery are assessed based on initial abort conditions**

Launch Vehicle LOC and LOM Comparison During Ascent

EELV results generated by using SPREAD and DARE Models



Safety & Abort Effectiveness – Variation Explanations

RL-10 Based Upperstage

- **Configuration 1**
  - The core and strap-on CBCs are fully loaded with propellant and the upperstage is relatively short, placing the Orion closer to any potential booster failures. Additionally, in the event of an upperstage failure, the stage height makes escaping the critical blast radius challenging.
- **Configuration 6**
  - This abort effectiveness is almost identical to Configuration 1 (due to identical vehicle geometries and nearly identical trajectories) however LOC improves due to benefits of human-rating.
- **Configuration 4**
  - Abort effectiveness is less than Configuration 6 because of the increased upperstage propellant load available in the event of propellant detonation.

J-2X Based Upperstage

- **Configuration 3**
  - Abort effectiveness is better than Configurations 4 & 6 due to the crew being higher on the stack. In addition more LAS coverage is provided over the upperstage trajectory given the shorter burn time for this stage due to the higher thrust and flowrates of the J2-X engine.
- **Configuration 2**
  - Compared to Configuration 3 there is a larger separation distance (~2x) provided by the upperstage, and the CBC propellant is 30% off-loaded on all 3 thereby reducing both the time and propellant available for any potential detonation on the CBCs.

No Upperstage

- **Configuration 5**
  - Compared to other configurations there is no 2nd stage propellant at all but the crew capsule is closer to any potential CBC failures. Therefore although this configuration was deemed the most reliable it is estimated to have the lowest safety.

Ares I Reasons for Higher Reliability and Safety

Reliability

- **Higher reliability of first/booster stage**
  - Single solid stage is provides one source of failure versus three sources (3 CBCs) for EELV with no benefits for additional boosters (e.g. no engine out capability)
  - Although lower performing (lower Isp) solid boosters provide more reliability per unit pound of thrust than liquid engines
    - Lower combustion pressures
    - Much less complex

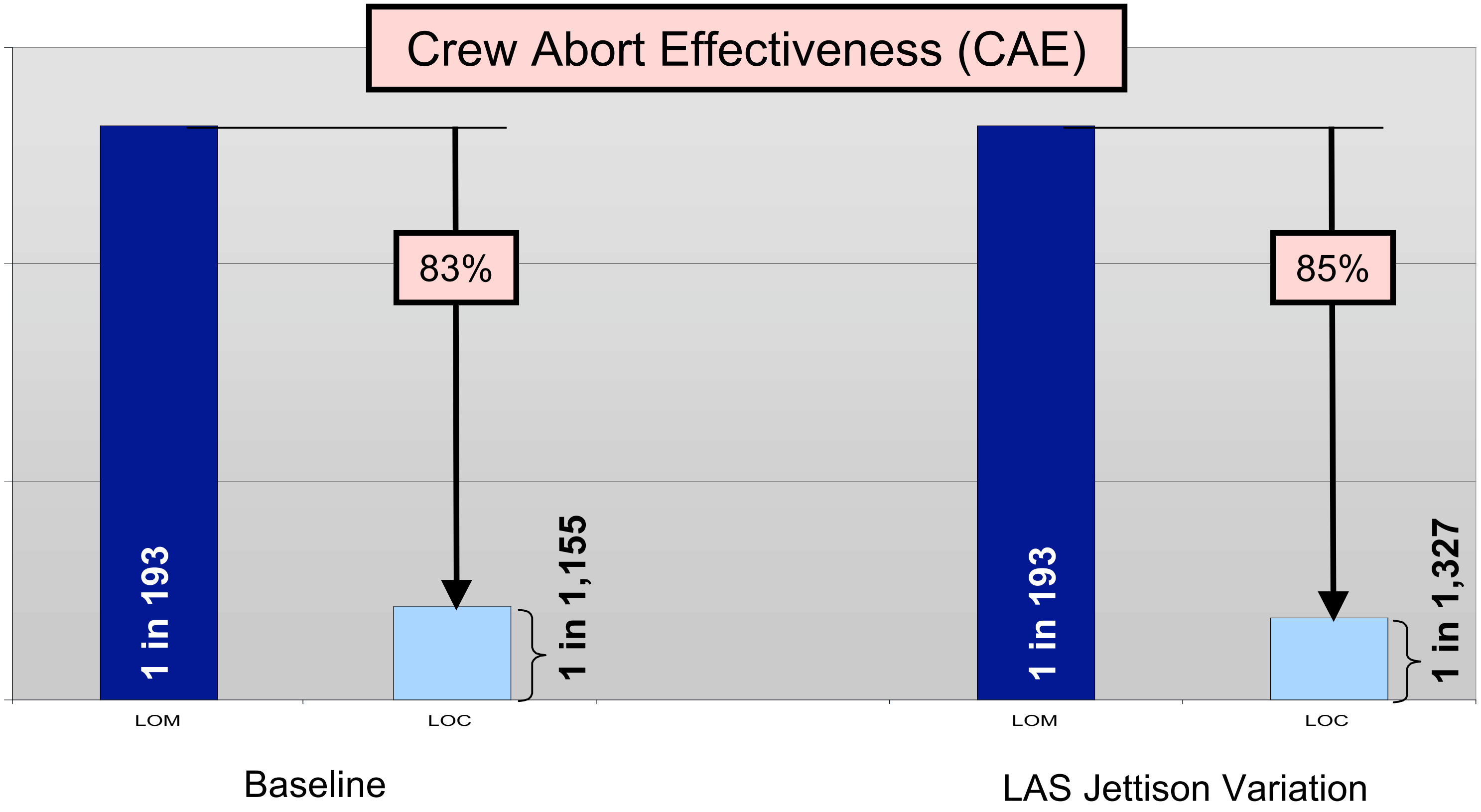
Safety

In the event of an uncontained First Stage failure on Ares I:

- **Low potential for rupture of the solid rocket first stage**
  - In the event of an uncontained failure, gas release may occur without rupture of the stage (e.g. Challenger) however abort analysis still assumes a conservative 30% of uncontained RSRB failures cause stage explosion
- **Low blast yield of the solid rocket first stage in the case of rupture**
  - The blast yield of a single RSRM is, at its worst, 20 times lower than that of the combined Strap-On and Core EELV CBCs
  - Solid rocket motors are pressure vessels which are more likely to rupture than detonate
- **Taller first stage height**
  - The first stage is ~30 ft taller than the EELV CBC, providing additional separation distance from a potential explosion

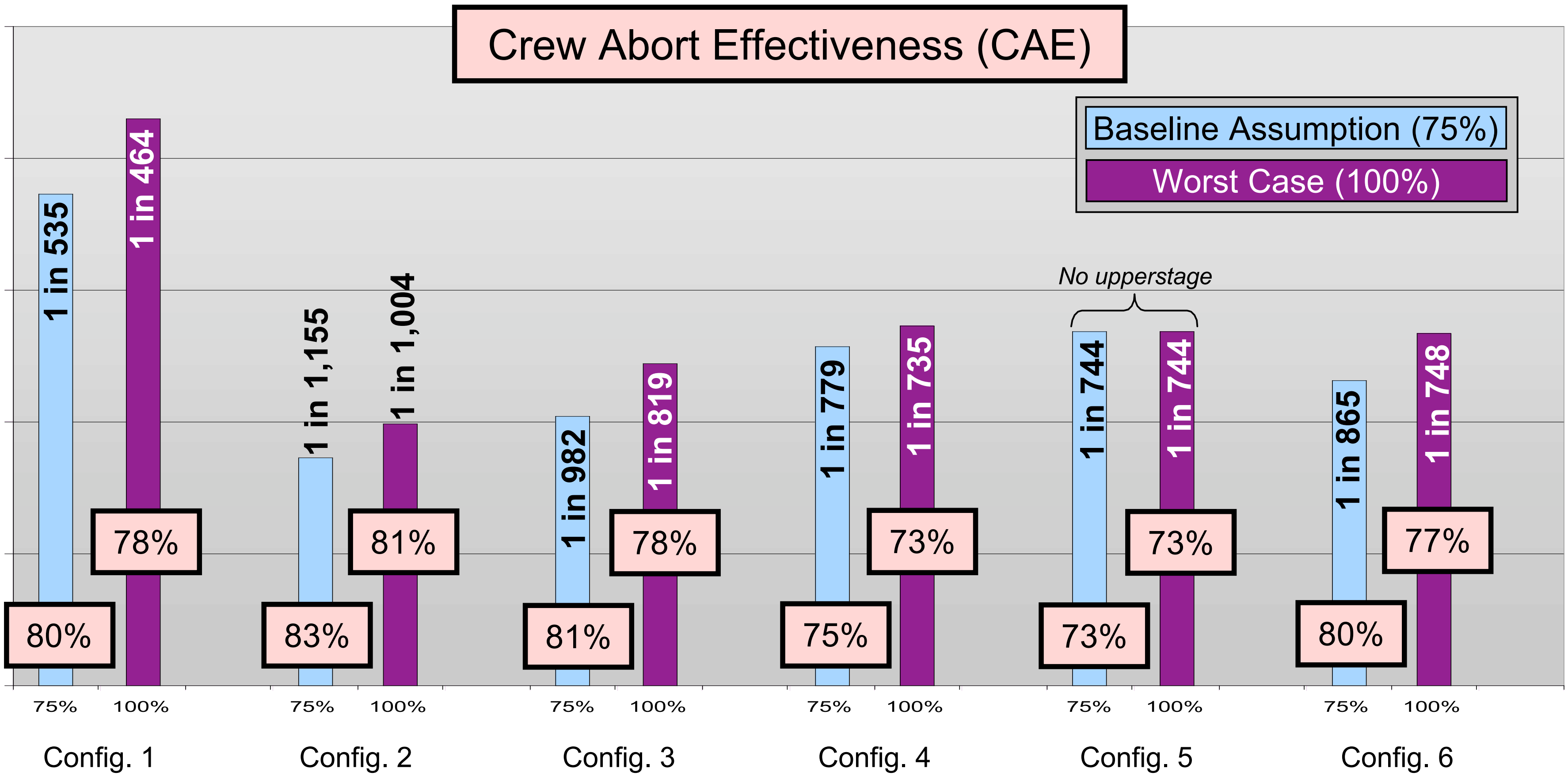
Sensitivity Assessment for LAS Jettison Time

- The baseline assumption is that LAS jettison occurs 30 seconds after first stage MECO (which also covers upperstage engine start)
- Configuration 2 has extra payload capability, so a sensitivity analysis was performed making the LAS available for the entire upperstage burn time. Below are the results (original results are shown to the left).



Sensitivity Assessment for Failure Propagation

- The baseline assumption is that there is a 75% mean likelihood of an uncontained failure of the first stage/booster propagating to the upperstage
- A sensitivity analysis was performed for the worst case, in which 100% of first stage/booster failures propagate to the upperstage. Below are the results (original results are shown to the left).



Summary Remarks

- **A substantial reduction in LOM risk is attributable to human-rating which directly leads to an improvement in safety (comparison of configurations 1 and 6 demonstrates this)**
- **The human-rated configurations are relatively close in LOM risk**
  - Vehicles with the lowest LOM risk either
    - have features in the upperstage design that improve reliability (configuration 4 has engine-out capability in the upperstage) or remove the upperstage entirely (configuration 5)
    - OR shed the booster stages (which use higher thrust engines) earlier thus removing the three RS-68s as potential failure sources (configuration 2)
- **LOM risk for lunar mission capable configurations can be improved by having engine-out capability on the 2nd stage (Config 4), though the overall effect is minor given the fact that this does not to attenuate the LOM risk from the CBCs (which make up a substantial portion of the LOM risk)**
- **Configurations with the lowest LOC risk make use of elongated upperstages which act as a buffer between Orion and the potential catastrophic failure of the booster stages**
- **LOC risk can be further reduced by extending the LAS jettison further into ascent (note that for short upperstages this advantage would be muted by the short reaction time required)**
- **Even under the best conditions (not jettisoning the LAS until 2nd stage MECO on the most capable and safest EELV-based option), the current Ares I still provides about twice as much safety during ascent (as measured by the LOC estimates)**

EELV Based Crew Launch Options Results Detailed Summaries by Configuration

BACK-UP

Configuration 1

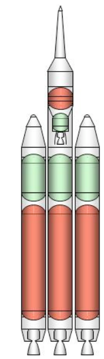
EELV Strap-On CBC	
Contained Engine Failure (Booster)	1 in 430
Uncontained Engine Failure (Booster)	1 in 711
Other (Booster)	1 in 1,300
Total	1 in 222

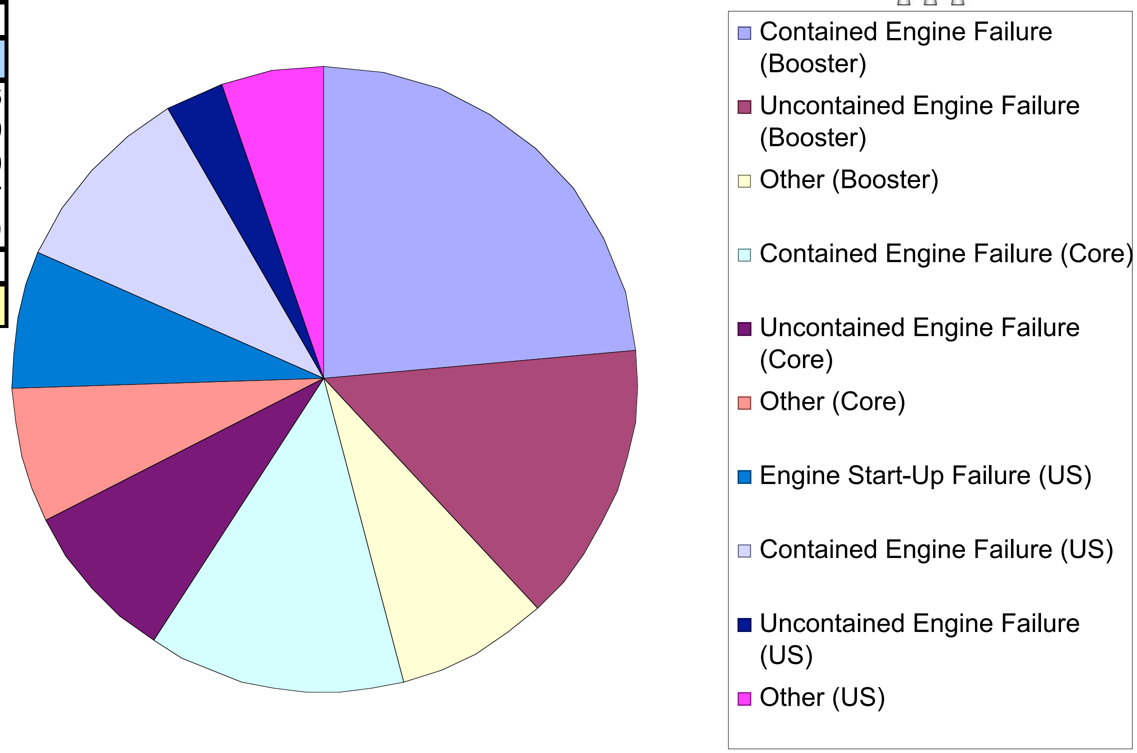
EELV Core CBC	
Contained Engine Failure (Core)	1 in 775
Uncontained Engine Failure (Core)	1 in 1,204
Other (Core)	1 in 1,476
Total	1 in 357

RL-10 B-2 Upperstage	
Engine Start-Up Failure (US)	1 in 1,406
Contained Engine Failure (US)	1 in 1,029
Uncontained Engine Failure (US)	1 in 3,170
Other (US)	1 in 1,977
Total	1 in 399

Vehicle Total	**1 in 102**

Strap-on	Planned (HUG
Core	Planned (HUG
Core/Strap-on Engine	RS-68A
Upperstage (US)	Existing
US Engine	1 RL-10 B2
Engine-Out	No





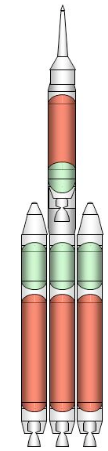
"Other" categories include:

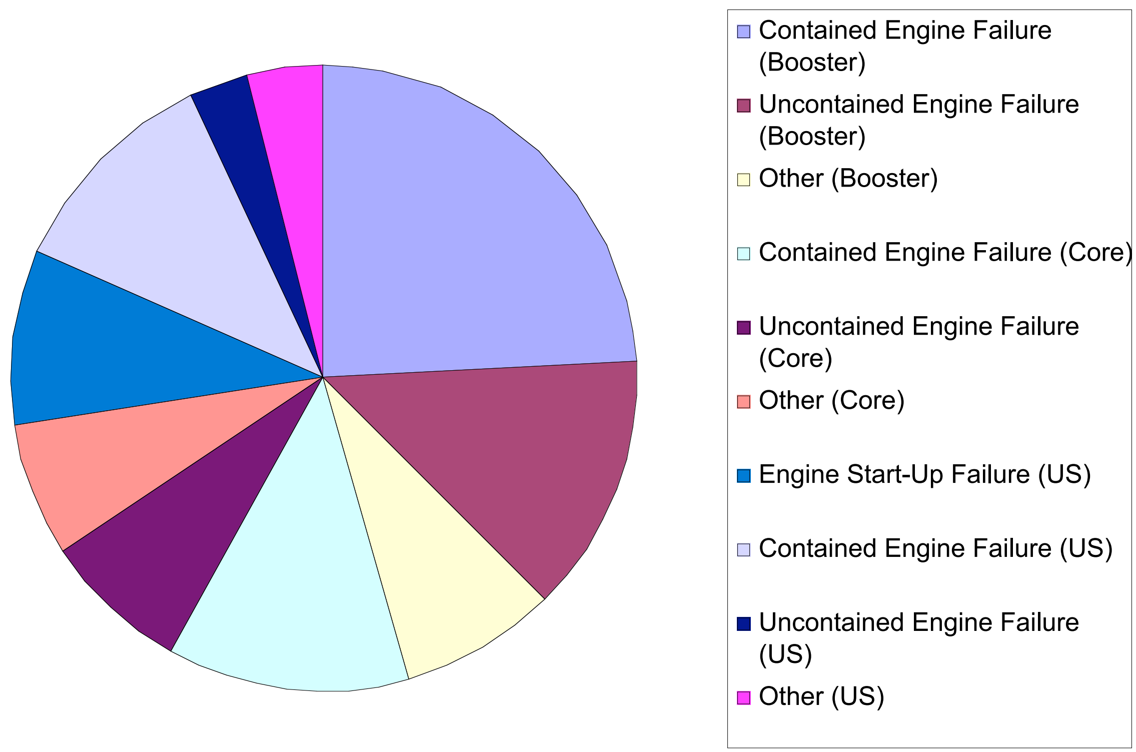
MPS, APU, TVC, TCS, RCS (Upperstage only), Separation

Configuration 2

EELV Strap-On CBC	
Contained Engine Failure (Booster)	1 in 803
Uncontained Engine Failure (Booster)	1 in 1,421
Other (Booster)	1 in 2,422
Total	1 in 423
EELV Core CBC	
Contained Engine Failure (Core)	1 in 1,548
Uncontained Engine Failure (Core)	1 in 2,602
Other (Core)	1 in 2,733
Total	1 in 716
J-2X Upperstage	
Engine Start-Up Failure (US)	1 in 2,137
Contained Engine Failure (US)	1 in 1,691
Uncontained Engine Failure (US)	1 in 6,017
Other (US)	1 in 5,007
Total	1 in 702
Vehicle Total	**1 in 193**

Strap-on	Human-Rated
Core	Human-Rated
Core/Strap-on Engine	RS-68B HR
Upperstage (US)	Ares I US
US Engine	1 J2-X
Engine-Out	No





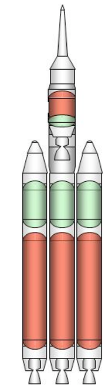
"Other" categories include:

MPS, APU, TVC, TCS, RCS (Upperstage only), Separation

Configuration 3

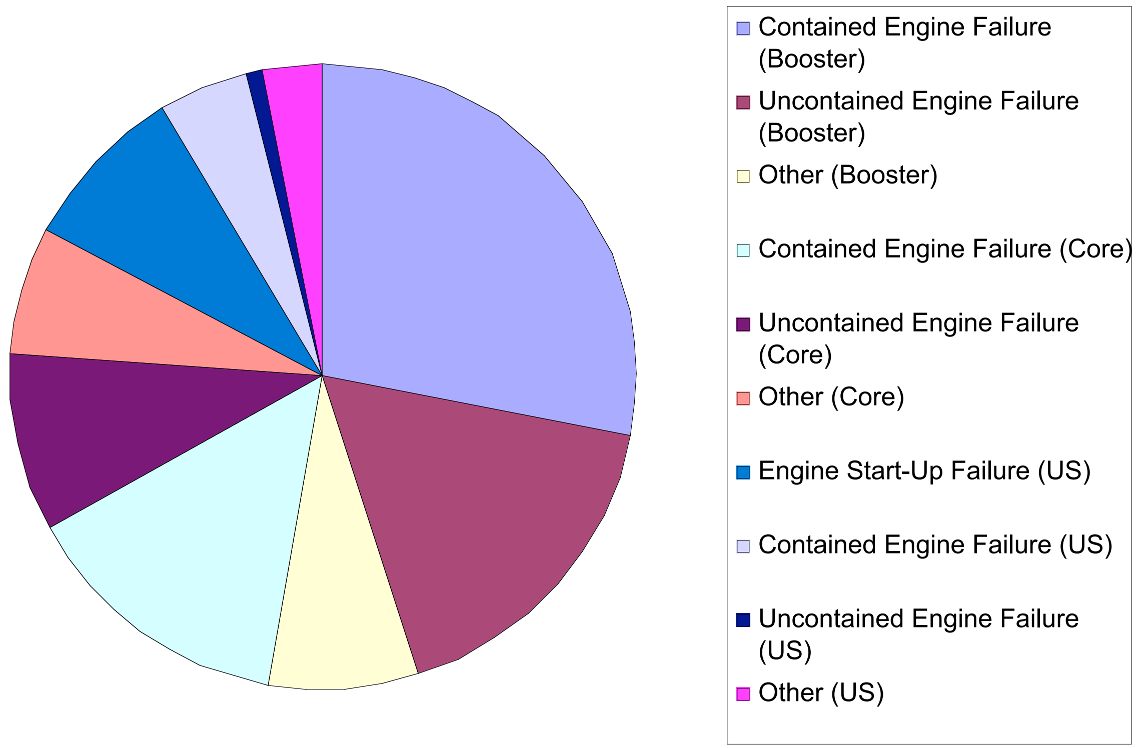
EELV Strap-On CBC	
Contained Engine Failure (Booster)	1 in 656
Uncontained Engine Failure (Booster)	1 in 1,093
Other (Booster)	1 in 2,352
Total	1 in 349
EELV Core CBC	
Contained Engine Failure (Core)	1 in 1,293
Uncontained Engine Failure (Core)	1 in 2,040
Other (Core)	1 in 2,668
Total	1 in 610
J-2X Upperstage	
Engine Start-Up Failure (US)	1 in 2,137
Contained Engine Failure (US)	1 in 4,050
Uncontained Engine Failure (US)	1 in 18,707
Other (US)	1 in 6,174
Total	1 in 1,075
Vehicle Total	**1 in 184**

Strap-on	Human-Rated
Core	Human-Rated
Core/Strap-on Engine	RS-68B HR
Upperstage (US)	Resized Ares I
US Engine	1 J2-X
Engine-Out	No



"Other" categories include:

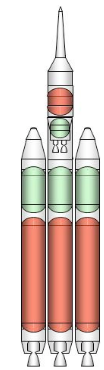
MPS, APU, TVC, TCS, RCS (Upperstage only), Separation

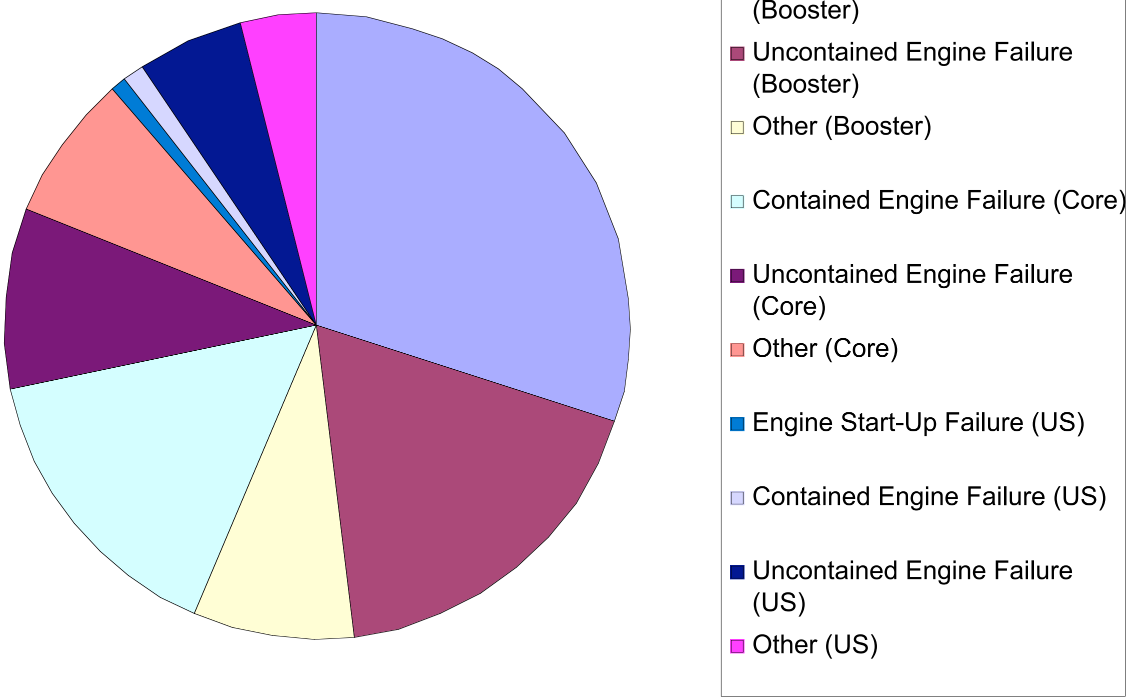


Configuration 4

EELV Strap-On CBC	
Contained Engine Failure (Booster)	1 in 656
Uncontained Engine Failure (Booster)	1 in 1,093
Other (Booster)	1 in 2,352
Total	1 in 349
EELV Core CBC	
Contained Engine Failure (Core)	1 in 1,293
Uncontained Engine Failure (Core)	1 in 2,040
Other (Core)	1 in 2,668
Total	1 in 610
RL-10 A-4-2 Upperstage	
Engine Start-Up Failure (US)	1 in 25,185
Contained Engine Failure (US)	1 in 15,860
Uncontained Engine Failure (US)	1 in 3,633
Other (US)	1 in 4,894
Total	1 in 1,717
Vehicle Total	**1 in 197**

Strap-on	Human-Rated
Core	Human-Rated
Core/Strap-on Engine	RS-68B HR
Upperstage (US)	New Human Rated US
US Engine	4 RL-10-A-4
Engine-Out	Yes





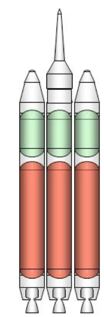
"Other" categories include:

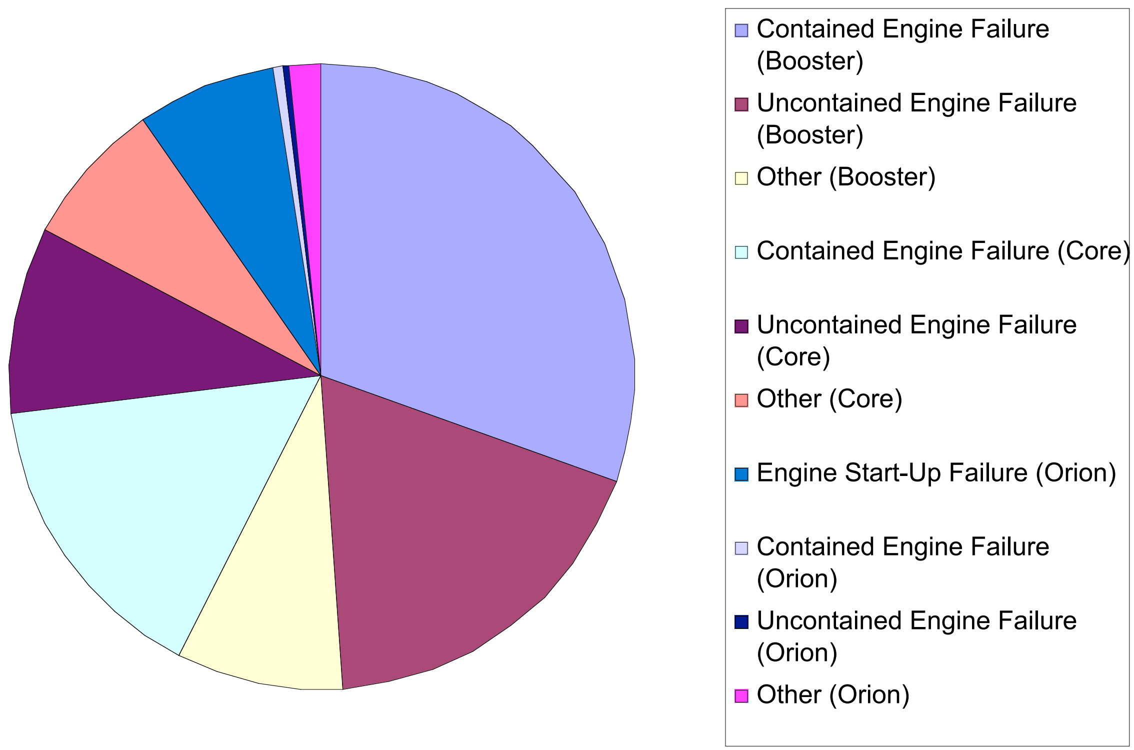
MPS, APU, TVC, TCS, RCS (Upperstage only), Separation

Configuration 5

EELV Strap-On CBC	
Contained Engine Failure (Booster)	1 in 656
Uncontained Engine Failure (Booster)	1 in 1,093
Other (Booster)	1 in 2,352
Total	1 in 349
EELV Core CBC	
Contained Engine Failure (Core)	1 in 1,293
Uncontained Engine Failure (Core)	1 in 2,040
Other (Core)	1 in 2,668
Total	1 in 610
Orion SM	
Engine Start-Up Failure (Orion)	1 in 2,726
Contained Engine Failure (Orion)	1 in 51,800
Uncontained Engine Failure (Orion)	1 in 54,923
Other (Orion)	1 in 12,419
Total	1 in 2,063
Vehicle Total	**1 in 200**

Strap-on	Human-Rated
Core	Human-Rated
Core/Strap-on Engine	RS-68B HR
Upperstage (US)	No US
US Engine	- - -
Engine-Out	- - -





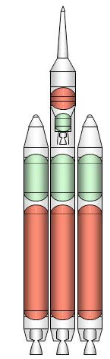
“Other” categories include:

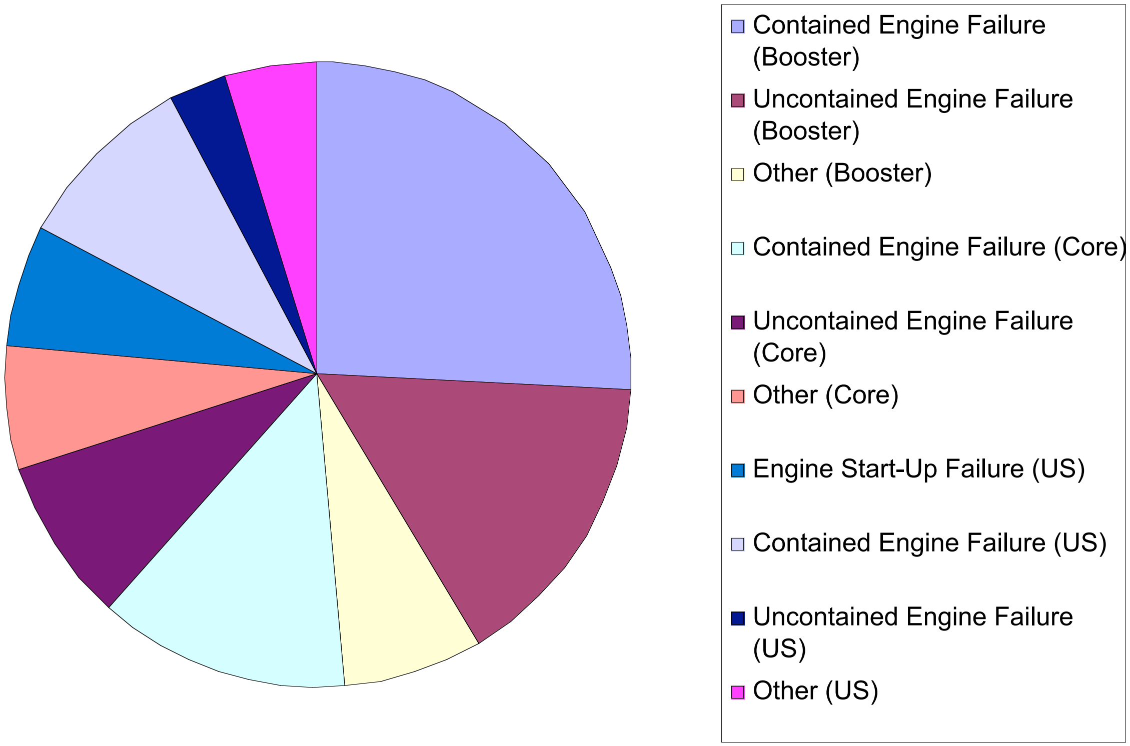
MPS, APU, TVC, TCS, RCS (Upperstage only)

Configuration 6

EELV Strap-On CBC	
Contained Engine Failure (Booster)	1 in 656
Uncontained Engine Failure (Booster)	1 in 1,093
Other (Booster)	1 in 2,352
Total	1 in 349
EELV Core CBC	
Contained Engine Failure (Core)	1 in 1,293
Uncontained Engine Failure (Core)	1 in 2,040
Other (Core)	1 in 2,684
Total	1 in 611
RL-10 A-4-2 Upperstage	
Engine Start-Up Failure (US)	1 in 2,564
Contained Engine Failure (US)	1 in 1,815
Uncontained Engine Failure (US)	1 in 5,593
Other (US)	1 in 3,558
Total	1 in 714
Vehicle Total	**1 in 169**

Strap-on	Human-Rated
Core	Human-Rated
Core/Strap-on Engine	RS-68B HR
Upperstage (US)	Ares I US
US Engine	1 RL-10-A-4
Engine-Out	No





"Other" categories include:

MPS, APU, TVC, TCS, RCS (Upperstage only), Separation