A Model-Based Systems Engineering Approach to the Heavy Lift Launch System Architecture Study

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Orbital HLS Study Team

Orbital Launch Systems Group

Orbital Advanced Programs Group

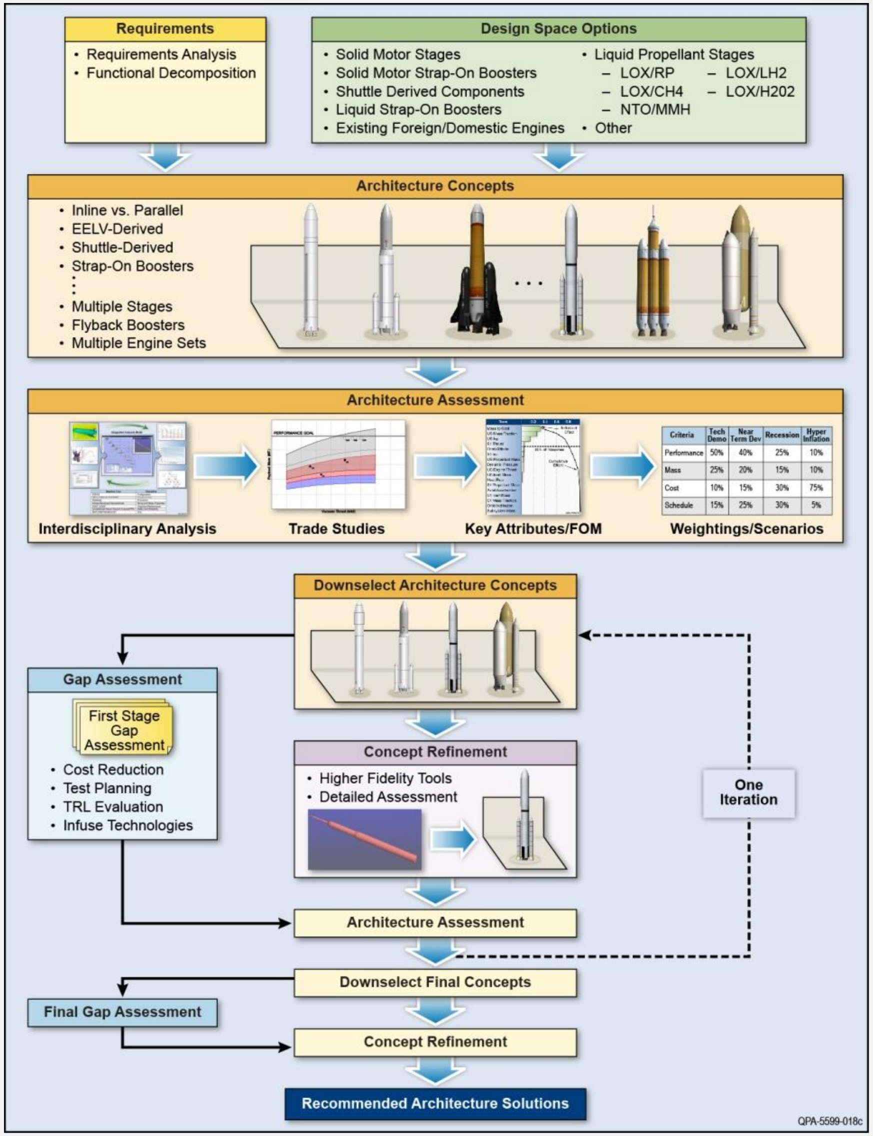
Other Major Contributors

Orbital HLS Architecture Study Overview

- **Orbital selected for NASA MSFC Heavy Lift & Propulsion Technology Systems Analysis and Trade Study (Nov. 2010 – May 2011)**

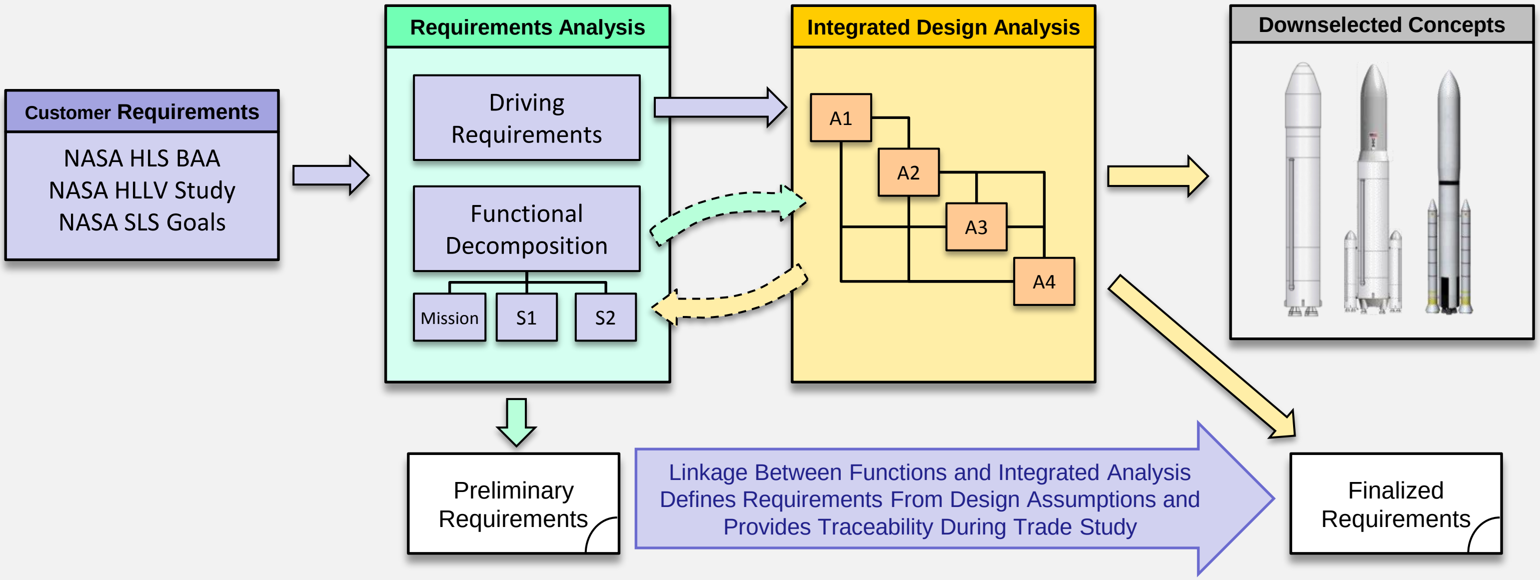
- **Primary study objective was to analyze multiple HLS architectures and make recommendations for system concepts capable of affordably conducting the NASA DRMs for LEO, Lunar exploration, and Mars exploration**

- **Orbital follows a Top-down, Goal-driven Study Approach to Develop Optimal, Robust Heavy Lift System Architectures**
  - Capture and synthesize requirements
  - Explore design space for architecture concepts
  - Perform assessments and sensitivities against weighted system attributes
  - Define candidate architecture concepts for refinement and gap assessment



HLS Model-Based Systems Engineering

- **Model-Based Systems Engineering (MBSE):** *the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual phase and continuing throughout development and later life cycle phases.*[(1)]
- **MBSE processes were utilized with the integrated design analysis to define top-level requirements and provide traceability during the HLS study**



Driving Requirements

- Core LV Min LEO Payload (100 mT)
- Evolved LV Min LEO Payload (150 mT)
- LEO Orbit (30x130 nmi @ 28.5°)
- Maximum LV Diameter (10 m)
- Launch Pad/Complex (KSC LC-39)
- Maximum Integrated LV Height (390 ft, VAB Doors)
- Human Rating (NASA 8705.2B)
- Annual Flight Rate (Min 2, Max 4)
- Launch System IOC (CY 2016)
- Max Launch System Costs from ATP thru 1st Flight ($11.5B)

Functional/Design Assumptions

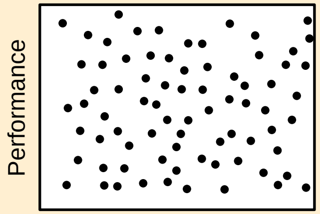
- Payload Shroud Shape & Diameter
- Payload Shroud Length
- Maximum Acceleration
- Maximum Dynamic Pressure
- LV Trajectory Guidance (pitch/gravity turn/alpha events)
- Launch System Elements Materials
- Launch System Factor of Safety
- Fairing Jettison Conditions and Sequencing
- Propellant Boil-off Rate
- Crew Module and Launch Abort System Mass
- LAS Jettison Conditions and Sequencing
- Unusable Tank Volume/Ullage

(1) INCOSE SE Vision, INCOSE-TP-2004-00402, Sep 2007

HLS Architecture Development & Assessment

HLS Architecture Development & Assessment

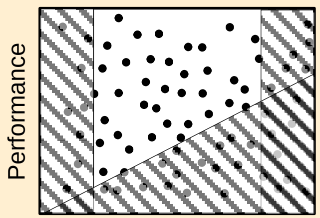
Developed Trade Space of HLS Concepts (1900+)



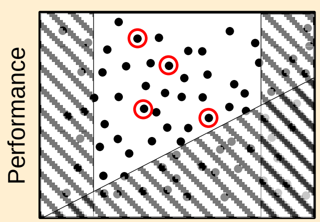
Design Concepts

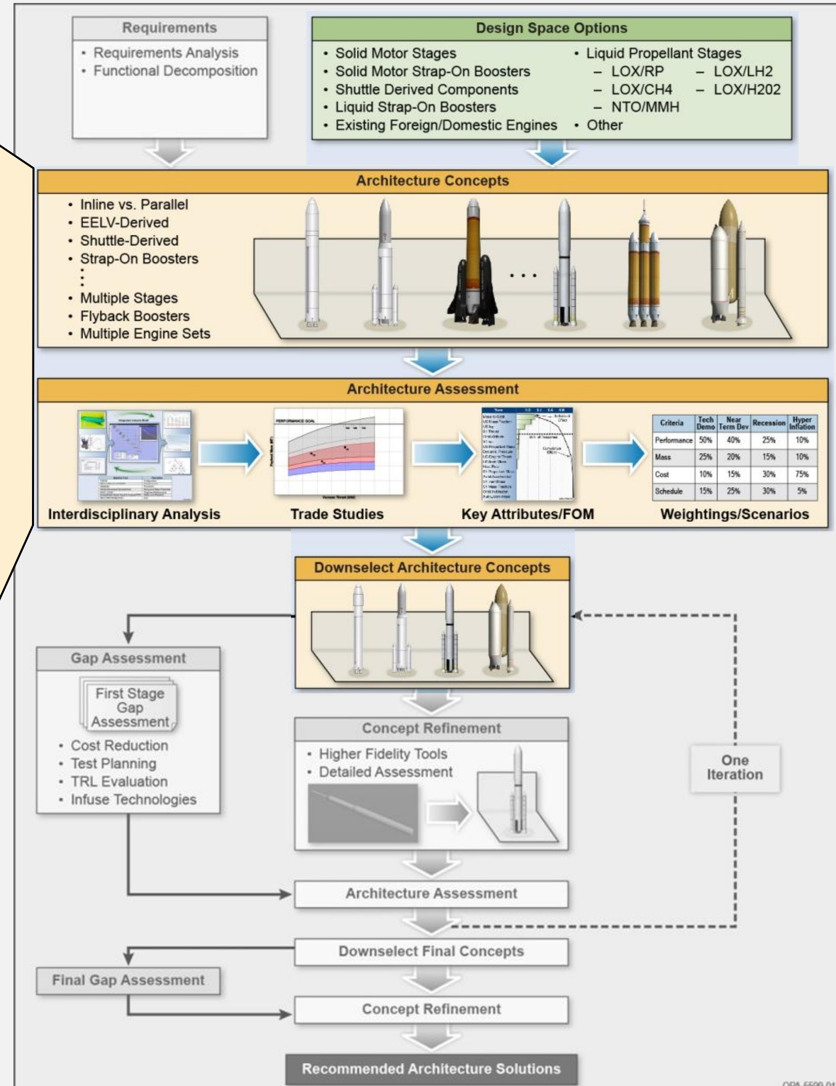
1. EELV-Derived
2. Shuttle-Derived
3. Strap-On Boosters
4. Multiple Stages
5. Flyback Boosters
6. Multiple Engine Sets

Feasibility Assessment based on Risk, Performance, & Cost



Concepts Selected for Refinement & Gap Assessment





HLS Architecture Trade Space Concepts

- **Full Factorial Trade Space Contains Almost 2000 Configurations**
- **Assess Each Concept based on a Qualitative Development Risk Assessment**
  - Risk defined as a potential threat to defined cost and schedule goals

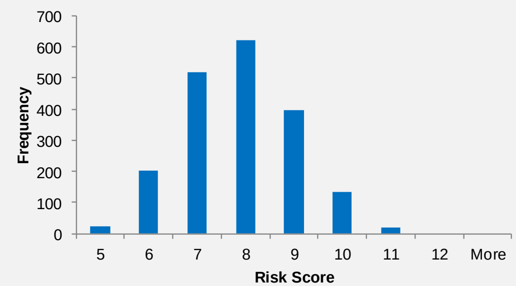
Stage 1	Boosters	Upper Stage
<u>Cores</u> • External Tank • Stretched External Tank • Delta IV CBC • Atlas V CCB • 1.125Klbf Thrust Core <u>Engines</u> • RS-68 • SSME (Expendable) • ORSC Derived / RS-84 • RD-170 / RD-180 • Other new development	Shuttle SRM (4-Segment) Shuttle SRM (5-Segment) 1.125Klbf Thrust LRB Taurus II Stage 1 Delta IV CBC Atlas V CCB Reusable Booster System	<u>LOX/LH2</u> • RS-68 • SSME (Expendable) • RL-60 • J-2X (1) • J-2X (2) • RL-10 <u>LOX/RP</u> • RD-0124 (or equivalent) • AJ-26 <u>LOX/CH4</u> <u>Solid Motors</u> • RSRM-Derived

Full Factorial Matrix of HLS Concepts

Concept #	*Core*	*Core Engine*	*Boosters*	*US Engine*
1	ET	RS-68	No Booster	RS-68
2	Stretched ET	RS-68	No Booster	RS-68
3	Delta IV CBC	RS-68	No Booster	RS-68
4	Atlas V CBC	RS-68	No Booster	RS-68
5	1.125klbm Core	RS-68	No Booster	RS-68
6	1.125klbm Core	RS-68	No Booster	RS-68
7	ET	SSME (Expendable)	No Booster	RS-68
8	Stretched ET	SSME (Expendable)	No Booster	RS-68
9	Delta IV CBC	SSME (Expendable)	No Booster	RS-68
10	Atlas V CBC	SSME (Expendable)	No Booster	RS-68
11	1.125klbm Core	SSME (Expendable)	No Booster	RS-68
12	1.125klbm Core	SSME (Expendable)	No Booster	RS-68
…	…	…	…	…
1917	Delta IV CBC	New Engine	1.125klbm Core	RSRM Derived
1918	Atlas V CBC	New Engine	1.125klbm Core	RSRM Derived
1919	1.125klbm Core	New Engine	1.125klbm Core	RSRM Derived
1920	1.125klbm Core	New Engine	1.125klbm Core	RSRM Derived

Element	Risk Score	Justification / Comment
<u>Cores</u>		
•External Tank	1	Existing hardware
•Stretched External Tank	2	Modification to existing hardware; extensively studied.
•Delta IV CBC	2	Modification to existing hardware; extensively studied.
•Atlas V CCB	2	Modification to existing hardware; extensively studied.
•1.125Klbf Thrust Core	2	Modification to existing hardware.
<u>Core Engines</u>		
•RS-68	2	Modification to existing hardware; extensively studied.
•SSME (Expendable)	2	Modification to existing hardware; extensively studied.
•ORSC Derived / RS-84	3	Design exists, no existing hardware.
•RD-170 / RD-180	2	Modification to existing hardware; extensively studied.
•Other new development	3	No existing hardware.
<u>Boosters</u>		
•No Booster	1	No dev req'd but may add risk to other elements
•Shuttle SRM (4-Segment)	1	Existing Hardware
•Shuttle SRM (5-Segment)	2	Unflown modification to existing hardware
•1.125Klbf Thrust LRB	2	Modification to existing hardware.
•Taurus II Stage 1	2	Existing hardware with new application
•Delta IV CBC	1	Existing hardware
•Atlas V CCB	1	Existing hardware
•Reusable Booster System	3	Significant development required.
Upper Stage Engines		
<u>LOX/LH2</u>		
•RS-68	2	Modification for air-start, restart required.
•SSME (Expendable)	2	Modification for air-start, restart required.
•RL-60	2	Many engines would be required to achieve T/W.
•J-2X (1)	1	Mature design.
•J-2X (2)	1	Mature design.
•RL-10	3	Many engines would be required to achieve T/W.
<u>LOX/RP</u>		
•RD-0124 (or equivalent)	2	Not a US engine.
•AJ-26	2	Not an upper-stage engine; would require modification / redesign.
<u>Solid Motors</u>		
•RSRM-Derived	3	No existing design

Trade Space Sorted by Risk Assessment



HLS Lowest Risk Trade Concepts

- **Trade Space Reduced to 30+ Concepts Based on Engineering Judgment and Qualitative Risk Assessment**

- **Eliminating :**
  - EELV-class cores stages as core options due to cost and performance
  - Un-stretched ET due to performance
  - Options without boosters due to the large number of main engines required to achieve sufficient T/W
  - All but the lowest risk booster options

- **Higher Risk Option Added:**
  - ➢RS-68 (w/ air-light capability) Upper Stage added to compare against J-2X

- **Further trade space options under consideration:**
  - ➢RS-25E w/ air-light capability
  - ➢AJ-26 & AJ-26X
  - ➢New 1M lbf LOX/RP-1 Engine
  - ➢Core Stage Diameter
  - ➢Upper Stage Diameter

LOX / LH2 Core

Concept	Core	Core Engine	Booster	Second Stage Engine	Risk Score
512	Stretched ET	RS-68	4 Seg SRM	J-2X (x1)	6
518	Stretched ET	SSME (Expendable)	4 Seg SRM	J-2X (x1)	6
602	Stretched ET	RS-68	Delta IV CBC	J-2X (x1)	6
608	Stretched ET	SSME (Expendable)	Delta IV CBC	J-2X (x1)	6
632	Stretched ET	RS-68	Atlas V CBC	J-2X (x1)	6
638	Stretched ET	SSME (Expendable)	Atlas V CBC	J-2X (x1)	6
752	Stretched ET	RS-68	4 Seg SRM	J-2X (x2)	6
758	Stretched ET	SSME (Expendable)	4 Seg SRM	J-2X (x2)	6
842	Stretched ET	RS-68	Delta IV CBC	J-2X (x2)	6
848	Stretched ET	SSME (Expendable)	Delta IV CBC	J-2X (x2)	6
872	Stretched ET	RS-68	Atlas V CBC	J-2X (x2)	6
878	Stretched ET	SSME (Expendable)	Atlas V CBC	J-2X (x2)	6
32	Stretched ET	RS-68	4 Seg SRM	RS-68	7
38	Stretched ET	SSME (Expendable)	4 Seg SRM	RS-68	7
122	Stretched ET	RS-68	Delta IV CBC	RS-68	7
128	Stretched ET	SSME (Expendable)	Delta IV CBC	RS-68	7
152	Stretched ET	RS-68	Atlas V CBC	RS-68	7
158	Stretched ET	SSME (Expendable)	Atlas V CBC	RS-68	7

LOX / RP Core

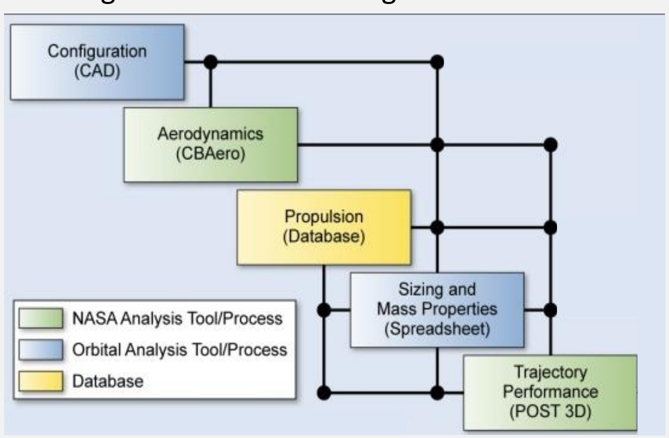
Concept	Core	Core Engine	Booster	Second Stage Engine	Risk Score
530	Stretched ET	RD-180	4 Seg SRM	J-2X (x1)	6
620	Stretched ET	RD-180	Delta IV CBC	J-2X (x1)	6
650	Stretched ET	RD-180	Atlas V CBC	J-2X (x1)	6
770	Stretched ET	RD-180	4 Seg SRM	J-2X (x2)	6
860	Stretched ET	RD-180	Delta IV CBC	J-2X (x2)	6
890	Stretched ET	RD-180	Atlas V CBC	J-2X (x2)	6
50	Stretched ET	RD-180	4 Seg SRM	RS-68	7
140	Stretched ET	RD-180	Delta IV CBC	RS-68	7
170	Stretched ET	RD-180	Atlas V CBC	RS-68	7
1490	Stretched ET	RD-180	4 Seg SRM	AJ-26	7
1580	Stretched ET	RD-180	Delta IV CBC	AJ-26	7
1610	Stretched ET	RD-180	Atlas V CBC	AJ-26	7

HLS Feasibility Assessment Approach

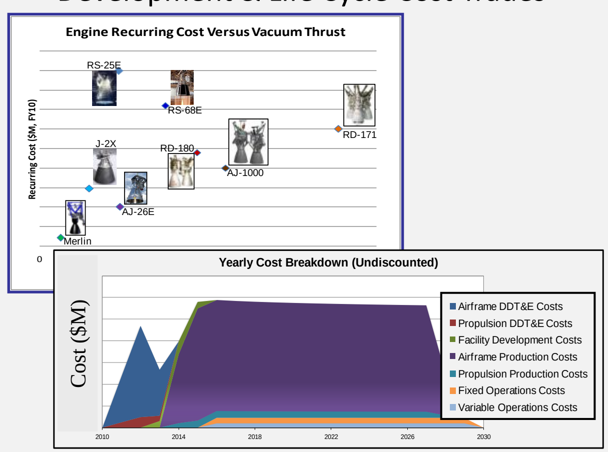
- **Feasibility Assessment Conducted for 30+ Low Risk Trade Concepts based on Performance, Development Cost, Life Cycle Cost, & Propulsion System Reliability**

Attribute	Figures of Merit	Feasibility Assessment
Performance	Payload Mass	• Sized Core and Upper Stage based on payload mass, propulsion parameters, and thrust-to-weight (T/W) – T/W at Liftoff: 1.2; T/W at Upper Stage Ignition: 0.8 – Validated Number of Engines Required to Match Total Thrust at Liftoff Fits on Core 27.5-ft Diameter • Performed POST 3DOF Trajectory Analysis to Estimate HLS Concept Payload Capability to LEO Orbit – LEO Orbit: 30 x 130 nmi @ 51.6°; Orbit Insertion at 130 nmi • Iterated on Payload Mass Between Sizing and Trajectory Analysis to Obtain Converged HLS Solution
Development Cost	DDT&E, TFU	• Development Cost estimated for Trade Space Concepts using NAFCOM08 • DDT&E + TFU Costs based on subsystem weights, booster/engine actual costs, and programmatic wraps • Programmatic wraps assumptions: Fee = 12%; Program Support = 12%, Contingency = 30%; Vehicle Level Integration = 8%
Life Cycle Cost	LCC, $/kg	• Spreads development costs and manufacturing costs as appropriate • Includes facility modification costs • Includes fixed annual operations costs and variable (per flight) operations costs
Reliability	LOM, LOV, LOC	• Reliability Block Diagram (RBD) based analysis of propulsion elements to estimate propulsion system reliability • Examined sensitivity of single engine-out capability on propulsion system reliability

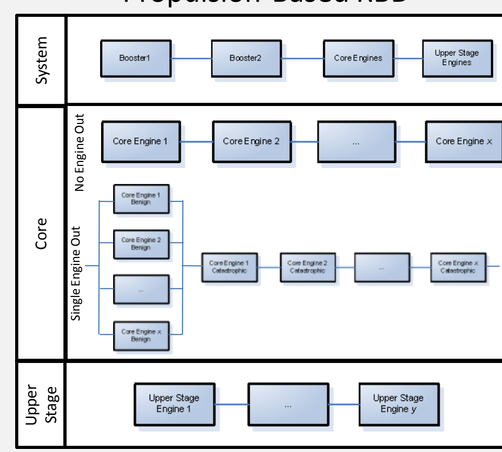
Sizing & Performance Design Structure Matrix



Development & Life Cycle Cost Trades

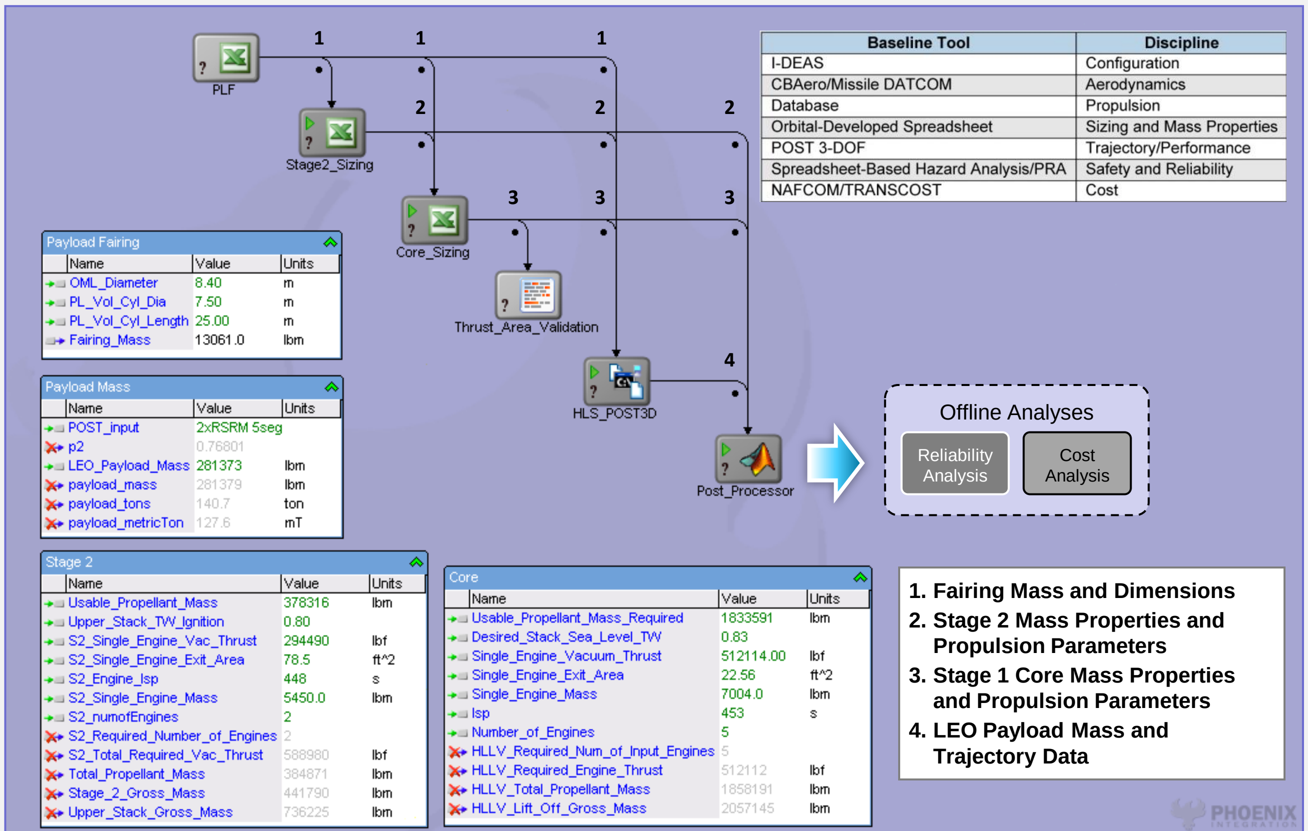


Propulsion-Based RBD



HLS Integrated Analysis ModelCenter Model

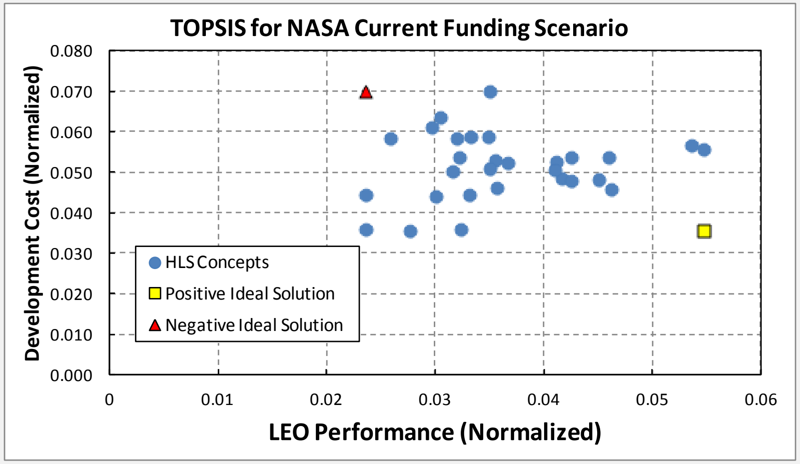
- **Orbital's Integrated Systems Analysis Model within Phoenix Integration ModelCenter® Collaborative Design Environment**
  - ➢ Model provides data transfer between tools & system-level MDO, and enforces constraints
  - ➢ Facilitated MBSE linkage between the integrated analysis and design requirements
- **Preliminary Reliability and Cost Analyses Performed Outside Integrated Model**



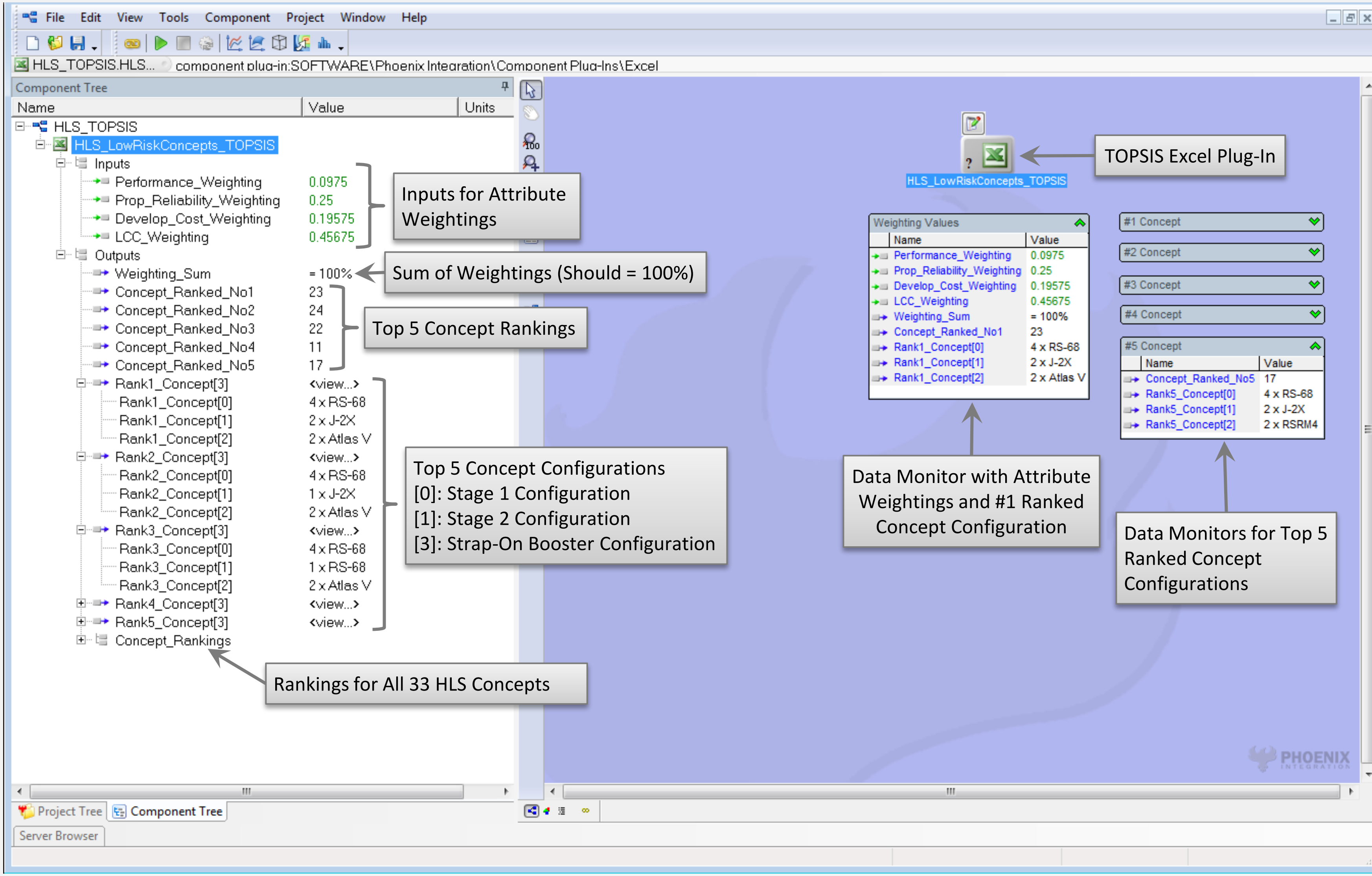
HLS Concept Downselect Process: TOPSIS

- **HLS concepts downselected based on technical, cost, and programmatic FOMs/attributes with weightings**
- **Downselect performed by ranking HLS concepts using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)**
  - TOPSIS is Multi-Attribute Decision Making (MADM) technique that ranks concepts based on their distance to FOM-based ideal solution
  - Normalized FOM Values Generated By TOPSIS Provide Relative Comparison Of Each HLS Concept To The Positive/Negative Ideal Solution
- **Downselect based on Technical and Cost FOMs since generated "Low Risk" Concepts most capable of meeting NASA programmatic/schedule constraints**
- **Attribute weightings show sensitivity of concepts rankings under different scenarios (political, economic, technical)**
- **Selected HLS robust concepts that remain top ranked regardless of weighting**

	Weighting Scenarios for NASA Funding 2012-2016			
Scenarios	Current Funding	Current Funding +10%	Current Funding -5%	Current Funding -10%
Performance	20%	20%	20%	14%
Reliability	25%	25%	25%	25%
Development Cost	28%	32%	23%	23%
Life Cycle Cost	27%	23%	32%	38%



HLS TOPSIS ModelCenter Model



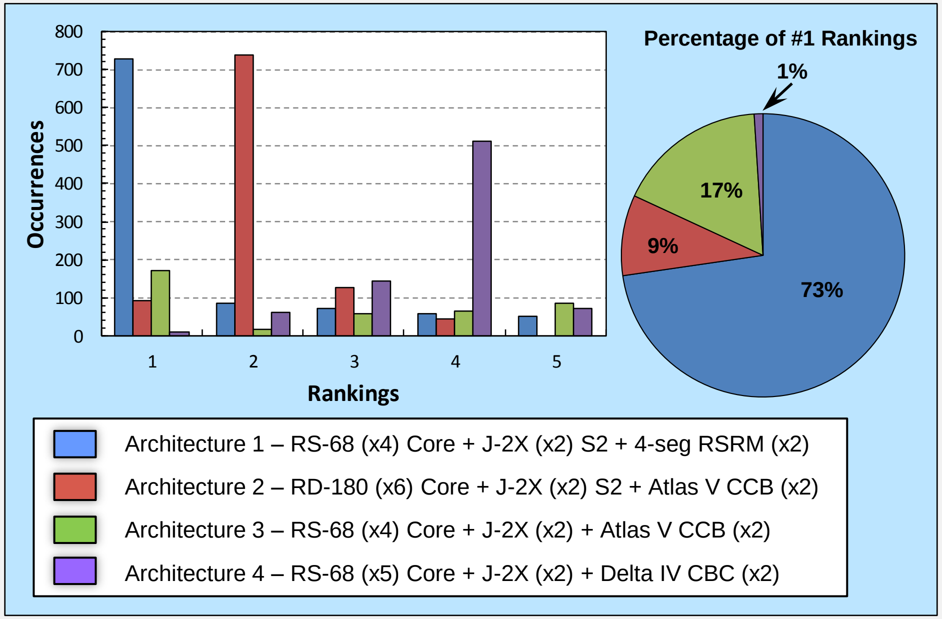
HLS Concept Downselect Process: Qualitative vs. Quantitative Weightings

- **Top HLS LOX/RP And LOX/LH2 Core Concepts Remain Top Ranked Across Qualitative NASA Funding Weighting Scenarios**
- **Performed Probabilistic Variation of FOM Weightings to Validate Qualitative Weightings**
  - Quantitative Approach Examines Sensitivity of Attribute Weightings on Concept Rankings within TOPSIS Multi-Attribute Decision Making Process
  - Variation Performed with Uniform Distributions Over Limited FOM Ranges
  - Probabilistic Analysis Conducted within ModelCenter (1,000 Runs)

NASA Funding Weighting Scenarios (Qualitative)

HLS Rankings	NASA Current Funding	NASA Current Funding +10%	NASA Current Funding -5%	NASA Current Funding -10%
1	RS-68 (x4) Core J-2X (x2) S2 4 seg RSRM (x2)	RS-68 (x4) Core J-2X (x2) S2 4 seg RSRM (x2)	RS-68 (x4) Core J-2X (x2) S2 4 seg RSRM (x2)	RD-180 (x6) Core J-2X (x2) S2 Atlas V CCB (x2)
2	RD-180 (x6) Core J-2X (x2) S2 Atlas V CCB (x2)	RD-180 (x6) Core J-2X (x2) S2 Atlas V CCB (x2)	RD-180 (x6) Core J-2X (x2) S2 Atlas V CCB (x2)	RS-68 (x4) Core J-2X (x2) S2 4 seg RSRM (x2)
3	RD-180 (x6) Core J-2X (x2) S2 Delta IV CBC (x2)	RD-180 (x6) Core J-2X (x2) S2 Delta IV CBC (x2)	RD-180 (x6) Core J-2X (x2) S2 Delta IV CBC (x2)	RS-68 (x4) Core J-2X (x2) S2 Atlas V CCB (x2)
4	RS-68 (x5) Core J-2X (x2) S2 Delta IV CBC (x2)	RS-68 (x5) Core J-2X (x2) S2 Delta IV CBC (x2)	RS-68 (x5) Core J-2X (x2) S2 Delta IV CBC (x2)	RS-68 (x5) Core J-2X (x2) S2 Delta IV CBC (x2)
5	RD-180 Core RS-68 S2 Atlas V CCB (x2)	RD-180 Core RS-68 S2 Atlas V CCB (x2)	RD-180 Core RS-68 S2 Atlas V CCB (x2)	RD-180 (x6) Core J-2X (x2) S2 Delta IV CBC (x2)

Probabilistic Variation (Quantitative)



HLS Architectures #1 and #2 Remain Top Ranked Across Both Qualitative and Quantitative Attribute Weighting Assessments

HLS Downselected Architecture Concepts

	NASA SLS (Apprx)	LH2 Core + SRB	RP Core + RP LRB	RP Core + RP LRB	LH2 Core + RP LRB	LH2 Core + RP LRB
Concept #	0	1	2	2A(4)	3	3A(4)
Core(3)	5 x RS-25E	4 x RS-68	6 x RD-180	9 x AJ-26X	4 x RS-68	4 x RS-68
Stage 2	2 x J-2X	2 x J-2X	2 x J-2X	2 x J-2X	2 x J-2X	2 x J-2X
Booster (ea)	5 seg SRB	5 seg SRB	1 Mlbf LRB (1 x RD-180)	1 Mlbf LRB (2 x AJ-26X)	1 Mlbf LRB (1 x RD-180)	1 Mlbf LRB (2 x AJ-26X)
Performance (1),(2)	120 mT	107 mT	104 mT	94 mT	69 mT	75 mT

Notes:

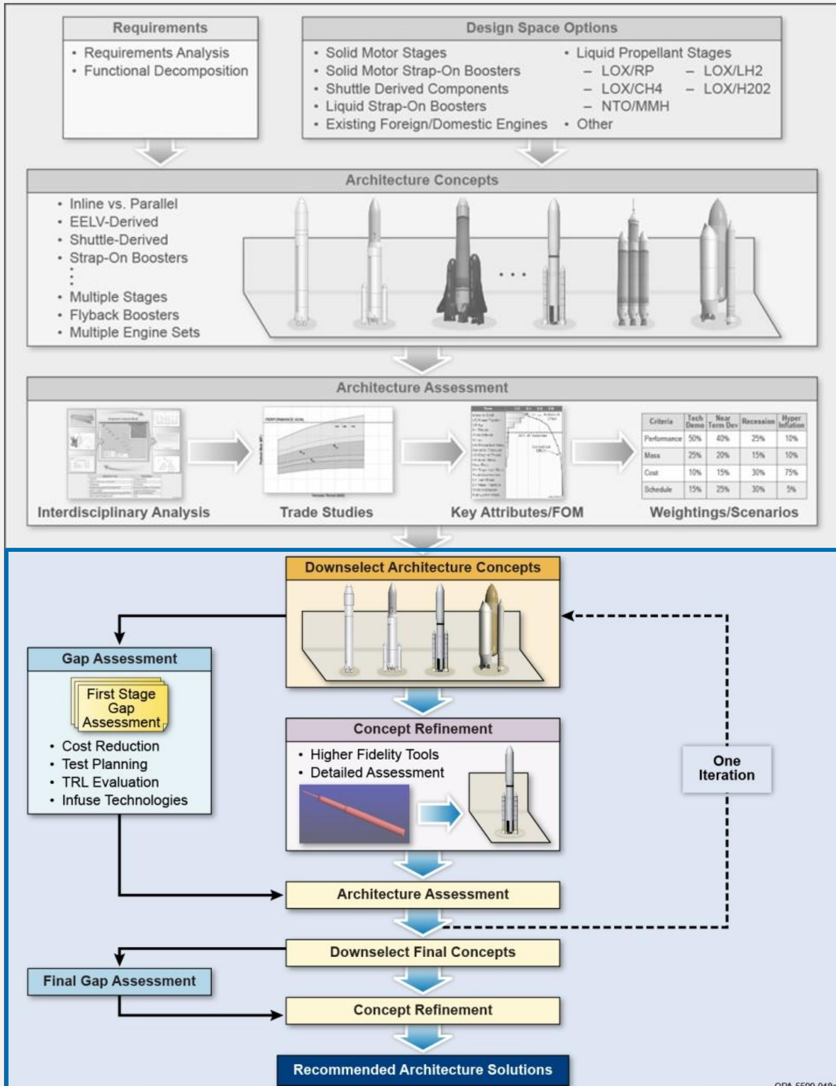
(1) Total Mass (mT) inserted into 30 x 130 nmi orbit at 285° inclination with insertion at 130 nmi and fairing jettisoned during Stage 2 burn.

(2) Fairing Cylindrical Envelope length and OML diameter are 25 m and 8.4 m, respectively.

(3) Stage 1 Core diameter is 8.4 m.

(4) Alternative concepts that replaced RD-180 engines with number of uprated AJ-26X engines that provide comparable total thrust.

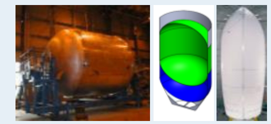
HLS Refinements + Gap Assessment Summary



Technology Gap Assessment

Engines

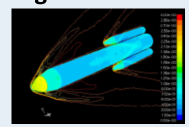
Tanks & Structures



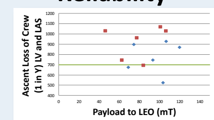
Avionics & Software

Architecture Concept Refinement

Sizing & Performance



Reliability



In-Space Propulsion

Costs Refinement

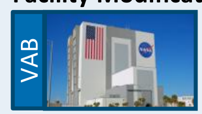
Refined Cost Modeling

NAFCOM

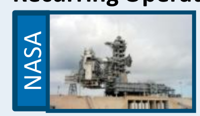
Custom Cost Modeling Tool

Commercial Development Modeling

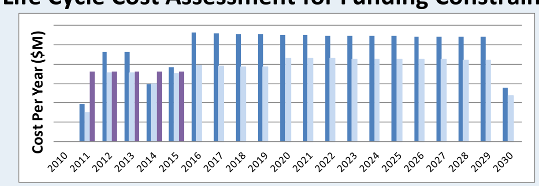
Facility Modifications Costs



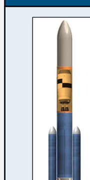
Recurring Operations Costs



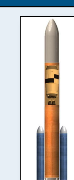
Life Cycle Cost Assessment for Funding Constraints



Recommended Architecture Solutions



Concept 2A
- 8.4-m LOX/RP Core Stage
- 9 x AJ-26X Core Engines
- 2 x J-2X LOX/LH2 Stage 2
- 3.9-m LOX/RP LRB
- 2 x AJ-26X LRB Engines
- 96 mT LEO Performance



Concept 3A
- 8.4-m LOX/LH2 Core Stage
- 4 x RS-68 Core Engines
- 2 x J-2X LOX/LH2 Stage 2
- 3.9-m LOX/RP LRB
- 2 x AJ-26X LRB Engines
- 75 mT LEO Performance

Summary

- **HLS Study Objective Was to Analyze Multiple HLS Architectures and Recommend System Concepts Capable of Affordably Conducting NASA DRMs**
  - Study Followed a Top-down, Goal-driven Approach to Develop Optimal, Robust HLS Architectures
  - MBSE Processes Utilized with Integrated Design Analysis to Define Top-level Requirements and Provide Traceability During the Study

- **Explored HLS Trade Space and Performed Feasibility Assessment for Configurations**
  - Reduced Trade Space of Nearly 2000 Configures to 30+ Low Risk Alternatives
  - Feasibility Assessment Conducted for 30+ Low Risk Trade Concepts based on Performance, Development Cost, Life Cycle Cost, & Propulsion System Reliability
  - Orbital's Integrated Systems Analysis Model within Phoenix Integration ModelCenter® Collaborative Design Environment

- **HLS Concepts Were Downselected Based on Technical, Cost, and Programmatic FOMs / Attributes with Weightings**
  - Downselect Performed by Ranking HLS Concepts Using TOPSIS
  - HLS Architectures #1 and #2 Remain Top Ranked Across Both Qualitative and Quantitative Attribute Weighting Assessments

- **Concepts Refinement and Gap Assessment Performed to Provide Recommended Architecture Solution**

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