HORIZONTAL LAUNCH:
A VERSATILE CONCEPT FOR ASSURED SPACE ACCESS

REPORT OF THE NASA-DARPA HORIZONTAL LAUNCH STUDY

NASA SP 2011-215994

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A VERSATILE CONCEPT FOR ASSURED SPACE ACCESS

Report of the NASA-DARPA Horizontal Launch Study

Horizontal Launch: A Versatile Concept for Assured Space Access

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FOREWORD

Fully reusable horizontal takeoff and landing single-stage-to-orbit (SSTO) launch vehicle systems have long been viewed by many countries, organizations, and individuals as the ultimate answer for providing low-cost, flexible, and assured access to space. As early as 1952, Wernher von Braun envisioned a reusable shuttle-type logistics vehicle to supply a space station. In the 1960s, the Air Force Aerospaceplane design study proposed scramjet propulsion and liquid oxygen supplied by an in-flight air collection and enrichment system, setting a goal to develop and prove these and other technologies that would be required to make such a system a reality.

In the late 1960s, a two-stage reusable—airbreathing and rocket—horizontal launch system was a proposed design option for the Space Shuttle. During this period, there was an intense debate about which shuttle design would provide the best combination of lifecycle costs and capability. The technologies needed for a fully-reusable system were found to be immature and too expensive to develop, and in 1972, the Space Shuttle design was fixed as a vertically-launched rocket-powered system with only partial reusability.

In the early 1980s, while expendable vertical launch vehicles were in wide use for military and commercial payloads, various studies continued to investigate horizontal launch opportunities, including the Reusable Aerodynamic Space Vehicle (RASV), Trans-Atmospheric Vehicle (TAV), Advanced Manned Spaceflight Capability (AMSC), and Advanced Manned Launch Systems studies. These efforts looked at airbreathing and rocket propulsion, at SSTO and multistage-to-orbit systems, and at sled-launch and air-launch.

Beginning in 1984, the $2 billion DoD-NASA National Aero-Space Plane (NASP) program was initiated to develop an airbreathing SSTO system similar to those studied in the 1960s. The program was cancelled in 1994, as the necessary technologies—while much more advanced than 20 years previous to this—were not sufficiently mature. The projected costs and cost uncertainties were too great.

Several new concepts for horizontal launch system were introduced in the 1980s and 1990s. A British program investigated the single-stage-to-orbit Horizontal Takeoff and Landing (HOTOL) concept using air-breathing rockets fed by pre-cooled air to reach Mach 5. A German program proposed the Sänger reusable two-stage system with a turboramjet-powered first stage to reach Mach 6 and a rocket-propelled orbiter stage. American efforts leveraged the NASA High-Speed Civil Transport (HSCT) program by adding high-efficiency turbojets to the carrier aircraft. These programs were terminated because the amortized design, development, test, and evaluation (DDT&E) costs overcame any return on investment when compared to long-range subsonic aircraft.

From the early 1990s through the mid-2000s, NASA investigated several next-generation space access candidates, including horizontal and vertical launch configurations, both airbreathing and rocket-powered. Payload classes of primary interest were initially comparable to the Space Shuttle—50,000 lb or less. By 2005, however, payload requirements to support the human space exploration program were increased to greater than 200,000 lb, with large volumes. This scenario overwhelmingly favored large vertical, rocket-powered launch systems.

In late 2010, the NASA-DARPA Horizontal Launch Study (HLS) was initiated. The HLS examined a wide range of horizontal takeoff space launch system concepts for military and civil applications. This report documents the results of the study.

With an intensive effort, outstanding contributions from a select group of experts, and an excellent support staff, the study team prepared the following report and recommendations. We commend the HLS study team for its thorough efforts.

The HLS conclusions were different than many prior studies that assumed high launch rates and therefore recommended advanced fully- and partially-reusable launch systems. In contrast, the HLS results documented the operational benefits, even with very low projected annual launch rates, of developing a new horizontal take-off space launch system using a modified existing carrier aircraft and launch vehicle system utilizing state-of-the-art systems and technologies. The significant benefits of aerial fueling of the carrier aircraft were also documented. Finally, the study team crafted a low-cost flight demonstration program centered around the existing NASA 747-100 Shuttle Carrier Aircraft (SCA).

While access to space has been a part of American life for decades, it remains a complex endeavor. In this report, we lay out the landscape with the hope that policymakers in the Department of Defense, the Congress, and the Administration will find this information useful as they develop options to ensure continuous and straightforward access to space. We also hope that the information contained herein will help scientists and engineers seeking to implement innovative ideas, and will inspire future generations to exceed the expectations that limit us today.

Vince Rausch
October 2011

PREFACE

In August 2010, a team was assembled with the charge to assess horizontal launch concepts for military and civilian applications, to recommend system concepts for subsonic and supersonic carrier aircraft options, to identify technology gaps for potential investments, and to identify a near-term horizontal launch demonstration. The core team members were:

- David F. Voracek, Project Manager, NASA
- Paul A. Bartolotta, Principal Investigator, NASA
- Alan W. Wilhite, Analysis Lead, Georgia Institute of Technology
- Paul L. Moses, Technology Lead, NASA
- Ramon Chase, Booz Allen Hamilton
- Walter C. Engelund, NASA
- Lawrence D. Huebner, NASA
- Roger A. Lepsch , NASA
- Unmeel B. Mehta, NASA
- Daniel Tejtel, Air Force Research Laboratory
- Randall T. Voland, ACEnT Laboratories LLC

Study Background

At its first meeting, the team began to develop standard figures of merit intended to facilitate an objective comparison of some widely varying approaches to the horizontal launch of payload to orbit. The team then undertook a comprehensive survey of previously published and unpublished studies of horizontal launch systems as well as systems currently proposed by government and industry organizations. During a series of teleconferences and face-to-face meetings, the results of each study were then evaluated using the figures of merit. Each concept was categorized by the time needed to develop it and the potential payload capability delivered to low Earth orbit.

In December 2010, the team briefed both the external review team and the study sponsors on its process and progress. The resulting guidance was then applied to the second phase of the team's analysis.

The team was charged with determining the payload that could be placed in low Earth orbit using currently available subsonic carrier aircraft with either solid- or liquid-fueled launch vehicles. A notional target of 15,000 lb of payload to low Earth orbit was established.

The following constraints were also applied:

- The cost per pound of payload should be the primary figure of merit.
- Annual launch rates should be consistent with current and projected global manifests.
- Gross weight limitations should be based on taking off from existing runways using currently available launch support infrastructure.

The team was also encouraged to use, where possible, existing or modified systems, subsystems, and components to minimize cost, time, and risk. An evolutionary path to a fully reusable system should be identified based on block improvements, and no technologies should be considered that had not been validated in a relevant use environment. Finally, the team was asked to identify potential system, subsystem, and component ground and flight testing or demonstration options that would decrease uncertainties, increase payload weight, decrease launch costs, and increase reliability.

The team carried out this analysis during the next few months and presented interim results in April 2011. The findings and conclusions were then refined and the team's work was concluded with this final report.

Acknowledgements

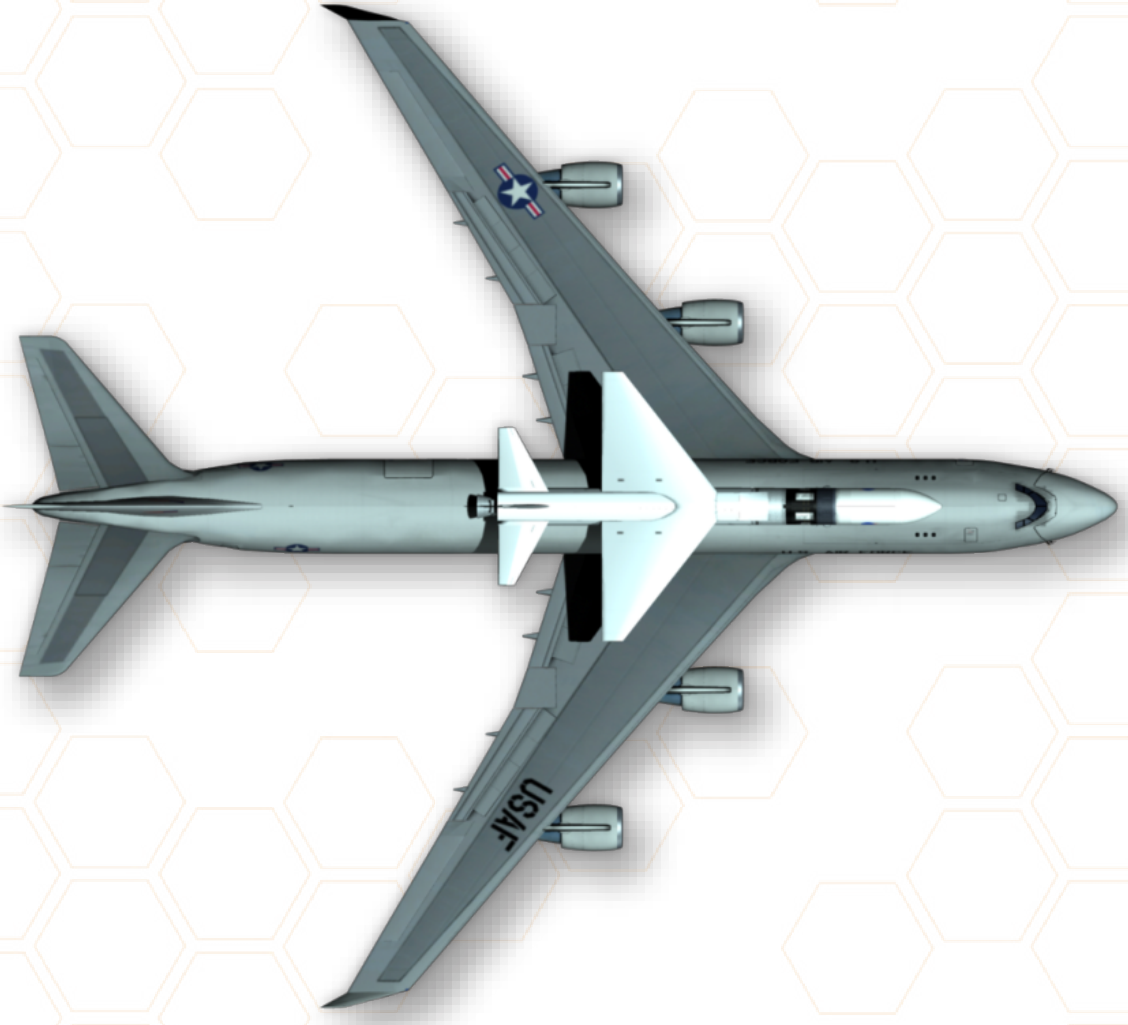
Many individuals and organizations made important contributions to the study team's process and to this report. The team wishes to thank these individuals, but recognizes that attempts to identify all and acknowledge each contribution would require more space than is available in this brief section. To begin, the team would like to thank the sponsors of this report. Funds for the team's work were provided by the Defense Advanced Research Projects Agency and the National Aeronautics and Space Administration.

The team gratefully acknowledges the contributions of several organizations and individuals who provided valuable data and analysis to support its work. Specific thanks go to SpaceWorks Enterprises, Inc., McKinney Associates, and Analytical Mechanics Associates for insightful and comprehensive contributions to the analysis. Many individuals also contributed their knowledge to the study as part of the core, analysis, technology, or report teams. These individuals and their affiliations are included on page 125.

As part of its work, the team received written submissions and presentations from many organizations. These helped the team understand the options and potential for horizontal launch systems and the perspectives of many stakeholder organizations. A list of these organizations is provided on page 127. The team is grateful for the time, effort, and valuable information provided by all of these dedicated individuals and organizations.

Finally, the team thanks the individuals who assisted in its work by reviewing the process and its outcomes. This study methodology and progress, as well as the interim and final reports, have been reviewed by five individuals chosen for their technical expertise and diverse perspectives. These individuals provided thorough, reasoned, and critical comments that ensured the objectivity of the analysis, integrity of the process, and responsiveness to the sponsor direction. The HLS team thanks the following external review team for their contributions to this report:

- Vincent Rausch, Private Consultant;
- William Heiser, Professor Emeritus, U.S. Air Force Academy;
- Douglas O. Stanley, Georgia Institute of Technology, National Institute of Aerospace;
- Uwe Hueter, SAIC; and
- Jay Penn, Aerospace Corporation.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EXECUTIVE SUMMARY

The vision of horizontal launch is the capability to provide a "mobile launch pad" that can use existing aircraft runways, cruise above weather, loiter for mission instructions, and provide precise placement for orbital intercept, rendezvous, or reconnaissance. This study identifies a viable path forward to make the vision of a robust and resilient horizontal launch capability a reality.

This report, jointly sponsored by the Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration (NASA), is the result of a comprehensive study to explore the trade space of horizontal take-off space launch system concepts. The Horizontal Launch Study (HLS) team identified potential near- and mid-term concepts capable of delivering 15,000 lb payloads, on a trajectory from Kennedy Space Center (28.5 degrees due East), to a 100 nautical-mile (low-Earth) circular orbit. The team produced a set of system concepts that meet this criterion. Results are presented for a range of near-term system concepts selected for their availability and relatively low design, development, test, and evaluation (DDT&E) costs.

This report describes the study background and assumptions, figures of merit, point design system concepts, and flight test system concepts. It also addresses details of the study processes, including the full trade space matrix encompassing concepts at both low and high speed regimes and various operational parameters. Also discussed are the benefits of targeted technology investments and of maintaining a horizontal launch flight capability.

The HLS team carried out a progressive analysis that began with developing a systematic, normalized basis to compare a variety of approaches. The next step was prescreening of representative system concepts gleaned from the breadth of past studies on horizontal launch. Finally, selected system concepts were screened to identify useful point designs. A thorough investigation of these point designs was performed to demonstrate feasibility. The process provided the basis for two proposed flight demonstration system concepts defined to mitigate risk and cost.

A number of assumptions and constraints were used to guide the study process. These included the limits of existing runways, current and projected launch rates in various payload classes, and the performance parameters of existing technologies and existing designs.

After considering an array of existing and near-term subsonic carrier aircraft, the HLS team determined a practical upper limit of payload mass to low Earth orbit of 50,000 lb. This would require development of a new, large subsonic carrier aircraft and a liquid hydrogen (LH2) fueled launch vehicle. The DDT&E costs for such a horizontal take-off space launch system were estimated, using traditional aerospace practices, to be between $4.8 billion and $7.2 billion.

For a more modest investment, a modified existing subsonic carrier aircraft with a liquid-propellant launch vehicle could carry an estimated payload up to 20,000 lb with lifecycle costs of $8,860 per pound. The DDT&E cost for this system, including modifying an existing carrier aircraft and assembling a conventional LH2-fueled launch vehicle, was estimated at less than $2 billion. This initial analysis established the potential to launch militarily-relevant payloads to low-Earth orbit with current, commercially-available carrier aircraft and available launch vehicle technology.

With a focus on achieving the reference payload of 15,000 lb to orbit, the HLS team next developed three reference point design system concepts. One near-term system was a two-stage launch vehicle with an RP-1 kerosene (RP) fueled first stage and an LH2 fueled second stage, both carried to a launch point at 25,000 ft of altitude by a modified Boeing 747-400F carrier aircraft. The nonrecurring costs for this point design system concept were estimated at $940 million, and a recurring cost of approximately $9,600 per pound of payload to orbit. Aerial fueling of the carrier aircraft could provide further performance and cost benefits by allowing a larger launch vehicle and payload weight while meeting the carrier aircraft's maximum take-off weight. The study team found that existing technologies were sufficient to immediately begin design of a subsonic carrier aircraft-based space launch system.

The HLS team also identified a flight technology demonstration concept using existing propulsion subsystems and technologies. This system concept consisted of the NASA Shuttle Carrier Aircraft (a modified Boeing 747-100) with either a solid or liquid propellant launch vehicle mounted on top. It was estimated that this demonstration program would cost less than $350 million over three to four years and would achieve two demonstration flights with up to 5,000 lb of payload to low Earth orbit. The flight demonstration would generate experience and understanding to reduce and mitigate risks. Most important among these are the ability for in-flight command and control of the launch vehicle and the aerodynamic parameters for separation of the carrier aircraft and launch vehicle.

CHAPTER 1

INTRODUCTION

The vision of horizontal launch is the capability to provide a “mobile launch pad” that can use existing aircraft runways, cruise above weather, loiter for mission instructions, and achieve precise placement for orbital intercept, rendezvous, or reconnaissance. Another compelling benefit of horizontal launch is that today’s ground-based vertical launch pads are a single earthquake, hurricane, or terrorist attack away from disruption of critical U.S. launch capabilities.

The study did not attempt to design a new system concept for horizontal launch, but rather focused on the refinement of many previously-studied horizontal launch concepts. Because of the large number of past horizontal launch studies, a process was developed to narrow the number of concepts through prescreening, screening, and evaluation of point designs. The refinement process was not intended to select the “best” concept, but rather to establish the feasibility of horizontal launch from a balanced assessment of figures of merit and to identify potential concepts that warrant further exploration.

Study Approach

The HLS team began its work by determining an appropriate set of figures of merit (FOMs) in four categories: safety and mission success, effectiveness and performance, programmatic factors, and affordability, as shown in Table 1. The two discriminating factors identified were pounds and cost per pound of payload delivered to orbit. Common requirements were also established, including projected annual launch rates and gross weight runway limits.

Once the FOMs were established, the team under took a survey of unclassified horizontal launch concepts from the broad range of designs, studies, and demonstrations that have been developed over the past six decades. A database of concepts was developed from the published literature and unpublished NASA and DoD horizontal launch studies. These were analyzed using the analytical hierarchy process (AHP) to identify 18 representative concepts. These 18 concepts were put through a prescreening process using analysis of alternatives and weighted figures of merit. The concepts were compared to present launch capabilities and projected payload markets to further narrow the field to four concepts that fit the study’s common requirements.

These four concepts were next expanded in a morphological matrix to thousands of possible configurations, with varying numbers of stages, engines, propulsion systems, propellants, and other features. These configurations were put through a screening process in an integrated, parametric engineering environment to level the concepts to the same level of analysis fidelity in order to compute performance metrics and figures of merit. From these results, the team selected three distinct configurations for higher fidelity analysis. These were intended to establish the feasibility of a generic mission that would be useful for both commercial and government launch customers.

Three point designs were generated using higher fidelity engineering methods than were used for screening. The point design results were used to identify DDT&E feasibility and risk factors. Performance was computed using analysis tools with mid-level fidelity. FOMs were computed for minimum turn-around time, workforce, and cost of operations; dynamic fault trees were used to calculate the probabilities of loss of vehicle and loss of mission; and the NASA/Air Force cost model (NAFCOM) was used to determine DDT&E and production costs.

To further assess the potential for horizontal launch systems, the team then examined the impact of several advanced technologies on the three point design baselines. Structures, materials, propulsion, propellants, instrumentation, and sensors were evaluated in a low-fidelity design environment in which the FOMs were corrected to match the point design parameters. The overall cost savings were compared to the estimated cost to mature each technology to achieve demonstration of a subsystem model or prototype. This step was intended to identify gains from key technology advances and to guide potential technology investments.

The team then specified two flight test system concepts focused on very near-term and low-cost subsystems with the goal of demonstrating the system performance and mitigating the highest risk factors. Finally, the HLS team assessed potential additional uses for a horizontal launch flight test capability.

These processes were used to progressively narrow the range of potential concepts considered, reserving higher-fidelity engineering analysis for a subset of the most promising concepts. This narrowing process is shown in Figure 1.

Selection and Definition of Figures of Merit

The team began the study process by developing a set of FOMs to characterize potential horizontal launch concepts. The FOMs were used as decision criteria at each level of analysis in the

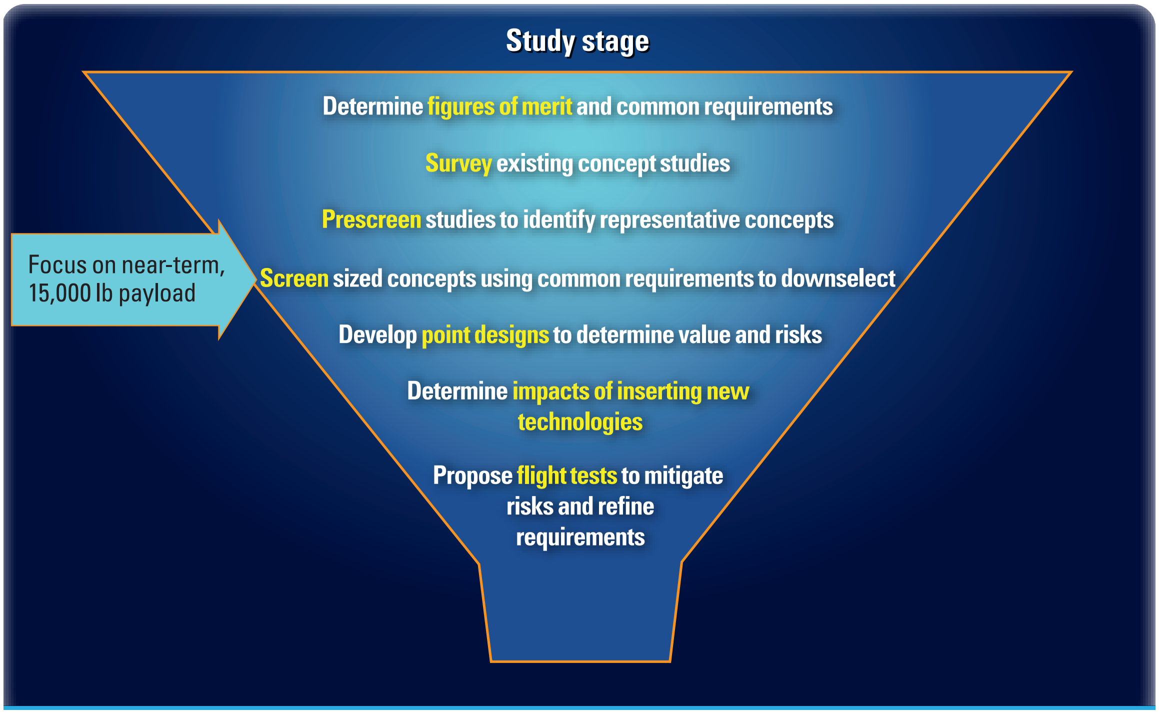

Figure 1 Graphic depiction of the study process, showing the narrowed focus as the analysis progressed.

study. Table 1 shows the four major categories of FOMs—safety and mission success, effectiveness and performance, programmatic factors, and affordability—and the 17 FOMs used in the study. Appendix A lists definitions for each FOM category and FOM and the proxy parameters that were used to inform the core team members during initial system concept qualitative differentiation.

As shown in Table 1 and detailed in Appendix A, some of the FOMs (in **bold**) were quantitatively calculated, and others (in *italics*) were qualitatively determined as a result of expert elicitation. All FOMs were initially assigned qualitative values using proxy parameters and were later refined as data was generated. For example, probability of loss of vehicle and probability of loss of mission were initially evaluated based on proxy parameters that included stage complexity and number of engines. Later, each of these probabilities was computed using situational fault trees based on estimated subsystem failure rates of similar space and aircraft components.

Table 1 Figures of Merit Used in the Study

Safety and mission success	Effectiveness and performance	Programmatic factors	Affordability
Loss of vehicle probability, by stage	**Payload**	*Failure to achieve DDT&E goals*	**Cost of DDT&E**
Loss of mission (LOM) probability	**Minimum turnaround time**	*Failure to achieve IOC date*	**Cost of facilities**
	Surge call-up time	*Technology maturity*	**Cost of acquisition and production**
	Basing flexibility	**Commercial viability**	**Cost of operations**
	Mission flexibility		**Cost of mission failure**
	Military viability		

Factors quantitatively calculated
Factors qualitatively determined using expert elicitation

Selection of Common Requirements

After selecting the FOMs, the team agreed on several initial goals for the study. These were treated less as figures of merit and more as starting ground rules that could be amended as analysis progressed. An overarching goal was to identify concepts with payloads approaching 15,000 lbs at the lowest possible DDT&E cost. As well, production and operations costs should approach those for current launch systems. Finally, to take full advantage of the horizontal launch configuration, the team set a goal to meet conventional runway requirements by limiting the gross takeoff weight of the system to less than 1.8 million lb.

A critical assumption was that flight rates would follow current market projections. (See Appendix B.) The team determined that DDT&E costs would be amortized using a launch rate of six flights per year, each carrying 15,000 lb of payload over a 20-year system life, for a total campaign of 120 flights. While many previous studies have assumed much higher flight rates attributed to looming national imperatives or order of magnitude increases in launch demand, the study team found no indications of these. Therefore, the rate of six flights per year was assumed throughout the study.

Survey of Horizontal Launch System Concepts

The promise of horizontal take-off space launch systems has inspired many studies over the past 60 years—spanning airbreathing and rocket propulsion, expendable and reusable launch vehicles, and various assisted launch concepts, such as ground sleds or rail-launch with magnetic levitation. These various studies proved difficult to compare, as each used its own, sometimes unique, ground rules, assumptions, and figures of merit. Most studies focused on narrow mission requirements, such as a single payload class, market, maximum gross take-off weight, or staging Mach number. Only a few included the process for and costs of design, development, testing, production, ground operations, and mission operations.[1]

Rather than designing a new horizontal launch concept, this study built on the understanding resulting from those many previous designs. Data was collated from 136 published and unpublished unclassified sources in order to assess each design against the figures of merit selected for this study. (See Appendix C.) A variety of factors were considered across these existing studies, from the concepts of operations (CONOPs) to technologies and system integration schemes.

Examples of the variables that were collected began with size, weight, and payload capability and extended to takeoff options, such as intact, sled assist, sled crossfeed, or towed. The staging options included the number of stages, staging speeds, and whether or not a drop tank was used. Integration options included internally contained launch vehicles, embedded launch vehicles, or various attachment methods, such as inline, top, or bottom. Additional data collected included reusability approaches, whether stages were expendable, fully reusable, partially reusable, or in combination. Propulsion options included solid, liquid, airbreathing, or integrated combinations. Two options for aerial fueling were subsonic tanker assist and air collection and enrichment (ACES). This depth and breadth of the body of knowledge served to reinforce the validity of the team's approach.

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[1] The Next Generation Launch Technology study was one that estimated many relevant figures of merit for a range of horizontal launch rocket and airbreathing vehicle concepts, and this study adopted many of these.

CHAPTER 2

PRESCREENING

Rather than carry the complete range of possible concepts and technologies throughout the study for quantitative analysis, a prescreening process was used to focus the team's efforts. Aspects that were considered and compared in this stage of the analysis included CONOPs, technologies, level of fidelity, and design maturity.

The HLS team began the process by applying expert judgment to categorize each design concept. The team labeled each concept according to three payload classes: less than 500 lb, 500 to 10,000 lb, and more than 10,000 lb; and according to three technology development timeframes: 0 to 3 years (near term), 4 to 9 years (mid term), and more than 10 years (far term).

At the end of the exercise, the following eighteen concepts represented the range of options deemed available for a future horizontal launch system.

1. Fighter Jet + Multistage Solid Rocket

Carrier aircraft	Modified Existing Supersonic Fighter Jet Aircraft
Launch vehicle	Small Expendable Multistage Solid Rocket
Technology Advancement	None

Supersonic Staging

Payload class	Less than 500 lb
Timeframe	Near-term
Concept of operation	Fighter jet aircraft carries small multistage rocket to supersonic release condition. Multistage rocket delivers payload to low-Earth orbit (LEO).
Specific example	Nanolauncher Black

2. Commercial Jet + Multistage Solid Rocket

Carrier aircraft	Modified Existing Subsonic Commercial Jet Aircraft
Launch vehicle	Expendable Multistage Solid Rocket
Technology Advancement	None

Subsonic Staging

Payload class	500 to 10,000 lb
Timeframe	Near-term
Concept of operation	Commercial jet carries multistage rocket to subsonic release condition. Multistage rocket delivers payload to LEO.
Specific example	Boeing AirLaunch Concept

3. Commercial Jet + Multistage Liquid Rocket

Carrier aircraft	Modified Existing Subsonic Commercial Jet Aircraft
Launch vehicle	Expendable Multistage Liquid Rocket
Technology Advancement	None

Subsonic Staging

Payload class	500 to 10,000 lb
Timeframe	Near-term
Concept of operation	Commercial jet carries multistage rocket to subsonic release condition. Multistage rocket delivers payload to LEO.
Specific example	QuickReach

4. Ground Sled + Multistage Liquid Rocket

Ground stage	Ground sled
Launch vehicle	Expendable Multistage Liquid Rocket
Technology Advancement	Ground sled

Subsonic Staging

Payload class	More than 10,000 lb
Timeframe	Near-term
Concept of operation	Ground sled accelerates multistage rocket to subsonic velocities. Multistage rocket delivers payload to LEO.
Specific example	Reusable Aerospace Vehicle (RASV) (Two stage to orbit (TSTO) version)

5. New Custom Subsonic Carrier + Multistage Liquid Rocket

Carrier aircraft	New Specially Designed Large Subsonic Carrier Aircraft
Launch vehicle	Expendable Multistage Liquid Rocket
Technology Advancement	None

Subsonic Staging

Payload class	More than 10,000 lb
Timeframe	Near-term
Concept of operation	Subsonic aircraft carries multistage rocket to subsonic release condition. Multistage rocket delivers payload to LEO.
Specific example	Dual-fuselage C-5

6. Advanced Fighter Jet + Multistage Liquid Rocket

Carrier aircraft	Enhanced Supersonic Fighter Jet Aircraft with Mass Injection Pre-Compressor Cooling (MIPCC)
Launch vehicle	Small Expendable Multistage Liquid Rocket
Technology Advancement	MIPCC

Supersonic Staging

Payload class	Less than 500 lb
Timeframe	Mid-term
Concept of operation	Fighter jet carries small multistage rocket to supersonic release condition. Multistage rocket delivers payload to LEO.
Specific example	DARPA RASCAL

7. Commercial Jet + Reusable All-Rocket Vehicle with Drop Tanks

Carrier aircraft	Modified Existing Subsonic Commercial Aircraft
Launch vehicle	Reusable Liquid Rocket Vehicle with Drop Tanks
Technology Advancement	None

Subsonic Staging

Payload class	500 to 10,000 lb
Timeframe	Mid-term
Concept of operation	Commercial carries reusable rocket vehicle to subsonic release condition. Reusable all-rocket upperstage vehicle delivers payload to LEO.
Specific example	AMSC 1.5 Stage

8. New Subsonic Carrier with Air Collection and Enrichment System (ACES) + Reusable All-Rocket Vehicle

Carrier aircraft	Reusable Turbofan and Liquid Rocket Aircraft with ACES
Launch vehicle	Reusable Liquid Rocket Vehicle
Technology Advancement	ACES

Supersonic Staging

Payload class	More than 10,000 lb
Timeframe	Mid-term
Concept of operation	Reusable booster vehicle uses turbofan to takeoff and climb to subsonic cruise, where ACES system to fill oxidizer tanks. Once tanks are full, booster engages rocket propulsion and accelerations to a supersonic staging condition. Reusable all-rocket upperstage vehicle carries payload to LEO.
Specific example	Gryphon

9. New Supersonic Carrier + Multistage Liquid Rocket

Carrier aircraft	Reusable Turbofan and Liquid Rocket Aircraft
Launch vehicle	Expendable Multistage Liquid Rocket
Technology Advancement	None

Supersonic Staging

Payload class	More than 10,000 lb
Timeframe	Mid-term
Concept of operation	Reusable booster vehicle uses turbofan to takeoff, then uses rocket propulsion to perform a zoom-climb to supersonic release condition. Multistage rocket delivers payload to LEO.
Specific example	Peregrine

10. Maglev + Reusable Rocket-based Combined Cycle (RBCC) Vehicle

Ground stage	Maglifter launch assist system
Launch vehicle	Reusable SSTO vehicle with supercharged ejector ramjet (SERJ) + Liquid Rocket RBCC Propulsion System
Technology Advancement	SERJ RBCC Propulsion System; Maglifter Launch Assist

Subsonic Staging

Payload class	More than 10,000 lb
Timeframe	Mid-term
Concept of operation	Maglifter launch assist accelerates reusable SSTO vehicle to subsonic velocities. Launch vehicle uses SERJ-mode to reach Mach 2 or 3, then fan-ramjet/ramjet mode to Mach 6, and pure rocket mode for the final leg to LEO.
Specific example	Argus

11. New Supersonic Carrier with a Revolutionary Turbine Accelerator (RTA) + Multistage Liquid Rocket

Carrier aircraft	Reusable Supersonic Aircraft with RTA
Launch vehicle	Expendable Multistage Liquid Rocket
Technology Advancement	Mach 4 Revolutionary Turbine Accelerator (RTA) Engine

Supersonic Staging

Payload class	More than 10,000 lb
Timeframe	Mid-term
Concept of operation	Reusable supersonic aircraft carries expendable liquid upperstage to Mach 4 staging condition using RTA propulsion system. Multistage rocket delivers payload to LEO.
Specific example	Flexible Aerospace System Solution for Transformation (FASST) Rocket 5b

12. New Supersonic Carrier with Turbo-Ramjet + Reusable All-Rocket Vehicle

Carrier aircraft	Reusable Supersonic Aircraft with Turbo-ramjet and Liquid Rocket Propulsion
Launch vehicle	Reusable Liquid Rocket Vehicle
Technology Advancement	Turbo-ramjet Proplusion System

Supersonic Staging

Payload class	More than 10,000 lb
Timeframe	Mid-term
Concept of operation	Reusable supersonic aircraft uses Turbo-Ramjet to reach Mach 4 or 4.5, then rocket propulsion to reach Mach 6 staging condition. Reusable all-rocket vehicle delivers payload to LEO.
Specific example	Sänger II

13. Commerical Jet + Reusable Turbine-based Combined Cycle (TBCC) Vehicle + Reusable All-Rocket Vehicle

Carrier aircraft	Modified Existing Subsonic Commercial Aircraft
Launch vehicle	Reusable Ramjet/Scramjet Vehicle Second Stage; Reusable All-Rocket Vehicle 3rd Stage
Technology Advancement	Dual-Mode Ramjet/Scramjet Propulsion System

Subsonic, Hypersonic Staging

Payload class	500 to 10,000 lb
Timeframe	Far-term
Concept of operation	Commercial jet carries system to subsonic release condition. Reusable second stage uses ramjet and scramjet propulsion to achieve hypersonic staging condition. Reusable all-rocket third stage delivers payload to LEO.
Specific example	Mustang

14. TBCC Vehicle + Reusable All-Rocket Vehicle

Booster stage	Reusable Hypersonic Aircraft with TBCC Propulsion
Launch vehicle	Reusable Liquid Rocket Vehicle
Technology Advancement	Dual-Mode Ramjet/Scramjet Propulsion System

Hypersonic Staging

Payload class	More than 10,000 lb
Timeframe	Far-term
Concept of operation	Reusable TBCC vehicle carries all-rocket reusable upperstage to hypersonic staging condition using turbine mode into supersonic speeds, then ramjet/scramjet mode to the hypersonic staging condition. Reusable all-rocket upperstage delivers payload to LEO.
Specific example	Integrated concept model (ICM)-2 TBCC

15. RBCC Vehicle + Reusable All-Rocket Vehicle

Booster stage	Reusable Hypersonic Aircraft with RBCC Propulsion
Launch vehicle	Reusable Liquid Rocket Vehicle
Technology Advancement	RBCC Propulsion System

Hypersonic Staging

Payload class	More than 10,000 lb
Timeframe	Far-term
Concept of operation	Reusable RBCC vehicle carries all-rocket reusable upperstage to hypersonic staging condition using ejector mode into supersonic speeds, then ramjet/scramjet mode to the hypersonic staging condition. Reusable all-rocket upperstage delivers payload to LEO.
Specific example	ICM-3 RBCC

16. Hypersonic Vehicle with Liquid Air Combustion Engine (LACE) and Scramjet + Expendable Rocket

Booster stage	Reusable Hypersonic Aircraft with Scramjet, LACE, and Tail Rockets
Launch vehicle	Expendable Liquid or Solid Rocket
Technology Advancement	LACE; Scramjet Propulsion System

Hypersonic Staging

Payload class	More than 10,000 lb
Timeframe	Far-term
Concept of operation	Reusable hypersonic vehicle carries all-rocket reusable upperstage to hypersonic staging condition using LACE mode to hypersonic velocity, then scramjet mode, and rocket mode to achieve suborbital staging condition. Expendable single stage rocket delivers payload to LEO.
Specific example	ICM-5 - Air breathing launch vehicle (ABLV) 4a (TSTO Implementation)

17. New Supersonic Carrier with RTA + Reusable RBCC Vehicle

Booster stage	Reusable Supersonic Aircraft with RTA
Launch vehicle	Reusable RBCC Vehicle
Technology Advancement	Revolutionary Turbine Accelerator (RTA) Engine; RBCC Propulsion System

Supersonic Staging

Payload class	More than 10,000 lb
Timeframe	Far-term
Concept of operation	Reusable supersonic aircraft carries expendable liquid upperstage to Mach 4 staging condition using RTA propulsion. Upperstage uses air-breathing propulsion to achieve hypersonic velocity, then transitions to rocket mode to reach orbit.
Specific example	FASST 1 / ICM-4

18. Compressed-Air Rocket Vehicle + Expendable Rocket

Booster stage	Reusable Compressed-Air Rocket Vehicle
Launch vehicle	Expendable Liquid or Solid Rocket
Technology Advancement	Compressed-Air Rocket Propulsion
Hypersonic Staging	
Payload class	More than 10,000 lb
Timeframe	Far-term
Concept of operation	Reusable vehicle uses compressed-air rocket propulsion to achieve suborbital staging condition using both air-breathing mode in the atmosphere and pure rocket mode at high altitude. Expendable single liquid or solid rocket delvers payload to LEO.
Specific example	Skylon (TSTO Implementation)

Weighting the FOMs

Next, the 18 concepts were assessed to identify the concepts that would proceed to the next analysis step. Members of the study team used the AHP to prioritize the concepts based on the impact on the FOMs established for the study—safety and mission success, effectiveness and performance, programmatic factors, and affordability.

The AHP is a group decision making method. Rather than leading the group to a "correct" decision, the AHP identifies a decision that best suits a set of stated goals. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. (Saaty, 2007)

Each member of the HLS core team provided ranking information for each FOM category from their perspective of either NASA or the United States military as a customer using their best understanding of the future requirements for a horizontal launch system. Numerical preferences were computed for each participant and statistics of the FOM category weight differences of the core team were generated to show the average and range of perspectives in the group, as displayed in Figure 2. As expected, the top FOM categories for NASA missions were safety and mission success and affordability, whereas the top priority for military missions was mission performance.

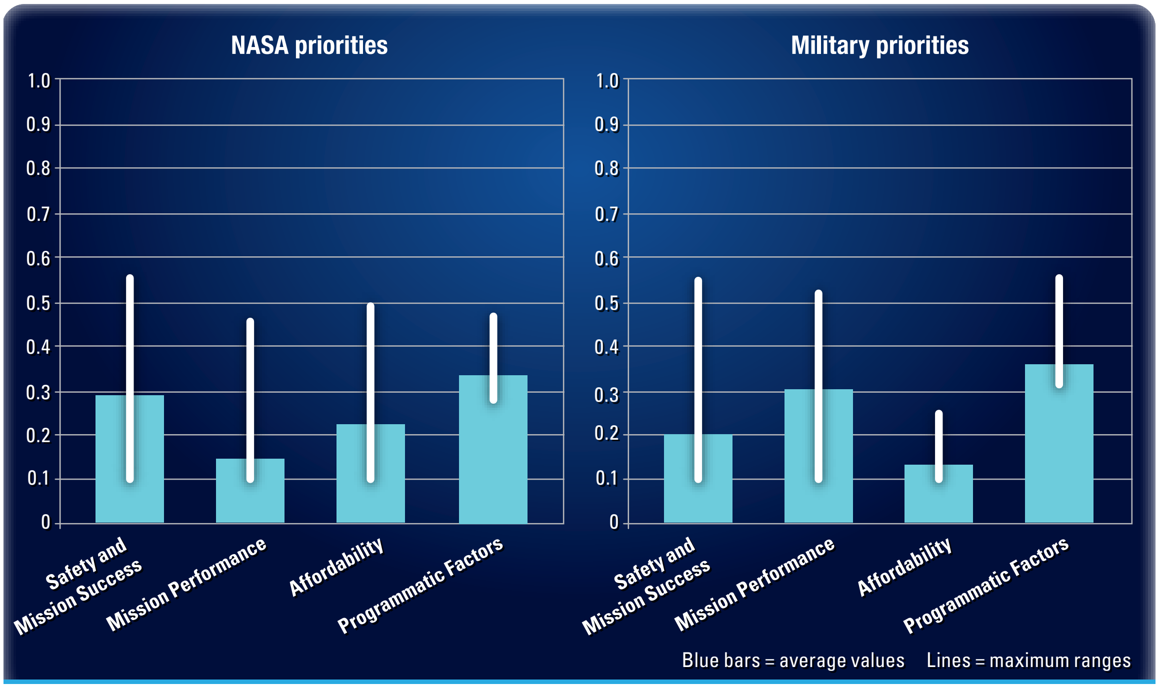


Figure 2 Example of the FOM weighting by the HLS core team. The blue bars represent average values, and the white lines indicate the maximum range of the expert opinions.

For the near term timeframe (1 through 5), the concepts were ranked as follows:

(2) Commercial Jet + Multistage Solid Rocket
(5) New Custom Subsonic Carrier + Multistage Liquid Rocket
(1) Fighter Jet + Multistage Solid Rocket
(3) Commercial Jet + Multistage Liquid Rocket
(4) Ground Sled + Multistage Liquid Rocket

These rankings were identical for civilian and military perspectives. The sled launch concept ranked lowest even though it was judged to carry a large payload. It was considered to have more costs and risks owing to the development costs of a new sled system, and a sled also limits launch site mobility.

For the mid-term timeframe (6 through 12), the concepts were ranked as follows:

(7) Commercial Jet + Reusable All-Rocket Vehicle with Drop Tanks
(6) Advanced Fighter Jet + Multistage Liquid Rocket
(12) New Supersonic Carrier w/Turbo-Ramjet + Reusable All-Rocket Vehicle
(9) New Supersonic Carrier + Multistage Liquid Rocket
(11) New Supersonic Carrier w/RTA + Multistage Liquid Rocket
(8) New Subsonic Carrier w/ACES + Reusable All-Rocket Vehicle
(10) Maglev + Reusable RBCC Vehicle

The subsonic commercial carrier aircraft with a reusable rocket launch vehicle was ranked highest, followed by four concepts with almost equal priority. The system incorporating ACES ranked lower, owing to development risk. As was observed in the near-term options, the sled concept ranked lowest.

For the far-term timeframe (13 through 18), the concepts were ranked as follows:

(14) TBCC Vehicle + Reusable All-Rocket Vehicle
(17) New Supersonic Carrier w/RTA + Reusable RBCC Vehicle
(13) Commerical Jet + TBCC Vehicle + Reusable All-Rocket Vehicle
(15) RBCC Vehicle + Reusable All-Rocket Vehicle
(18) Compressed-Air Rocket Vehicle + Expendable Rocket
(16) Hypersonic Vehicle w/LACE and Scramjet + Expendable Rocket

A carrier concept with a TBCC propulsion system was ranked highest. This was followed by a FASST-like Mach 4 turbojet with a RBCC powered launch vehicle and a subsonic carrier aircraft with a reusable RBCC powered launch vehicle. A Skylon-like air-breathing rocket and a dual mode scramjet with LACE, both with a liquid propellant launch vehicle, were the lowest ranked concepts.

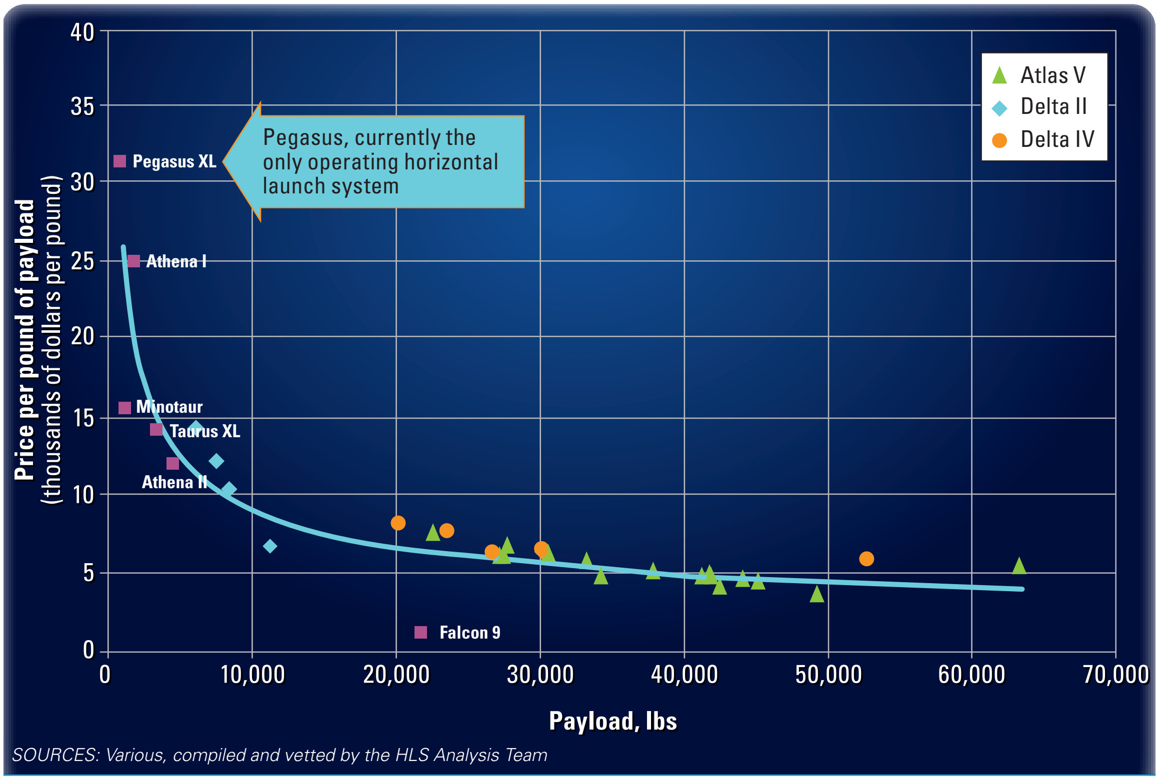
Analyzing Economic Feasibility

The team next conducted a simple economic feasibility analysis to better understand the viability of competing systems. This analysis began by extracting cost data from a wide range of past and present launch systems. Nonrecurring costs included ground facilities costs and DDT&E costs, including purchase and modifications to the carrier aircraft. This assessment did not include technology maturation costs estimated to bring any subsystems or components to a technology readiness level (TRL) of 6. As described in Appendix D, this meant that all specified components were assumed to have achieved a system or subsystem model or prototyping demonstration in a relevant end-to-end environment, either on the ground or in space.

Recurring costs included production and acquisition of expendable elements. It also included operations costs such as fuel and ground crew, and the cost of doing business—overhead, general and administrative costs, and profit. Nonrecurring and recurring costs were added to determine the lifecycle cost, which was then amortized over the number of flights or over the pounds of payload delivered to orbit.

Figure 3 shows a spectrum of the price per pound of payload for U.S. launch vehicles. The curve reflects the overall trend in industry pricing, but of course does not necessarily scale directly to cost. The highest price per pound of payload on this graph is attributed to Pegasus, the only currently available horizontal launch system. Pegasus is a bottom-mounted launch vehicle with a two-stage solid rocket released from a modified L-1011 aircraft. It can deliver 950 lb of payload to orbit at a price of over $30,000 per pound.

The team also analyzed trends in DDT&E costs. As seen in Figure 4, DDT&E tends to increase with the inert weight of a system. The box at the top, right hand corner of Figure 4 represents the required inert weight range—100,000 lb or more—of a carrier aircraft needed to deliver



Pegasus, currently the only operating horizontal launch system

SOURCES: Various, compiled and vetted by the HLS Analysis Team

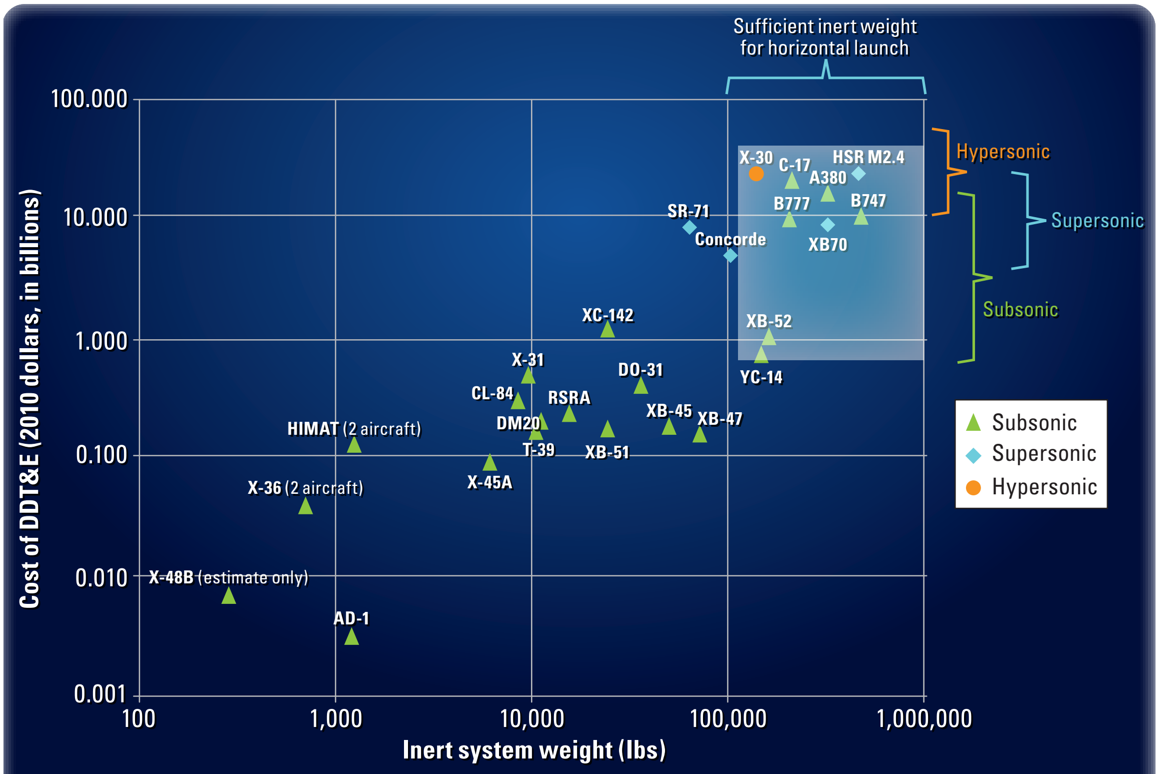
Figure 3 Price per pound of payload for existing U.S. launch vehicles. The price trend line is empirically fitted to existing price data.

15,000 lb to orbit. As observed in the study survey, variations in cost for a given inert weight could be attributed to system complexity, system maturity, customer requirements, or testing requirements.

Figure 4 plots a mix of concept aircraft, such as the XB series, and more fully-detailed aircraft intended for commercial production. Average DDT&E costs for a new Earth-to-orbit technology demonstrator aircraft were estimated to be $10 billion (in 2010 dollars) for a new subsonic carrier aircraft, and as high as $17 billion for a new supersonic and $25 billion for a new hypersonic carrier aircraft.

When amortized, these DDT&E costs can add $6,000 to $13,000 to each pound of payload to orbit and can easily overwhelm operations costs. This analysis found that a new aircraft developed solely for a new horizontal launch system presented a substantial risk to commercial viability.

A number of external factors may mitigate this outcome. For example, a government agency could fund the DDT&E costs of the new system to meet a national imperative for a mobile launch capability. Other scenarios exist that could escalate the flight rate more quickly, thereby reducing the amortized cost significantly. Production may incorporate adaptive and open manufacturing processes, which can reduce development costs by as much as an order of magnitude.



SOURCES: Various, including published data on existing aircraft, projected data from High-Speed Civil Transport studies, and other data from Morris R Betry, "The History of Technology Viability, Technology Demonstrator and Operational Concept Prototype Program Costs," Air Force Directorate of Science and Technology, July 1994. Assembled and vetted by the HLS analysis team.

Figure 4 DDT&E costs for inert system weight for existing carrier aircraft. The box (upper right) highlights the range of inert system weight sufficient for horizontal launch.

Choosing a Carrier Aircraft

The analysis parameters in the study were selected to enable valid comparisons among the various representative concepts. The outcomes of this comparison served to narrow the focus of the study.

Small supersonic carrier aircraft (e.g., fighters) were found to have very small payload capacity, up to perhaps one hundred pounds. These aircraft had low market potential and high projected costs. Larger existing supersonic aircraft, such as the B-1 Lancer, a variable-sweep wing strategic bomber with supersonic capabilities, were found to have sufficient capability to support a 75,000 lb launch vehicle and could launch payloads up to 5,000 lb. However, the B-1 does not have adequate internal volume for internal carriage of a launch vehicle, nor does it have the needed transonic thrust-minus-drag performance to enable external carriage.

Several new supersonic and hypersonic aircraft were evaluated representing a range of staging Mach numbers and technologies with the potential for larger payloads. Uncertainty in development costs and in operations costs persists across these concepts, driven by varying assumptions in launch rate, reliability, and maintenance requirements. The team found that many of these system concepts could be very competitive if launch rates increased over current market projections of six flights per year. Toward this day, an assessment of the development needs for super- and hypersonic carrier aircraft is provided in Appendix E.

The remaining aircraft considered were existing subsonic carriers. The most widely available option was the Boeing 747-400F, the cargo version of the commercial airliner that entered into service in 1993. It can be modified to carry an external payload of 308,000 lb. A very similar option was the Airbus A380-800F was another commercially available airliner, a wide-body aircraft with an upper deck that extends along the entire length of the fuselage. It can be modified to carry an external payload of 320,000 lb.

Several unique carrier aircraft options were also analyzed. The Antonov An-225 Mriya was a Ukranian-built strategic airlift cargo aircraft designed in the 1980s to ferry the Soviet Buran orbiter. It was the world's heaviest aircraft with a maximum external payload of 440,000 lb. Two Boeing 747 NASA Shuttle Carrier Aircraft, SCA-905 and SCA-911, used for piggy-back ferrying of the Space Shuttle orbiter, were added to the mix. These were purpose-modified Boeing 747-100s with a maximum external payload of 192,000 and 240,000 lb, respectively.

Significantly modified carrier aircraft were also considered, such as a dual-fuselage variant of the C-5 Galaxy strategic airlift aircraft with a maximum payload of 771,000 lb. Note that a runway wider than 300 feet is required for the breath of the landing gear on the two fuselages which would restrict launch mobility.

Two additional derived designs were the White Knight X and White Knight XX, enlarged dual-fuselage variants based on the Scaled Composites White Knight Two. The White Knight X was conceived to carry roughly 5 times more payload than the White Knight Two, approximately 176,000 lb. The White Knight XX was conceived as a commercial variant of the dual-fuselage C-5, targeting 750,000 lb payload and using the same development and production methods as the existing White Knight aircraft. The White Knight XX had landing gear wider than 175 feet and would not easily take off from a standard runway.

Choosing a Launch Vehicle Configuration

One of the main decisions driving the design on a horizontal launch system is the placement of the launch vehicle relative to the carrier aircraft. A range of configuration options were considered. The launch vehicle may be carried externally on the top of or on the bottom of the carrier aircraft, stored internally, or towed. All have advantages and disadvantages, as follows:

Internally stowed launch vehicles could have the highest altitude and fastest staging condition for a given carrier aircraft; however, the size of the launch vehicle was limited by the internal payload configuration of the carrier aircraft. The launch vehicle could also need deployable aerodynamic surfaces.

Towed launch vehicles had the fewest modifications to the carrier aircraft and the least constrained separation conditions, but required launch vehicle attachments and wings designed for takeoff, attachments for the dropped takeoff gear, and must be designed for the dynamic loads from the tow line. Towing offered larger payloads than internal stowing, and could achieve the goal of 15,000 lb of payload to orbit in some configurations.

Top-mounted launch vehicles on new, large carrier aircraft could carry up to 50,000 lb of payload to 100 nm due-east orbit.

Bottom-mounted launch vehicles such as the Pegasus rocket on the single-fuselage Lockheed L-1011 Stargazer, were limited by ground clearance that restricts the diameter and length of the launch vehicle. Significant payload performance gains were possible with high-wing, dual-fuselage designs, such as a dual-fuselage C-5 or White Knight-derived carrier aircraft, which could carry a launch vehicle bottom-mounted on the center wing. This configuration could be tailored to meet almost any payload requirement, and enabled a wide range of launch trajectories. However, these advantages were offset by the need to develop and operate a one-of-a-kind carrier aircraft, and the wingspan and associated takeoff and landing gear that limited basing flexibility.

Results of the Prescreening Analysis

A number of configuration decisions were made as a result of the prescreening process. A difficult decision was the elimination of supersonic and hypersonic carrier aircraft. A launch vehicle in this speed regime for a moderate payload of 15,000 lb would require an entirely new aircraft, and cost projections for any new aircraft were prohibitive when amortized over 6 flights per year. The study therefore focused primarily on existing aircraft with modifications to accommodate the launch vehicle.

The next decision was to eliminate towed concepts that require the development of a winged cradle for launch vehicle takeoff, and internally-loaded concepts that are volume constrained and can't accommodate moderate payloads to orbit. Existing bottom-mount concepts were eliminated because the carrier landing gear length constrained the launch vehicle size and system payload. Top separation has been demonstrated with the Space Shuttle orbiter, and bottom-mount separation from a dual-fuselage aircraft may be the easiest to accomplish.

Another decision was to eliminate sled- or rail-based system concepts. Sled-based launch concepts were generally inconsistent with the desire for a completely mobile capability and the ability to use existing runways. For some sled concepts, the sled could double as takeoff and landing gear resulting in weight savings and reduced complexity. However, the sled- and rail-launched systems did not have the ability for launch offset, loiter, or crossrange performance.

Based on these results, the following four system concepts were carried forward. These options were selected to span the lowest cost and highest payload opportunities among the near-term options.

Commercial Jet + Multistage Solid Rocket

Carrier aircraft	Modified Existing Subsonic Commercial Jet Aircraft
Launch vehicle	Expendable Multistage Solid Rocket

Commercial Jet + Multistage Liquid Rocket

Carrier aircraft	Modified Existing Subsonic Commercial Jet Aircraft
Launch vehicle	Expendable Multistage Liquid Rocket (RP fuel)

Commercial Jet + Reusable Liquid Rocket with Drop Tanks

Carrier aircraft	Modified Existing Subsonic Commercial Jet Aircraft
Launch vehicle	Reusable Liquid Rocket (LH2 fuel) with Drop Tanks

New Custom Subsonic Carrier + Multistage Liquid Rocket

Carrier aircraft	New Specially Designed (Bottom Carry) Large Subsonic Carrier Aircraft
Launch vehicle	Expendable Multistage Liquid Rocket

Chapter 3

CHAPTER 3

SCREENING

The team next evaluated the range of possible configurations of the set of four representative concepts that survived prescreening. To do this, each concept was expanded to many concept configurations by combining the various stage and technology options in a morphological matrix. This allowed the team to evaluate and screen many configurations in an integrated, parametric, low-fidelity, engineering environment, similar to that used to compute the FOMs.

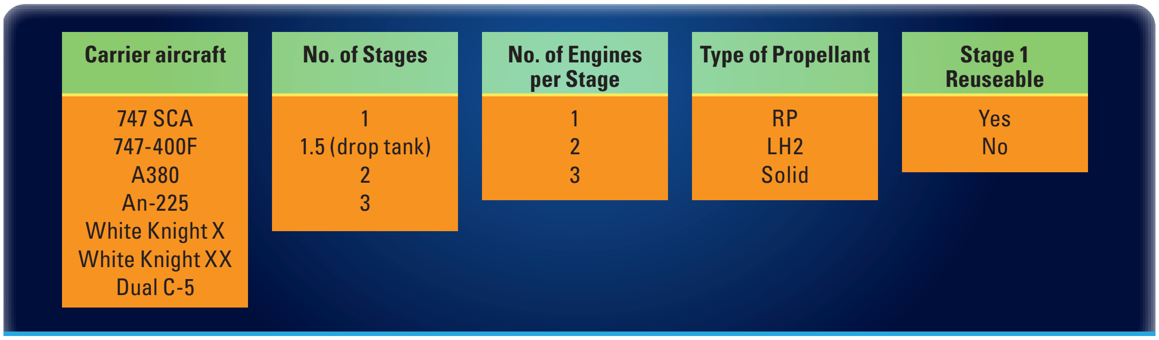
Methodologies for Concept Screening

The concept trade space consisted of a morphological matrix with the following elements: seven carrier aircraft, three types of propellants, and the number of stages, propulsion mode, propellants, and reusability. As shown in Figure 5, each launch vehicle could have one, two, or three stages, and the first stage could be either expendable or reusable, and could be configured with or without a drop tank.

The integration framework used to trade the payloads, costs, and loss of mission probabilities was known as Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA). (Crocker, 2001) ROSETTA was a design simulation tool that utilizes a multidisciplinary process that was intended to simulate design optimization. The fidelity level of the analysis carried out in ROSETTA was low—0 or 1 according to the definitions presented in Appendix F.

The payload and corresponding launch vehicle were sized to meet the maximum payload weight of the carrier aircraft while satisfying major constraints such as stage mass ratio, stage thrust-to-weight ratio, and wing loading for separation. Geometry as well as propellant tanks were sized to meet the mass ratio, wings were sized for wing loading, and engine thrust and engine mass were sized for thrust-to-weight ratio. Because all of these parameters were mutually dependent, ROSETTA iterated using feedforward and feedback loops to determine the maximum payload.

This sizing approach allowed ROSETTA to generate the parameters for an idealized system where the system and all subsystems and components were sized precisely to meet mission requirements. Such concepts were referred to as "rubberized", reflecting the way components



Carrier aircraft	No. of Stages	No. of Engines per Stage	Type of Propellant	Stage 1 Reuseable
747 SCA 747-400F A380 An-225 White Knight X White Knight XX Dual C-5	1 1.5 (drop tank) 2 3	1 2 3	RP LH2 Solid	Yes No

Figure 5 Elements used in the morphological matrix.

were stretched to create an idealized system. Once the maximum payload was determined, engineering parameters for cost and reliability were computed based on subsystem and component size, system performance, and CONOPs.

ROSETTA significantly reduced the time to achieve design convergence over a broad analysis of alternatives by approximating results for each discipline using response surfaces rather than running detailed discipline codes for each instance. These response surfaces were generated using a design of experiments method to guide the range of inputs to the various analysis tools.

This conceptual framework was used to specify the design of each propulsion system to meet all thrust constraints across 1,365 different configurations. Launch vehicles were optimized within size and gross weight constraints depending on the carrier aircraft, but were not constrained to previously-developed engines and solid motors. All launch vehicles, at this step in the analysis, were considered new developments rather than existing designs, and therefore required similar development and acquisition costs for a new system. DDT&E costs were amortized over a campaign of 120 flights.

A detailed list of the assumptions and methodologies used in ROSETTA is provided in Appendix G.

Analysis of Carrier Aircraft Alternatives

The initial results of the analysis of alternatives are shown in Figure 6. Out of the 1,365 combinations, 1,296 feasible solutions were generated.

As was observed, the majority of the cases analyzed could carry more payload than the industry price trend line (as determined in Figure 3), but at a higher cost. The maximum payload ranged from 11,180 to 52,290 lb, which varied as the external weight capacity for each carrier aircraft. (See Table 2.)

The launch vehicles with the most promising characteristics for each carrier aircraft are shown in Table 3. The highlighted values represent the best results for each category—payload, recurring costs per flight, and lifecycle cost per pound of payload. The lowest costs of the 1,365 possibilities were either the two- or three-stage solid propellant stage concepts for all of the carrier aircraft.

Table 2 System Concept Configurations

Carrier aircraft	External weight capacity (lb)	Maximum payload to LEO (lb)
White Knight X	176,000	11,180
747-100 SCA-911	240,000	15,440
A380-800F	264,550	17,090
747-400F	308,000	20,000
An-225 Mriya	440,930	30,380
White Knight XX	750,000	49,940
Dual-fuselage C-5	771,620	52,290

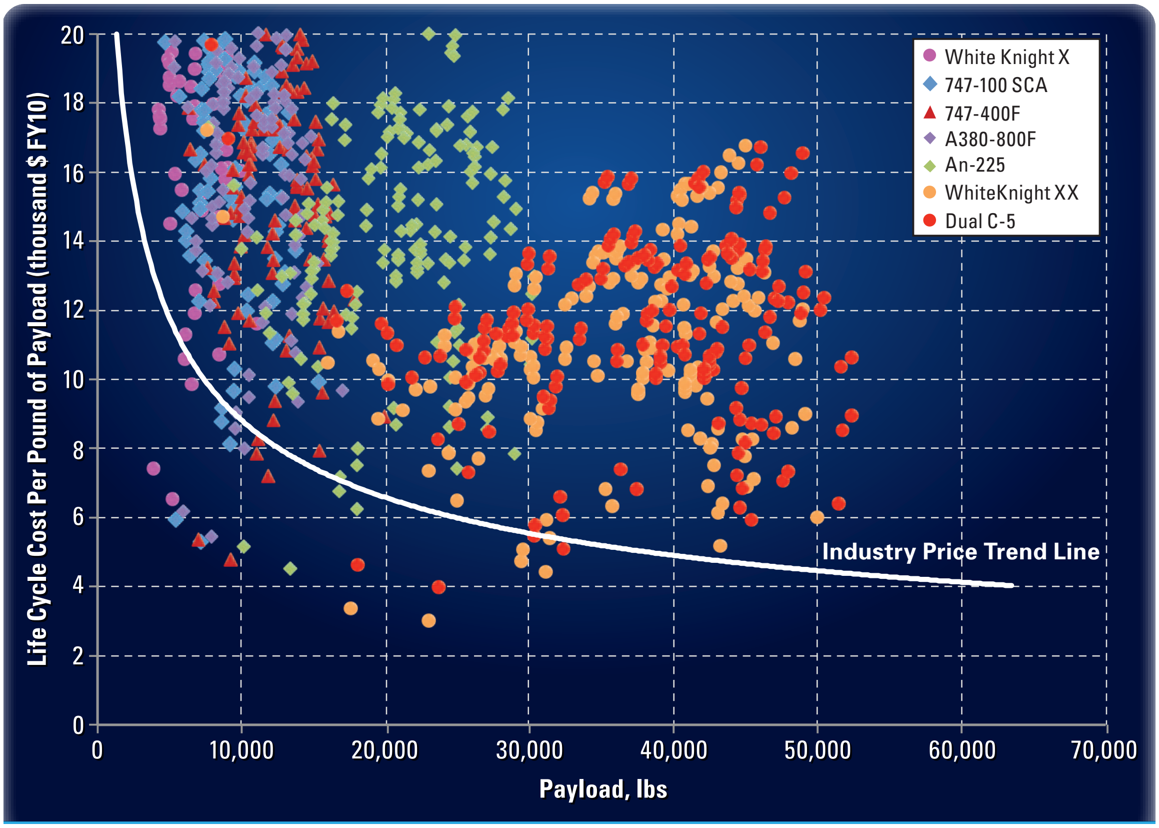


Figure 6 Results of the initial analysis of lifecycle cost and payload capability for 1,296 cases. The line is the industry price trend line originally plotted in Figure 3.

Among the existing carrier aircraft—the A380-800F, 747-400F, 747-100 SCA, An-225 Mriya—the highest payload capability results from a configuration with a single stage, drop tank, and LH2 fuel. Two-stage LH2 concepts were found to carry less payload than the drop tank concept primarily because the length of the launch vehicle was constrained to fit on top of the carrier aircraft. These length constraints produced concepts with low fineness ratios and reduced the propellant mass fractions from 0.91 to 0.84, 0.82, and 0.67 for each stage in the three-stage concept, thus reducing the maximum payload achievable. For the very large An-225, the launch vehicle length constraints were not a limiting factor, resulting in the best two-stage LH2 concept.

DDT&E cost values for the 747-100 SCA, 747-400F, and A380-800F were relatively low, owing to the assumption to acquire used aircraft. The three dual-fuselage aircraft were all treated as new acquisitions. The dual-fuselage C-5 development costs were based on the assumption that modifications would be extensive on an airplane of this vintage. On the other hand, optimistic development assumptions were made for the White Knight configurations based on the aggressive development history at Scaled Composites. The DDT&E costs for the White Knight XX were lower than for the dual-fuselage C-5, in spite of the fact that the C-5 is an existing production aircraft.

Table 3 Concepts with the Most Promising Characteristics ($ in millions, all costs in 2010 dollars)

	Stage 1	Stage 2	Stage 3	Payload (lb)	Recurring cost/flight	Lifecycle cost/lb	Total Facilities	Total DDT&E	Total Production	Total Operations	Total Lifecycle	Probability of LOM
White Knight X												
	Drop Tank/LH2	LH2		11,180	$113	$11,540	$91	$1,470	$12,430	$1,460	$15,460	1.9%
	Solid	Solid		4,040	$21	$7,360	$77	$660	$2,270	$550	$3,560	2.1%
	Solid	Solid	Solid	5,330	$27	$6,490	$89	$760	$2,620	$680	$4,150	2.4%
747-100 SCA-911												
	Drop Tank/LH2	LH2		15,450	$136	$9,860	$110	$1,550	$14,790	$1,800	$18,250	2.6%
	Solid	Solid		5,550	$24	$5,880	$94	$640	$2,490	$690	$3,910	2.7%
	Solid	Solid	Solid	7,300	$31	$5,240	$110	$760	$2,870	$840	$4,590	3.1%
747-400F												
	Drop Tank/LH2	LH2		20,000	$157	$8,860	$129	$1,860	$17,140	$2,090	$21,230	2.8%
	Solid	Solid		7,150	$26	$5,320	$112	$860	$2,800	$770	$4,550	2.9%
	Solid	Solid	Solid	9,390	$34	$4,730	$132	$1,000	$3,230	$950	$5,310	3.3%
A380-800F												
	Drop Tank/LH2	LH2		17,090	$144	$9,630	$117	$1,630	$15,980	$1,920	$19,650	3.0%
	Solid	Solid		6,120	$25	$6,130	$101	$680	$2,930	$730	$4,440	3.1%
	Solid	Solid	Solid	8,060	$32	$5,400	$118	$810	$3,330	$890	$5,150	3.5%
An-225 Mriya												
	LH2	LH2		30,390	$347	$12,910	$284	$3,590	$40,260	$2,730	$46,860	2.7%
	Solid	Solid		10,300	$31	$5,130	$146	$870	$4,120	$1,040	$6,170	2.7%
	Solid	Solid	Solid	13,500	$40	$4,480	$172	$1,040	$4,600	$1,270	$7,080	3.1%
White Knight XX												
	Drop Tank/LH2	LH2		49,950	$266	$5,950	$240	$2,940	$28,670	$3,770	$35,610	2.0%
	Solid	Solid		17,650	$39	$3,330	$217	$1,560	$3,920	$1,340	$7,030	2.1%
	Solid	Solid	Solid	23,060	$50	$2,980	$257	$1,780	$4,500	$1,670	$8,220	2.5%
Dual C-5												
	LH2	LH2		52,290	$478	$10,560	$388	$6,880	$54,980	$3,810	$66,060	2.1%
	Solid	Solid		18,170	$39	$4,600	$222	$3,550	$4,790	$1,330	$9,900	2.1%
	Solid	Solid	Solid	23,730	$50	$3,940	$263	$3,780	$5,380	$1,670	$11,100	2.5%

The White Knight X had the lowest payload capability and the highest recurring costs per pound of payload, leading to the observation that a concept sized between the White Knight X and XX may have struck a better balance between mobility and payload. The dual-fuselage C-5 had the largest external payload capability and the highest delivered payload in a two-stage LH2 configuration.

The FOMs other than payload and cost did not provide many discriminators. The solid propellant stage concepts were assumed to have less restrictive handling and propellant storage requirements as compared to liquid engines. Although much lower in cost and with less propellant infrastructure than liquid stage concepts, they had the lowest payload capability—approximately half that of the LH2 concepts owing to the differences in specific impulse. Finally, the probability of loss of mission for all cases ranged from 1.9 to 3.5 percent. In this low-fidelity screening analysis, this variation was considered insignificant.

While all the carrier aircraft analyzed could arguably meet the goals established in the study, each had their own strengths and weaknesses in the FOMs analysis. The White Knight X had the lowest payload capability compared to other existing commercial aircraft, with no compensating advantages. The White Knight XX and dual-fuselage C-5 both displayed wild uncertainty in performance. The capability of A380-800F aircraft essentially duplicated the 747 capabilities, and it was found to be more expensive to acquire. Finally, only one An-225 Mriya aircraft exists currently and the team considered the risks of purchasing and maintaining such a unique specimen very high.

Based on these results, only the 747-400F was carried forward for further analysis. The 747-400F is widely available as a used aircraft and is well characterized in many discipline models. For these reasons, it was judged by the study team as having the greatest potential to demonstrate overall feasibility.

Analysis of Launch Vehicle Alternatives

Various launch vehicle configurations also had different strengths and weaknesses. The system concepts with two- and three-stage solid rockets generally had the lowest costs and the lowest payload capability. At the other end of the spectrum, the three-stage LH2 system concept had the highest lifecycle costs, but not always the highest payload. The one-stage LH2 concept with drop tank generally had the best payload capability. The low-density and high-volume of the two-stage LH2 systems required a very low fineness ratio, and the multiple stages and engine nozzle lengths required long interstage adapters. For example, the two-stage and three-stage LH2 concepts had less payload than the drop tank concept on the 747-400F because the launch vehicle length was constrained to 127 ft.

The results plotted in Figure 7 reveal the potential to meet the HLS goals with the 747-400F carrier aircraft. The payload capability estimates for a 747-400F ranged from 7,150 lb with solid rockets to 20,000 lb with liquid engines. Of specific interest is two-stage RP launch vehicle, which delivered more than 10,000 lb of payload in this configuration while avoiding the operational complexities of storage and handling of liquid hydrogen.

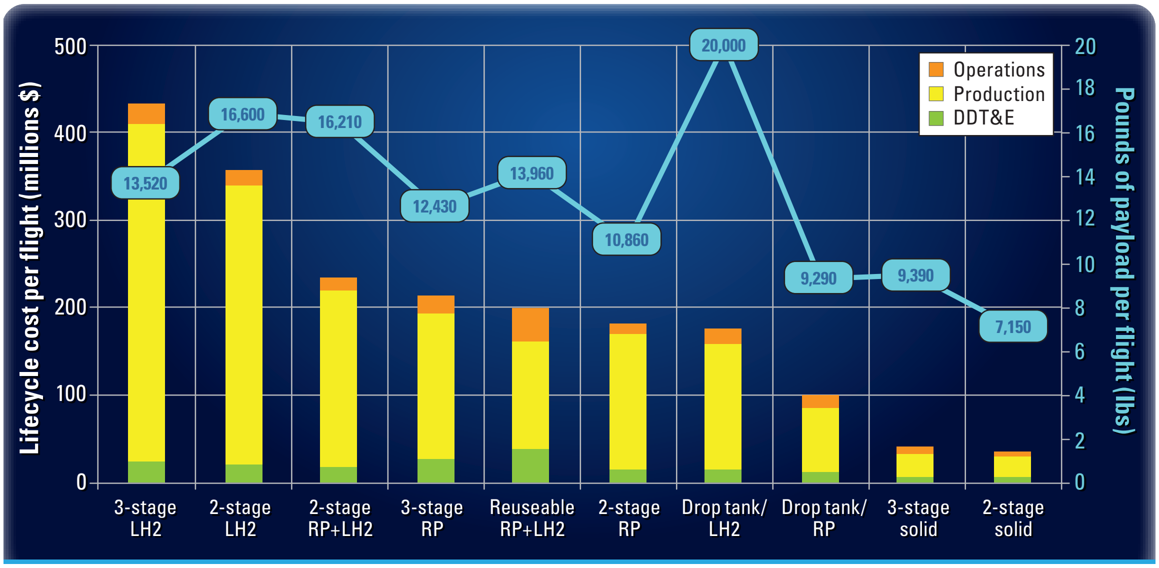
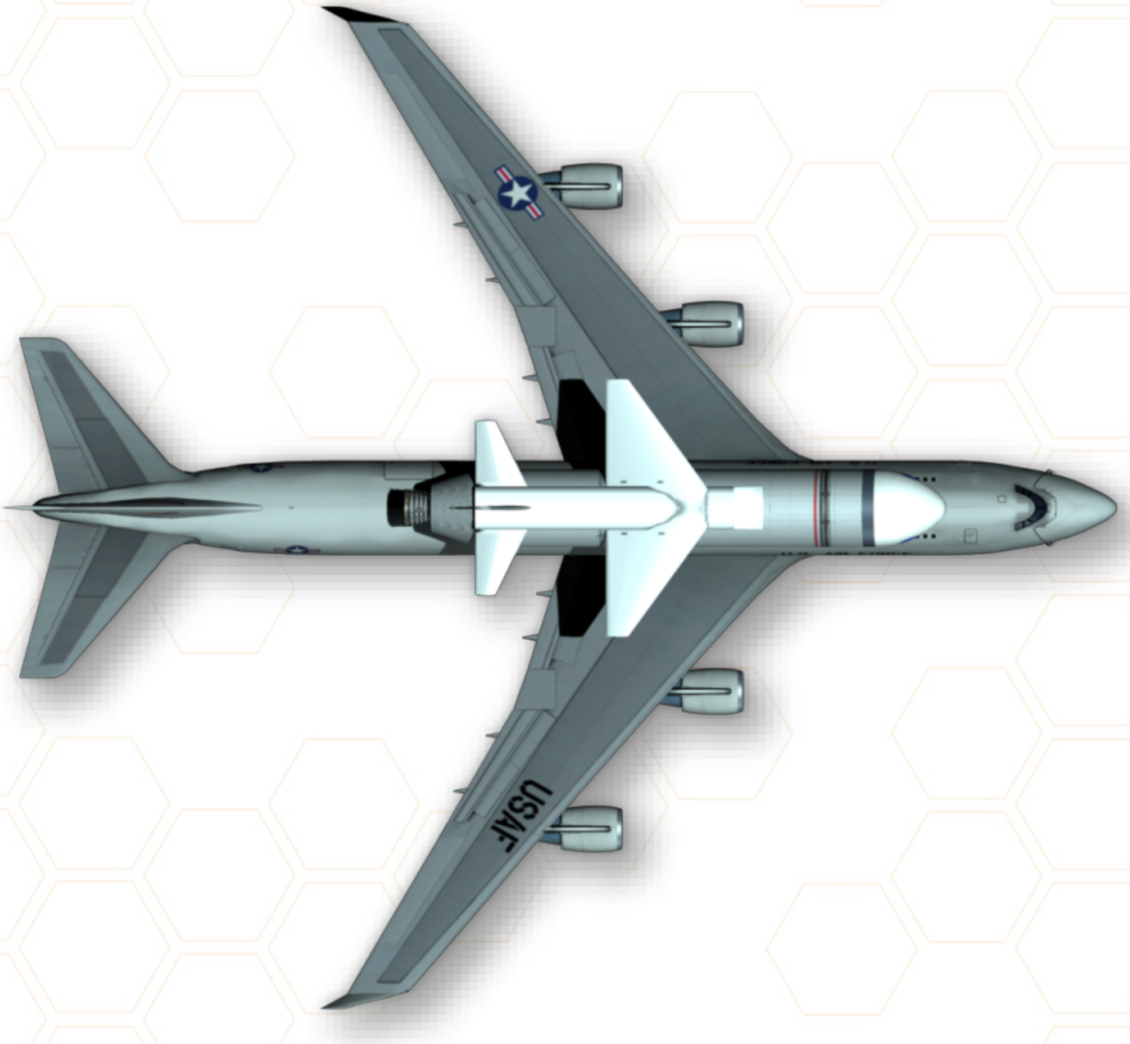


Figure 7 Comparison of costs and payload for the 747-400F carrier aircraft and several launch vehicle configurations. The cost per flight is shown in the bars on the left, and the corresponding payload capability is shown by the green line.

Results of the Screening Analysis

This analysis of horizontal launch concepts showed their competitiveness as compared to the industry price trend line in Figure 3. It is difficult, however, to project better performance than the advertised price of modern vertical launch systems such as the Falcon 9 two-stage RP system or the Taurus II RP+solid (plus optional hypergol third stage). While the cost of the two- and three-stage solids could be in range considering the conservative assumptions of this model, the costs of the liquid rocket system concepts were substantially larger.

The team selected three configurations the next round of higher fidelity analysis. Based on the screening results, a low cost solid concept, a high payload two-stage LH2 concept, and a compromise RP+LH2 vehicle were chosen. The drop tank concept, while promising, did not have a detailed model available to fully compare this configuration. The study team recommends further consideration of this potentially competitive concept.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Chapter 4

CHAPTER 4

POINT DESIGNS

The three selected concepts that emerged from the screening exercise were further refined to determine development feasibility and risk at a higher level of fidelity. These concepts were developed into point design system concepts (PDs), intended to represent the expected range of performance, reliability, cost, and risk for a class of horizontal launch concepts.

The analyses optimized the various design parameters in order to maximize the payload delivered to orbit, and determined the best existing rocket motor or engine and other critical subsystems to reduce the development risk and uncertainty of system weight and cost predictions.

Methodologies for Point Designs

The FOMs for each point design were determined using a mix of low- and mid-level fidelity tools, and system performance was calculated using level 1 fidelity tools. The methodology centered on dynamic fault trees for probability of loss of vehicle and probability of loss of mission and NAFCOM for DDT&E and production costs. As for the screening process, Appendix F contains details on the assumptions and methodologies used.

Major aspects of the point design methodology include the following:

- The launch vehicle gross weight was sized to meet the maximum carrying capacity of the carrier aircraft.
- The performance and costs were calculated based on the properties of existing engines rather than rubberized engines.
- The technical discipline tools (e.g., trajectory, aerodynamics, propulsion, mass properties), rather than response surfaces, were used.
- The NAFCOM cost model was used (rather than TRANSCOST) because NAFCOM computes DDT&E and theoretical first unit cost at the subsystem level.

The goals for the vehicle concept exploration were to identify concepts with useful payloads approaching 15,000 lbs due east to a 100-nautical mile, low Earth orbit with low development costs and with production and operations costs approaching those of current launch systems. To ensure military and commercial usefulness, the concepts were constrained to existing runways with a gross takeoff weight less than 1.8 million lb.

Flight rates were set at current market projections of 6 flights per year. This nominal 60 days between flights was used to size the operations crew needed for the campaign. The crew size was also used to determine surge call-up time and minimum turn around time.

To select the best existing engines and other subsystems while optimizing the payload of the system, an array of analysis tools were integrated into a framework to link control variables. A parametric geometry model scaled the wing geometry based on wing loading constraints, stage length and diameter based on propellant requirements and carrier aircraft constraints. Aerodynamics, rocket performance, and system weight were communicated to the Program to

Optimize Simulated Trajectories (POST) program to maximize payload. If the launch vehicle did not meet all the constraints, the vehicle geometry (diameter and length), aerodynamic surfaces, and thrust were resized until the payload was optimized and all constraints were met.

The results of the aerodynamic analyses for the point designs, along with configuration details and trajectory analyses, are included in Appendix H.

Point Design Definitions

As modified, the 747-400F was assumed to have a total length of 231 feet, a wingspan of 211 feet, and a design payload capacity of 305,000 lb.

The three configurations analyzed are listed in Table 4. The PD-1 was selected to represent the lowest DDT&E costs, and PD-3 was selected to represent the highest payload. The PD-2 configuration was selected as a compromise between performance and cost. Because the launch vehicles were modeled from existing solid rocket motors, the total gross weight in PD-1 is somewhat less than the design goal.

Table 4 Configurations for the Point Design Launch Vehicles

	PD-1	PD-2	PD-3
	3-stage solid	2-stage RP+LH2	2-stage LH2
Total Gross Weight†	288,480 lb	305,000 lb	305,000 lb
Payload to LEO	5,660 lb	12,580 lb	17,810 lb
Total Length	100 ft	102 ft	114 ft
Maximum Diameter	7.8 ft	12.5 ft	16.4 ft
Wing Span	57 ft	62 ft	53 ft

† Includes inert system weight margin

Weight Breakdown Comparisons

The resulting weight breakdown statements for each system concept are shown in Table 5. In all cases, the integrated aerodynamic surface module was jettisoned early in the trajectory modeling and thus its weight has only a few hundred pounds of impact on the payload delivery capability.

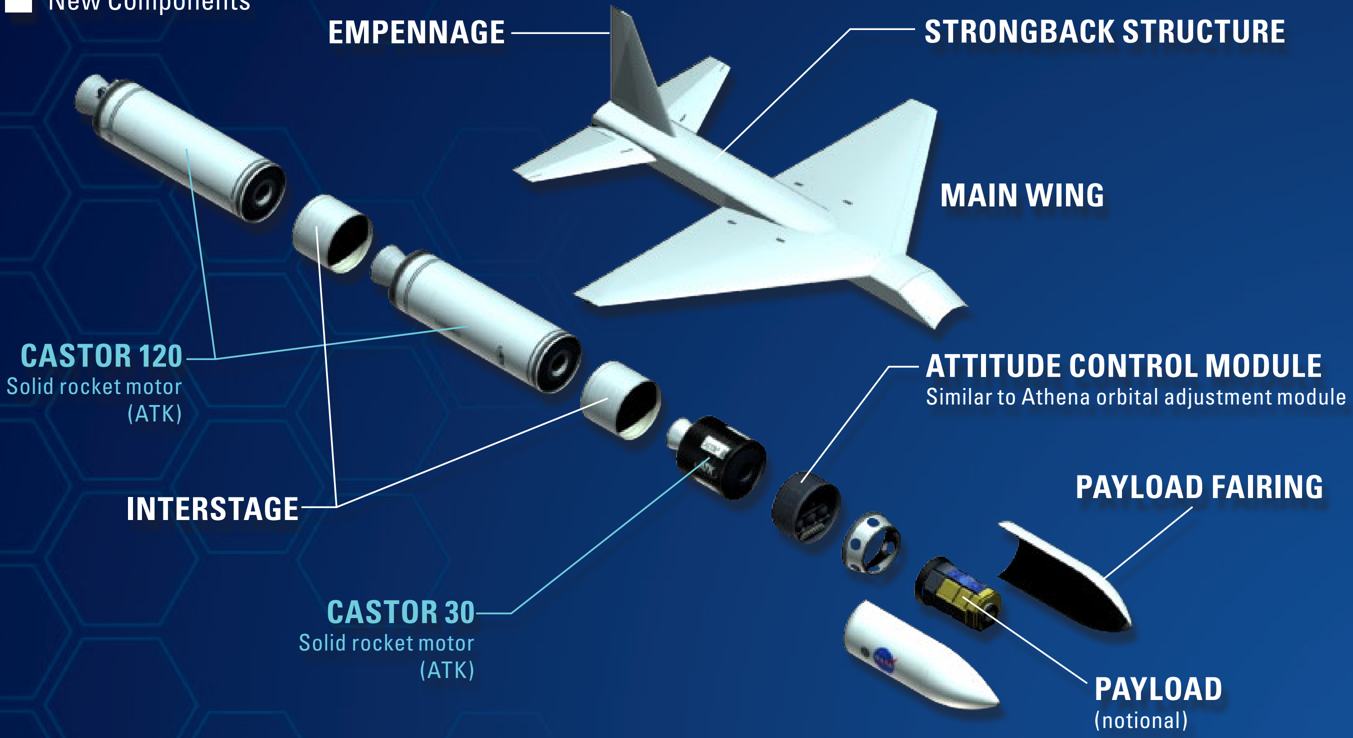
For PD-1, the selection of the three existing solid rocket motors meant the optimized gross weight of the launch vehicle was less than the maximum the 747-400F could carry. This allowed a reduction in the internal structural modifications and lowered the development costs of the 747. The payload delivered by PD-1 was computed to be 5,660 lb. For PD-2, payload delivery was computed to be 12,580 lb for the closed vehicle, and PD-3, payload delivery was computed to be 17,810 lb.

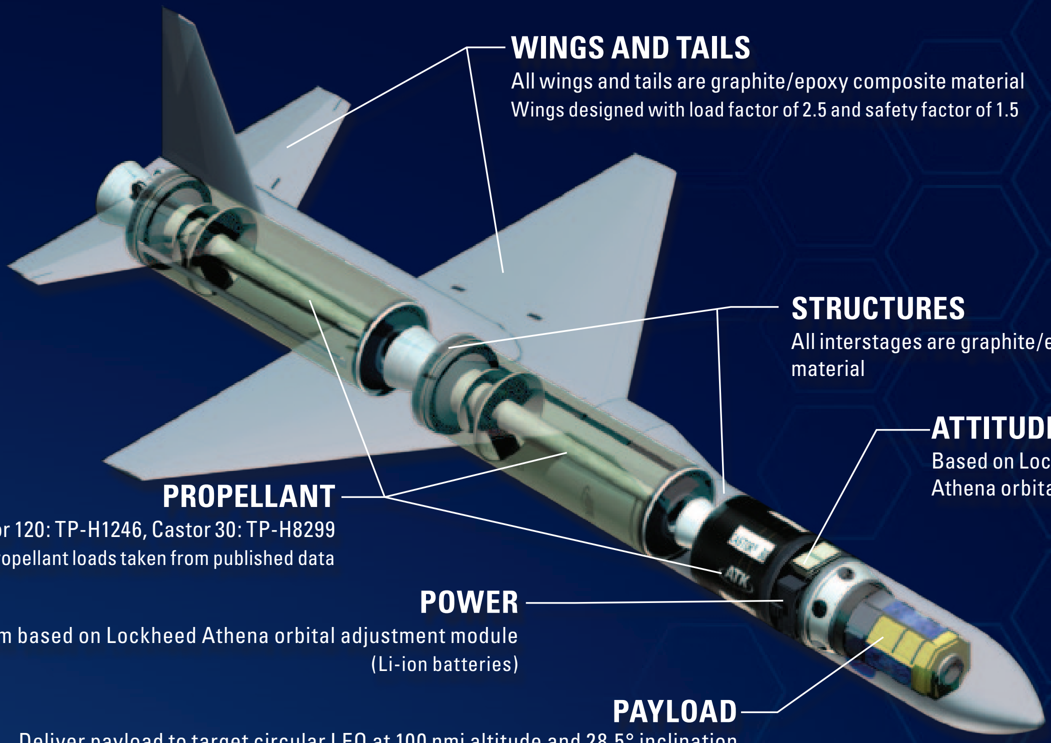
Table 5 Weight Breakdown Statement for Point Design System Concepts (all weights in lb)

Stage 1	**PD-1**	**Stage 1**		**PD-2**	**PD-3**
Motor	8,980	Structure		8,970	16,610
Subsystems	250	Propulsion		9,190	11,490
Interstage	750	Thermal control		330	520
Propellant	108,040	Power		160	160
Loaded	*118,010*	Avionics		46	46
Stage 2			*Inert*	*18,700*	*28,830*
Motor	8,980	Consumables		1,940	1,820
Subsystems	350	Main propellants		193,440	179,160
Interstage	640	Start-up losses		580	540
Propellant	108,040		*Fueled*	*214,670*	*210,350*
Loaded	*118,000*	**Stage 2**			
Stage 3		Structure		6,110	7,340
Motor	2,700	Propulsion		2,140	2,170
Subsystems	130	Thermal Control		280	180
Propellant	28,300	Power		160	160
Loaded	*31,130*	Avionics		480	480
Control Module			*Inert*	*9,190*	*10,340*
Structures, tanks	470	Consumables		810	770
Subsystems	260	Reaction propellants		440	570
Reaction control	210	Main propellants		53,390	50,310
Propellant	930	Start-up losses		160	150
Loaded	*1,860*		*Fueled*	*64,000*	*62,130*
Aerosurface Module		**Aerosurface Module**			
Wing	6,830	Wing		6,860	6,090
Fins	2,030	Fins		1,650	2,450
Actuators	1,280	Actuators		1,040	1,540
Strongback	2,260	Strongback		2,130	2,250
	12,400			*11,680*	*12,310*
Fairing and adapter	1,420	Fairing and adapter		2,090	2,400
Payload	5,660	Payload		12,580	17,810
Total	**288,490**			**305,000**	**305,000**

Point Design 1

🟦 Existing Components
⬜ New Components





WINGS AND TAILS

All wings and tails are graphite/epoxy composite material
Wings designed with load factor of 2.5 and safety factor of 1.5

STRUCTURES

All interstages are graphite/epoxy composite material

ATTITUDE CONTROL

Based on Lockheed
Athena orbital adjustment module

PROPELLANT

HTBP (Castor 120: TP-H1246, Castor 30: TP-H8299
Solid motor propellant loads taken from published data

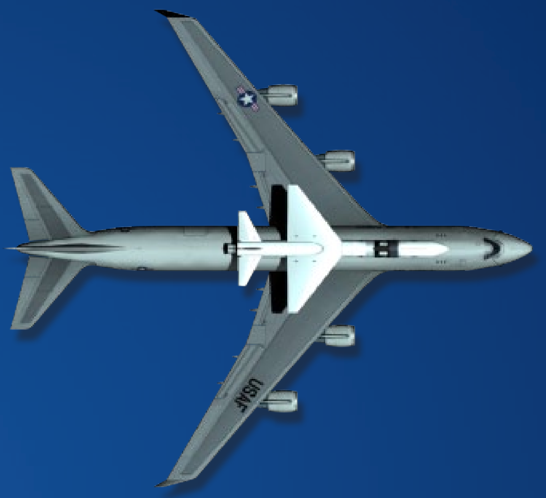
POWER

Power system based on Lockheed Athena orbital adjustment module
(Li-ion batteries)

PAYLOAD

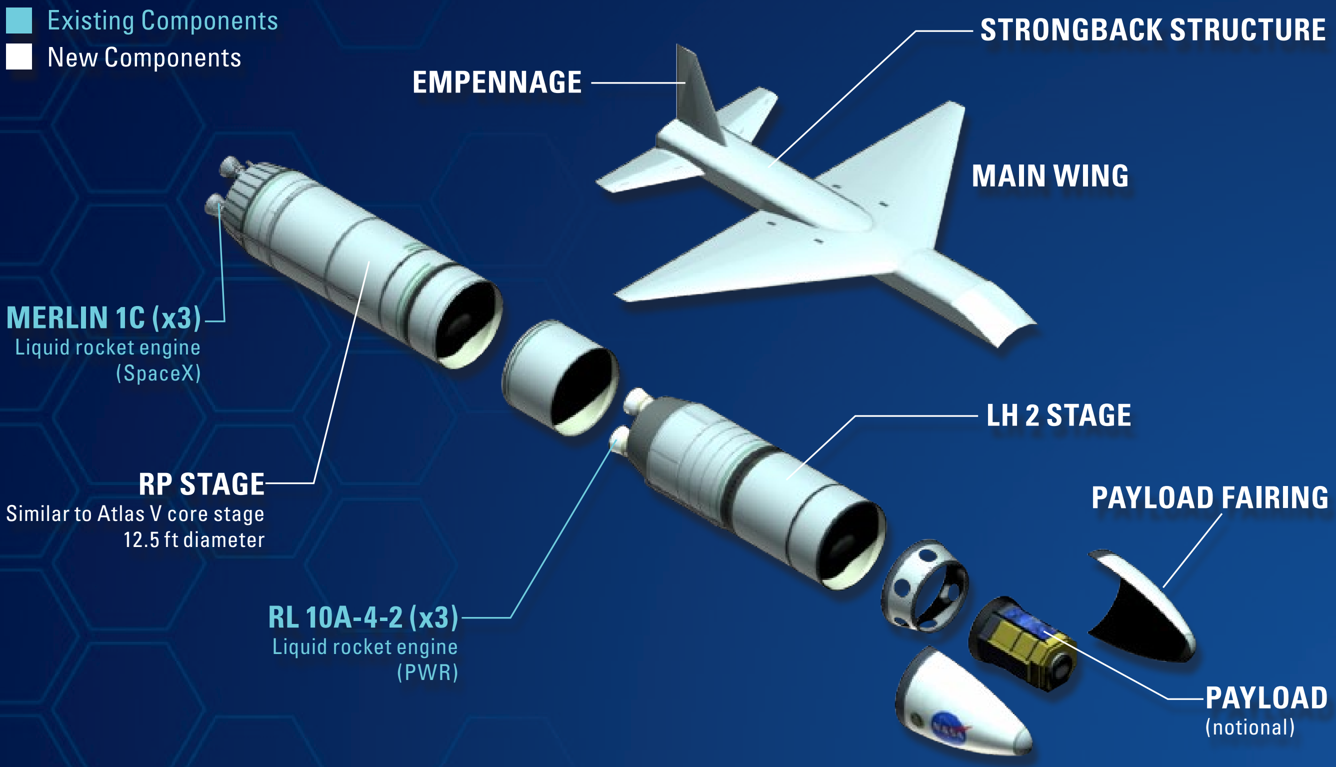
Deliver payload to target circular LEO at 100 nmi altitude and 28.5° inclination
Performance data is shown for due East launch from 28.5° latitude

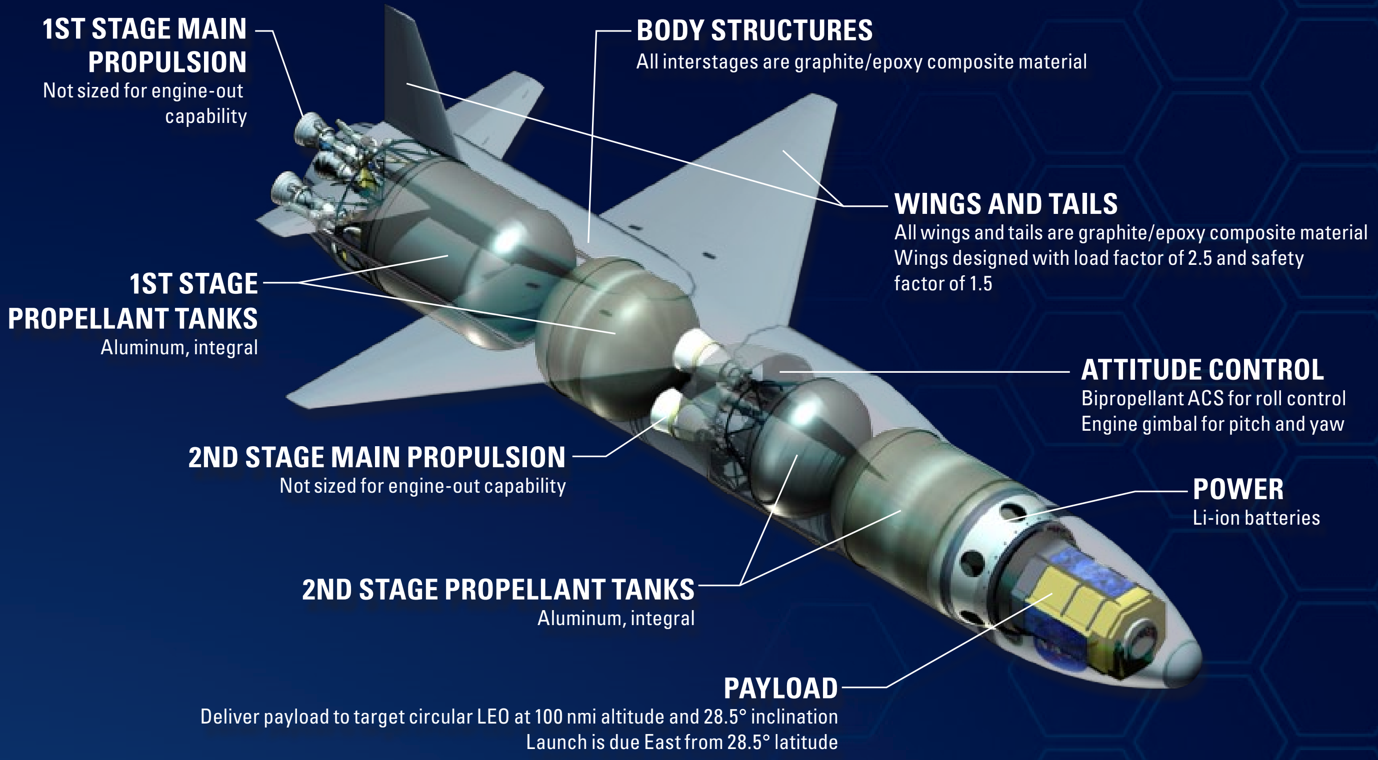
747-400F carrier aircraft / 3-stage solid rocket launch vehicle



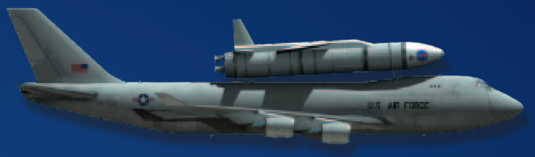
PD-1 consisted of the 747-400F carrier aircraft and a three-stage solid rocket launch vehicle. The solid rocket motors were selected for the maximum payload—two Castor 120 motors for stages one and two and a Castor 30 motor for stage three. The wing and empennage were attached to the first stage with a winged "strong-back", a nonintegral structural interface connecting the aerodynamic surfaces to the launch vehicle. The intertanks, interstages, and aerodynamic surfaces were made with graphite-epoxy composite materials. Power and attitude control subsystems were based on the Lockheed Athena orbit adjust module.

Point Design 2





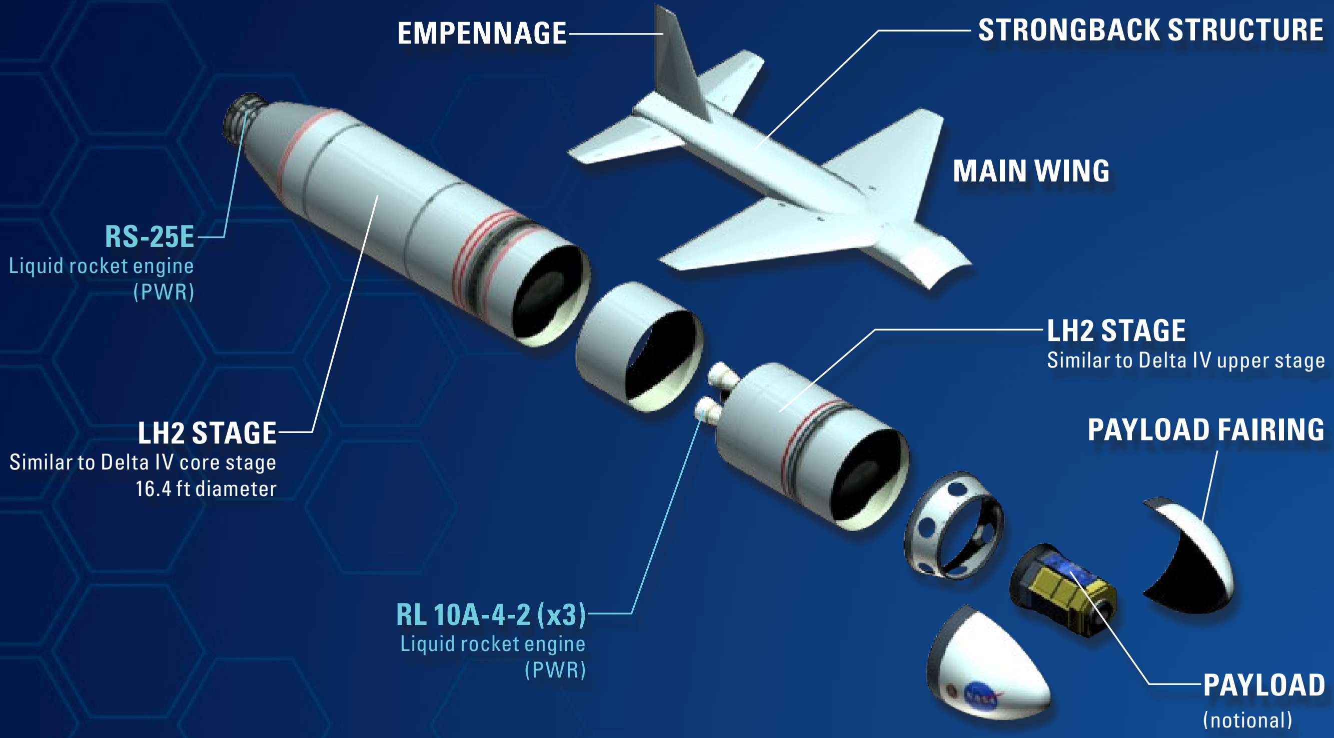
747-400F carrier aircraft / 2-stage RP+LH2 launch vehicle

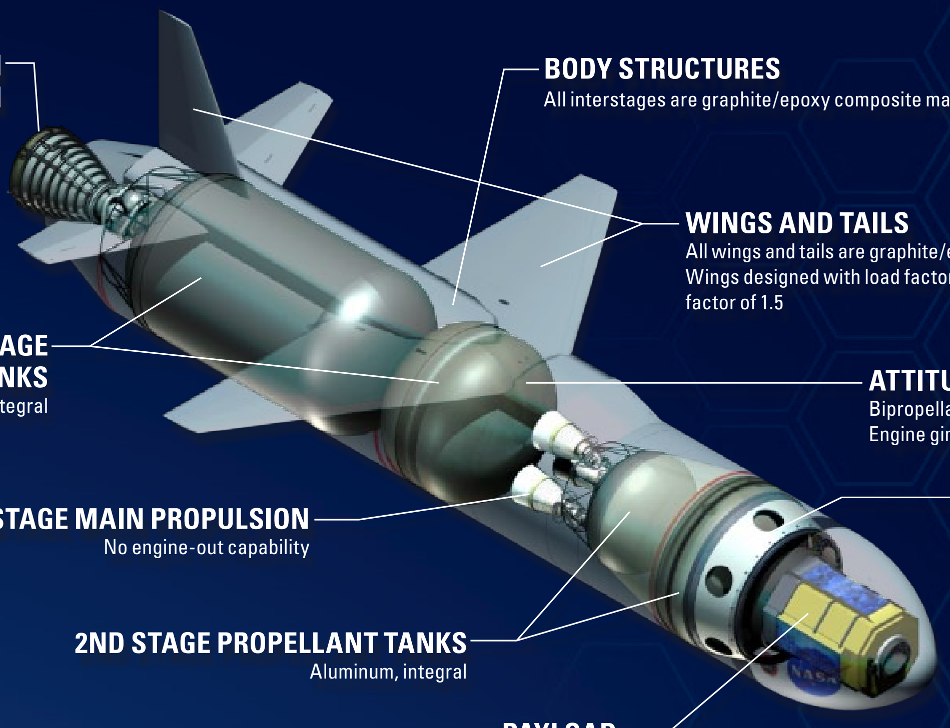


PD-2 consisted of the 747-400F carrier aircraft and a two-stage launch vehicle with an RP first stage and an LH2 second stage. The first stage was made up of three RP Merlin 1C engines from SpaceX. The second stage had three RL10A-4-2 LH2 engines from Pratt&Whitney Rocketdyne. The wing and empennage were attached to the first stage with a strongback. All interstages, fairings and aerodynamic surface were graphite-epoxy composite materials. The selection of the liquid engines brings the system to the maximum external payload limit of the 747-400F. The gross weight of the launch vehicle equals 305,000 lbs which was the maximum external payload limit of the 747-400F.

Point Design 3

🟦 Existing Components
⬜ New Components





1ST STAGE MAIN PROPULSION

BODY STRUCTURES
All interstages are graphite/epoxy composite material

WINGS AND TAILS
All wings and tails are graphite/epoxy composite material
Wings designed with load factor of 2.5 and safety factor of 1.5

1ST STAGE PROPELLANT TANKS
Aluminum, integral

ATTITUDE CONTROL
Bipropellant system for roll control
Engine gimbal for pitch and yaw

POWER
Li-ion batteries

2ND STAGE MAIN PROPULSION
No engine-out capability

2ND STAGE PROPELLANT TANKS
Aluminum, integral

PAYLOAD
Deliver payload to target circular LEO at 100 nmi altitude and 28.5° inclination
Launch is due East from 28.5° latitude

747-400F carrier aircraft / 2-stage LH2 launch vehicle

PD-3 consisted of the 747-400F carrier aircraft and a two-stage LH2 launch vehicle. Owing to the large diameter of this launch vehicle, lateral directional stability and dynamic loads from buffet will require more in-depth analyses. The first stage had one RS-25E, an air-start, expendable Space Shuttle Main Engine. The second stage had three RL10A-4-2 LH2 engines. The wing and empennage were attached to the first stage with a strongback. All interstages, fairings and aerodynamic surface were graphite-epoxy composite materials. The gross weight of the launch vehicle equals 305,000 lbs which was the maximum external payload limit of the 747-400F.

Reliability Comparisons

Using failure rates of existing systems and the reliability exponential growth history of past systems, the loss of mission (LOM) probabilities are shown in Table 6. Analysis of the most important elements revealed no dominating unreliable components.

Table 6 Reliability Assessment for Point Design System Concepts

		PD-1		PD-2		PD-3	
		Probability (Mean flights before failure)					
4th Flight	Loss of 747-400F	0.006%	(17,241)	0.006%	(17,241)	0.006%	(17,241)
	Failed separation	1.0%	(101)	1.0%	(101)	1.0%	(101)
	Loss of Stage 1	2.07%	(48)	1.72%	(58)	1.95%	(50)
	Loss of Stage 2	1.35%	(74)	2.37%	(42)	2.36%	(41)
	Loss of Stage 3	2.09%	(48)				
16th Flight	Loss of 747-400F	0.001%	(71,428)	0.001%	(71,428)	0.001%	(71,428)
	Failed separation	0.24%	(419)	0.24%	(419)	0.24%	(419)
	Loss of Stage 1	0.50%	(199)	0.47%	(212)	0.47%	(212)
	Loss of Stage 2	0.32%	(300)	0.56%	(178)	0.56%	(178)
	Loss of Stage 3	0.24%	(419)				

Costs Comparisons

Program costs, listed in Table 7, were estimated using a number of assumptions. Chief among these was the acquisition and modification of a used 747-400F for $86 million, and the subsequent DDT&E of $122 million for this aircraft. These estimates were based on past Boeing AirLaunch studies, using current year dollars. DDT&E costs of the strongback aerosurface modification were based on traditional aerospace practices modeled with the NAFCOM model. In addition, the typical government oversight for the program was based on previous manned system development, and government facilities (and their associated costs) were used for testing and demonstration.

- For PD-1, market price was used for the solid rocket stages. The recurring costs per pound of payload were calculated to be $51 million, or $8,930 per pound of payload.
- For PD-2, the Merlin 1C costs were calculated in NAFCOM based on the advertised price of the SpaceX Falcon 1 and Falcon 9. The recurring costs per pound of payload were estimated at $120 million, or $9,560 per pound of payload.
- For PD-3, the RS-25E costs were estimated using NAFCOM. Note that the RS-25E technology development costs (primarily for air-start capability) have not been added to DDT&E estimates. The recurring costs per pound of payload were $130 million, or $7,300 per pound of payload.

Table 7 Projected Costs for the Point Design System Concepts

FY10 Dollars, Assuming 6 Flights Per Year

	PD-1	PD-2	PD-3
DDT&E and Facilities Costs			
747-400F	$122 M	$122 M	$122 M
Stage 1	$48 M	$272 M	$1,780 M
Stage 2	$48 M	$305 M	$295 M
Stage 3	$13 M		
Aerosurfaces	$104 M	$103 M	$106 M
Attitude control system and fairing	$31 M	included	included
Facilities and ground service equipment	$109 M	$134 M	$132 M
Subtotal for DDT&E and facilities	*$475 M*	*$940 M*	*$2,440 M*
Acquisition and Production Costs			
747-400F acquisition and modifications	$86 M	$86 M	$86 M
Stage 1	$13 M	$34 M	$51 M
Stage 2	$13 M	$67 M	$58 M
Stage 3	$2 M	$11 M	NA
Aerosurfaces	$10 M	$11 M	$12 M
Attitude control and fairing	$3 M	included	included
Subtotal expendable average production	*$41 M*	*$112M*	*$120 M*
Total recurring costs per pound of payload	$8,930 / lb	$9,560 / lb	$7,300 / lb
Total recurring costs	*$52 M / flight*	*$120 M / flight*	*$130 M / flight*
Operations Burden			
Turn-around time	43 hours	68 hours	57 hours
Call-up time	3.8 hours	5.9 hours	7.2 hours

Summary of Point Design System Concepts

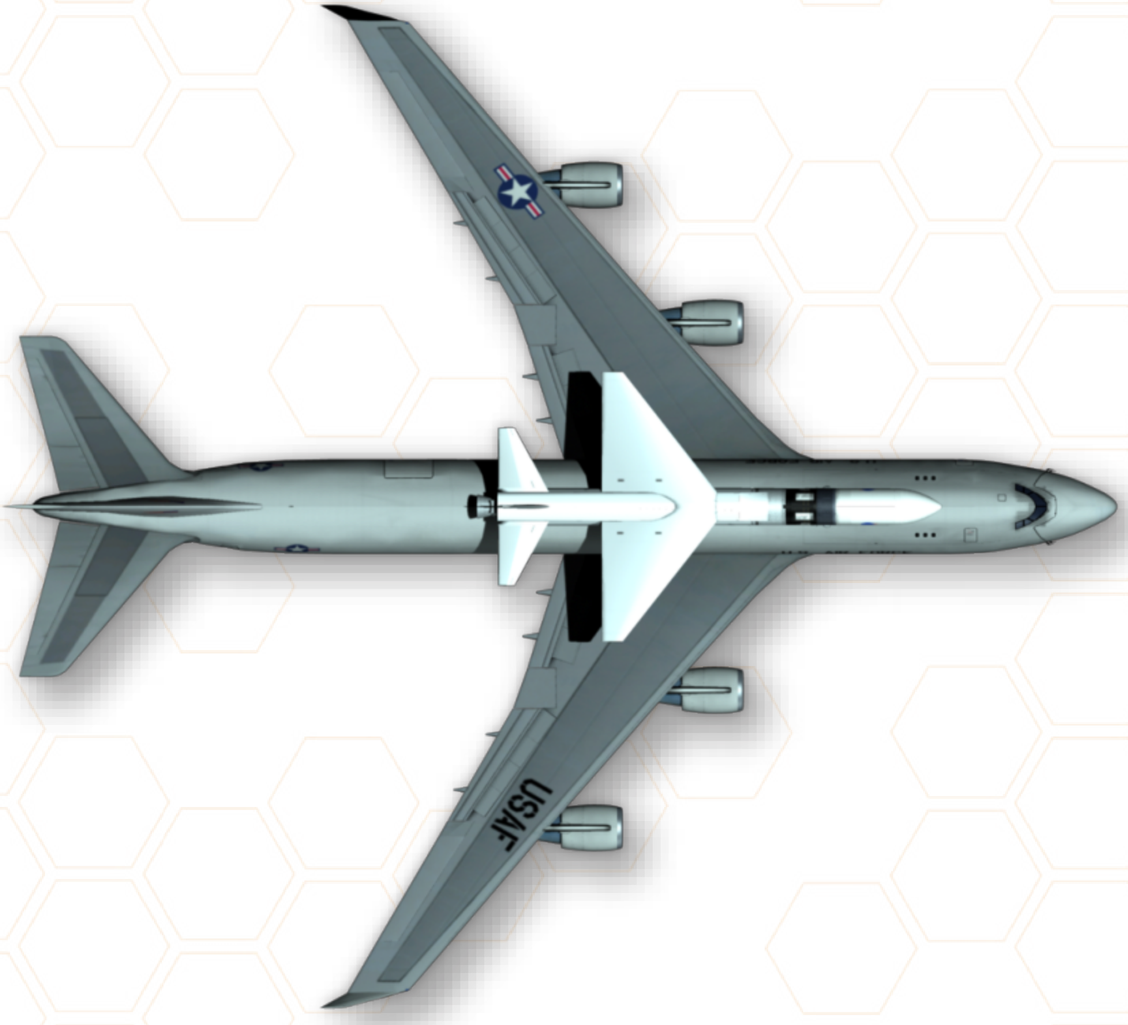
The summary figures of merit for each system concept are shown in Table 8. Expanded definitions and proxy parameters for each FOM are listed in Appendix A.

The results of the analysis show that even within the constraint of using existing engines, the resulting systems still produced good payload performance, cost, and reliability. The three-stage solid, PD-1, had the lowest DDT&E costs. The two-stage LH2 PD-3 had the highest payload delivery and the lowest lifecycle cost per pound of payload.

Table 8 Figures of Merit for each Point Design

	PD-1	PD-2	PD-3
Carrier aircraft	747-400F	747-400F	747-400F
Launch vehicle	3-stage Solid	RP+LH2	2-stage LH2
Safety and Mission Success (16th flight)			
Loss of mission probability – contribution from Stage 1	0.50%	0.41%	0.47%
Loss of mission probability – contribution from Stage 2	0.32%	0.57%	0.56%
Loss of mission probability – contribution from Stage 3	0.50%	-	-
Loss of mission probability – contribution from takeoff through LV release	0.24%	0.24%	0.24%
Total loss of mission probability at 16th flight	1.56%	1.22%	1.27%
Effectiveness and Performance			
Payload to LEO	5,660 lb	12,580 lb	17,810 lb
Minimum turnaround time	36 hrs	68 hrs	57 hrs
Surge call-up time	3.8 hrs	5.9 hrs	7.2 hrs
Basing flexibility	high	moderate	moderate
Mission flexibility	high	high	high
Military viability	moderate	moderate	moderate
Programmatic Risk			
Failure to achieve DDT&E goals	low	moderate	high
Failure to achieve IOC date	low	low	low
Technology maturity	TRL 6+	TRL 6+	TRL 6+
Commercial viability	-15%	-37%	-45%
Affordability (FY2010 dollars; total over campaign of 120 flights)			
Cost of DDT&E (total)	$0.37 B	$0.80 B	$2.31 B
Cost of Acquisition and Production (total over campaign)	$5.10 B	$13.4 B	$14.5 B
Cost of Facilities and Ground Support Equipment (total)	$0.11 B	$0.14 B	$0.13 B
Cost of Operations (total over campaign)	$1.06 B	$1.09 B	$1.16 B
Cost of Mission Failure (total over campaign)	$0.14 B	$0.16 B	$0.18 B

Factors quantitatively calculated
Factors qualitatively determined using expert elicitation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Chapter 5

CHAPTER 5

TECHNOLOGY TRADES

Once the feasibility of the three point designs was established, the potential for block upgrades and technology development was evaluated to guide potential technology investment strategies. The study team identified a number of promising technologies that could, with appropriate investment, improve payload-to-orbit performance, reduce costs, improve reliability, or add to military utility of horizontal launch systems. These were "traded" into each point design system concept to understand the impact of the upgrade.

ROSETTA was used with models anchored to the point designs to assess the impacts of structures, materials, propulsion, propellants, instrumentation, sensors, and operations technology trades on the system concepts. This arrangement produced results with high confidence and allowed for rapid execution.

Methodologies

The methodology for the technology trade analysis was developed to take advantage of the speed of ROSETTA while improving its accuracy for the specific concepts represented by the point designs. Specific ROSETTA models were developed for each point design that aligned specific technical performance metrics between the model and the point design system concept. This anchored the model to produce results that matched point design results at each specific design point. Remaining performance metrics were varied to model the technology being traded.

Each technology trade analysis was run individually in each point-design ROSETTA model. In each analysis, a single existing technology was exchanged for an improved technology. The trade involved determination of a set of multipliers, referred to as knockdown, or "k"-factors, that were applied against appropriate performance metrics. These metrics were physical parameters, such as thrust-to-weight ratio, component weight, component reliability, or component costs. The k-factors for each technology trade were determined through a combination of existing data and expert opinion.

For each trade, a set of k-factors was put into the model which was then run to closure for a fixed gross takeoff weight, while the payload was allowed to vary. In some cases, a technology was applied to all appropriate stages of the launch vehicle for a single trade.

While many of the technologies were well-developed, some of those considered currently exist at a low TRL. To create a consistent basis, each trade excluded technology maturation costs required to bring the technology to TRL 6. Estimates of readiness and maturation costs were highly uncertain, generally far smaller than DDT&E costs, and their inclusion could have clouded results. Traditionally, technology maturation costs were paid by a technology maturation program and were not accounted in lifecycle cost calculations.

All other costs driven by use of a particular technology were captured in the lifecycle cost analysis. This was important because, design, development, test, evaluation, acquisition, and other factors increase as the complexity of operations increases. This approach allowed the results of each trade to be compared in a consistent manner.

Technologies were grouped into the following areas: structures, subsystems, propulsion, propellants, manufacturing, and operations. As expected, technologies applied to different system configurations yielded different results.

Selection of Included Technologies

The technology content in previous horizontal launch studies showed a varied list of technologies employed in launch vehicles and carrier aircraft. Technology readiness crossed the spectrum from TRL of 1 (theory) to a TRL of 9 (state-of-the-art production). Some of the older studies assumed relatively low TRLs for technologies that have now matured, such as composite materials for primary airframe structures. Other studies proposed advanced technologies that still remain at low or medium TRL, such as combined cycle propulsion systems with high Mach turbines and dual-mode ramjets.

The full-scale development timeframe for each point design was limited to one to three years of maturation for near-term technologies and 4 to 9 years of maturation for mid-term technologies. This constraint eliminated many promising technologies from consideration, including many technologies related to supersonic and hypersonic carrier aircraft and reusable airbreathing and rocket launch vehicles.[2]

The scope of this study focused on near-term launch market projections. While the HLS team recognized that many advanced technologies could demonstrate advantages with larger payloads and more launches, the payload market projections limited the systems studied to expendable launch vehicles. Reusable systems, where higher DDT&E and nonrecurring costs can be spread over many flights, were not feasible at the launch rates considered in this study.

Because the technology content of the 747-400F was well defined, only technologies that would improve the performance, improve the reliability, or reduce the costs of the launch vehicles or to increase efficiency of system operations were included in the analysis.

Structures

Because the historical studies used for concept screening were generated over decades, some technologies were found to have matured to state-of-the-art over time. In the point design analyses, composite materials were baselined for airframe primary structure and aluminum alloys were baselined for liquid propellant tanks, including cryogenics. For the solid propellant rocket motors, the case material was as supplied by the manufacturer, and the motor case mass was included in the inert weight of the rocket motor.

A great deal of research and development has been carried out on composite tanks for RP, LH2, and LOX (liquid oxygen) propellants. Experimental tanks have been built and tested, and significant weight reductions have been demonstrated. More may be possible as compared to aluminum alloys with design methods specific to composites.

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[2] A discussion of some potential areas for investment in technologies that were eliminated from consideration is included in Appendix E.

Three general challenges were met through research and development. The first was size; large tanks required in current and future rocket vehicles were limited by production methods, and this has been addressed by out-of-autoclave fabrication and progress in joining tank sections. The second challenge was material compatibility with the propellants; this has been successfully tested for all liquid propellants without undue hazards. The third challenge was material porosity and leakage; while leakage at the molecular level cannot be eliminated, porosity has been reduced to the point where propellant leakage can be managed. The goal was to achieve leak rates so small that explosive mixtures cannot be formed in the confined spaces of the vehicle during the mission. If this result was not achievable, then leak rates must be managed through the use of purge systems, with the accompanying penalty to vehicle performance.

Relatively conservative weight reduction factors were selected to use in the structural trades for these tanks. A 27 percent weight reduction was used for RP and LH2 composite tanks, and 20 percent for LOX tanks. Although composites tanks may eventually cost less than aluminum, cost was not reduced in this trade owing to the added complexity of baffles, internal plumbing, and penetrations for feed, fill, and drain lines.

Aluminum-lithium alloys Al 2195 and Al 2050 were traded against conventional aluminum alloy (Al 2219) for all tanks on the vehicle. Aluminum-lithium alloy was a relatively straightforward substitute for conventional aluminum alloys.

The use of Al 2195 for the Space Shuttle external tank reduced its weight by 7,500 lbs, or approximately 11 percent. More complex manufacturing processes such as friction stir welding were needed to manufacture aluminum-lithium tanks, leading to higher production costs for large structures. Less complex tanks, as envisioned here, will likely be less expensive, but the present study did not take advantage of projected cost reductions. Even so, the Al 2195 trade was positive for increased payload and reduced cost per pound.

Al 2050 was a commercially available aluminum-lithium alloy that has comparable mechanical properties to Al 2195, but was available at thicknesses up to five inches. This allows deeper integrally machined stiffeners and an additional 10 to 12 percent weight reduction over Al 2195. As for the Al 2195 trade, potential reduced costs were possible, but not accounted.

If Al 2050 alloy performs as expected at cryogenic temperature, Al 2050 could approach the effectiveness of graphite-epoxy composites.

Subsystem—Shape Memory Alloy Actuators

An actuator system built using shape memory alloys was traded against a conventional hydraulic actuator system. A shape memory alloy, such as nickel-titanium (NiTi), was one that will deform under application of either electrical or thermal input in a controlled manner. This action can be mechanically utilized to move a control surface or other component. Given their high energy density and low form factor, shape memory alloys were an enabling technology for many adaptive structures. When heat was applied, either externally or through direct resistance via electrical current, shape memory alloys can respond with sufficient force and a large stroke to actuate mechanisms. A shape memory alloy rotary actuator weighing one pound can replace a 41-pound torque motor and gear box as well as eliminating extraneous hydraulic and pneumatic systems. (Padula, 2010)

The shape memory actuators offer very slightly improved payload, but marginally increased costs per pound. These results affected the baseline so slightly that they were likely inside the margin of error, making this technology an unlikely choice to be pursued in this application.

Propulsion

Advanced or improved rocket engines were traded against the current production rocket engines. The improved RS-25E, with 15 percent higher thrust-to-weight ratio, was traded against the current RS-25E design performance. An advanced RP engine, with vacuum specific impulse (I_{sp}) increased from 304 seconds (s) to 332 s, and thrust-to-weight ratio increased from 92 to 154, was traded against the SpaceX Merlin 1C engine.

The RL 10A-4-3 engine was traded against the RL 10A-4-2. The RL 10A-4-3 was a proposed upgrade that substitutes nozzle components from the RL 10B-2 version of the engine to increase area ratio and increase vacuum I_{sp} from 450 s to 452 s, at the expense of the thrust-to-weight ratio, which decreased from 61 to 57.

A single MB-60 engine was traded against the three RL 10A-4-2 engines. The MB-60 was a 60,000 lb-thrust-class engine. The engine utilize an expander cycle and improved technology in many areas. Where key components of the engine have been demonstrated through ground testing, full scale development has not yet taken place. The original engine design has an area ratio of 300, but this was reduced to 100 to allow easier integration with the vehicle stages. This trade increased the vacuum I_{sp} from 450 s to 455 s and decreased the thrust-to-weight ratio from 61 to 46.

An air augmented rocket (AAR) was traded against the baseline three Merlin 1C engines. An air augmented rocket is a RBCC engine operated at low speed (less than Mach 2) with the dual-mode ramjet/scramjet inlet doors open while the integrated rockets are on; the rockets create a suction effect, sucking in additional air to combust in parallel with the burning rockets. The weight of the AAR shroud was estimated at 3,500 lb and was added to the first stage inert system weight. First stage vacuum I_{sp} was improved by 10 percent. The complexity of the engine was not altered for cost purposes; instead the cost of the AAR shroud was estimated separately. The mating complexity of the first stage was also increased by 5 percent in the operations model and the failure rate of the engines was increased by a factor of 1.125.

These technology trades yielded a mixed set of results. The advanced RP engine and the AAR improved payload, but their costs increased such that resulting costs per pound of payload were significantly increased. The remaining trades produced about the same payload, but costs were also somewhat increased.

Advanced propellants were traded against conventional propellants. Advanced solid monopropellants were simpler to handle than traditional bipropellants with a 5.5 percent reduction in propellant density and a 3 percent improvement in vacuum I_{sp} over traditional solids. These monopropellants can reduce the overall gross weight by reducing booster length—making them more compact or, alternatively for the same booster length, increase payload carrying capability. These two parameters can be optimized to allow the designer more packaging options that can lead to more efficient launch vehicle design concepts.

A three-stage hydroxyl-terminated polybutadiene (HTPB) hybrid rocket (solid fuel with liquid oxidizer) was traded against a three-stage solid rocket. The solid rocket mass and sizing model was used to size the solid portion of the hybrid motor, while the LOX tanks, skirts, intertank structures, feed systems, and pumps were sized using the liquid rocket mass and sizing models. The volume of the solid and LOX portions were based on the propellant mass required and oxidizer-to-fuel ratio of 2.0. The vacuum I_{sp} for stage 1 and 2 was 314 s, and was 335 s for stage 3. The structures and mechanisms were sized based on volume. Standard procedures were used to cost the tanks, feed systems, and pumps in the same manner as the liquid rockets.

An improved hydrocarbon fuel, quadricyclane, was traded against the baseline RP fuel. The improved fuel was representative of a class of alternative high-energy-density fuels of interest for aerospace applications. The primary advantage of quadricyclane was an increase in vacuum I_{sp} from 304 s to 356 s, but disadvantages were high production costs and complex handling operations.

Cryogenic propellants that were sub-cooled below their normal boiling point temperatures to increase density were traded against the baseline normal boiling point propellants. Densified propellants have been studied extensively for launch system applications and the technology was relatively mature. Density increases assumed for LH2 and LOX were approximately 7 and 10 percent, respectively.

Trades for solid propellants yielded significant payload increases on a percentage basis, but the cost results were mixed. Life cycle costs increased in proportion to payload and recurring cost per pound went down, but nonrecurring costs went up substantially due to the increased effort to design, develop, test, and evaluate motors using such new propellants.

The two liquid engine technologies produced very different results. Use of improved hydrocarbon fuel increased payload nearly 40 percent, but the cost per pound of payload increased as well. Densified cryogenic propellants made no practical difference in payload and costs were increased to a small degree in all costs per pound of payload.

Manufacturing

Advanced manufacturing processes can involve advanced technology or simply be a new or different way of processing the vehicle and components. These technologies were not found to increase payload, but they did reduce costs of fabrication and added flexibility, yielding modest reductions in costs per pound of payload.

New processes for assembling and curing composite materials without use of an autoclave were traded against conventional autoclave processing. This process allows for more flexibility in how work flows within a plant and encourages co-curing of larger integrated assemblies. (Gardiner, 2011) A 10 percent cost reduction was predicted for this technology over traditional autoclaved production.

Simplification and cost reduction for adaptive manufacturing methods were traded against traditional manufacturing processes. Adaptive manufacturing employs high-level verification and validation methodologies to test and troubleshoot system integration during the design phase. This enables minimum processing steps, moveable tooling, and reduced handling of materials and components as compared to traditional manufacturing facilities with widely-separated fabrication steps, fixed tooling in every setting, and repeated movements of materials and components. A 15 percent reduction of production costs was predicted for adaptive manufacturing over traditional manufacturing.

Operations

The following trades were a combination of added systems technology for the carrier aircraft and changes to baseline CONOPs. Neither technology trade was performed for PD-1, but the HLS team recognized that aerial fueling of the carrier aircraft could improve overall system performance for this system as well.

The launch vehicle was allowed to grow until either the maximum aircraft weight or the maximum allowable rocket length of 127 ft was reached. The total system weight of the aircraft was not allowed to exceed the maximum published gross takeoff weight of 910,000 lb at any point during the flight, which was a significantly conservative assumption.

A CONOPs was evaluated that allows taking off with lower fuel quantity on the carrier aircraft and then fueling in flight. This allows a larger gross weight launch vehicle to be carried aloft. The costs and benefits of this practice were traded against the standard CONOPS where the launch vehicle was weight-limited by the fully fueled take-off weight of the carrier aircraft.

A CONOPs was evaluated that includes an ACES on the carrier aircraft to produce liquid oxygen from atmospheric air and then transfer it to the launch vehicle. This allows a larger, higher gross weight vehicle to be carried aloft as compared to the standard CONOPs.

The ACES trade provides additional mass to the system in flight to offset fuel used by the carrier aircraft during takeoff. The system timing was critical so as not to exceed the carrier aircraft maximum weight limit. While cruising to the launch point, ACES generates liquid oxygen by separating it from the nitrogen in atmospheric air through a series of heat exchangers and a rotational fractional distillation unit. The resulting LOX was then pumped from the ACES system on the carrier aircraft into the LOX tanks on the launch vehicle during flight. The LOX tanks on the launch vehicle can be partially empty at takeoff. This allows a larger rocket and larger payload to be carried on a given carrier aircraft. The tank for converting the captured oxygen into a liquid was sized based on the volume of LH2 required by the system. Additional mass was added to account for the modifications to the 747-400F required to house the ACES system.[3]

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[3] The ACES system model was developed based in part on nonproprietary information provided to the HLS team from Andrews Space, Inc.

Summary of Technology Trade Results

Results of the trades showed mixed results. As shown in Tables 9 through 11, certain technology insertions could achieve increased payloads without significant cost increases; or conversely, costs could decrease without a decrease in payload. Benefits of varying degrees were predicted for aerial fueling, ACES, aluminum-lithium tank materials (Al 2195 and Al 2050), composite tank materials and out-of-autoclave fabrication, shape memory actuators, and adaptive manufacturing. The remaining technologies were not strong drivers of increased payload within the constraints of this study and drive up overall lifecycle costs in almost all circumstances. Many of these technologies will certainly be valuable in other applications, but this set of constraints—specifically, a campaign of 120 total flights—limits their cost effectiveness for horizontal launch.

With the exception of aerial fueling and ACES, all of the technologies traded in the current study were as applicable to vertical launch and other aerospace systems as they were to horizontal launch. Aerial fueling and ACES were specific to horizontal launch and have the potential to yield substantial payload increases at lower costs per pound of payload. Aerial fueling was especially powerful because there was little added cost to employ the technique in any horizontal launch operation.

The technology for ACES promises an effective increase in payload, although at higher cost and greater technical risk as compared to aerial fueling. Implementation of ACES will require design changes on both the carrier aircraft and the launch vehicle, while aerial fueling of the carrier aircraft could be included in a baseline vehicle concept immediately. Either or both technologies could be added as block upgrades with only moderate impact to an operational system.

Because low launch rates forced the use of expendable launch vehicles in this study, it was difficult to find many technologies that could “buy their way” into the point designs. Some technologies that were expected to have significant advantages did not demonstrate improvements in this analysis. Among these were improved rocket engines, other advanced propulsion technologies, and improved propellants. Although the model predicted increased payloads for these technologies, the model also predicted very high costs.

Table 9 Technology Trade Results as Applied to PD-1—Solid rocket system

(Each trade made separately against the system baseline)

	Payload (lb)	Life cycle costs ($/lb of payload)	Recurring costs ($/lb of payload)	Non-recurring costs ($/lb of payload)
Baseline System	5,660	$10,310	$9,270	$1,040
Structures				
Aluminum alloy primary structure	5,060	$11,770	$10,600	$1,170
Subsystems				
Shape memory alloy actuators	5,700	10,420	9,370	1,050
Propellants				
Improved Solid Fuels	6,670	10,640	7,900	2,740
Hybrid Rockets	7,560	14,150	11,360	2,790
Manufacturing				
Out-of-autoclave fabrication	5,660	10,070	9,050	1,020
Adaptive manufacturing	5,660	9,950	8,940	1,010

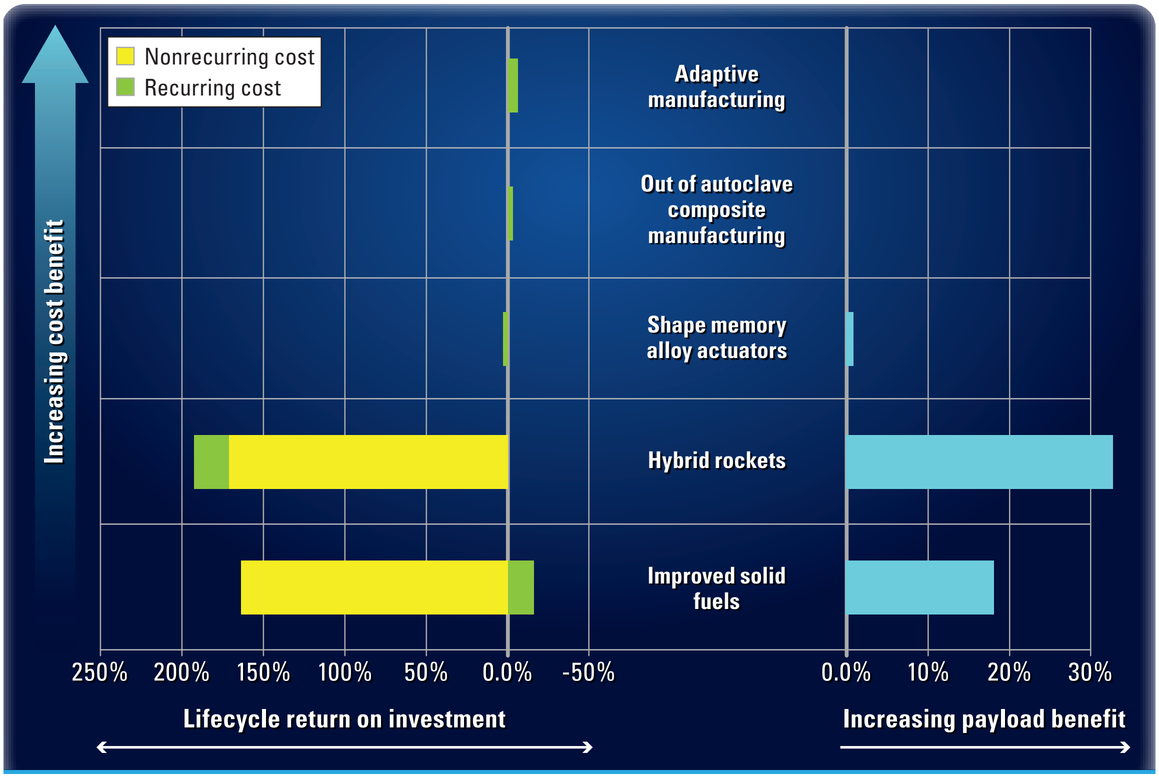


Table 10 Technology Trade Results as Applied to PD-2—RP/LH2 system
(Each trade made separately against the system baseline)

	Payload (lb)	Life cycle costs ($/lb payload)	Recurring costs ($/lb payload)	Non-recurring costs ($/lb payload)
Baseline System	12,600	$10,130	$9,360	$770
Structures				
Aluminum alloy primary	10,400	$12,290	$11,360	$930
Composite tanks, RP	12,660	10,050	9,290	770
Composite tanks, LOX	12,780	9,940	9,180	760
Composite tanks, LH2	12,980	9,790	9,050	750
Aluminum-lithium tanks; Al 2195	12,910	10,070	9,310	760
Aluminum-lithium tanks; Al 2050	13,170	9,930	9,180	750
Subsystems				
Shape memory alloy actuators	12,750	10,080	9,310	770
Propulsion system				
Advanced RP Engine (IHPRPT P2)	15,670	11,290	8,560	2,730
RL 10A-4-3 Engine	12,480	10,240	9,460	780
MB-60 Engine	12,750	11,190	9,640	1,550
Air-augmented rocket	14,930	11,380	10,530	850
Propellants				
Improved hydrocarbon fuel	17,460	13,530	11,350	2,180
Densified cryogenic propellants	12,790	10,340	9,510	830
Manufacturing				
Out-of-autoclave fabrication	12,600	9,920	9,160	760
Adaptive manufacturing	12,600	9,650	8,910	740
Operations				
Aerial fueling of carrier aircraft	17,140	8,100	7,450	650
ACES	17,020	8,430	7,700	740

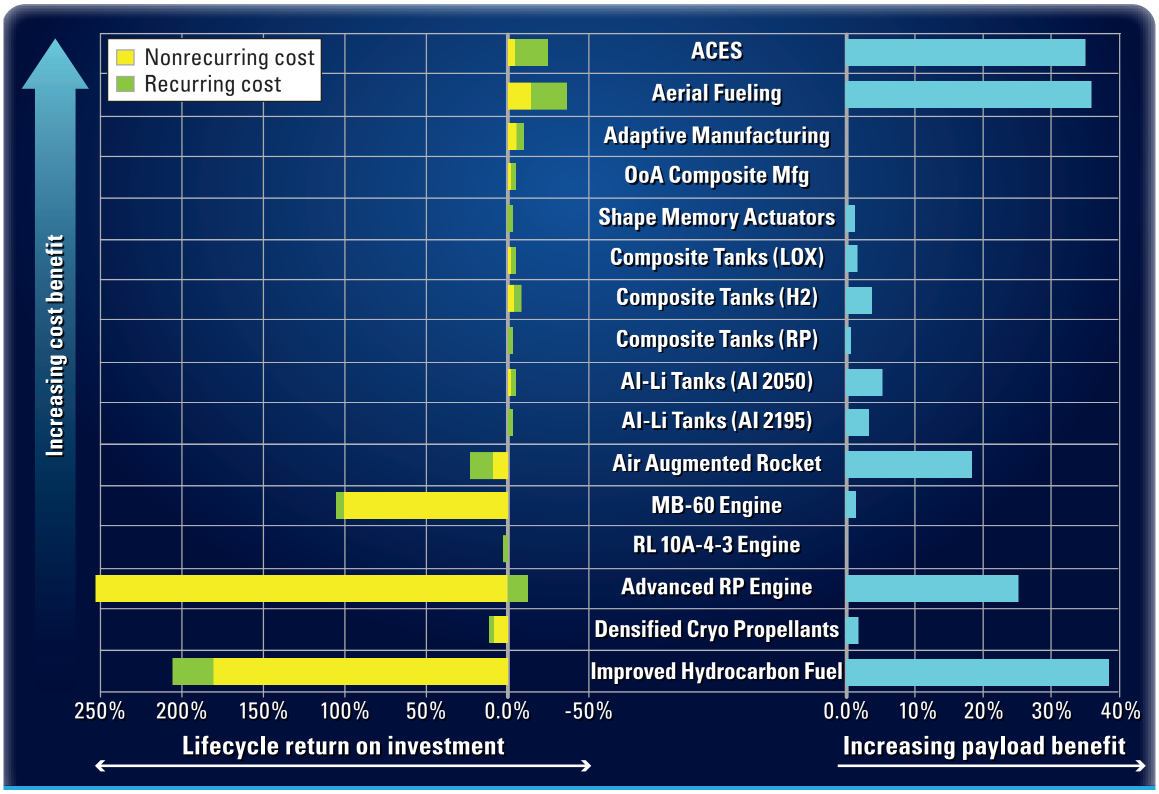
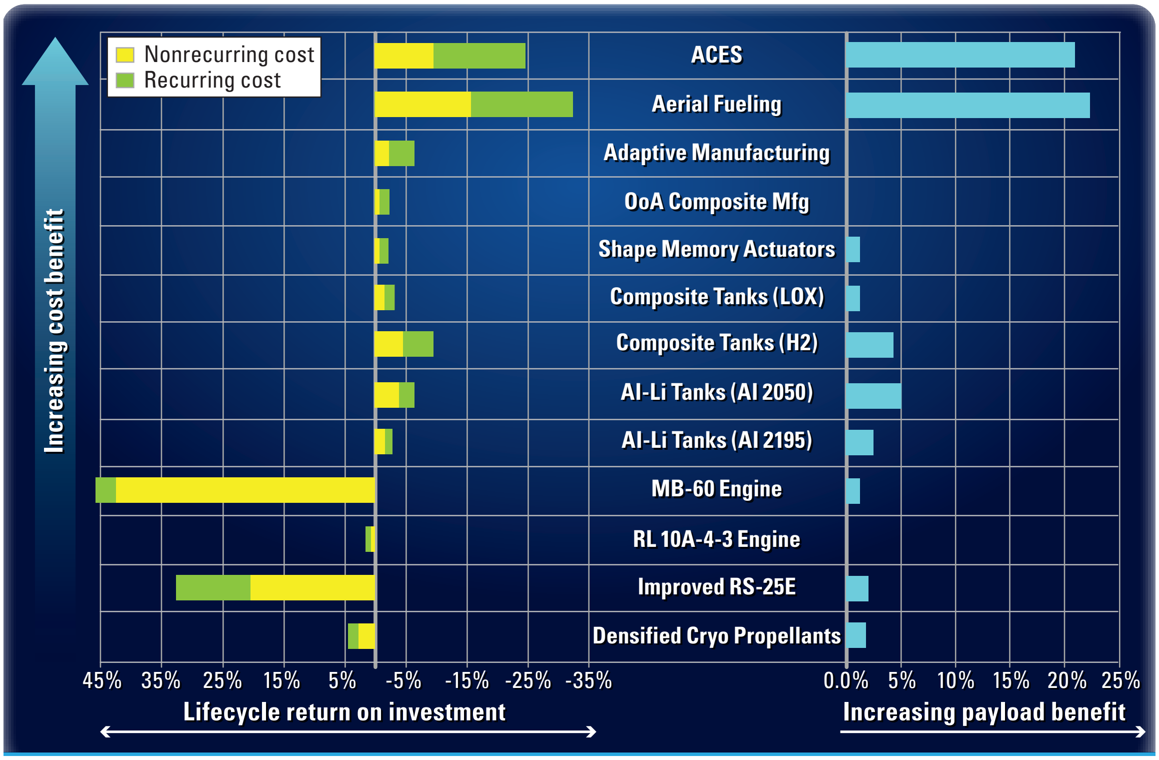
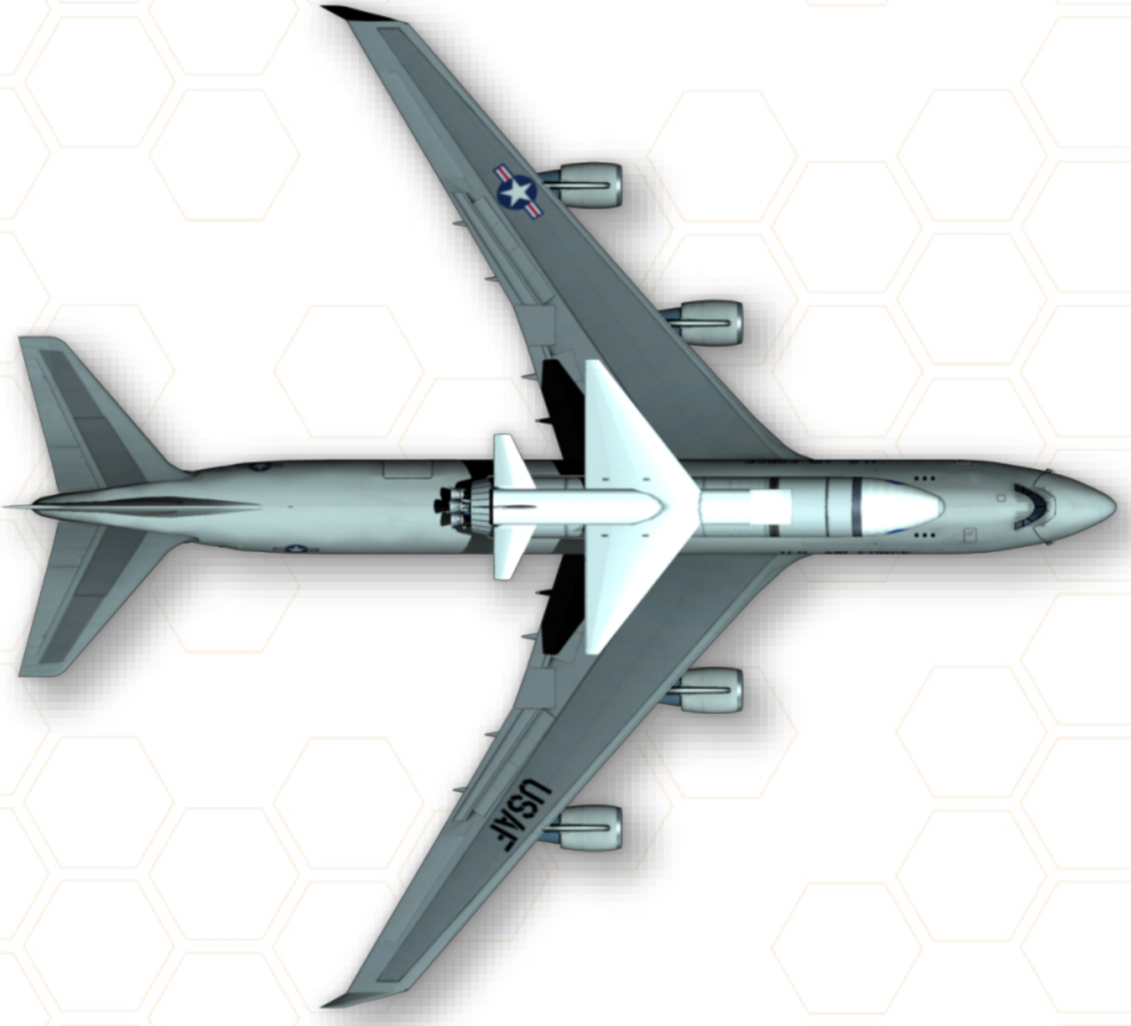


Table 11 Technology Trade Results as Applied to PD-3—2-stage LH2 system
(Each trade made separately against the system baseline)

	Payload (lb)	Life cycle costs ($/lb)	Recurring costs ($/lb)	Non-recurring costs ($/lb)
Baseline System	17,920	$9,110	$7,860	$1,260
Structures				
Aluminum alloy primary	14,470	$11,360	$9,800	$1,560
Composite tanks, LOX	18,140	8,980	7,740	1,240
Composite tanks, LH2	18,700	8,660	7,460	1,200
Aluminum-lithium tanks; Al 2195	18,400	9,010	7,780	1,230
Aluminum-lithium tanks; Al 2050	18,800	8,870	7,660	1,210
Subsystems				
Shape memory alloy actuators	18,160	9,030	7,780	1,250
Propulsion systems				
Improved RS-25E Engine	18,280	10,270	8,750	1,520
RL 10A-4-3 Engine	17,810	9,180	7,910	1,260
MB-60 Engine	18,110	9,850	8,050	1,800
Propellants				
Densified cryogenic propellants	18,230	9,270	7,980	1,290
Manufacturing				
Out-of-autoclave fabrication	17,920	8,980	7,730	1,250
Adaptive manufacturing	17,920	8,780	7,550	1,230
Operations				
Aerial fueling of carrier aircraft	21,850	7,580	6,520	1,060
ACES	21,720	7,580	6,720	1,130

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CHAPTER 6

FLIGHT TEST SYSTEM CONCEPTS

The study team determined the critical development risks for the proposed system concepts and identified flight demonstrations as mitigation strategies. Two flight test system concepts (FTs) were developed to define design requirements and program costs. The results of this exercise serve to quantify the next steps required for the development of a national horizontal launch capability.

Flight Test System Concept Configurations

The flight test concepts were derived by modifying existing expendable, vertical launch vehicles to produce horizontal launch vehicles. Two existing launch vehicles were used as baselines, and modified for horizontal launch. (See Table 12.) The carrier aircraft for both was the 747-100 SCA-905. As modified, this aircraft was assumed to have a total length of 231 ft, a wingspan of 196 ft, and a design payload capacity of 192,000 lb.

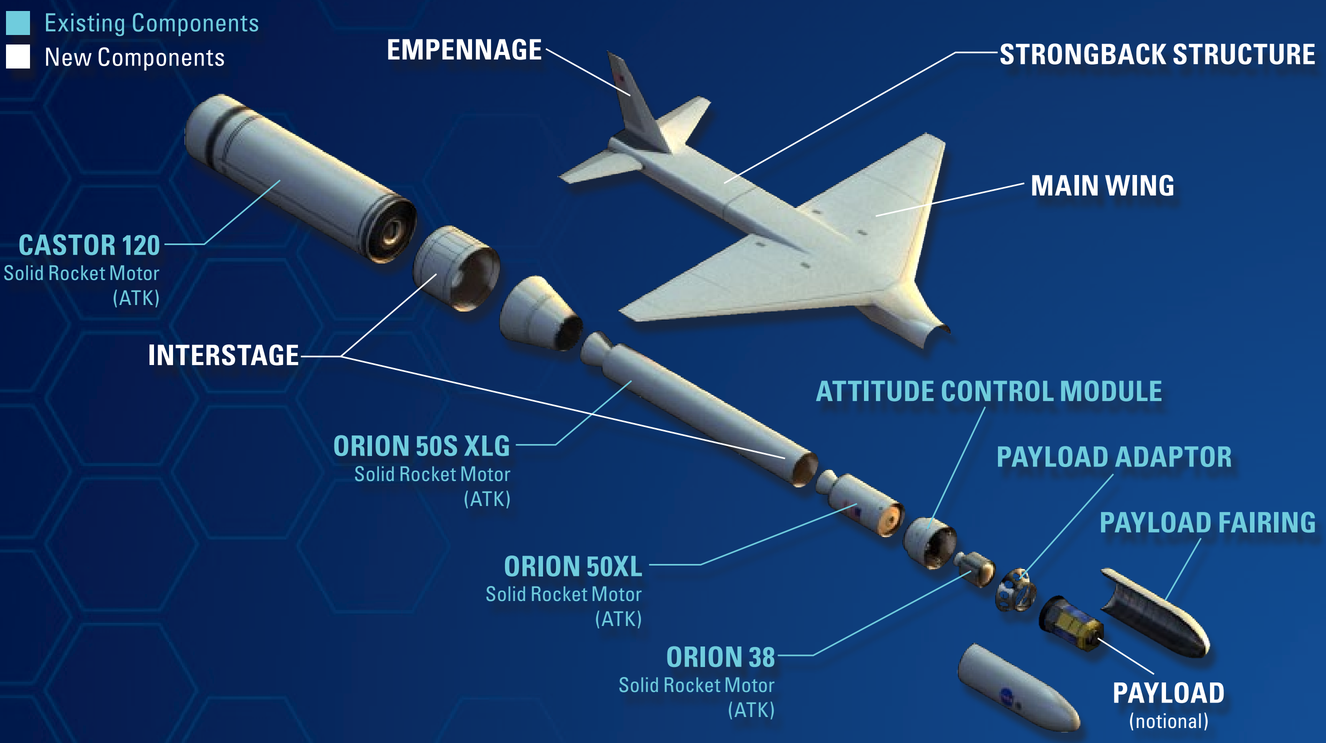
The analysis followed the same methods as for the point designs to determine weight, development costs, and reliability. Flight test costs were based on current production costs, operations costs, and an estimate of government and contractor flight test support requirements based on past programs.

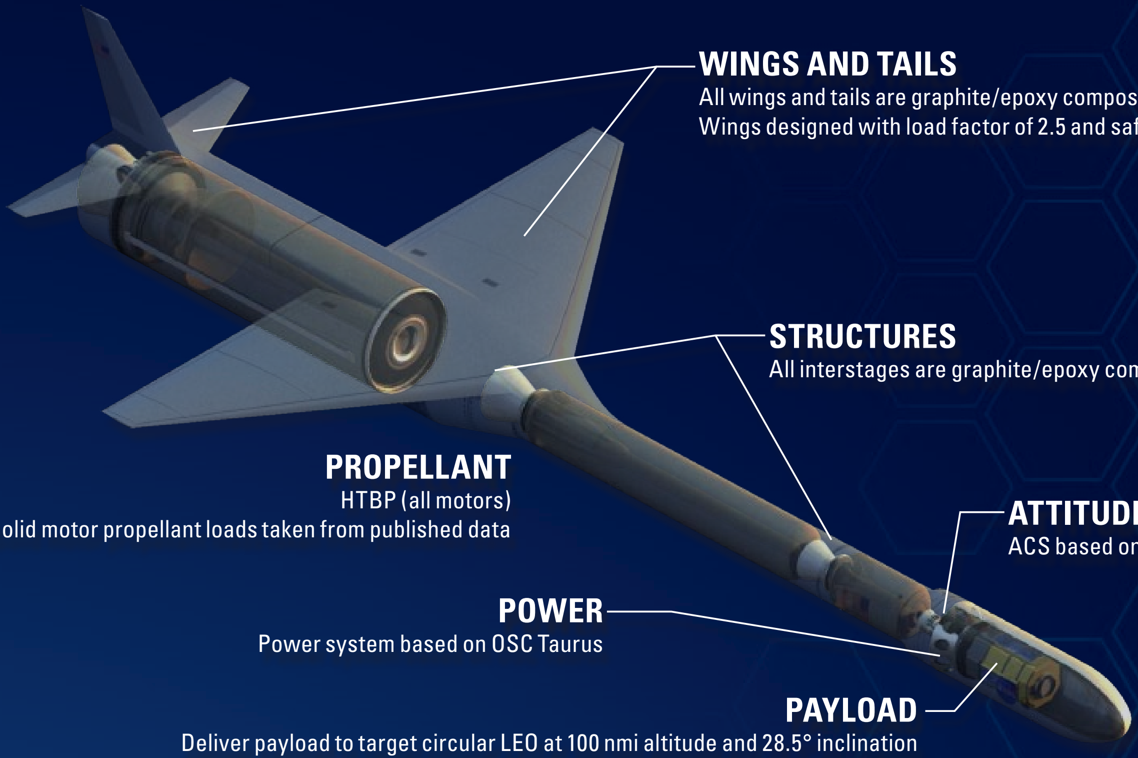
Table 12 Summary of Flight Test System Concepts

	FT-1	FT-2
Air-launch vehicle	modified Taurus XL	modified Falcon 1e
Total gross weight	179,470 lb†	81,990 lb†
Payload to LEO	4,560 lb	2,750 lb
Total length	99 ft	81 ft
Maximum fuselage diameter	7.8 ft	5.5 ft
Wing span	47 ft	26 ft

† Includes inert mass margin

Flight Test Demonstrator 1





WINGS AND TAILS
All wings and tails are graphite/epoxy composite material
Wings designed with load factor of 2.5 and safety factor of 1.5

STRUCTURES
All interstages are graphite/epoxy composite material

PROPELLANT
HTBP (all motors)
Solid motor propellant loads taken from published data

ATTITUDE CONTROL
ACS based on OSC Taurus

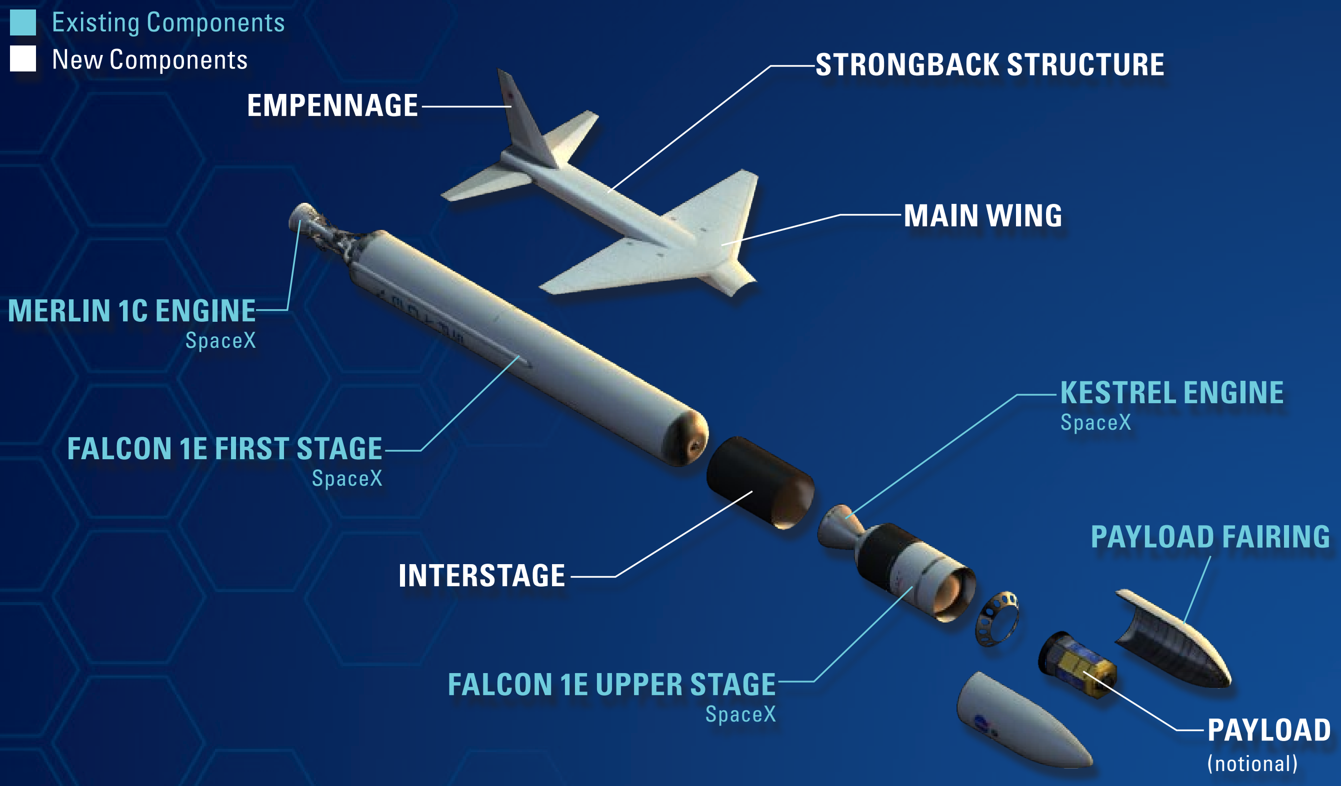
POWER
Power system based on OSC Taurus

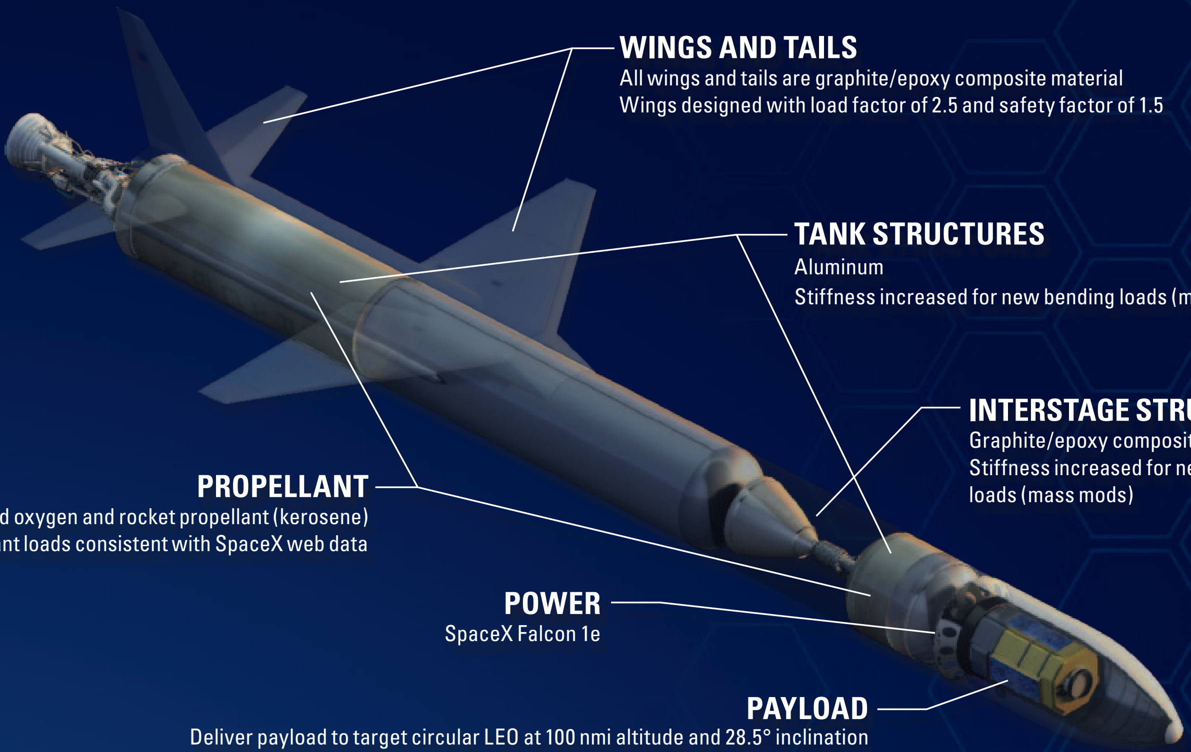
PAYLOAD
Deliver payload to target circular LEO at 100 nmi altitude and 28.5° inclination
Performance data is shown for due East launch from 28.5° latitude

747-100 SCA-905 carrier aircraft / 4-stage solid launch vehicle

FT-1 consisted of the 747-100 SCA-905 carrier aircraft and a multistage solid launch vehicle. This approach was selected to minimize DDT&E costs. The launch vehicle configuration was a Taurus XL rocket modified for the demonstration vehicle. It consisted of a Castor 120 stage, an Orion 50S XLG stage, an Orion 50XL stage, and an Orion 38 kick stage, for a total of four stages. The wing and empennage were attached to the first stage with a strongback. Structural modifications are required to adapt the exisitng attachment hardware, designed specifically for the Space Shuttle Orbiter, to the demonstration vehicle. All interstages, fairings and aerodynamic surfaces were composite materials. Power and attitude control subsystems were based on existing systems.

Flight Test Demonstrator 2





WINGS AND TAILS
All wings and tails are graphite/epoxy composite material
Wings designed with load factor of 2.5 and safety factor of 1.5

TANK STRUCTURES
Aluminum
Stiffness increased for new bending loads (mass mods)

INTERSTAGE STRUCTURE
Graphite/epoxy composite
Stiffness increased for new bending loads (mass mods)

PROPELLANT
Liquid oxygen and rocket propellant (kerosene)
Propellant loads consistent with SpaceX web data

POWER
SpaceX Falcon 1e

PAYLOAD
Deliver payload to target circular LEO at 100 nmi altitude and 28.5° inclination
Performance data is shown for due East launch from 28.5° latitude

747-100 SCA-905 carrier aircraft / 2-stage RP+LH2 launch vehicle

FT-2 consisted of the 747-100 SCA-905 carrier aircraft and a two-stage launch vehicle with RP+LH2 propulsion. The Falcon 1e launch vehicle, modified for the demonstration concept, was selected as a convenient example of a low-cost, low-risk system concept. The first stage was equipped with a RP Merlin 1C engine and the second stage with a Kestrel engine, both developed by SpaceX. Structural modifications are required to adapt the existing attachment hardware, designed specifically for the Space Shuttle Orbiter, to the demonstration vehicle. In particular, because the vehicle was substantially shorter than the shuttle, the attachment points may have to be moved and an active separation mechanism may have to be added.

Weight Breakdown Analyses

The resulting weight statements for the Flight Test System Concepts are shown in Table 13.

Note that the aerodynamic surfaces were jettisoned early in the trajectory and thus have a relatively small impact on the payload.

Table 13 Weight Breakdown Statement for FT System Concepts (in lb)

FT-1	Stage 1	FT-2		Stage 1
Motor	8,980	Structure		2,030
Subsystems	220	Propulsion		1,520
Interstage	1,360	Thermal control		34
Propellant	108,040	Power		42
Loaded	*118,590*	Avionics		20
	Stage 2		*Inert*	*3,650*
Motor	2,600	Consumables		230
Subsystems	72	Main propellants		61,010
Interstage	200	Start-up losses		180
Propellant	33,100		*Fueled*	*65,080*
Loaded	*35,980*			**Stage 2**
	Stage 3	Structure		570
Motor	870	Propulsion		240
Subsystems	67	Thermal Control		16
Interstage	150	Power		190
Propellant	8,650	Avionics		140
Loaded	*9,740*		*Inert*	*1,160*
	Stage 4	Consumables		140
Motor	270	Reaction propellants		13
Subsystems	13	Main propellants		8,950
Propellant	1,700	Start-up losses		27
Loaded	*1,980*		*Fueled*	*10,280*
Aerosurface Module				
Wing	4,780			1,700
Fins and actuators	1,130			1,220
Strongback	1,320			650
	7,220			3,580
Attitude control module and power	610			--
Fairing and adapter	800			310
Payload	4,560			2,750
Total	**179,470**			**81,990**

Trajectory and Separation Analyses

Using the thrust patterns and launch vehicle aerodynamics, the resulting trajectories were calculated using POST using assumptions tabulated in Appendix G. Once the launch vehicle attained a typical vertical flight profile, the aerodynamic surfaces were jettisoned.

In FT-1, the launch vehicle reaches a maximum dynamic pressure (q) of 2,248 psf which was very aggressive compared with a nominal launch vehicle maximum q of approximately 800 psf. The team considered, however, that the X-43A airframe-integrated scramjet vehicle was designed to an upper limit greater than 2,000 psf during its ascent to the test point on a modified Pegasus booster. (Joyce, 1998) The payload performance versus constrained maximum q was not studied in this analysis, but the possibility exists that this state could negatively impact the payload capability—perhaps by requiring a stiffer outer structure. The nonconstrained trajectory payload delivery was computed to be 4,560 lb.

For FT-2, the launch vehicle reaches a maximum q of 980 psf. The nonconstrained trajectory payload delivery was computed to be 2,750 lb.

Preliminary separation analysis indicates that these separation scenarios were adequate, but further detailed analysis must be conducted for verification. Further details of the configuration, aerodynamics, and trajectory analyses for the two FTs are provided in Appendix H.

Reliability Comparisons

Using failure rates of existing systems, the success probabilities are shown in Table 14.

For FT-1, the fairing separation has been determined based on two recent consecutive Taurus rocket fairing failures. As shown in the rankings of failures, the fairing separation was an order of magnitude higher than all other propulsion and human error events. The predicted reliability improves with each flight based on historical reliability growth curves for past systems. Because these issues were expected to be resolved for the Taurus rocket for future missions, the reliability predictions presented here may be considered very conservative.

For FT-2, the Falcon 1e has had similar flight test performance as previous liquid rocket systems. The probability of success was therefore somewhat higher than the four-stage solid case.

Table 14 Reliability Assessment for FT System Concepts

	FT-1	FT-2
	Probability	
Demonstrated average historical reliability of each LV	67%	60%
Predicted reliability—First test	78%	83%
Predicted reliability—Second test	80%	85%
Biggest risk factor	Fairing separation	Off nominal payload insertion

Cost Analyses

Program costs, shown in Table 15, were estimated assuming that the 747 SCA-905 would be available at the current funding levels for two demonstration flights over 3.5 years. Component costs were calculated using NAFCOM which was anchored to the prices for components and systems advertised by the manufacturers—e.g., Orbital Sciences and SpaceX. The costs of government oversight and insight into the program and government facilities (and their associated costs) for testing and demonstration were determined through expert elicitation.

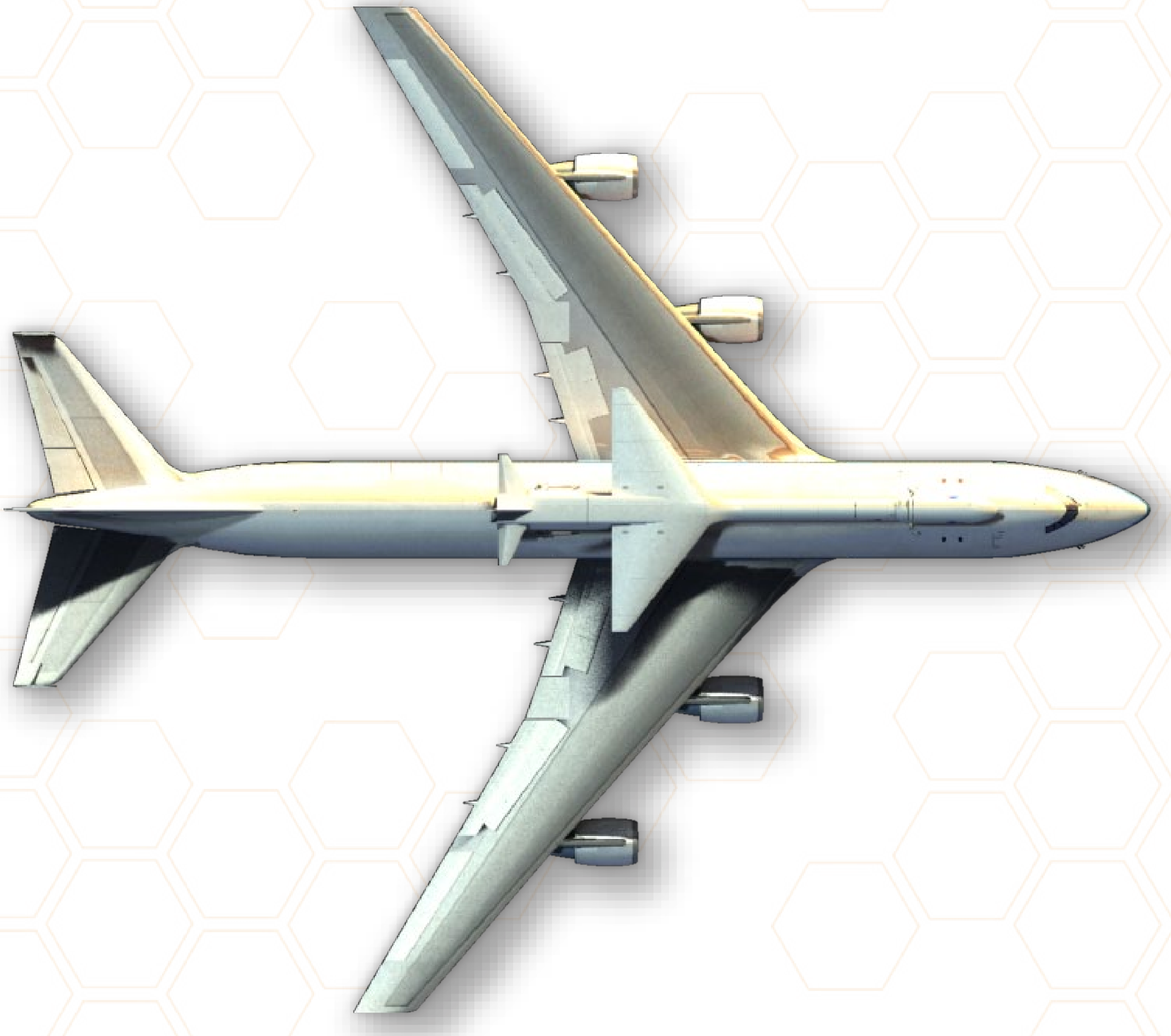
Table 15 Program Cost Summary for Flight Test System Concepts (FY2010 dollars)

	FT-1	FT-2
Development phase costs	$91 M	$85 M
Test program phase costs	$109 M	$52 M
Total government team and program management	$67 M	$67 M
Total contingency (20%)	$53 M	$41 M
Total test program costs	$320 M	$245 M

Summary of Flight Test System Concepts

The four-stage solid FT-1 has an estimated higher payload but also higher development costs compared to FT-2. Based on the assumption that the two-stage liquid FT-2 can be developed at the same cost as the SpaceX Falcon family of launch vehicles, total cost favors the two-stage liquid FT-2. The failure risk for the solid FT-1 was higher but was based on the recent history of payload separation failures of the Taurus launch vehicle. If these problems were solved and typical failure rates prevail, the risks were similar for the two configurations.

The FT-2 two-stage liquid has a number of advantages for a demonstration. This option would demonstrate all the necessary operational needs including LOX logistics, storage on ground, and storage in flight. In addition, it was anticipated that the configuration would allow the payload to be increased by lengthening the stages (within the limits determined by a structural bending loads analysis).



CHAPTER 7

SUMMARY OF RESULTS

The design reference mission (DRM) used in this study was overly generic—to show that a subsonic carrier aircraft can be economically developed and utilized to deliver a 15,000 lb payload. But without a true DRM, it was impossible to state that this was "the best" launch option. Suitability depends entirely on the mission, and missions were each unique to the end user. One size will never fit all.

Launch system performance such as payload volume and weight, orbital inclination and altitude, and other factors were also highly dependent on the mission. All these factors affected recurring costs and lifecycle costs. Completing the cycle, higher annual launch rates or the ability to combine multiple payloads into a single launch was a direct function of payload capability; both had the potential to significantly reduce recurring costs. Development of a horizontal launch system will require specific DRMs to define design requirements. While the results from this study can be used as guidance for these future developments, it does not represent a definitive solution.

To define a DRM for a future horizontal launch vehicle system, several tradeoffs must be mutually understood by the designer and stakeholder early in the design cycle. The most important trades have to do with the characteristics of the payload. These include total volume, total mass, center of gravity, mass distribution, and maximum diameter and length. Payload characteristics directly affect recurring costs by allowing a wider range of launch market opportunities for different payload types, thereby increasing launch rates and decreasing costs. No other design factor (i.e., component reusability, advanced technologies, efficient operations, etc.) has a greater significance in lowering lifecycle cost than flight rate.

This study used estimated launch system costs as a figure of merit. Recurring costs, DDT&E costs, and lifecycle costs (LCC) were all considered. The assumptions that go into a lifecycle cost analysis include projected annual flight rates, program duration, estimated decreased production costs over time, anticipated maintenance schedules for reusable systems, and increased operational efficiencies over time. Using only LCC without considering the cost breakdown can be misleading if highly optimistic launch rates were used. This was the case for the NASA Shuttle program, where a 440-launch design life was projected with a minimum of 28 launches per year (and as high as 55 launches per year). During its best year in 1985, the Shuttle launched 9 times and the program totaled just 135 launches overall.

The realities of flight rate are shown in Table 16 for the Space Shuttle, where the launch rate ranged from a high of 9 to a low of zero launches per year. Amortizing the $5.1 billion (1970 dollars) over 440 launches resulted in DDT&E costs of a seemingly-affordable $12 million per launch. In reality, the Shuttle's DDT&E costs consumed over 50 percent of NASA's annual budget for six years. For these reasons, a conservative and realistic launch rate was assumed in this study.

Table 16 Space Shuttle Cost Analysis

Operations function	Total cost (M$)	Percent
Hardware acquisition, integration, turnaround		9%
Element receipt and acceptance	1.4	
Landing and recovery	19.6	
Vehicle assembly and integration	27.1	
Launch	51.5	
Offline payload and crew	75.9	
Turnaround	112.3	
Indirect system support		22%
Vehicle depot maintenance	237.5	
Traffic and flight control	199.4	
Operations support infrastructure	318.6	
Management support		69%
Concept-unique logistics	842.7	
Operations planning and management	1,477.4	
Total	*3,363.4*	*100%*

Source: Study on Access to Space, 1994. Figures in 1994 dollars.

Concerns about DDT&E costs drove the selection of a subsonic carrier aircraft over supersonic and hypersonic carrier concepts. An existing subsonic carrier vehicle, the 747-400F, was also selected over a new subsonic carrier. With total DDT&E costs of less than $2 billion for the entire system, the 747-400F provided the payload capability at a fraction of the DDT&E costs of a new subsonic carrier alone.

No existing supersonic or hypersonic vehicle can carry a launch vehicle capable of delivering a 15,000 lbs payload to LEO. While these would have the potential for larger payloads and lower operations costs over the subsonic concepts, the DDT&E costs estimated in this study—$17 billion to develop a new supersonic carrier and $25 billion to develop a new hypersonic carrier—would challenge any budget justification. Because the common requirements used in this study did not have a DRM that required a high speed carrier aircraft, the wide variation in DDT&E costs made this a decisive discriminator among carrier aircraft options.

Cost per Pound of Payload

Traditionally, launch costs have been compared by cost per pound of payload. The HLS team observed from the start of the study that horizontal launch will never trade off well with heavy lift vertical launch systems based on this metric. While the launch vehicle used in vertical or horizontal launch may be similar, when used for horizontal launch the launch vehicle must have additional subsystems such as aerodynamic surfaces and other reinforcing structures to enable carrying, separation, and pull-up maneuvers. These additions, along with the maintenance and launch costs of the carrier aircraft, will almost invariably make horizontal launch a more expensive option when compared to vertical launch systems.

Any DRM, however, depends on more than a single metric such as cost per pound of payload. Horizontal launch provides the potential for improved basing flexibility, covert launch, weather avoidance, and offset launch for orbital intercept and reconnaissance. These benefits may outweigh any increased cost. A more useful comparison may be to look at recurring costs on a per launch basis instead of a per pound basis. This was an especially useful metric for military utility, where horizontal launch can provide for many small covert payloads launched within hours or days rather than larger payloads launched within months or years.

Technology Block Upgrades

The use of advanced technologies applied to any new system should be limited prior to achieving the initial operational capability (IOC). This was a lesson learned from many major defense acquisitions, and of specific interest to this study, the NASA X-vehicle programs. All of these have found that the utilization of multiple advanced technologies significantly increases and complicates the risk of success. For this reason, this study assumed all major components intended for initial use have a TRL 6 or higher prior to program start. In today's environment, a program manager can no longer wait on the maturation of a new technology to enable a major component capability. The DDT&E schedule for a new launch vehicle was expected to be less than 5 years.

Today's design engineers need to plan for design versatility and modularity to enable easy technology insertion and component modifications. The use of "block upgrades" has been prevalent in civilian aircraft and automotive industries, and their use in major defense systems was growing rapidly. For these reasons, this study assumed that promising advanced technologies will be inserted as they become available after initial operating capability was established.

Decision Making

The method to choose the best option for a specific DRM depends on the perspective of the stakeholder or decision maker. Historically, stakeholders have used different tools to aid in this process. These include AHP, Multi-Attribute Utility Theory (MAUT), Kepner-Tregoe, Quality Function Deployment (QFD), Value Engineering, and many other decision methods. All of these start with a well-defined set of system level requirements and figures of merit that relate directly to the stakeholder's DRM. These requirements must address the salient characteristics of the launch vehicle such as the payload class, insertion orbit, fuels, or infrastructure, as well as risk tolerance, DDT&E budgets, schedules, and availability of critical technologies.

For close to 40 years, many DoD decision makers have used what is called Heilmeier's Catechism to aid in their decision process. George Heilmeier was the director of DARPA in the mid 1970s. Heilmeier would use a standard set of questions to decide which research proposal to invest in, as follows:

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What's new in your approach and why do you think it will be successful?
- Who cares?
- If you're successful, what difference will it make?
- What are the risks and the payoffs?
- How much will it cost?
- How long will it take?
- What are the midterm and final "exams" to check for success?

These questions were most useful for making mission-based technology investment decisions. For external decisions with a public or customer focus—such as Congress or a venture capitalist—a different set of questions is presented. The automotive industry uses a set of four questions:

- What is it?
- Why should I care?
- What's in it for me?
- Why should I believe you?

Answers to these four questions were needed to support investment decisions for any potential stakeholder to support a large development program for a new launch vehicle concept. As engineers, the first two questions were relatively easy to answer. The final two questions were more difficult and may be more important.

Flight Testing

Several horizontal launch vehicle concepts have been presented in this study as realistic options to launch a nominal 15,000 lb payload to LEO utilizing a 747-400F with a winged launch vehicle carried on top. While the use of existing technologies for the major system elements has greatly reduced the uncertainties in each concept, three major technical uncertainties remain that will require flight tests to reduce them:

1. Separation physical mechanism and aerodynamics
2. In-flight command and control of the launch vehicle
3. Cryogenic handling and storage

Additional technical challenges identified that were best reduced through flight testing include:

4. Efficient and low-cost design, development, mission, and ground and flight operations of a horizontal take-off space launch system
5. Loads and structural interfaces between the carrier aircraft and launch vehicle at takeoff, climb, cruise, and launch
6. Launch altitude, velocity, and flight path angle
7. Launch vehicle transition from initial separated state to the optimum ascent trajectory
8. Validation of cost and operations models

The first major uncertainty was launch vehicle separation. This could be reduced to a limited extent by modeling and wind tunnel tests. Accurate characterization of the aerodynamic interactions between the carrier aircraft and launch vehicle would, however, require flight tests. These tests would also include inert separation flights to validate separation simulations utilizing a dummy launch vehicle identical in size and mass distribution. This would be used to calibrate separation analysis to ensure a clean separation prior to launching a fully fueled launch vehicle.

The second major uncertainty was in-flight command and control. The most important benefit of horizontal launch was the ability to launch a payload from anywhere in the world without significant ground support infrastructure. This would require an in-flight command center that was capable of observing and predicting downrange weather conditions, winds aloft, and air traffic. This system was not only necessary for the structural integrity of the launch vehicle but was critical to assure accurate orbit insertion for mission success.

The third major uncertainty was cryogenic handling and storage. The complexity of the fuel transfer arrangement creates the potential for boil-off and leakage through normal operation, with a heightened risk from human error of equipment failure. Such a system requires intensive monitoring and control during storage and transfer. Reliable structures for containment tanks are critical, as are all materials at cryogenic temperatures.

In addition to addressing these three major uncertainties, well-designed flight testing would also validate and optimize the models used for aerodynamics, carrier aircraft and launch vehicle control, structural loads, and overall system performance. It would be critical to carry out this validation prior to beginning a significant design and development program.

Flight tests were also critical to demonstrate operability factors including turnaround time, crew size, launch vehicle integration, ground and in-flight cryohandling, in-air propulsion start, and on-board mission and flight control. Current launch costs (assuming the full payload capability was used for each) range from $30,000 per pound for the Pegasus, to $5,000 to $8,000 per pound for evolved expendable launch vehicles, and to $2,500 per pound for a Falcon 9. The factors that drive this large range include approaches to hardware acquisition, system integration, test and evaluation, and mission planning. A solid understanding of all of these factors would be needed to respond to the requirements of a new DRM.

The recurring launch costs for the Space Shuttle—an average of $13,000 per pound of payload—reveal an opportunity: only 9 percent of the cost was accounted in hardware acquisition, integration, and system turnaround, and only 22 percent was in indirect system support. The majority, almost 70 percent, was attributed to management support. Thus, a key driver for any planned flight test was to demonstrate a change to the traditional processes that contributed to the staggering overhead burden. These will include changes not only to management oversight methods, but to quality control, logistics support, traffic and flight control approaches, and launch and support infrastructure.


USAF

CHAPTER 8

FUTURE SYSTEM CONCEPT STUDIES

This study was intended to provide the foundation, both through the historical review and the integrated analysis, to aid in defining requirements for any future horizontal launch vehicle system development program. A number of design decisions can be informed by this analysis, including launch rate, separation speed of the carrier aircraft, and technology development. Other factors, such as orbit altitude, launch location, and carrying crews to orbit warrant more attention than has been provided here.

The most important factor affecting recurring costs was launch rate, and cost remains the biggest challenge to widespread adoption of horizontal launch. This HLS team, therefore, believes this will drive a concept with the versatility to accommodate many different missions. A successful horizontal launch enterprise should encompass both military and commercial users across a wide range of payloads.

A successful enterprise may also be designed to span inclinations and altitudes from low to geosynchronous orbits. The reference mission systems used in this study, a capability to launch 15,000 lb to LEO at 100 nautical miles, will not be able to launch the same payload mass to geosynchronous orbit (GEO) at over 22,000 nautical miles. The same system may, however, be capable of launching a smaller payload, roughly one third the size, to GEO.

The ability to launch from a number of global launch sites will clearly be one of the most important factors from the perspective of both commercial and military users. However, by over-specifying payloads, fuels, orbit inclinations, altitudes, abort scenarios, or airspace restrictions, users could unnecessarily limit the development of a launch system concept.

The opportunity for the horizontal launch of crews or tourists to orbit also warrants consideration. This study showed a horizontal launch system concept with ideal subsystem sizing could launch a 20,000 lb payload to LEO. It remains a subject for future studies as to what decrease a human-rated horizontal launch system would take compared to the baseline.

Perhaps the most important factor in any system development was choosing the right technology availability date for critical subsystems and component technologies. Many design and development programs in the past have failed to meet operational requirements because they were overly optimistic on the availability of new technologies. It was extremely important to confirm and demonstrate the technology readiness when selecting and specifying technologies. It was also critical to make the needed technology investments in a timely manner once an implementation was planned.

Technology Demonstrations

Advanced technologies that increase system level performance, decrease maintenance down time, and reduce costs will have to "buy their way in" after initial operations of the horizontal launch system. To do this, these technologies will have to be validated at operating conditions for the application (as specified to achieve TRL 6). Those technologies with potential for improved operations, increased system level performance, or lower costs would go through a rigorous ground test validation prior to incorporation into a flight test evaluation program.

Flight test validation could be accomplished on the actual operating system but that would increase the risk of grounding the operational system. A better way may be to continue to operate the flight test demonstrator as a flying test bed. While the flight test demonstrators identified in this study do not satisfy the 15,000 lb payload goal, they should be effective in reducing major uncertainties and risks associated with horizontal launch. If a candidate technology was deemed through systems analysis to be low risk, it may make sense to launch as a nonprimary system on an operational vehicle. Once the technology passes through all of these gates, the design engineer can use it in a scheduled block upgrade of the horizontal launch system.

The list of conceivable technologies considered was limited in this study. It was not the intent of this study to include every potential technology improvement, but to identify the value of technologies to upgrade the expendable horizontal launch vehicle system concept. The HLS team considered the full impact of a given technology for this particular set of requirements—including payload performance, ground and flight operations, reliability, and costs. When subjected to this broad analysis, it became apparent that some initially attractive technology benefits did not warrant investment at this time. Many of these technologies may offer value in other instances, in particular for horizontal launch applications that employ reusable hardware, or if they provide benefits to multiple systems.

Alternate Capabilities for Horizontal Launch Systems

In addition to the traditional payload launch capability to low Earth orbit missions that horizontal launch systems can provide, a number of other suborbital, largely NASA and DoD unique, technology demonstration or potentially operational capabilities may be enabled or strongly enhanced by these types of systems. As examples, NASA's Office of the Chief Technologist has recently sponsored the development of a series of Space Technology Roadmaps, which define new and innovative technology capabilities and investment recommendations spanning a 20-year development cycle.[4]

For example, hypersonic airbreathing propulsion technology, while not currently mature enough for use in near term horizontal launch systems was a key element of the Launch Propulsion Space Technology Roadmap and has many elements that will require maturation through flight testing. The technologies included in the roadmap include Mach 4+ turbines for TBCC, long-duration Mach 7+ scramjet operation, stable mode transitions of RBCC and TBCC vehicles, ACES, and detonation wave engine operation. Each of these component level technologies will require extensive ground tests and certification at the component level, and will ultimately require flight testing and qualification of these systems at or near full scale.

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[4] A total of 15 draft technical area (TA) roadmaps cover a broad range of technology disciplines and capabilities. The TA-01 "Launch Propulsion Systems" and TA-09 "Entry, Descent, and Landing" roadmaps explicitly call out the need for advanced flight test capabilities to develop new and innovative technologies to transform our space transportation infrastructure. Available at: http://www.nasa.gov/offices/oct/home/roadmaps/index.html

The availability of a horizontal launch platform to deliver large scale advanced air breathing propulsion technology demonstration elements to high energy (i.e., high Mach, high q) suborbital test conditions could result in greatly enhanced flight test capabilities. Much like the modified the Pegasus launch vehicle did for the subscale X-43A scramjet vehicle flight test, such a capability could enable qualification of engine and vehicle system technologies at much lower cost and risk.

The current fleet of suborbital sounding rockets was performance limited in the volume and scale of their payloads and only have limited capabilities for payload delivery in suppressed altitude trajectory flight tests. The rocket launch systems evaluated in this study—Falcon or Taurus—could be modified to perform the suborbital suppressed trajectory missions required. However, they were not currently designed to carry large horizontal launch loads, and significant requalification would be required. An air-launched horizontal launch system, designed to accommodate these types of trajectories and loads, would require only straightforward modifications to support these flight test missions.

With current component-level engine ground test articles and X-43A and X-51 flight demonstrations defined as “1x scale”, the hypersonics project in NASA’s Aeronautics Research Mission Directorate, calls for a 10x and ultimately a 100x scale engine and vehicle systems technologies that will need to be flight qualified. The horizontal launch systems described here would likely be capable of testing support to the 10x level system scale in a manner similar to how Pegasus supported testing X-43A at the 1x scale.

By allowing the new engine component technologies to be boosted and flight tested as individual elements to their requisite test conditions on a standalone carrier vehicle, the need for a full-scale integrated flight system development testing using an airbreathing propelled test vehicle with low-speed and high-speed propulsion cycles may not be necessary. This could allow for multiple advanced high speed propulsion system technology developments to occur in parallel, or staggered over a period of years and development cycles, and then removed individually from the critical path in an airbreathing flight vehicle system. The technologies could be developed and qualified individually, and only after qualified and flight proven at the component or subsystem level would they be integrated on a dedicated airbreathing launch vehicle flight system. A number of other advanced launch system technologies, not directly propulsion system related, could be tested at or near full scale including boundary layer and turbulent transition experiments, warm and hot structure, actively and passively cooled, thermal protection systems, and so on.

In addition to hypersonic airbreathing propulsion, flight test demonstrations and launch capabilities were needed that exceed today’s state of the art with sounding rockets and balloon launch rocket assist systems. These include multiple technologies, ranging from hypersonic and supersonic inflatable aerodynamic decelerators, rigid and flexible deployable aerodynamic decelerator systems, new slender body entry aeroshells with high performance maneuvering capabilities, to supersonic retro-propulsion for large mass payload descent systems at Mars. For many of the human scale entry, descent, and landing (EDL) systems, and even some of the large robotic EDL technologies, the mass and volume requirements far exceed capabilities that exist with suborbital test platforms today. All of these will ultimately require flight testing at or near full scale.

In order to fully qualify these systems, they must be tested in a relevant environment at or near full scale. In the late 1960s and early 1970s, NASA developed a supersonic parachute technology for the Mars Viking mission. In order to test the Viking parachutes at relevant Mars conditions, a flight test capability was developed that utilized high altitude balloons that carried a rocket propelled launch systems to altitudes of approximately 100,000 feet. The payload was severed from the balloon at altitude and rocket propelled to supersonic conditions. While this type of capability can still be utilized, it was severely limited in mass and volume capabilities, and would not be capable of delivering the large scale human class or robotic precursor decelerator system technologies to the high altitude high Mach number conditions require for full or near full scale qualification and flight certification. Notional examples of several of these advanced EDL system technologies are shown in Figure 8.

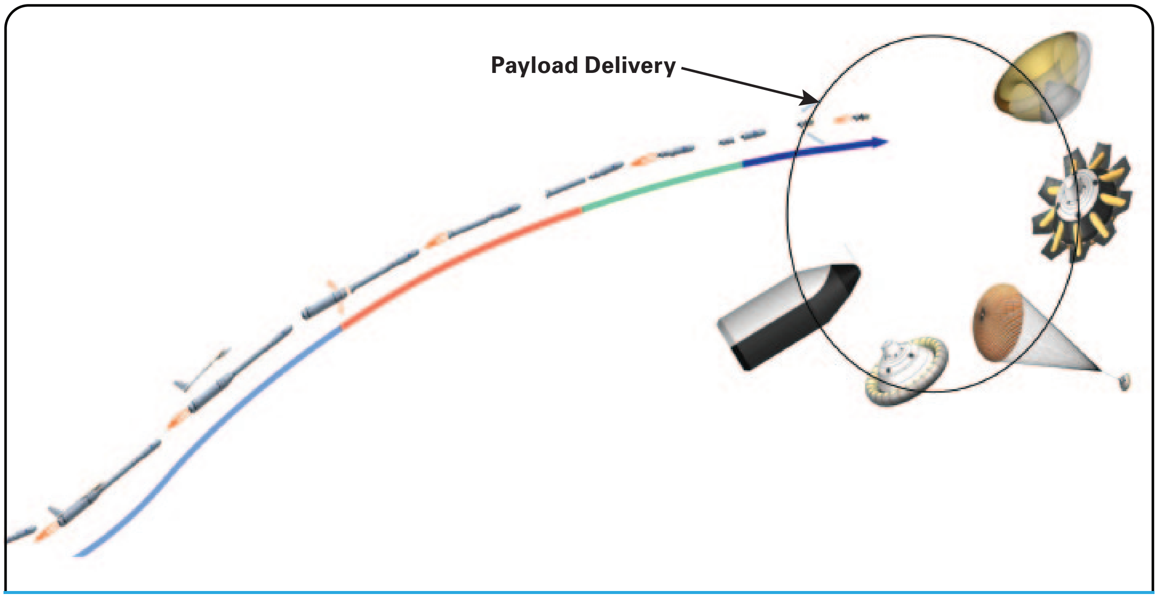


Figure 8 A flight test demonstrator can provide suborbital depressed trajectory launch capability for unique high q/high Mach systems technology demonstrations.

Appendices

APPENDIX A

FIGURES OF MERIT

Figure of Merit	Definition	Measures	Proxy Parameters
Safety and mission success			
Loss of vehicle probability, by stage	Probability of a critical failure occurring resulting in loss of stage	P(Loss of Vehicle)	Number of engines; inherent reliability and redundancy strategy of engines and other subsystems; stage complexity; emergency stage separation complexity; number of stage return options
Loss of mission probability	Probability of a critical failure occurring resulting in loss of one or more major mission objectives	P(Loss of Mission).	Number and type of system risks and mission hazards; subsystem inherent reliability; system/subsystem functional redundancy (e.g., engine-out capability); number and complexity of stages; number of engines and stages; total mission duration.
Effectiveness and performance			
Payload	Compatibility of payload accommodations for commercial and military missions	Payload weight delivered to LEO; payload volume; payload services	None
Minimum turnaround time	Minimum time needed between mission completion and mission ready	Operational readiness after mission completion	System complexity; mean time between maintenance; Stage integration complexity; Propellant safeing
Surge call-up time	Time between the announcement of a surge mission need and launch	Time to launch after operational readiness	Complexity of payload integration; time to fill tanks; launch checkout time; mission software load time
Basing flexibility	The ability to launch from various launch sites and airports	System on-ground safety, takeoff and landing requirements	Propellant type, system and subsystem maturity, wing loading.
Mission flexibility	The ability to adapt to mission requirements.	Mission flexibility (crossrange, downrange, loiter time, cruise margin, payload weight and volume)	Aspect ratio, specific fuel consumption, mass ratio, propellant type
Military viability	Unique mission capability for investment cost	Qualitative assessment of military viability	DDT&E costs; fixed and variable recurring cost; flight rate; payload capability uniqueness; system launch mobility; system launch availability; system turnaround time

Factors quantitatively calculated
Factors qualitatively determined using expert elicitation

Figure of Merit	Definition	Measures	Proxy Parameters
Programmatic Risk			
Failure to achieve DDT&E goals	Likelihood of development activities to exceed schedule and budget constraints and consequence of occurrence	Risk exposure score using five-level qualitative assessment of likelihood and consequences of development maturity and complexity of major subsystems; total risk exposure = (likelihoodi x consequencesi)	Number of critical subsystems at TRL 7 or below; number and type of large-scale integrated ground demonstrations required; number and type of flight tests required
Failure to achieve IOC date	Date of projected initial operating capability (IOC)	Technology development time, system DDT&E time	Lowest TRL of the most critical subsystems; projected technology and development time; Criticality of mission needs.
Technology maturity	Likelihood of architecture DDT&E activities to exceed planned schedule and consequence of occurrence	TRL6 or above	Number of technologies required; average TRL of technologies; average RD3 score of technologies; number and type of large-scale integrated ground demonstrations required; number and type of flight tests required
Commercial viability	Ability to establish and serve a sustainable business base	Estimated lifecycle cost below price of existing or planned launch options	Price and projections of existing launch systems
Affordability			
Cost of DDT&E	Cost to design, develop, test, and evaluate all architecture elements prior to IOC	DDT&E costs; peak annual cost	Total inert mass; Number and level of complexity of architecture systems; number of interfaces between major architecture elements/systems; percent of new hardware and hardware that uses new technologies used in architecture systems; management and acquisition approaches used in the development of architecture systems
Cost of facilities	Cost to establish new or modified facilities (e.g., manufacturing, launch, processing, propellant production) needed to conduct missions.	Facilities costs; ground support equipment costs; peak annual costs.	Total volume and mass of facilities required; Level of complexity of facilities; Percent of new hardware and hardware that uses new technologies used in facilities; Management and acquisition approaches used in the development of new facilities
Cost of acquisition and production	Unit cost of acquiring or producing all carrier aircraft, launch vehicle stages, aerosurfaces, and fairings	Unit production costs	Inert mass, system complexity

Factors quantitatively calculated
Factors qualitatively determined using expert elicitation

Figure of Merit	Definition	Measures	Proxy Parameters
Cost of operations	Average annual integration and maintenance costs after IOC (fixed and variable)	Average annual costs	Annual and per-mission System mass; level of communications and navigation infrastructure required; number and complexity of major architecture elements/systems; level of autonomy (for ground and flight operations) of architecture systems; maintainability/ life of architecture systems; level of reusability of architecture systems
Cost of mission failure	Average cost of failure occurring during a mission, including all direct and indirect return-to-flight costs.	Average cost of mission failure; time to return to flight after mission failure	Number and type of alternate launch systems; level of commonality and modularity between systems; system production costs; recurring cost per flight

Factors quantitatively calculated
Factors qualitatively determined using expert elicitation

APPENDIX B

PAYLOAD MARKET AND COMMERCIAL VIABILITY ANALYSIS

A realistic payload demand forecast underpins the commercial viability analysis performed in this study. The market forecast was derived by projecting future launch demand forward from the last ten years of satellite launch history. Sources of data included the Union for Concerned Scientists, the NASA National Space Science Data Center (NSSDC), AMSAT, and other independently verified sources. The demand forecast was calibrated with near-term forecasts published by industry monitoring organizations such as Teal Group, Euroconsult, and the Commercial Space Transportation Advisory Committee (COMSTAC). A Gompertz curve (an S-curve function commonly used for economic applications) was employed as the forecast model. The shape of this curve was determined by solving for the inflection point and growth parameter that best fit the historical data as well as near-term growth estimates. Market demand was projected for the period of 2010 to 2060. All historical data was normalized to low-Earth orbit equivalent delivered payload in order to represent the total demand to all orbital destinations.

In order to produce meaningful demand predictions across the broad range of vehicle payload capabilities examined, the market forecast was stratified into payload classes (by mass). To account for the fact that the payload capability of an available launch vehicle would likely influence the design mass of real world payloads, the payload classes were binned according to a span of plus or minus 20 percent from the target payload mass. Thus, multiple forecast curves were produced representing the forecast with error bands of plus or minus 20 percent of payload masses. Competition in the marketplace would prevent a launch vehicle from capturing the entirety of the forecasted demand, so a market capture percentage is applied to the overall demand forecast.

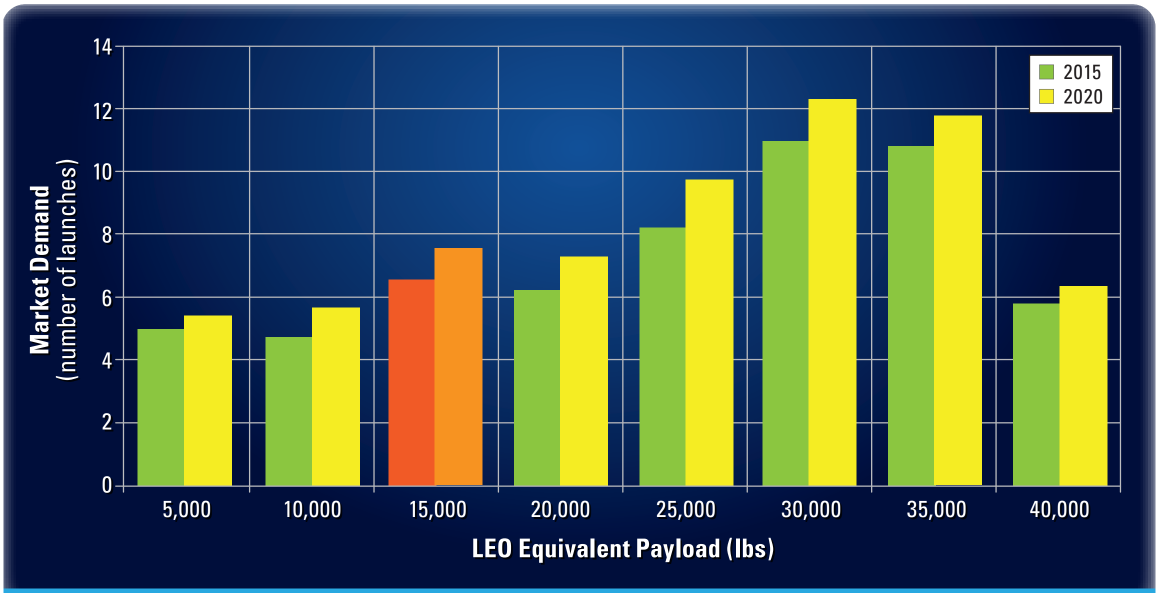
The potential for dual manifesting was accounted for by summing the market forecast at the target payload together with half the market forecast of the payload class that is half the mass of the target payload.

Examples of the binned market demand are shown on page 79 in the growth of market demand over time. In the detailed analysis, payloads were binned at a higher fidelity.

Commercial viability was assessed for all concepts considered in the screening process, as well as for the three point designs. The commercial viability margin was defined as the difference of the breakeven price from the market price, divided by the breakeven price.

Commercial Viability Margin = (Market Price – Breakeven Price) / Breakeven Price

A positive value represented commercial viability, meaning the breakeven price is lower than the market, and the concept could generate profit. A negative value indicated that the market price was lower than the breakeven price, and the concept would not be profitable over the campaign.



Global Market Demand for Commercial Launches

APPENDIX C

STUDY SURVEY

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
ABLV-02	US/NASA	Astrox	2001	25,000 lb	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-04 (LACE)	US/NASA	Langley Research Center	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-04a (LOX)	US/NASA	Langley Research Center	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-04b (AceTR)	US/NASA	Langley Research Center	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-04c (ABTJ)	US/NASA	Langley Research Center	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-04e (ABTJ)	US/NASA	Langley Research Center	2003	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-05	US/NASA	Pratt and Whitney	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating system engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Hunt , 2001)
ABLV-06 (RBCC Rocketdyne)	US/NASA	Boeing, Aerojet, McKinney Associates	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with RBCC in Air-Augmented Rocket mode to DMSJ takeover at M2.5+, followed by transition to rocket propulsion (Moses , 1999)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
ABLV-07a (RBCC Aerojet)	US/NASA	Boeing, Aerojet, McKinney Associates	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with RBCC in Air-Augmented Rocket mode to DMSJ takeover at M2.5+, followed by transition to rocket propulsion (Moses , 1999)
ABLV-07c (RBCC Aerojet)	US/NASA	Boeing, Aerojet, McKinney Associates	2001	25,000 lb	2-Med	3-Far	Air breathing launch vehicle with RBCC in air-augmented rocket mode to DMSJ takeover at M2.5+, followed by transition to rocket propulsion (Moses , 1999)
ABLV-07c-LaunchAssist (RBCC Aerojet)	US/NASA	Boeing, Aerojet, McKinney Associates	2001	25,000	2-Med	3-Far	Air breathing launch vehicle with launch assisst with RBCC in Air-Augmented Rocket mode to DMSJ takeover at M2.5+, followed by transition to rocket propulsion (Moses , 1999)
ABLV-08 (PDE GE)	US/NASA	Lockheed	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with PDE low speed operating system DMSJ takeover at M3+, followed by transition to rocket propulsion (Moses , 1999)
ABLV-09 (AceTR / ATSD)	US/NASA	Boeing Company	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating systems engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Moses , 1999)
ABLV-10	US/NASA	Boeing Company	2001	25,000	1-Low	3-Far	Air breathing launch vehicle with various low speed operating systems engine concepts accelerating vehicle to DMRSJ takeover at M3+, followed by various methods of transitioning to rocket propulsion (Moses , 1999)
ABLV-GT	US/NASA	Aerojet, Georgia Tech	2000	25,000	1-Low	3-Far	ABLV-GT accelerates with aerospike tail rocket and turboramjet to Mach 3. From Mach 3-18 the vehicle uses DMSJ and aerospike rocket. From Mach 18 to orbit, thrust is provided by the rocket exclusively. (Bradford, 2000)
ABLV-VTHL	US/NASA	Boeing, Aerojet, McKinney Associates	2000	25,000	1-Low	3-Far	Same as ABLV-07c, except for VTO (configuration assumed compatible with VTO, not technically correct) - analysis done solely as "what if?" trade (Moses, 1999)
Advanced Reusable Small Launch System	US/NASA	Langley Research Center	1999	2,000	1-Low	3-Far	Air-launched from An-225 (Moses, 1999)
Airbourne Microlauncher "MLA"	NA	Dassault	2008	154	1-Low	1-Near	Two stage solid/liquid upper stage air-launched from Rafale fighter (Dassault, 2008)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
Air-launched SS-520	Japan	IHI Aerospace	NA	37	1-Low	1-Near	SS-520 sounding rocket air-dropped from a C-130 (HLS Team, 2011)
ALS - Boeing Airlaunch with 747 (Fuselage)	US/Air Force	Boeing Company	1999	7,500 lb	2-Med	1-Near	Modified Boeing 747 carrier aircraft air-launches a three-stage, winged upper stage. Upperstage is basically an Athena rocket with wings. (Boeing, 2000)
ALS - Boeing AirLaunch with 747 (Underwing)	US/Air Force	Boeing Company	2000	7,500	1-Low	1-Near	Modified Boeing 747 carrier aircraft air-launches a three-stage, winged upper stage. Upper stage is basically an Athena rocket with wings. (Boeing, 2000)
ALSV - Air Launched Sortie Vehicle	US/Air Force	Boeing Company	1981	3,000	1-Low	1-Near	Modified Boeing 747 (attachment hardware, dewar, tail rocket) carries an all-rocket orbiter and cylindrical drop tank to altitude for air launch. (Day, 2010)
ALSV - Air Launched Sortie Vehicle	US/Air Force	General Dynamics	1981	5,000	1-Low	1-Near	Modified Boeing 747 (new H-tail, attachment hardware) carries an all-rocket orbiter and V-shaped drop tank to altitude for air launch. (Day, 2010)
ALSV - Air Launched Sortie Vehicle	US/Air Force	Rockwell International	1981	3,000	1-Low	1-Near	Modified Boeing 747 (new V-tail, attachment hardware) carries an all-rocket orbiter and drop tank to altitude for air launch. (Day, 2010)
AMSC - Trans-Atmospheric Vehicle (747-Launched 1.5 Stage)	US/Air Force	Rockwell	1984	10,000	1-Low	2-Mid	Modified Boeing 747 air-launches reusable orbiter and drop tanks. Orbiter accelerates to orbit using rocket propulsion. (Sanborn, 1984)
AMSC - Trans-Atmospheric Vehicle (GEM-Launched SSTO)	US/Air Force	Rockwell	1984	10,000	1-Low	3-Far	Ground effect machine (GEM) launch assist is used to accelerate a reusable delta-winged orbiter to takeoff velocity. Orbiter continues to accelerate using rocket thrust. (Sanborn, 1984)
ARTS	IRAD	SpaceWorks, Gray Research	2003	40,000	1-Low	3-Far	Maglev launch assist accelerates vehicle to Mach ~0.8. Dual-fuel, all-rocket propulsion used during remained of mission. Vehicle is reusable. (Wallace, 2003)
Astroliner	IRAD	Kelly Aerospace	1993	10,030	1-Low	2-Mid	Astroliner towed to altitude by 747. Used LOX/Kerosene rocket engines to accelerate to Mach 6.5 staging point. Released upper stage. (Sarigul-Klijn, 2001)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
Athena	US/NASA	University of Michigan	1994	3,773	1-Low	1-Near	Three stage liquid rocket air-dropped from C-5B carrier aircraft. Rocket carried in C-5B cargo bay. (Booker, 1994)
ATS Option 3 SSTO (AB/R)	US/NASA	Langley Research Center	1993	25,000 lb	2-Med	3-Far	Vehicle takes off under low-speed airbreathing plus rocket mode. Transition to ramjet mode occurs at Mach 3, followed by transition to scramjet mode at Mach 6. Rocket mode accelerates the vehicle from Mach 15 to orbit. (NASA, 1994)
ATS Option 3 TSTO (AB/R)	US/NASA	Ames Research Center	1994	25,000	2-Med	3-Far	Vehicle takes off under turbo-ramjet thrust. Staging between the booster and orbiter occurs at Mach 5. (NASA, 1994)
AVATAR	India	DRDO	2001	2,500	1-Low	3-Far	AVATAR takes off horizontally using turbo-ramjet engines. Scramjet mode is then used from Mach 4 to 8. During this phase, air is collected and liquid oxygen is stored. A rocket mode is then used to complete the ascent to orbit. (HLS Team, 2011)
B-52H Responsive Air Launch	US/DARPA	Orbital Sciences, Schafer	2004	500	2-Med	1-Near	Three-stage rocket air-launched from B-52. (Frick, 2004)
Bantam-X Argus	US/NASA	Georgia Tech	1999	300	1-Low	3-Far	Ground launch assist system provides 800 ft/s initial velocity. Vehicle accelerates with supersonic ejector ramjet (SERJ) in ejector mode, transitions to ramjet mode at Mach 3, transition from ramjet to rocket primary at Mach 6 and continues to orbit. (St. Germain, 1999)
Bantam-X KLIN Argus	US/NASA	Georgia Tech	1999	20,000	1-Low	3-Far	Ground launch assist system provides 800 ft/s initial velocity. Deeply cooled turbojet operate together up to Mach 1.5, DCTJ alone provides thrust to Mach 4, rockets throttled back up between Mach 4 and 6, final transition to rocket mode at Mach 6 and above (St. Germain, 1999)
Bantam-X PDRE Argus	US/NASA	Georgia Tech	1999	20,000	1-Low	3-Far	Ground launch assist system provides 800 ft/s initial velocity. PDRE provides all thrust until Mach 2, ramjets used from Mach 2 to 6, and then PDREs propel vehicle to orbit (St. Germain, 1999)
Bantam-X Stargazer	US/NASA	Georgia Tech	1999	300	1-Low	3-Far	Vehicle accelerates in ejector mode from liftoff to Mach 3, dual-mode ramjet/scramjets accelerate to Mach 10, transition to rocket mode from Mach 10 to Mach 14 staging point. Rocket upper stage continues to orbit. (Olds, 1999b)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
Bantam-X Starsaber	US/NASA	Georgia Tech	2001	300	1-Low	2-Mid	Vehicle accelerates in ejector mode until Mach 3.5, utilizes ramjet mode from Mach 3.5 to 5.5, and then rocket mode from Mach 5.5 to staging at Mach 10. Rocket upper stage continues to orbit (St. Germain, 2001)
Beta	US/NASA	Boeing Company	1991	50,000	1-Low	3-Far	Fully reusable system with combined air-breathing and rocket propulsion on the booster, and rocket propulsion on the orbiter. Staging at Mach 8. (Nadell, 1992)
Beta II	US/NASA	LaRC, Boeing	1992	17,500 lb	1-Low	3-Far	Fully reusable system with air-breathing booster and rocket orbiter. Mach 6.5 staging point. (Nadell, 1992)
Black Colt	US/Air Force	Martin Marietta	1994	1,000	2-Med	2-Mid	Black Colt takes off under turbojet power, climbs, and rendezvous with tanker. Tanker transfers liquid oxygen enabling Black Colt to accelerate to a Mach 12 staging condition. From there, Star-48 motor accelerates payload to orbit. (Zubrin, 1995)
Black Horse	IRAD	Pioneer Astronautics	2000	1,000	1-Low	2-Mid	Black Horse takes off under turbojet power, climbs to altitude, and rendezvous with tanker. Tanker transfers liquid oxygen enabling Black Horse to accelerate to orbit using a tail-mounted rocket. (Zubrin, 1995)
BladeRunner	US/Air Force	SMC	2004	2,000	1-Low	2-Mid	Bladerunner can be air-dropped from a C-17A at Mach 0.8, 40 kft. System accelerates to Mach 11 under rocket power. Staging occurs and upper stage proceeds to orbit. Booster is re-used. (Hampsten, 2004)
Boeing F-15 Global Strike Eagle (F-15 GSE)	IRAD	Boeing Company	2006	600	2-Med	1-Near	Modified F-15 aircraft carries two-stage rocket upper stage on top of fuselage. Staging is supersonic. (Chen , 2006)
Crossbow	IRAD	Teledyne Brown	2010	NA	1-Low	2-Mid	Specialized, all-new carrier aircraft is used to deploy a two-stage liquid rocket at high gamma. (Sorensen, 2004)
Dedalus Air Launch Concept	France	CNES, ONERA	NA	330	1-Low	1-Near	Air-launch from new carrier aircraft at Mach 0.7. A three-stage solid upper stage carries the payload to orbit. (Talbot, 2008)
DF-09 RBCC	US/Air Force	Boeing Company	1998	5,000	1-Low	3-Far	Vehicle uses RBCC propulsion. Staging point is Mach 10. (Scuderi, 1998)
DF-09 TBCC	US/Air Force	Boeing Company	1998	5,000	1-Low	3-Far	TBCC DF-9 takes off under turbo-ramjet thrust and transitions to ramjet-scramjet operation starting at Mach 4. The vehicle uses a linear rocket system to provide thrust during a pop-up maneuver. (Scuderi, 1998)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
DF-10 TBCC	US/Air Force	Boeing Company	1996	10,000	2-Med	2-Mid	Study produced a quick-reaction, global reach ISR Mach 10 aircraft capable of delivering a 10 klb payload globally and returning to CONUS (Scuderi, 1998)
DRLV	Israel	Israel Inst. Tech.	2008	165	1-Low	1-Near	F-15I carrier aircraft deploys 2-stage solid rocket. (HLS Team, 2011)
F-15 Microsatellite Launch Vehicle	US/Air Force	Boeing Company	2003	440	2-Med	1-Near	Solid rocket upper stage carried on centerline beneath F-15 fighter. (HLS Team, 2011)
FALCON Quick Reach	US/DARPA	AirLaunch LLC	2004	1,000 lb	2-Med	1-Near	Quick Reach is air-dropped from a C-17 and uses 2 liquid stages to put its payload in LEO. (AirLaunch, 2007)
Frequent Flyer (Dan DeLong)	IRAD	Teledyne Brown	NA	1,000	1-Low	2-Mid	Frequent Flyer is boosted by an expendable rocket first stage. After first stage burnout, a winged-body second stage proceeds to a second staging point. A rocket upper stage accelerates the payload to orbit under rocket thrust. (XCOR, 2011)
Global Range TAV	IRAD	ANSER, McKinney Associates	2009	20,000	3-High	1-Near	All-rocket vehicle derived from RASV database, with detailed scaling algorithms. (HLS Team, 2011)
HOTOL	UK	British Aerospace	1982	17,600	1-Low	2-Mid	HOTOL takes off using a rocket-propelled sled. The vehicle then uses a novel RB545 air/LH2/LOX rocket engine to accelerate to Mach 5. From Mach 5 to orbit the vehicle uses pure rocket propulsion. (Sarigul-Klijn, 2001)
HOTOL - Interim with An-225	UK	British Aerospace	1991	NA	1-Low	3-Far	Air-launched from a Ukrainian An-225 Mriya aircraft. Interim HOTOL would separate from the carrier aircraft at subsonic speeds, and would then pull up for the ascent to orbit. It would return via a gliding re-entry and landing on gear on a conventional runway. (Neiland, 1991)
HRST Argus	US/NASA	Georgia Tech	1998	20,000	1-Low	3-Far	Argus utilizes Maglifter launch assist to reach 800 ft/s at launch. Main engines are initially in supercharged ejector mode and transitions to fan-ramjet mode between Mach 2 and 3. Argus flies in fan-ramjet/ramjet mode until Mach 6, at which point it transitions to rocket mode for the final leg to orbit. (Olds, 1998)
HRST ATS with MHD	US/NASA	Lockheed, Aerojet, ANSER, McKinney Associates	1998	25,000	1-Low	3-Far	Lockheed HRST concept used the NASA ATS configuration with a MHD Energy By-Pass engine system to “shift” the Aerojet StrutJet engine performance back up along the Mach axis. (HLS Team, 2011)
HRST ERJ / LACE SSTO	US/NASA	Langley Research Center	1998	52,800	1-Low	3-Far	Vehicle uses LACE Ejector Ramjet (ERJ) RBCC propulsion. (HLS Team, 2011)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
HRST Hyperion	US/NASA	Georgia Tech	1998	20,000	1-Low	3-Far	Hyperion uses its RBCC engines in ejector mode during take-off and up to Mach 3. Between Mach 3 and Mach 5.5 the vehicle uses ramjet mode, and from Mach 5.5 to Mach 10 scramjet mode is used. Mach 10 to orbit is accomplished using rocket thrust. (Olds,1999a)
HRST Space America Concept	US/NASA	Space America	1998	25,000	1-Low	3-Far	SSTO all-rocket vehicle with launch assist. Limited definition available. (NASA, 1998)
HRST SSTO Waverider	US/NASA	Rockwell	1998	20,000 lb	1-Low	3-Far	Waverider configuration (length/diameter=5). Uses maglev launch assist for take-off and 8 turbojets for low-speed propulsion. High speed propulsion is RBCC. (NASA, 1998)
HSDTV	India	DRDO	2007	NA	1-Low	3-Far	Vehicle uses scramjet and rocket propulsion modes. Staging point is at Mach 6.5. (HLS Team, 2011)
HTS-1 Turbines (+ Tail Rocket) / Rocket	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicle uses turbines plus tail rockets on the booster, and rocket propulsion on the upper stage. (HLS Team, 2011)
HTS-2 RBCC / Rocket	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicle uses RBCC propulsion on the booster and rockets on the upper stage. (HLS Team, 2011)
HTS-3 TBCC: Turbines/RJ/SJ (+ Tail Rocket) / Rocket	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicle uses TBCC and tail rockets on the booster and rockets on the upper stage. (HLS Team, 2011)
HTS-4 ACES/RBCC / Rocket	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicles uses RBCC propulsion with ACES on the booster and rockets on the upper stage. (HLS Team, 2011)
HTS-5 Turbines (+ Tail Rocket) / RBCC	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicle uses turbines and tail rockets on the booster and RBCC on the upper stage. (HLS Team, 2011)
HTS-6 TBCC: Turbines/RJ/SJ (+ Tail Rocket) / RBCC	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicle uses TBCC propulsion on the booster and RBCC on the upper stage. (HLS Team, 2011)
HTS-7 Turbines (+ Tail Rocket) w/ 2nd stage Rocket	US/NASA	Boeing Company	2000	25,000	1-Low	3-Far	Vehicle uses turbines and tail rockets on the booster and rockets alone on the upper stage. (HLS Team, 2011)
JSS - RALV-B	US/NASA	Langley Research Center	2010	20,000	2-Med	3-Far	TBCC booster stage. (NASA, 2010)
LauncherOne (WK2 + upper stage)	IRAD	Scaled Composites	2010	440	2-Med	1-Near	White Knight 2 carries three-stage upper stage. (Amos, 2009)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
Lazarus	IRAD	Georgia Tech	2006	5,000	1-Low	3-Far	Lazarus accelerates to 500 ft/s using a rocket sled. At take-off, the main engines are in ejector mode. Transition from ejector to ramjet mode occurs at Mach 3. Transition from ramjet to scramjet occurs at Mach 6. A final transition to rocket mode occurs at Mach 10. (Young, 2006)
Lynx II	IRAD	XCOR	NA	22	2-Med	1-Near	Mark II version of Lynx capable of carrying dorsal payload pod weighing up to 650 kg. A solid rocket upper stage could be used to launch a nanosatellite. (XCOR, 2008)
MAKS - M	USSR	NPO Molniya	1989	12,000	2-Med	2-Mid	MAKS-M is air-launched from an An-225 carrier aircraft. A rocket powered stage-and-a-half with a reusable, unmanned orbiter accelerates to orbit. (Lozino-Lozinsky, 1997)
MAKS - OS	USSR	NPO Molniya	1989	18,200 lb	2-Med	2-Mid	MAKS-OS is air-launched from an An-225 carrier aircraft. A rocket powered stage-and-a-half with a reusable, manned orbiter accelerates to orbit. (Lozino-Lozinsky, 1997)
Mustang	IRAD	UCF	2003	8,000	1-Low	3-Far	NASA 747 SCA used to air-launch a reusable ramjet/scramjet 2nd stage and a reusable rocket powered orbiter. Staging between 2/3 is Mach 15. (Bloss, 2003)
NanoLaunch LLC concept	IRAD	Premier Space Systems	2010	100	1-Low	1-Near	F-15 carrier aircraft launches hybrid rocket upper stage with nanosatellite payload. (Premier, 2010)
Nano-Launcher Black	IHI	SpaceWorks + IHI	2010	81	2-Med	1-Near	Su-27 carrier aircraft launches three-stage solid upper stage. Upperstage components are existing equipment. (DePasquale, 2010)
NAS 377 - TSTO - ESJ	US/NASA	Lockheed-Marquardt	1967	20,000	2-Med	3-Far	RBCC ejector scramjet booster stage. Staging point at Mach 12. (Olds , 1996)
NAS 377 - TSTO - LACE	US/NASA	Lockheed-Marquardt	1967	25,000	2-Med	3-Far	RBCC ejector scramjet booster stage with LACE. Staging point at Mach 12. (Olds , 1996)
NASP - BWB-2 SSTO LACE/DMSJ/Rocket	US/NASA, DoD	McDonnell Douglas	1987	NA	1-Low	3-Far	Dual-mode scramjet plus rockets. (Stueber , 2010)
NASP - Early Aerospace-plane (Gregory)	US/NASA	Langley Research Center	1970	20,000	1-Low	3-Far	Early concept for a fully reuseable SSTO space plane. (HLS Team, 2011)
NASP - GD	US/NASA, DoD	General Dynamics	1988	5,000	1-Low	3-Far	General Dynamics concept for the NASP vehicle (Jenkins, 2003)
NASP - McDonnell Douglas	US/NASA, DoD	McDonnell Douglas	1988	5,000	2-Med	3-Far	This culminated in the NCB-3 configuration: Spatular body with truncated nose and 2-d rectangular inlet (Jenkins, 2003)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
NASP - NCB-3 SSTO LACE/DMSJ/Rocket	US/NASA, DoD	McDonnell Douglas	1987	5,000	1-Low	3-Far	Final configuration for Aircraft Concept review (ACR) in Aug 1987 and subsequent down-select: Spatular body with truncated nose, 2-d rectangular inlet. Became new "Gov't Baseline" as National Team/JPO established (Lau, 2008)
NASP - Rockwell	US/NASA, DoD	Rockwell	1988	5,000	1-Low	3-Far	This was "The Government Baseline" concept: A conical body, with semicircular "smile" inlet - low performance at higher Mach numbers led to development of NCB family of concepts with "spatular" nose/forebodies and 2-d inlets (Jenkins, 2003)
NASP Derived Vehicle	US/NASA	McDonnell Douglas	1991	30,000	1-Low	3-Far	An operational version of the McDonnell Douglas X-30 / NCB-3 vehicle (Jenkins, 2003)
NGLT - FASST	US/NASA	Boeing Company	2003	20,000 lb	2-Med	3-Far	A unique concept for NGLT: HC Mach 4 first stage using Mach 4.2 RTA TJs, "shoehorned" underneath a larger Mach 4-14 LOX/ LH2 RBCC/Rocket 2nd stage (Bradley, 2003)
NGLT - Gryphon	US/NASA	Andrews Space	2003	18,900	2-Med	2-Mid	Uses Air Collection & Enrichment System (ACES) in large, loitering carrier aircraft to fill up rocket vehicle propellant tanks (Andrews, 2003)
NGLT - ICM-2 TSTO HTHL TBCC/Rocket	US/NASA	SAIC, McKinney Associates	2003	20,000	2-Med	3-Far	Mach 8 TBCC booster with LOX/LH2 rocket 2nd stage (SAIC, 2003)
NGLT - ICM-3 TSTO HTHL RBCC/Rocket	US/NASA	SAIC, McKinney Associates	2003	20,000	2-Med	3-Far	Mach 8 RBCC booster with LOX/LH2 rocket 2nd stage (SAIC, 2003)
NGLT - ICM-4 TSTO HTHL Turbine/ RBCC/ Rocket	US/NASA	SAIC, McKinney Associates	2003	20,000	2-Med	3-Far	A unique concept for NGLT: HC Mach 4 first stage using Mach 4.2 RTA TJs, "shoehorned" underneath a larger Mach 4-14 LOX/ LH2 RBCC/Rocket 2nd stage (SAIC, 2003)
NGLT - ICM-5 SSTO HTHL TBCC/Rocket	US/NASA	SAIC, McKinney Associates	2003	20,000	2-Med	3-Far	ABLV-4e scaled down to 20 klb due east from 25 klb to ISS orbit (SAIC, 2003)
NGLT - Spaceliner 100	US/NASA	Marshall Space Flight Center	1999	20,000	1-Low	3-Far	RBCC SSTO concept with launch assist. (Dankhoff, 2000)
NGLT - SSTO TBCC/ Rocket with MHD	US/NASA	ANSER, Lockheed, McKinney Assoc	1998	20,000	1-Low	3-Far	ABLV-4c scaled down to 20 klb due east from 25 klb to ISS orbit (HLS Team, 2011)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
Pathfinder	IRAD	Pioneer Rocket-plane	1998	5,070	2-Med	2-Mid	Reusable winged-body booster stage takes off under turbojet thrust and rendezvous with a tanker aircraft. After taking on LOX, vehicle accelerates to Mach 15 staging point and releases rocket upper stage. (Sarigul-Klijn, 2001)
Pegasus	IRAD	Orbital Sciences Corp	2010	1,000	3-High	1-Near	Three-stage solid rocket upper stage is carried to an air-drop point by a modified L-1011 aircraft. (Orbital, 2011)
Peregrine	IRAD	Andrews Space	2004	15,000	1-Low	2-Mid	Reusable, airplane-like first stage uses turbojets and a tail rocket to takeoff, climb, and accelerate. A multistage solid rocket upper stage carries the payload to orbit. (Andrews, 2008)
Polyut	Russia	Air Launch System, Inc.	NA	6,600	1-Low	2-Mid	Three stage liquid rocket upper stage air-dropped from An-124 (HLS Team, 2011)
Rafael Light Air Launch (LAL)	Israel	Rafael	2006	100 lb	1-Low	1-Near	An upper stage based on Rafael's "B" missile is carried aloft by an F-15I fighter plane. The upper stage release occurs at supersonic speed. (HLS Team, 2011)
RASCAL - Coleman	US/DARPA	Coleman	2003	165	2-Med	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)
RASCAL- Delta Velocity	US/DARPA	Delta Velocity	2003	165	2-Med	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)
RASCAL - GT	IRAD	Georgia Tech	2005	165	1-Low	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)
RASCAL - Northrop Grumman	US/DARPA	Northrop Grumman	2003	165	2-Med	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
RASCAL- Pioneer Rocketplane	US/DARPA	Pioneer Rocket-plane	2003	165	2-Med	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)
RASCAL - Space Access LLC	US/DARPA	Space Access LLC	2003	165	2-Med	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)
RASCAL- Space Launch Corp.	US/DARPA	Space Launch Corp.	2003	165 lb	2-Med	2-Mid	DARPA program to design and develop low-cost orbital insertion capability for dedicated micro-size satellite payloads. The concept is to develop a responsive, routine, small payload delivery system capable of providing flexible access to space using a combination of reusable and low-cost expendable vehicle elements. (Young, 2005)
RASV SSTO HTHL Rocket	IRAD	Boeing Company	1976	10,000	2-Med	1-Near	RASV takes off using a 600 ft/s ground accelerator. The vehicle then ascends to orbit under pure rocket power supplied by 2 SSMEs. (Boeing, 1976)
Reusable Orbital Carrier	US/NASA	Lockheed	1964	25,000	1-Low	2-Mid	Turbojet and rocket propulsion. (HLS Team, 2011)
Reusable Orbital Carrier	US/NASA	Rockwell	1964	25,000	1-Low	2-Mid	Rockwell concept for the ROC vehicle. (HLS Team, 2011)
Robust Scramjet - Quicksat	US/Air Force	Space-Works	2004	13,090	1-Low	3-Far	TBCC booster stage with tail rockets. All-rocket upper stage. Staging point is at Mach 9. (Bradford, 2006)
Robust Scramjet - Spiral-2	US/Air Force	Space-Works	2006	15,000	1-Low	3-Far	TBCC booster stage with tail rockets. All-rocket upper stage. Staging point is at Mach 9. (Bradford, 2006)
SA-1	IRAD	Space Access LLC, McKinney Associates	1999	20,000	1-Low	3-Far	The SA-1 is a 747-size spaceplane that takes off under ejector ramjet mode. Ramjet-scramjet mode is then used to Mach 8 at which point pure rockets take over. (FAA, 2001)
Sänger 2	Germany	MBB	1991	20,000	1-Low	2-Mid	Sänger 2 uses turbo-ramjet propulsion to accelerate to Mach 4.4. The vehicle then uses rocket thrust to reach a Mach 6 staging point for upper stage release. (HLS Team, 2011)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
Salkeld C-5 (underwing)	IRAD	System Development Corp.	1970	5,500	1-Low	1-Near	Orbiter with drop tanks air-dropped from under wing of C-5A carrier aircraft. (Salkeld, 1978)
Salkeld Dual C-5 (underwing)	IRAD	System Development Corp.	1970	12,000	1-Low	2-Mid	Winged orbiter and drop tanks air-dropped from dual C-5A carrier aircraft. (Salkeld, 1978)
Sea Argus	IRAD	Space-Works	2004	1,000	1-Low	2-Mid	Next-generation TSTO system with electromagnetic launch assist horizontal takeoff from aircraft carrier. Reusable booster stage with combined-cycle propulsion, expendable rocket upper stage (Spaceworks, 2004)
Shenlong	China	China	2007	110	1-Low	1-Near	Shenlong is air-launched from an H-6 Badger (Tu-16) bomber. A three-stage solid upper stage carries a small payload to LEO. (HLS Team, 2011)
Skylon	NA	Reaction Engines Ltd.	2010	26,000	1-Low	3-Far	Skylon uses two Sabre RBCC engines in air/LH2 mode to accelerate to Mach 5.5, and then uses pure rocket mode to ascend to orbit. (Reaction, 2010)
Space Clipper	Russia	Yuzhnoyes SDO	NA	1,100 lb	1-Low	1-Near	Two stage solid upper stage air-dropped from AN-124 (HLS Team, 2011)
Space Operations Vehicle	US/Air Force	Faulkner Consulting, McKinney Associates	2004	12,000	3-High	2-Mid	TSTO, VTHL, hydrocarbon-fueled, RBCC subsonic-combustion for reliable, rapid military space access, launched from KSC into polar and 28-deg 118 x 56 nmi orbits. Three payloads: SMV, CAV, MIS (Bradley, 2003)
Spaceplane (Dan DeLong)	IRAD	Teledyne Brown	NA	12,000	1-Low	2-Mid	Winged-body, rocket powered orbiter air-launched from modified Boeing 747. (XCOR, 2011)
Spiral 50-50	USSR	NPO Molniya	1965	22,000	2-Med	3-Far	LH2 fueled turbojets accelerate vehicle to Mach 6 staging point. Rocket upper stage boosts reusable orbiter. (Biltgen, 2004)
StarRunner	IRAD	Georgia Tech	2004	25,000	1-Low	3-Far	TBCC with ACES SSTO concept. (Biltgen, 2004)
SuperLACE / ACES Aerospace-plane	NA	General Dynamics	1962	35,000	1-Low	3-Far	SSTO aerospace plane concept using LACE in air-breathing mode and ACES in rocket mode ascent to orbit. (Heppenheimer, 2007)
Svitiaz	Ukraine	National Space Agency	2005	14,500	1-Low	1-Near	Zenit rocket air-launched from the top of an An-225. (HLS Team, 2011)
SwiftLaunch	IRAD	University of California, Davis	2001	1,800	1-Low	2-Mid	C-5 or An-124 carrier aircraft is used to air-drop a novel orbiter-aft, 1.5 stage system with drop tanks. (Sarigul-Klijn, 2001)

Concept Name	Government/ Agency	Performer	Last Year	Design Payload (lbs)	Design Maturity	Technology Timeframe	System Description
TAV Science Dawn Reusable Aero-dynamics Space Vehicle (RASV)	US/Air Force	Boeing Company	1990	10,000	3-HIgh	1-Near	Sled-launched all-rocket spaceplane (Sanborn, 1984)
TAV Science Dawn ZEL	US/Air Force	Lockheed	1990	10,000	1-Low	3-Far	ZEL uses 1.5 Mlb thrust booster stage to lift-off from a 30 deg nose-up starting position. Reusable winged ZEL accelerates to orbit under all-rocket thrust. (Sanborn, 1984)
Telemaque	France	CNES	NA	550	1-Low	1-Near	Liquid/solid/liquid upper stages launched from the top of an Airbus A330. (Talbot, 2008)
URETI Aztec	US/NASA	Georgia Tech	2004	20,000	1-Low	3-Far	TBCC booster stage with HEDM. Staging point at Mach 8.2. (Kokan, 2004)
US Spaceplane	IRAD	US Spaceplane Sys.	2010	15,000	1-Low	3-Far	TBCC booster stage with all-rocket upper stage. Staging point at Mach 6. (US Spaceplane, 2006)
Vozdushny Start	Russia	Energia	2000	6,600	1-Low	1-Near	Solid upper stage air-dropped from An-124 (HLS Team, 2011)
X-34B	IRAD	Orbital Sciences Corp	2000	880 lb	2-Med	2-Mid	X-34B was to be air-launched from the 747 carrier aircraft at Mach ~0.8. The X-34B used rocket main propulsion, as did its small upper stage. (HLS Team, 2011)
Yakovlev High Altitude Aerial Launch (HAAL)	Russia	Yakovlev	1994	2,500	1-Low	2-Mid	ICBM-based upper stage air-launched from Tu-160 carrier aircraft. (Sarigul-Klijn, 2001)

APPENDIX D

TECHNOLOGY READINESS LEVELS

TRL 1	Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
TRL 2	Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
TRL 4	Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
TRL 5	System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
TRL 6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
TRL 7	System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
TRL 8	Actual system completed and “mission qualified” through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.
TRL 9	Actual system “mission proven” through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

APPENDIX E

SUPERSONIC AND HYPERSONIC CARRIER AIRCRAFT TECHNOLOGIES

A major finding of this study was the overwhelming effect of the cost of design, development, test, and evaluation (DDT&E) of new supersonic and hypersonic carrier aircraft technologies. This appendix summarizes some of the fundamental and critical technologies that will drive these costs prior to integration of a supersonic or hypersonic carrier aircraft into a horizontal launch system.

The main benefit of maximizing the separation Mach number was to lower the ΔV required by the launch vehicle to attain orbital velocity, thus allowing potentially greater payload mass to orbit. This advantage could also be used for additional structural margin to increase reliability and system robustness or to add systems that allow a fully reusable launch vehicle. (Bilardo, 2003) Numerous studies in the past ten years have identified technologies needed to realize a supersonic or hypersonic carrier aircraft for horizontal launch options.

Supersonic Carrier Aircraft

Many of the technologies used in existing supersonic aircraft can be utilized for horizontal launch but will need larger airframes to increase payload capability. The study team found that the small size of existing supersonic aircraft limited the size of payloads that could be launched. The internal dimensions limit the size of a launch vehicle carried internally, and external carriage of a launch vehicle on a supersonic aircraft was currently impractical without very large excess thrust to overcome the transonic drag.

Novel aircraft configurations may increase the payload capability of supersonic aircraft. Examples include a modified structural design to maximize internal volume or a radical airframe design that aims to solve the transonic pinch point problem. Promising propulsion technologies include larger-scale supersonic turbojet engines or efficient aerodynamic and thermal integration of clustered turbojets to increase thrust to levels. Additionally, several specific propulsion integration technologies could enhance supersonic staging horizontal launch, including variable cycle turbo accelerator engines,[5] tail rockets, (Andrews, 2005) the use of mass injection precompressor cooling, (Carter, 2003) or the use of liquid oxygen in turbojet afterburners. (Balepin, 2008) Alone or in combination, these would allow a significant transonic thrust margin and an acceleration-climb maneuver to enable a more optimal launch of the rocket powered launch vehicle with a high flight path angle and low dynamic pressure.

Hypersonic Carrier Aircraft

Hypersonic staging horizontal takeoff and landing carrier aircraft concepts have been proposed in many studies with a variety of different propulsion system and vehicle architectures. (Boeing,

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[5] Such as the Revolutionary Turbine Accelerator (RTA).

2005; McClinton, 2004; 2008; CPIAC, 2001; Stanley, 2010; NRC 2004) Several enabling technologies described in these studies that will require development or demonstration investments to achieve TRL 6 are summarized here. This list was not intended to be all-inclusive or comprehensively detailed, but only to provide a summary perspective on major areas of technology development requirements.

The hypersonic carrier aircraft included here were assumed to deploy the launch vehicle between Mach 6 and 10. For a higher Mach number, carrier aircraft or a single-stage-to-orbit vehicle, TRLs were likely to be lower in almost every subsystem than supersonic systems.

Specific technologies that need to be addressed were partly configuration dependent. That is, some technologies will require early attention during conceptual design of a hypersonic carrier aircraft depending on specific attributes to be utilized or traded. Where TRLs were identified in previous studies, they were specifically referenced. Further, where technologies can also be linked to the following NASA Space Technology Roadmaps, they were shown by technology area number after each technology.[6]

Vehicle-Level System Design

1. Develop and verify multidisciplinary design optimization (MDO) tools to include the ability to enhance existing scaling laws and related analysis tools to properly design carrier aircraft of sufficient size to carry launch vehicles of sufficient size; to perform vehicle geometry parameterization to efficiently explore the vehicle design space; to generate automated external and internal grid surfaces to expedite analysis of computational fluid dynamics (CFD); to perform trajectory optimization for an accelerator carrier aircraft to maximize performance and operability of the airbreathing engines across the speed regime; to improve discipline-level analysis tool fidelity; to improve modeling and analysis of aerodynamic heating, engine heating, and thermal management; and to include cost and safety analyses in all phases of system design. [TRL 3-4; TRL 2-5] [Roadmap sections TA01 1.3.8; TA11 2.2.2.4; TA12 2.5.3]
2. Develop methods to efficiently design for vehicle stability and control across the speed regime is needed to address the aeropropulsive effects on vehicle trim and their sensitivity to Mach number and engine throttle setting. [TRL 3-4] [Roadmap section TA01 1.3.5]
3. Develop verified methods to predict transonic propulsion integrated with airframe performance and operability is needed to achieve a solution to the transonic pinch-point problem. [TRL 2-3]
4. Develop methods to efficiently incorporate uncertainty into analysis and design methods using probabilistic analyses. [TRL 2-3] [Roadmap sections TA12 2.2.2 and 2.3.6]

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[6] NASA Space Technology Roadmaps. Available at http://www.nasa.gov/offices/oct/home/roadmaps/index.html

5. Verify understanding of effects of critical data and communications transmission through shock layers and/or ionized flowfields.
6. Assess the potential uses of magnetohydrodynamics for drag reduction, vehicle and flow-path flow control, and combustion enhancement. [TRL 1-2]

Propulsion and Propellants

1. Revive efforts on a revolutionary turbine accelerator to determine upper speed limit capability (with a goal of at least Mach 4) and develop a flight-weight version engine. [TRL 4-6] [Roadmap section TA01 1.3.1]
2. Revive RBCC development efforts with emphasis on inlet/isolator/rocket performance and compatibility, augmentation/air capture requirements at subsonic speeds, trading inlet starting Mach number with high speed capture requirements, and long life high performance thrust chamber development. [TRL 4] [Roadmap section TA01 1.3.2]
3. Exercise and determine the low-speed limit of the dual-mode scramjet with reasonable performance and operability via inlet bleed systems, a cold-start system, and improvements to flameholding. [TRL 3] [Roadmap section TA01 1.3.5]
4. Experimentally demonstrate mode transition from a low-speed engine (such as a turbojet) to a high-speed engine (ramjet/scramjet) and the effect on overall vehicle performance and engine operability. [Roadmap section TA01 1.3.1]
5. Address options for integration of multiple engine systems, including turbojet cocooning, air augmentation, inlet systems, and nozzle systems. [TRL 3-4] [Roadmap section TA01 1.3.1]
6. Assess possible solutions for transonic thrust (e.g., external burning or tail rockets). [TRL 3-4]
7. Develop variable geometry and multiple fueling location options for improved high-speed engine multiMach number performance. [TRL 4-6] [Roadmap section TA01 1.3.1]
8. Develop system (hardware and software) to control propulsion performance and operability. [TRL 4-6]
9. Renew efforts to determine performance, durability, and integration of linear aerospike tail rockets. [TRL 4-5]
10. Continue to understand hypersonic propulsion physics challenges via “unit” experiments in such areas as natural and forced boundary-layer transition; boundary layer turbulence; separation caused by shock-boundary layer interaction; shock-shock interaction heating; inlet-isolator shock trains; cold-wall heat transfer; fuel injection, penetration and mixing; finite rate chemical kinetics; turbulence-chemistry interaction; boundary layer relaminarization; recombination chemistry; and catalytic wall effects. [Roadmap section TA01 1.3.5]

11. Develop advanced (i.e., high energy density) fuels. [Roadmap sections TA01 1.3.5; TA02 2.3.4]
12. Develop capability for generating, storing, and transferring triple point cryogenic propellants. [Roadmap section TA13 2.1.1]

Aerodynamics

1. Develop verified predictive capability of CFD to capture such critical physical processes as unsteady flows within inlets and isolators, as well as for vehicle aeroelasticity determination; aerodynamic heating; shock wave/boundary-layer interaction; and fuel mixing, ignition, and combustion. [Roadmap section TA12 2.5.3]
2. Develop innovative three-dimensional propulsion/airframe integration, including the need to incorporate combined cycle engine systems. [Roadmap section TA01 1.3.1]
3. Improved/verified boundary-layer transition predictive capability.
4. Verified capability to predict separation aerodynamic effects at high Mach number and high dynamic pressure conditions.

Materials and Structures

1. Develop new engine and airframe materials to enable lighter, more durable propulsion and airframe structures. [TRL 5; TRL 3-6] [Roadmap section TA12 2.1.1]
2. Develop actively-cooled leading edges for vehicle and engine. [TRL 3-4; TRL 4-6]
3. Mature metallic, regeneratively-cooled engine panels for thermal effectiveness and long life. [TRL 3-4; TRL 3-7]
4. Evolve variable geometry engine parts and wings/control surfaces for thermal and load resiliency. [TRL “low”]
5. Develop and verify durable thermal protection system for extreme load conditions (high Mach number and high dynamic pressure). [TRL 3-6] [Roadmap sections TA12 2.1.4; TA14 2.3.1]
6. Develop reusable cryogenic tanks for both conformal and multilobed vehicle architectures. [TRL 5; TRL 3-5]
7. Mature static and dynamic seals, bearings, bushings, and wear surfaces for high-temperature, high-pressure environments. [TRL 5; TRL 3-4] [Roadmap sections TA01 1.3.5]
8. Develop high-speed (takeoff and) landing system, including deployment mechanism, tires, brakes, and truck structure. [TRL 5]

Thermal Management

1. Verify closed-loop engine regenerative cooling and fuel conditioning tools. [TRL 3] [Roadmap section TA01 1.3.8]
2. Develop verified shock interaction heating prediction and mitigation.
3. Develop innovative, robust, low subsystem impact cooling concepts for highly-loaded airframe and propulsion structures (e.g., film cooling and transpiration cooling).

Ground Test Technologies and Flight Operations

1. Develop methodology for test and evaluation of larger-scale systems (e.g., engines, thermal panels, structural components) and mode transition.
2. Verify fundamental physics understanding through well designed "unit" experiments for tool validation.
3. Develop diagnostic capabilities for acquiring additional types and amounts of data from ground and flight tests. [Roadmap section TA13 2.1.3]
4. Develop capability for faster turnaround time through highly automated vehicle operations, where the vehicle itself will report to the ground personnel what maintenance it needs via Integrated Vehicle Health Management. [TRL 2-3] [Roadmap sections TA04 2.1.5; TA09 1.1.5; TA11 2.2.2.2; TA12 2.2.3 and 2.3.5; TA13 2.3.3 through 2.3.6]
5. Develop new range operations to minimize ground-based personnel needed for a given mission.
6. Develop launch vehicle processing methods to integrate the launch vehicle and the carrier aircraft with minimum crew and turnaround times.
7. Address launch-assist options such as magnetic levitation or electromagnetic rails. [Roadmap section TA13 2.3.1]

APPENDIX F

FIDELITY OF ANALYSIS

The analysis requirements and methodology differs for performance-related disciplines at various levels of analytical fidelity. The levels zero through four are described here for eight categories of analysis.

Configuration, geometry and packaging

0	Parametric, empirical or analytical geometry model
1	External and major internal components modeled such as propellant tanks; payload bay, propulsion, etc., modeled for volume, area, and key linear dimensions
2	All components modeled, packaged, and analyzed for geometric properties including center of gravity; geometry redrawn and packaged to match closure model
3	All components modeled, packaged, and analyzed for geometric properties including center of gravity and inertia characteristics; geometry redrawn and packaged to match closure model
4	All components modeled, packaged, and analyzed for geometric properties including center of gravity and inertia characteristics; geometry re-drawn and packaged to match closure model

Structures and materials

0	Parametric or historical equation adjusted to level 1 or higher for similar technology and vehicle configuration
1	One-dimensional bending loads analysis based on structural theory of beams, shell, etc. with nonoptimums based on level 2 or higher results
2	Limited three-dimensional finite element analysis (less than 20,000 nodes) for all major load cases, structure sized to allowables, nonoptimums determined empirically or analytically
3	Three-dimensional finite element analysis (more than 20,000 nodes) for all major load cases, structure sized to allowables, nonoptimums determined empirically or analytically; dynamic frequencies estimated.
4	Three-dimensional finite element analysis (more than 100,000 nodes) for all major load cases, structure sized to allowables, nonoptimums determined empirically or analytically. Dynamic frequencies estimated.

Sizing and closure

0	Weight and volume closure with consistent bookkeeping of all propellants and fluids based on commensurate fidelity level inputs from other disciplines; as-flown vehicle photographic scale factor less than +/- 15% from as-drawn
1	Weight and volume closure with consistent bookkeeping of all propellants and fluids based on commensurate fidelity level inputs from other disciplines; as-flown vehicle photographic scale factor less than +/- 10% from as-drawn
2	Weight and volume closure with consistent bookkeeping of all propellants and fluids based on commensurate fidelity level inputs from other disciplines; as-flown vehicle photographic scale factor less than +/- 5% from as-drawn
3	Weight and volume closure with consistent bookkeeping of all propellants and fluids based on commensurate fidelity level inputs from other disciplines; as-flown vehicle photographic scale factor less than +/- 3% from as-drawn
4	Weight and volume closure with consistent bookkeeping of all propellants and fluids based on commensurate fidelity level inputs from other disciplines; as-flown vehicle photographic scale factor less than +/- 1% from as-drawn

	Trajectory, guidance, navigation and control
0	Rocket equation or energy methods; path-following simulation
1	Optimized ascent, flyback and reentry three-degrees of freedom point mass simulation; untrimmed
2	Optimized ascent, flyback and reentry three-degrees of freedom (pitch trim) point mass simulation; longitudinal stability and control evaluation
3	Optimized ascent, flyback and reentry 6-degree of freedom simulation; longitudinal, lateral and yaw stability and control evaluation; perfect guidance, navigation, and control
4	Optimized ascent, flyback and reentry 6- degree of freedom simulation; longitudinal, lateral and yaw stability and control evaluation; real guidance, navigation, and control with gain scheduling or similar lags, noise, etc

	Propulsion design and performance
0	Scaled empirical
1	One-dimensional cycle analysis adjusted to level 2 or higher results; military standard or other installation effects included
2	Two- and three-dimensional finite difference inviscid (Euler) flowfield analysis with heat conduction and transfer and integral boundary layer analysis. Propulsive moments, installation effects and thermal balance computed.
3	Two- and three-dimensional parabolized Navier-Stokes finite difference and volume flowfield analysis with heat conduction and transfer and integral boundary layer analysis. Propulsive moments, installation effects and thermal balance computed. Full mechanical design.
4	Three-dimensional full or thin-layer Navier-Stokes flowfield analysis including pressure feedback, shear stress and heat transfer effects computed directly. Propulsive moments, installation effects and thermal balance computed. Full mechanical design.

	Aerodynamics and aerotherodynamics
0	Scaled empirical
1	Linear or impact methods with all empirical drag increments adjusted to level 2 or higher; vehicle satisfies all takeoff and landing speeds, glide path, and runway length requirements
2	Three-dimensional computational fluid dynamics inviscid (Euler) with integral boundary layer or potential with semiempirical drag increments or thin layer Navier Stokes with semiempirical nonviscous drag increments; vehicle satisfies all takeoff and landing speeds, glide path, runway length, and longitudinal stability requirements
3	Three-dimensional computational fluid dynamics parabolized Navier-Stokes finite difference / volume flowfield analysis with heat conduction / transfer and integral boundary layer analysis; vehicle satisfies all takeoff and landing speeds, glide path, runway length, and longitudinal, lateral and yaw stability requirements
4	Three-dimensional computational fluid dynamics full or thin layer Navier-Stokes flowfield analysis including pressure feedback, shear stress and heat transfer effects computed directly; vehicle satisfies all takeoff/landing speeds, glide path, runway length, and longitudinal, lateral and yaw stability requirements

	Aerothermal and sizing of thermal protection systems
0	Parametric or historical
1	Aerothermal loads based on one-dimensional engineering methods; one-dimensional through-the-thickness sizing of thermal protection systems
2	Two- and three-dimensional engineering methods or computational fluid dynamics based aerothermal loads with quasi-two-dimensional sizing of thermal protection systems
3	Two- and three-dimensional computational fluid dynamics methods for aerothermal loads with quasi-two-dimensional sizing of thermal protection systems
4	Three-dimensional computational fluid dynamics methods for aerothermal loads with three-dimensional sizing of thermal protection systems

Airframe and engine subsystems	
0	Parametric or historical
1	Functional definition and evaluation or one-dimensional or generic modeling of subsystem
2	Quantitative thermal and fluid analysis of subsystem; component weights estimated with empirical, historical or analytical data or analysis
3	Quantitative thermal and fluid analysis of subsystem; component weights estimated with empirical, historical or analytical data or analysis
4	Quantitative thermal and fluid analysis of subsystem; component weights estimated with empirical, historical or analytical data or analysis

APPENDIX G

ASSUMPTIONS AND METHODOLOGIES

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Fiscal year for cost data	FY10	FY10	FY10	FY10
Weights and sizing				
Model / methodology	Compilation of mass estimating relationships from the StageSizer model, previous studies, and other references	Compilation of mass estimating relationships from the StageSizer model, previous studies, and other references	Compilation of mass estimating relationships from the StageSizer model, previous studies, and other references	Compilation of mass estimating relationships from the StageSizer model, previous studies, and other references
Stage sizing philosophy	All stages were fully parametric; no existing hardware assumed	Used existing launch vehicle stages with fixed thrust and weight; all other stage components fully parametric	Used existing launch vehicle stages with fixed thrust and weight; all other stage components fully parametric	Used existing hardware for propulsion and stages; interstages, aerosurfaces, and attachment hardware sized parametrically
Stage thrust-to-weight ratio at ignition for sizing	1st Stage = 1.20; 2nd Stage = 1.15; 3rd Stage = 1.10	Number of engines selected to provide sufficient thrust based on trajectory simulation	Number of engines selected to provide sufficient thrust based on trajectory simulation	Number of engines selected to provide sufficient thrust based on trajectory simulation
Solid motor propellant mass fraction	0.93	Based on existing solid stages	Based on existing solid stages	Based on existing solid stages
Liquid propellant tank unit weight (fuel and oxidizer)	0.8 lb/ft^3	Function of maximum load, segment length, and tank volume	Function of maximum load, segment length, and tank volume	Not applicable - all existing stages with fixed stage weights
Wing unit weight	5.0 lb/ft^2	Function of wing surface area and aspect ratio	Function of wing surface area and aspect ratio	Function of wing surface area and aspect ratio
Payload density	8.0 lb/ft^3	7.0 lb/ft^3	7.0 lb/ft^3	NA - existing payload fairing with fixed dimensions and weight
Payload fairing unit weight	2.75 lb/ft^2	2.5 lb/ft^2	2.5 lb/ft^2	NA - existing payload fairing with fixed dimensions and weight
Interstage/intertank unit weight	4.3 lb/ft^2	Function of maximum load and segment length	Function of maximum load and segment length	Function of maximum load and segment length
Propellant reserves, residuals, and start-up losses	1.8% of ideal propellant mass	1.8% of ideal propellant mass	1.8% of ideal propellant mass	1.8% of ideal propellant mass

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Propellant ullage	2.0% of required propellant volume	2.0% of required propellant volume	2.0% of required propellant volume	2.0% of required propellant volume
Inert system weight growth margin	15%	15% for new components; 5% for existing components	15% for new components; 5% for existing components	15% for new components; 5% for existing components
Carrier aircraft payload carrying capacity	White Knight X: 176,000 lb 747-100 SCA-911: 240,000 lb A380-800: 264,550 lb 747-400F: 308,000 lb An-225: 440,925 lb White Knight XX: 750,000 lb Dual C-5: 771,618 lb	747-400F: 305,000 lb	747-400F: 305,000 lb	747-100 SCA-905: 192,000 lb
Propulsion				
Propulsion sizing philosophy	No existing hardware assumed (All engines/rockets were fully parametric)	Existing engines/rockets	Existing engines/rockets	Existing engines/rockets
Performance	Solid rocket motor: 290s (1st stages) 292s (2nd/3rd stages) RP engine: 346s (1st stages) 354s (2nd/3rd stages) RP engine: T/W = 100 LH2 engine: 450s (1st stages) 460s (2nd/3rd stages) LH2 engine: T/W = 55	Castor 120: 279s Castor 30: 295s Merlin 1C: 304s Merlin 1C Vacuum: Thrust= 138,400 lbf, T/W = 92 RS-25E: 453s RS-25E: Vacuum Thrust = 490,850 lbf, T/W = 73 RL 10A-4-2: 450s RL 10A-4-2: Vacuum Thrust = 22,289 lbf, T/W = 61	Castor 120: 279s Castor 30: 295s Merlin 1C: 304s Merlin 1C Vacuum: Thrust= 138,400 lbf, T/W = 92 RS-25E: 453s RS-25E: Vacuum Thrust = 490,850 lbf, T/W = 73 RL 10A-4-2: 450s RL 10A-4-2: Vacuum Thrust = 22,289 lbf, T/W = 61	FT-1: Castor 120: 279s Orion 50S XLG: 287s Orion 50XL: 291s Orion 38: 289s Solid rocket motor thrust traces taken from ATK Space Propulsion Products Catalog FT-2 Merlin 1C: 304s Kestrel: 325s Merlin 1C: 138,400 lbf Kestrel: 6,245 lbf
Trajectory				
Model / Methodology	Application of rocket equation with assumed total ΔV and losses based on POST I simulation	Application of rocket equation with assumed total ΔV and losses based on POST I simulation	POST I simulation - 3 degrees of freedom optimized untrimmed trajectory with constraints	POST I simulation - 3 degrees of freedom optimized untrimmed trajectory with constraints
Carrier aircraft release conditions	Altitude: 35,000 ft Mach number: 0.75	Altitude: 25,000 ft Mach number: 0.7	Altitude: 25,000 ft Mach number: 0.7	Altitude: 25,000 ft Mach number: 0.7

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Simulation Constraints	Maximum q: Less than 1,000 psf	Maximum q: Less than 1,000 psf	Maximum q: Less than 1,000 psf	Maximum q: Less than 1,000 psf
	Maximum q-Alpha: Less than 5,000 psf-degrees	Maximum q-Alpha: Less than 5,000 psf-degrees	Maximum q-Alpha: Less than 5,000 psf-degrees	Maximum q-Alpha: Less than 5,000 psf-degrees
Acceleration constraints	Maximum wing normal factor: Less than 1.5g	Maximum wing normal factor: Less than 1.5g	Maximum wing normal factor: Less than 1.5g	Maximum wing normal factor: Less than 1.5g
	Maximum acceleration: Less than 5.0 g	Maximum acceleration: Less than 5.0 g	Maximum acceleration: Less than 5.0 g	Maximum acceleration: Less than 5.0 g
Separation timing	10s delay after separation before engine ignition	10s delay after separation before engine ignition	10s delay after separation before engine ignition	10s delay after separation before engine ignition
	Minimum of a two second delay after rocket staging event before ignition of next stage engine	Minimum of a two second delay after rocket staging event before ignition of next stage engine	Minimum of a two second delay after rocket staging event before ignition of next stage engine	Minimum of a two second delay after rocket staging event before ignition of next stage engine
	Wing and tails dropped time chosen by optimizer, must be before first stage burnout and separation	Wing and tails dropped time chosen by optimizer, must be before first stage burnout and separation	Wing and tails dropped time chosen by optimizer, must be before first stage burnout and separation	Wing and tails dropped time chosen by optimizer, must be before first stage burnout and separation
	Payload fairing release when dynamic pressure falls below 0.1 psf	Payload fairing release when dynamic pressure falls below 0.1 psf	Payload fairing release when dynamic pressure falls below 0.1 psf	Payload fairing release when dynamic pressure falls below 0.1 psf
Orbit	Targeted direct injection into 100 nmi circular due east orbit from a latitude of 28.5 degrees	Targeted direct injection into 100 nmi circular due east orbit from a latitude of 28.5 degrees	Targeted direct injection into 100 nmi circular due east orbit from a latitude of 28.5 degrees	Targeted direct injection into 100 nmi circular due east orbit from a latitude of 28.5 degrees
Aerodynamics				
Model / Methodology	Based on Missile DATCOM analysis, with gradient-based optimization to reach sizing goals	Based on Missile DATCOM analysis, with gradient-based optimization to reach sizing goals	Based on Missile DATCOM analysis, with gradient-based optimization to reach sizing goals	Based on Missile DATCOM analysis, with gradient-based optimization to reach sizing goals
Simulation parameters	Alpha range: -20 to 20 degrees	Alpha range: -20 to 20 degrees	Alpha range: -20 to 20 degrees	Alpha range: -20 to 20 degrees
	Mach range: 0.75 to 30	Mach range: 0.5 to 30	Mach range: 0.5 to 30	Mach range: 0.5 to 30
Wing sizing basis	300 lb/ft2 (gross weight wing area)	Function of wing surface area and aspect ratio	Function of wing surface area and aspect ratio	Function of wing surface area and aspect ratio

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Configuration	Wing mounted at 5° incidence to rocket body X-axis	Wing mounted at 5° incidence to rocket body X-axis	Wing mounted at 5° incidence to rocket body X-axis	Wing mounted at 5° incidence to rocket body X-axis
	Horizontal tail control surface set to 50% of chord	Horizontal and vertical tails sized to achieve in-flight static stability	Horizontal and vertical tails sized to achieve in-flight static stability	Horizontal and vertical tails sized to achieve in-flight static stability
	Vertical tail area and planform same as horizontal tails	Vertical tail area and planform same as horizontal tails	Vertical tail area and planform same as horizontal tails	Vertical tail area and planform same as horizontal tails
Campaign				
Duration	20 years	20 years	20 years	3.5 years
Flight Rate	6 and 12 flights per year	6 flights per year	6 flights per year	2 flights
Development and Unit Costs				
Models / methods employed	Development and test hardware estimated using custom implementation of TRANSCOST v.8.0, and historical data; Facilities cost derived from Facility and Ground Support Equipment Operations Analysis (FGOA) Model	Development and test hardware estimated using subsystem-level response surface equations of NAFCOM 2007 supplemented by TRANSCOST v.8.0 and historical data; Facilities cost derived from Facility and Ground Support Equipment Operations Analysis (FGOA) Model	Development and test hardware estimated using NAFCOM 2007, and historical data; Facilities cost derived from Facility and Ground Support Equipment Operations Analysis (FGOA) Model	Development and test hardware estimated using NAFCOM 2007
Industry standard wraps	Contractor fee: 10%	Contractor fee: 10%	Contractor fee: 10%	Contractor fee: 10%
	Program support: 11%	Program support: 11%	Program support: 11%	Program support: Costs include 36 government team personnel and supporting contractors for 4 years
	Contingency: 20%	Contingency: 20%	Contingency: 20%	Contingency: 20%
	Vehicle integration: 4%	Vehicle integration: 4%	Vehicle integration: 4%	Vehicle integration: 4%
DDT&E baseline	DDT&E costs assume previous maturation to TRL6+	DDT&E costs assume previous maturation to TRL6+	DDT&E costs assume previous maturation to TRL6+	DDT&E costs assume previous maturation to TRL6+
Aircraft DDT&E Costs	747-100 SCA: $10M			747-100 SCA-905: $0M
	747-400F: $144M	747-400F: $122M	747-400F: $122M	
	An-225: $20M			
	White Knight X: $125M			
	Dual-fuselage C-5: $2.38B			
	White Knight XX: $400M			

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Aircraft acquisition cost	747-100 SCA: $0M			747-100 SCA-905: $0M
	747-400F: $30M	747-400F: $30M	747-400F: $30M	
	An-225: $1.03B			
Aircraft modification cost	747-100 SCA: $5M			FT-1: 747-100 SCA-905: $10M FT-2: 747-100 SCA-905: $12M
	747-400F: $62M	747-400F: $56M	747-400F: $56M	
	An-225: $10M			
Aircraft production cost	White Knight X: $50M			Taurus unit cost: $33.5M Falcon unit cost: $11M
	Dual-fuselage C-5: $1.02B			
	White Knight XX: $180M			
Non-recurring engine/rocket costs	Engine DDT&E calculated in model	RS-25E DDT&E cost: $750M (does not include system integration or wraps)	RS-25E DDT&E cost: $750M (does not include system integration or wraps)	
Existing engine unit costs		Castor 120 unit cost: $8.7 M	Castor 120 unit cost: $8.7 M	
		Castor 30 unit cost: $1.6 M	Castor 30 unit cost: $1.6 M	
		Merlin I-C unit cost: $2.8M (unit cost at beginning of campaign)	Merlin I-C unit cost: $2.8M (unit cost at beginning of campaign)	
		RL 10A-4-2 unit cost: $10.9M (unit cost at beginning of campaign)	RL 10A-4-2 unit cost: $10.9M (unit cost at beginning of campaign)	
		RS-25E unit cost: $31.4M (unit cost at beginning of campaign)	RS-25E unit cost: $31.4M (unit cost at beginning of campaign)	
Production learning curve	95%	RL 10A-4-2 and Merlin I-C: 95% RS-25E: 90% Other new subsystems: 90%	RL 10A-4-2 and Merlin I-C: 95% RS-25E: 90% Other new subsystems: 90%	
Operations				
Models / methods employed	Hardware costs estimated using custom model based on TRANSCOST v.8.0 and historical data; Operations cost estimated using custom implementation of TRANSCOST v.8.0; Operations cost and time metrics derived from TRANSCOST v.8.0 and historical data with multipliers	Hardware costs estimated using subsystem-level response surface equations of NAFCOM 2007 supplemented by TRANSCOST v.8.0 and historical data; Operations cost and time metrics derived from TRANSCOST v.8.0 and historical data	Hardware costs estimated using NAFCOM 2007 and historical data; Operations cost and time metrics derived from TRANSCOST v.8.0 and historical data	Ground and flight operations estimated using a composite of Hyperport, Comet OCM and D4Ops

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Surge call-up time	Assumes all systems in near-ready state; Includes fueling of carrier aircraft, accelerated final assembly, fueling of upper stages	Assumes all systems in near-ready state; Includes fueling of carrier aircraft, accelerated final assembly, fueling of upper stages	Assumes all systems in near-ready state; Includes fueling of carrier aircraft, accelerated final assembly, fueling of upper stages	
Minimum turnaround time	Includes carrier aircraft preparation, rocket stage assembly and integration, and final assembly	Includes carrier aircraft preparation, rocket stage assembly and integration, and final assembly	Includes carrier aircraft preparation, rocket stage assembly and integration, and final assembly	
Recurring operations	Includes operational costs of 747 carrier aircraft, support staff for 747 technician team, rocket stage and vehicle assembly/integration technicians, support staff for assembly/integration team, propellants	Includes operational costs of 747 carrier aircraft, support staff for 747 technician team, rocket stage and vehicle assembly/integration technicians, support staff for assembly/integration team, propellants	Includes operational costs of 747 carrier aircraft, support staff for 747 technician team, rocket stage and vehicle assembly/integration technicians, support staff for assembly/integration team, propellants	Includes operational costs of 747 carrier aircraft, support staff for 747 technician team, rocket stage and vehicle assembly/integration technicians, support staff for assembly/integration team, propellants
Recurring operations cost contingency	15%	20%	20%	20%
Recurring operations program management wrap	20%	Calculated directly in model	Calculated directly in model	Calculated directly in model
Reliability				
Models / methods employed	Excel-based Event Sequence Diagram supported by Fault Trees; failure rates derived from historical data	Excel replication of Relex-based Event Tree supported by Fault Trees; failure rates derived from historical data	Relex-based Event Tree Diagram supported by Fault Trees; failure rates derived from historical datas	Relex-based Event Tree Diagram supported by Fault Trees; failure rates derived from historical data
Failure rate: booster separation from aircraft	747-100 SCA: 1 in 100 flights			747-100 SCA: 1 in 100 flights
	747-400F: 1 in 100 flights	747-400F: 1 in 100 flights	747-400F: 1 in 100 flights	
	An-225: 1 in 125 flights			
	White Knight X: 1 in 1000 flights			
	Dual-fuselage C-5: 1 in 667 flights			
	White Knight XX: 1 in 667 flights			

	Screening Process (Fidelity Level 0)	Tech Trades (Fidelity Level 0)	Point Designs (Fidelity Level 1)	Flight Tests (Fidelity Level 1)
Failure rate: stage separation event	1 in 107 flights	1 in 429 flights	1 in 429 flights	1 in 429 flights
Engine out capability	All engines required for all phases of flight	All engines required for all phases of flight	All engines required for all phases of flight	All engines required for all phases of flight
Commercial Viability				
Models / methods employed	Discounted cash flow analysis supported by custom commercial and military launch demand model	Discounted cash flow analysis supported by custom commercial and military launch demand model	Discounted cash flow analysis supported by custom commercial and military launch demand model	
Government Contribution to DDT&E Cost	$400 M	$400 M	$400 M	
Launch Market	Commercial + Military	Commercial + Military	Commercial + Military	
Anticipated Inflation Rate	2.1%	2.1%	2.1%	
Tax Rate	30%	30%	30%	
Flight rate for commercial viability analysis	Calculated according to market demand and capture. Ranges between ~3 to ~7 flights per year based on payload class.	Calculated according to market demand and capture. Ranges between ~3 to ~7 flights per year based on payload class.	Calculated according to market demand and capture. Ranges between ~3 to ~7 flights per year based on payload class.	

APPENDIX H

DETAILS OF THE AERODYNAMIC AND TRAJECTORY ANALYSES

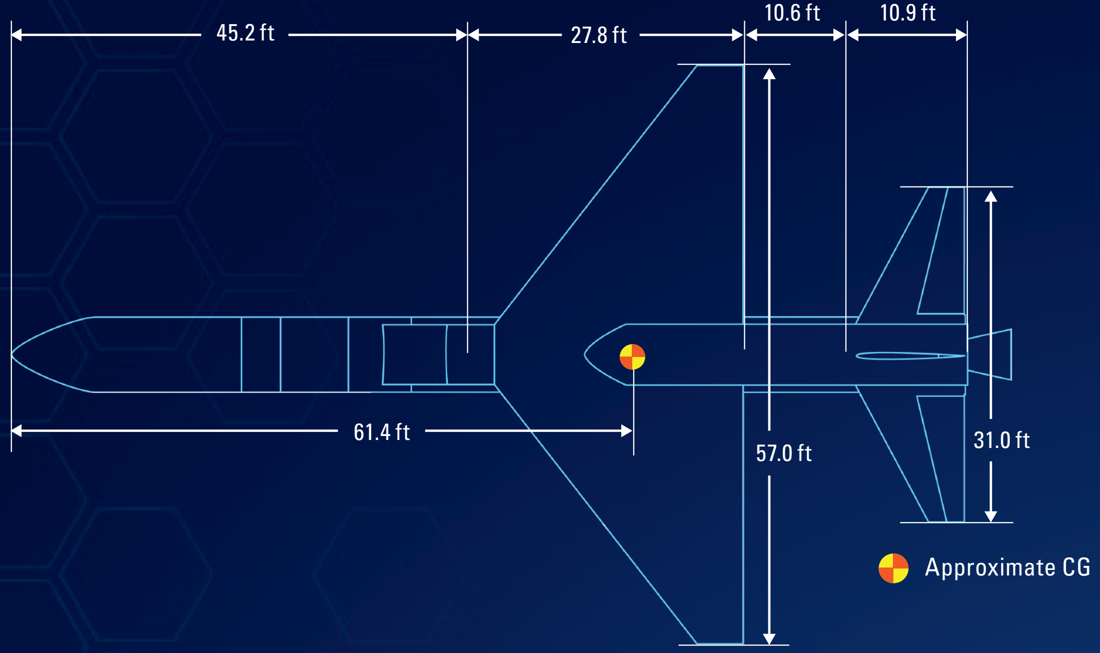
Dimensions Used in Aerodynamic Analysis for the Point Design System Concepts

Parameter	PD-1	PD-2	PD-3
Wing			
Aspect Ratio	3.5	4.1	3.5
Taper Ratio	0.17	0.09	0.2
LE Sweep Angle	38.5°	38.3°	36.4°
Platform Area	923 ft^2	940 ft^2	803 ft^2
Thickness-to-Chord Ratio	0.1	0.1	0.1
Loading at 1 g	310 lb/ft^2	320 lb/ft^2	380 lb/ft^2
Incidence Angle	5°	5°	5°
Tails (Horizontal and Vertical)			
Aspect Ratio	4.0	4.0	4.0
Taper Ratio	0.43	0.34	0.36
LE Sweep Angle	21.8°	26.2°	25.4°
Platform Area	120 ft^2	97 ft^2	145 ft^2
Thickness-to-Chord Ratio	0.1	0.1	0.1

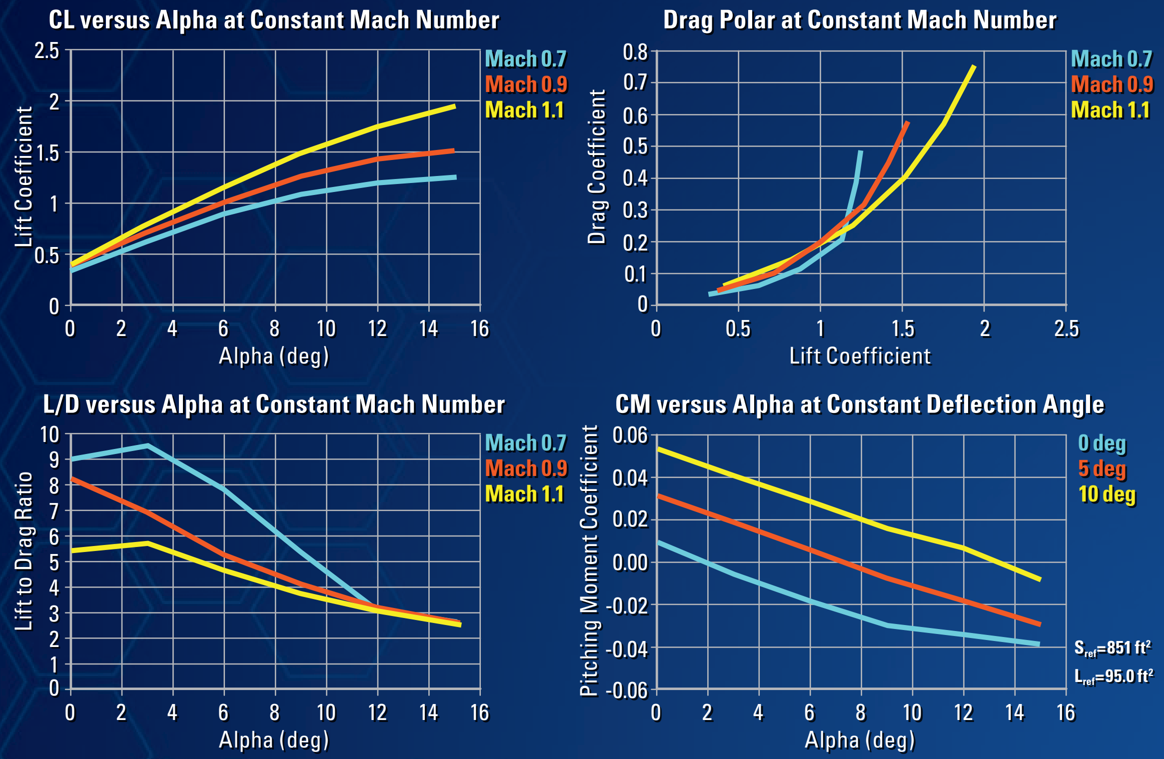
Dimensions Used in Aerodynamic Analysis for the Flight Test System Concepts

Parameter	FT-1		FT-2	
Wing				
Aspect Ratio	3.8		3.5	
Taper Ratio	0.15		0.19	
LE Sweep Angle	37.5°		37.3°	
Platform Area	598 ft^2		193 ft^2	
Thickness-to-Chord Ratio	0.1		0.1	
Incidence Angle	0°		5°	
Tails	Horizontal	Vertical	Horizontal	Vertical
Aspect Ratio	4.6	3.7	5.0	3.8
Taper Ratio	0.30	0.35	0.30	0.30
LE Sweep Angle	25.0°	40.0°	23.1°	40.0°
Platform Area	51.2 ft^2	51.2 ft^2	35.5 ft^2	35.2 ft^2
Thickness-to-Chord Ratio	0.1	0.1	0.1	0.1

Point Design 1

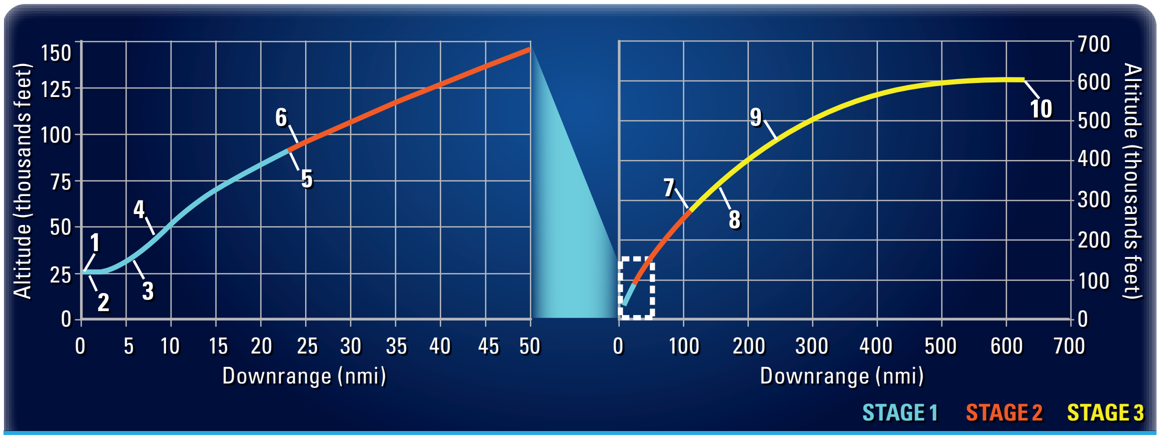


Schematic used in aerodynamic analysis



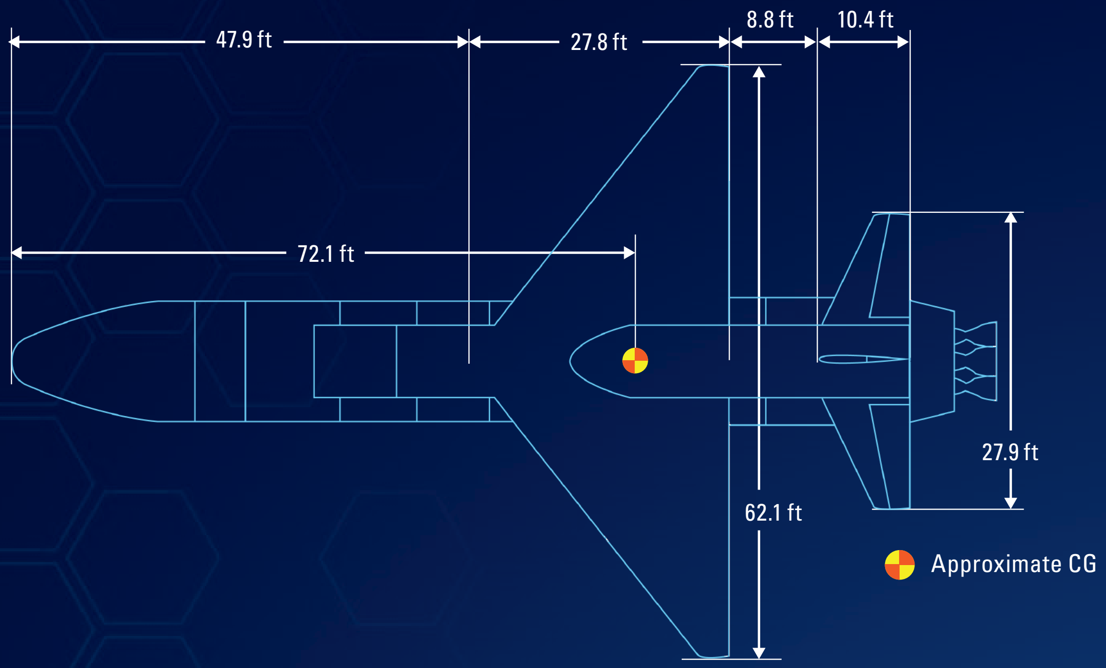
Aerodynamic results

Trajectory Analysis for the Point Design 1



ID	Event	Time (s)	Weight (lb)	Altitude (ft)	Relative Velocity (f/s)	Mach Number	Dynamic Pressure (psf)	Gamma (deg)	Alpha (deg)
1	Aircraft separation	0	288,490	25,000	711	0.7	270	5.0	8.0
2	Stage 1 ignition	10	288,490	25,244	674	0.7	240	-1.4	8.0
3	Maximum dynamic pressure	38	248,198	33,459	1,460	1.5	835	32.7	6.0
4	Aerosurface jettison	47	234,596	41,864	1,668	1.7	747	39.0	6.0
5	Stage 1 burnout and separation	89	168,166	90,407	3,298	3.3	283	21.1	11.8
6	Stage 2 ignition	92	158,077	93,288	3,297	3.3	247	20.1	12.1
7	Stage 2 burnout and separation	171	50,117	263,736	12,606	13.6	2.7	16.5	6.3
8	Fairing jettison	190	40,073	327,786	12,446	13.9	0.1	14.7	3.9
9	Stage 3 ignition	235	38,650	446,839	12,162	13.6	0.0	10.1	-1.4
10	Stage 3 burnout and separation	376	10,396	605,877	24,189	27.0	0.0	0.0	-10.5

Point Design 2



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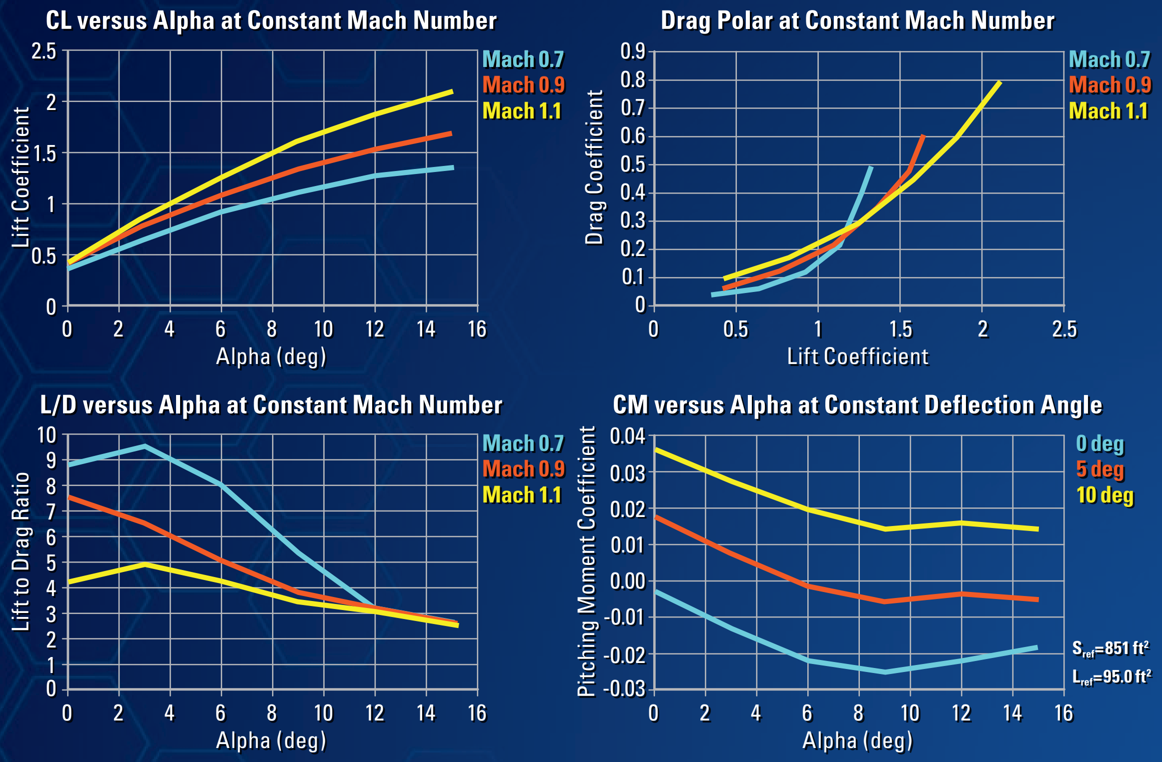

CL versus Alpha at Constant Mach Number

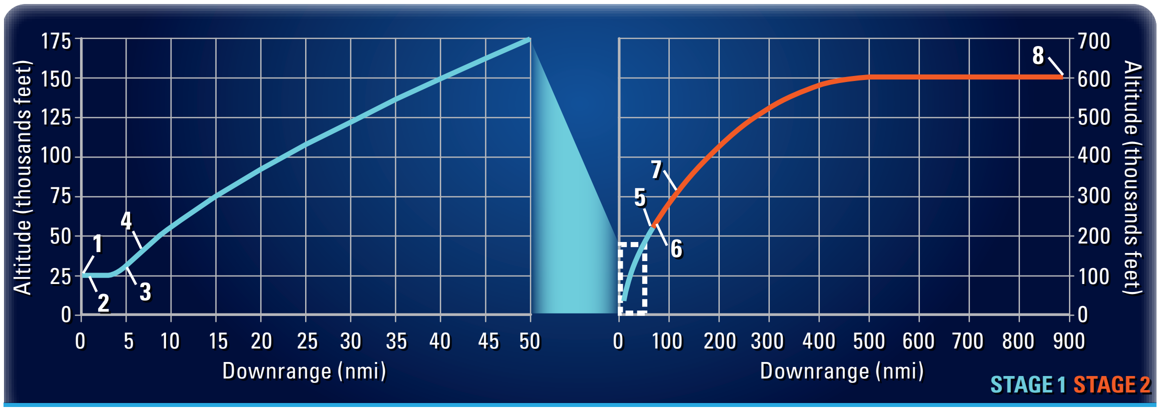
Drag Polar at Constant Mach Number

L/D versus Alpha at Constant Mach Number

CM versus Alpha at Constant Deflection Angle

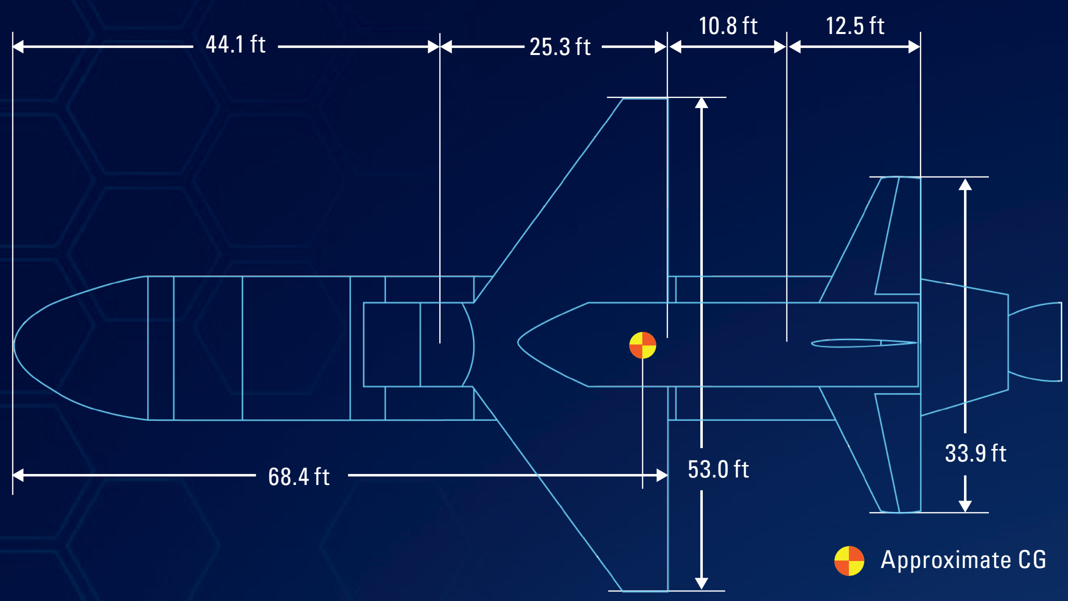
Aerodynamic results

Trajectory Analysis for the Point Design 2

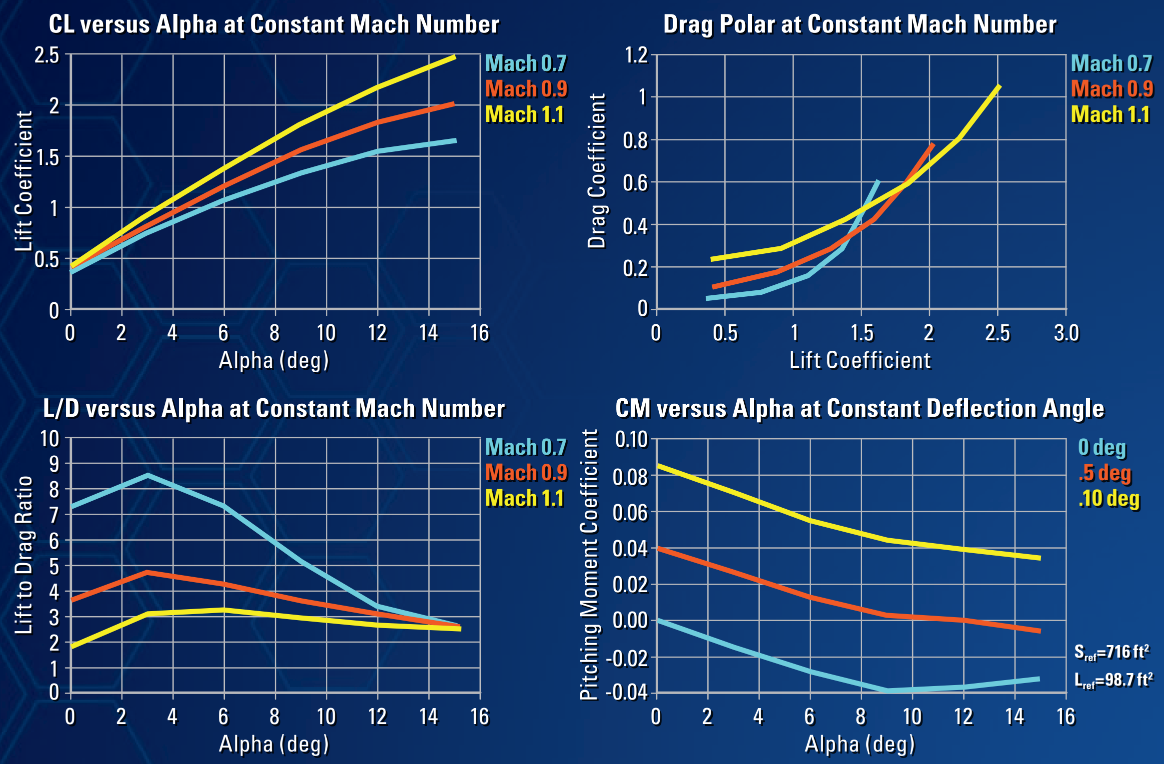


ID	Event	Time (s)	Weight (lb)	Altitude (ft)	Relative Velocity (ft/s)	Mach Number	Dynamic Pressure (psf)	Gamma (deg)	Alpha (deg)
1	Aircraft separation	0	305,000	25,000	711	0.7	270	5.0	8.0
2	Stage 1 ignition	10	305,000	25,243	673	0.7	239	-1.5	8.0
3	Maximum dynamic pressure	33	273,006	30,176	1,271	1.3	715	30.6	6.7
4	Aerosurface jettison	46	255,852	40,848	1,461	1.5	602	44.4	6.7
5	Stage 1 main engine cut off and separation	152	99,303	223,283	8,251	8.4	7.2	20.8	9.0
6	Stage 2 ignition	154	78,657	229,081	8,229	8.4	5.6	20.4	8.9
7	Fairing jettison	185	73,836	312,473	8,791	9.8	0.1	16.2	12.1
8	Stage 2 main engine cut off	513	22,969	606,934	24,189	27	0.0	0.0	2.5

Point Design 3

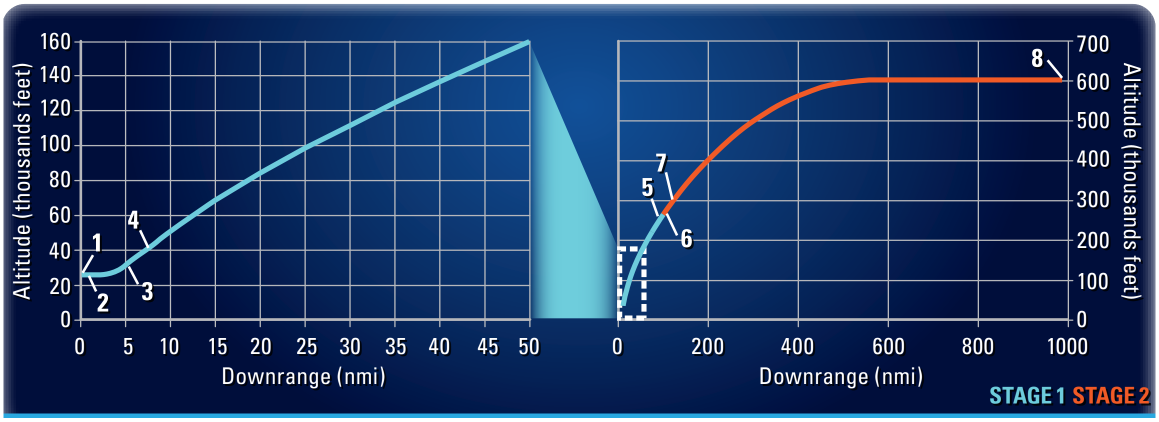


Schematic used in aerodynamics analysis



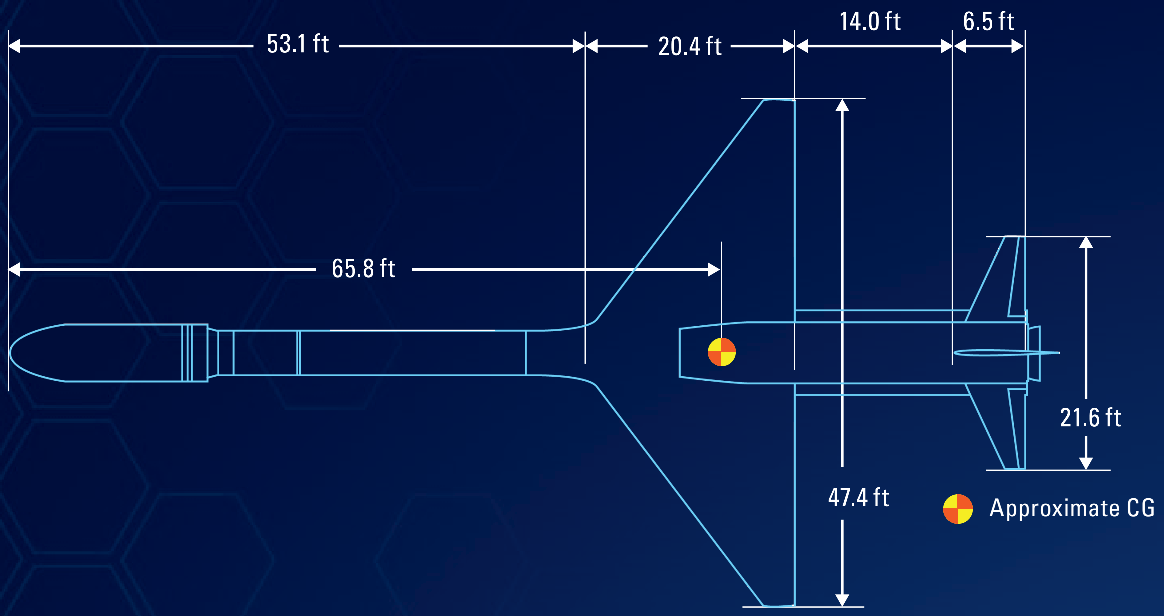
Aerodynamic results

Trajectory Analysis for the Point Design 3

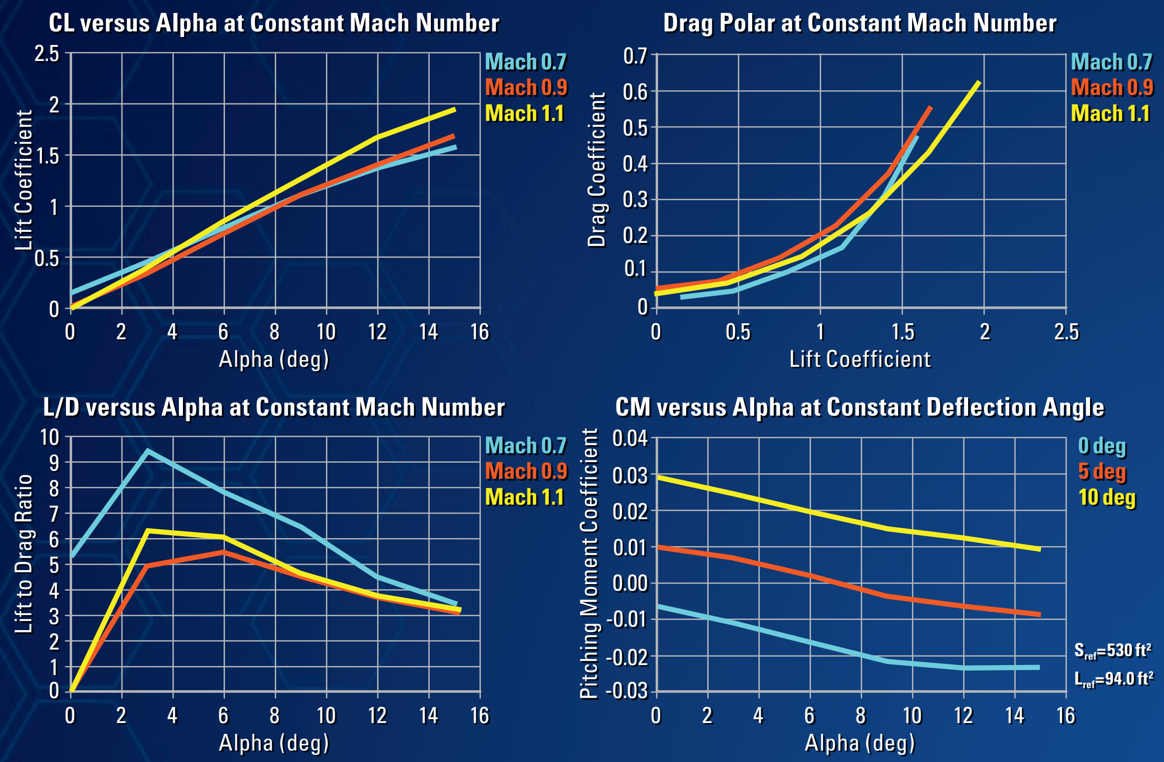


ID	Event	Time (s)	Weight (lb)	Altitude (ft)	Relative Velocity (ft/s)	Mach Number	Dynamic Pressure (psf)	Gamma (deg)	Alpha (deg)
1	Aircraft separation	0	305,000	25,000	711	0.7	270	5.0	8.0
2	Stage 1 ignition	10	305,000	25,238	670	0.7	237	-1.6	8.0
3	Maximum dynamic pressure	35	277,274	31,292	1,368	1.4	794	28.4	6.1
4	Aerosurface jettison	48	251,295	41,676	1,594	1.6	688	37.9	6.8
5	Stage 1 main engine cut off and separation	175	112,991	266,870	10,749	11.7	1.7	15.7	6.3
6	Stage 2 ignition	177	82,339	272,644	10,732	11.8	1.3	15.5	6.2
7	Fairing jettison	195	77,169	320,843	11,060	12.4	0.1	13.6	7.8
8	Stage 2 main engine cut off	516	29,437	607,161	24,118	27.0	0.0	0.0	2.5

Flight Test Demonstrator 1



Schematic used in aerodynamics analysis


CL versus Alpha at Constant Mach Number

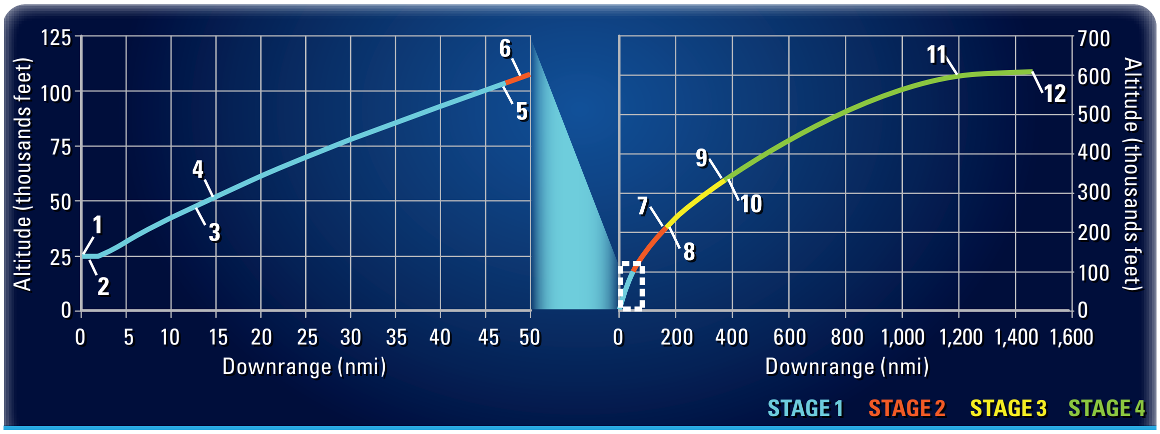
Drag Polar at Constant Mach Number

L/D versus Alpha at Constant Mach Number

CM versus Alpha at Constant Deflection Angle

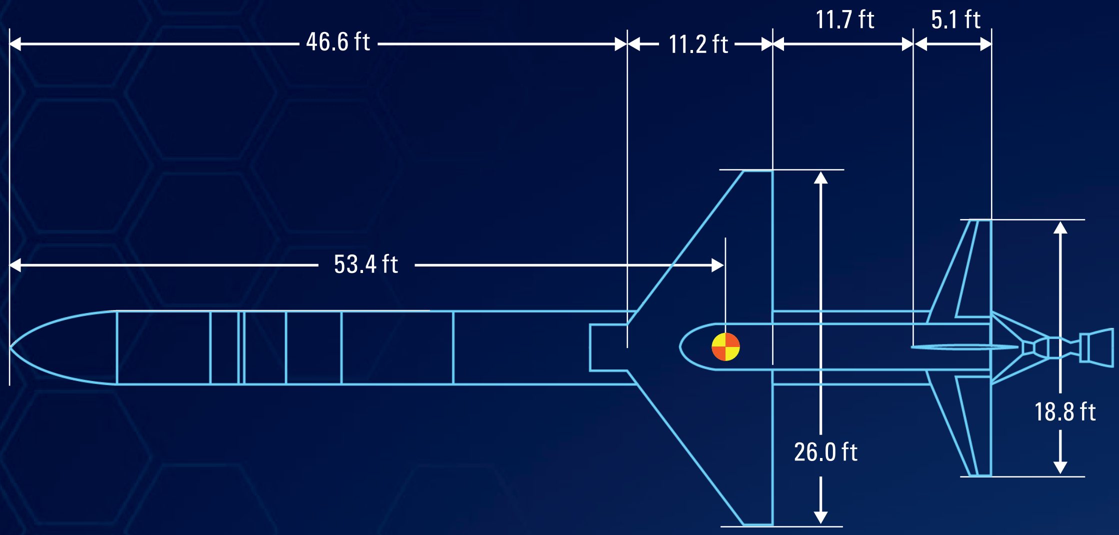
Aerodynamic results

Trajectory Analysis Data Summary for the Flight Test 1

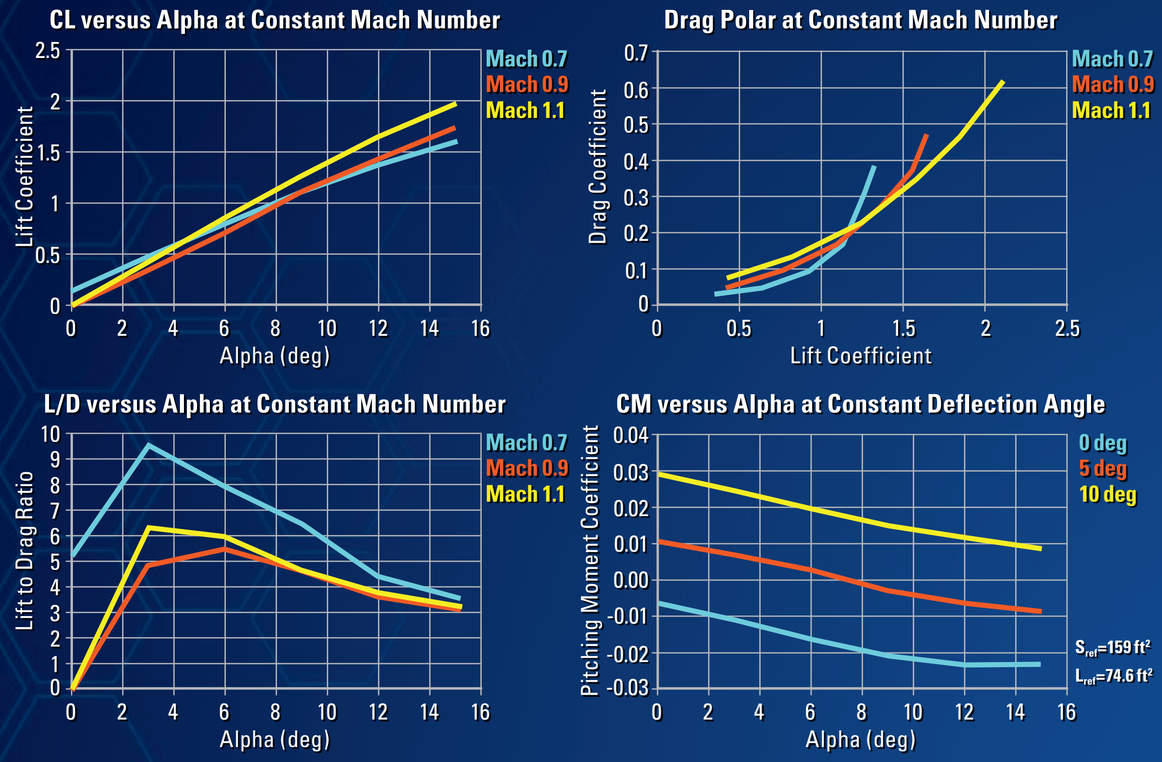


ID	Event	Time (s)	Weight (lb)	Altitude (ft)	Relative Velocity (ft/s)	Mach Number	Dynamic Pressure (psf)	Gamma (deg)	Alpha (deg)
1	Aircraft separation	0	179469	25,000	711	0.7	270	5.0	8.0
2	Stage 1 ignition	10	179468	25,322	657	0.6	228	-0.4	8.0
3	Aerosurface jettison	50	121005	47,690	3,314	3.4	2,232	19.0	2.2
4	Maximum dynamic pressure	53	109764	50,736	3,577	3.7	2,248	18.3	2.2
5	Stage 1 burnout and separation	90	64215	102,540	7,715	7.8	877	12.6	4.1
6	Stage 2 ignition	92	53666	105,871	7,687	7.7	745	12.3	4.3
7	Stage 2 burnout and separation	159	20561	215,168	16,106	16.1	38.0	6.7	1.8
8	Stage 3 ignition	161	17691	218,903	16,098	16.2	32.6	6.6	1.6
9	Stage 3 burnout and separation	229	9083	335,239	22,128	24.7	0.2	4.5	0.4
10	Fairing jettison	236	7950	347,474	22,111	24.7	0.1	4.4	0.2
11	Stage 4 ignition	462	7150	593,720	21,768	24.3	0.0	1.2	-7.5
12	Stage 4 burnout and separation	528	5460	607,444	24,187	27.0	0.0	0.0	-6.5

Flight Test Demonstrator 2

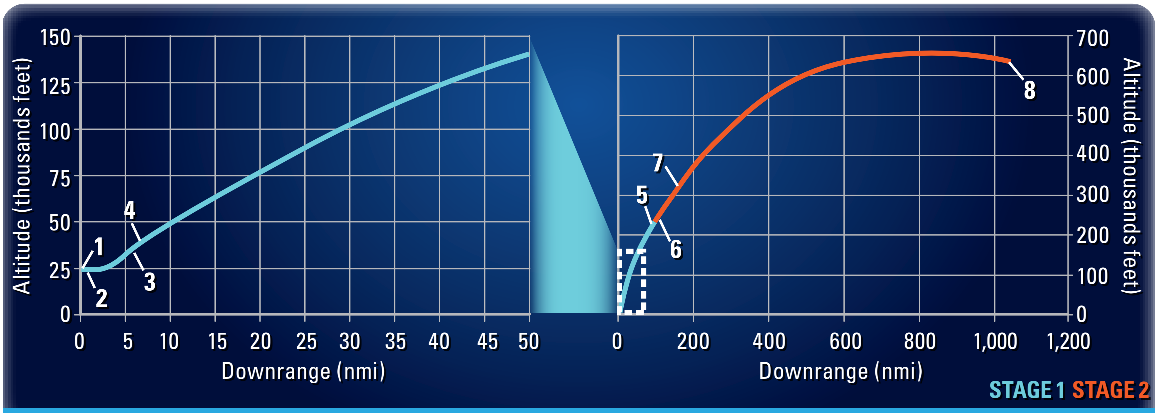


Schematic used in aerodynamics analysis

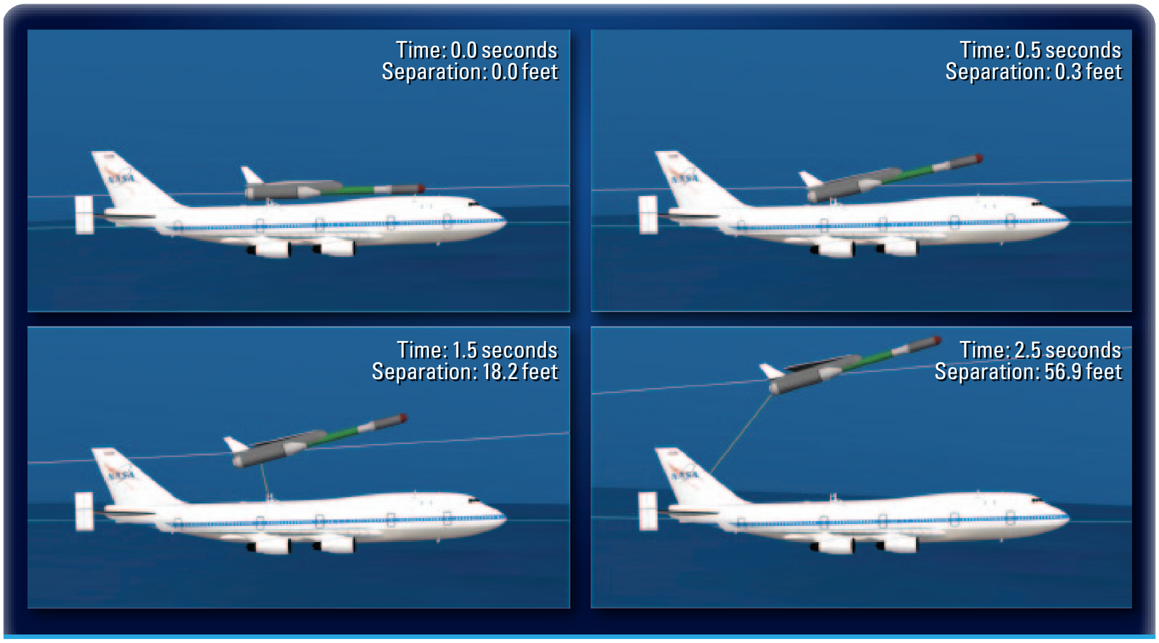


Aerodynamic results

Trajectory Analysis Data Summary for the Flight Test 2



ID	Event	Time (s)	Weight (lb)	Altitude (ft)	Velocity (ft/s)	Mach Number	Dynamic Pressure (psf)	Gamma (deg)	Alpha (deg)
1	Aircraft separation	0	81,914	25,000	711	0.7	270	5.0	8.0
2	Stage 1 ignition	10	81,914	25,250	665	0.7	233	-1.5	8.0
3	Aerosurface jettison	40	68,249	37,264	1,703	1.8	970	35.1	5.1
4	Maximum dynamic pressure	44	62,673	41,662	1,902	2.0	980	32.7	5.1
5	Stage 1 main engine cut off and separation	144	17,141	228,996	13,125	13.5	14.2	15.5	5.2
6	Stage 2 ignition	146	13,259	235,960	13,108	13.6	10.5	15.3	5.2
7	Fairing jettison	175	12,676	329,295	13,333	14.9	0.1	12.9	7.2
8	Stage 2 main engine cut off and separation	612	3,980	606,306	24,189	27.0	0.0	0.0	10.8

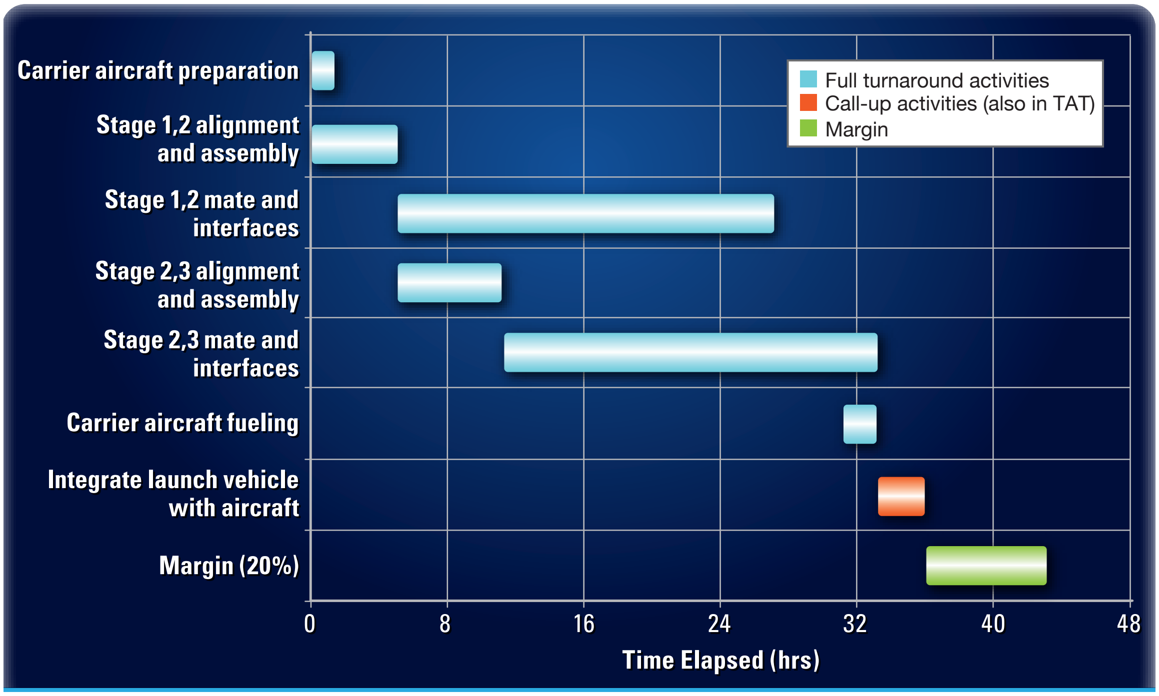


Separation simulation snapshots for a Flight Test Demonstrator

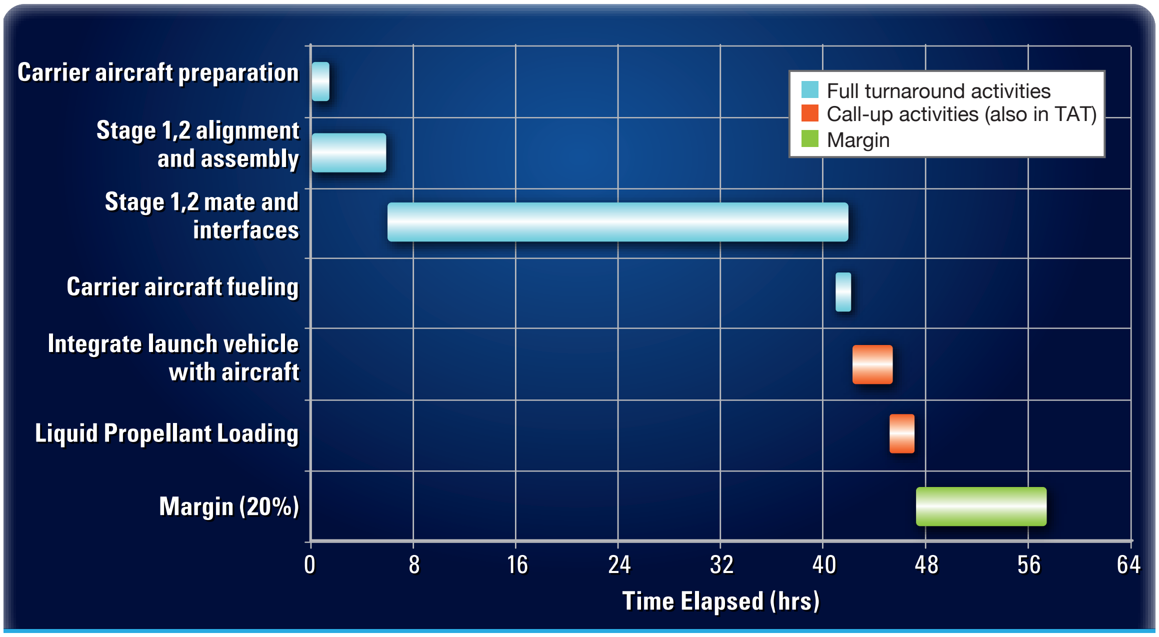
GROUND CREW REQUIREMENTS

Surge call-up time and minimum turn around time (TAT) were calculated for the three point designs. Minor variations in the necessary crew sizes were calculated, which can be attributed to factors such as smaller LOX tanks that take less time to fuel or an increased diameter which allows more technicians to work on integration. If staff sizes are assumed to be the same, turnaround times would generally equalize for these vehicles.

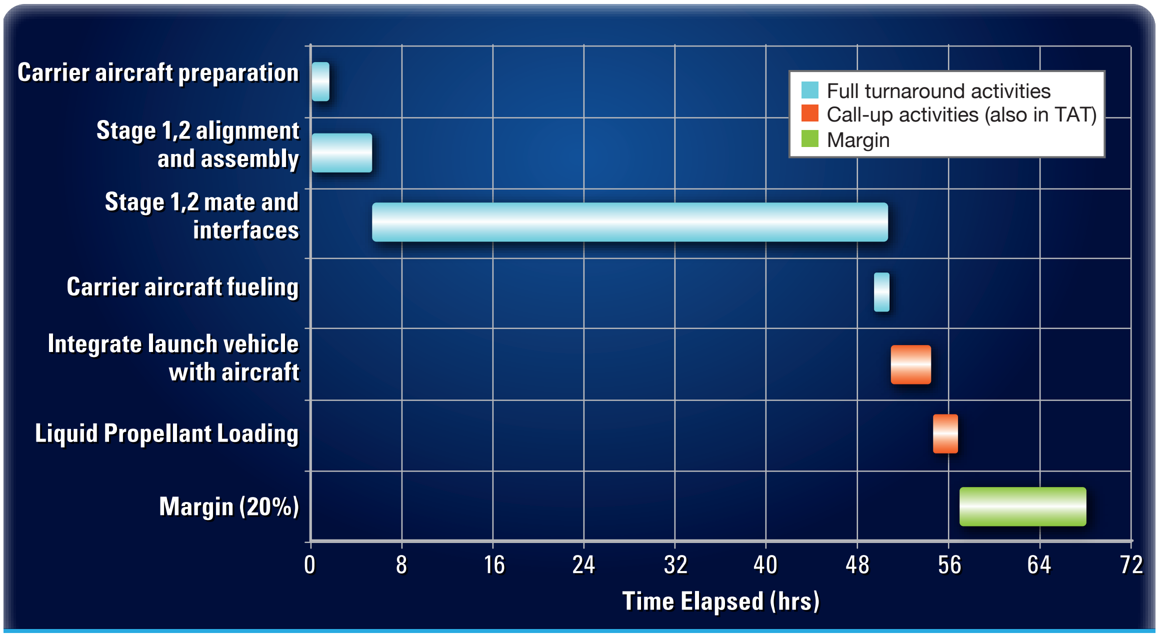
The following figures show the results of the operational analysis using current integration and checkout practices for launch vehicles.



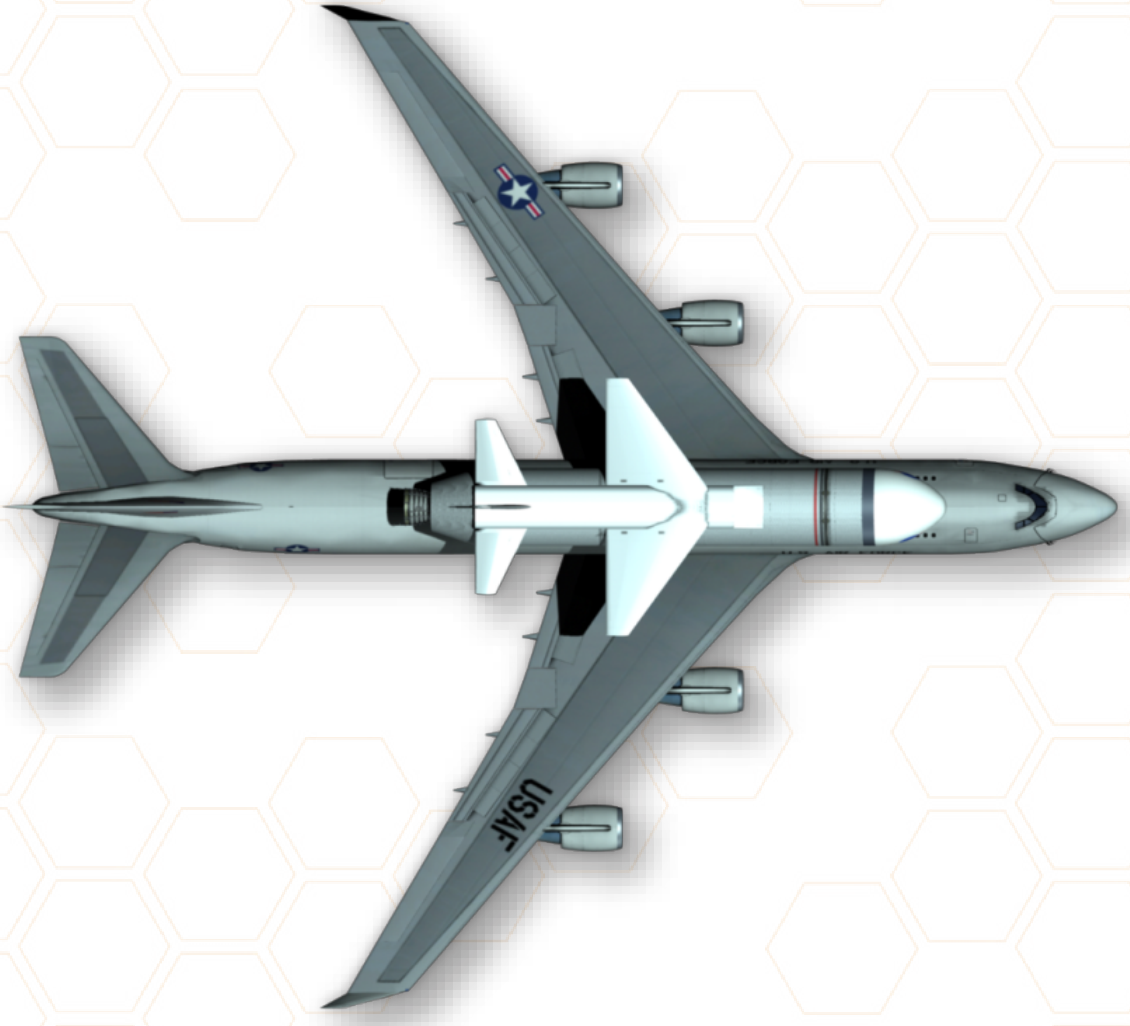
Results of the operational analysis for Point Design 1.



Results of the operational analysis for Point Design 2.



Results of the operational analysis for Point Design 3.


USAF

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- NASA's John F. Kennedy Space Center
- L-3 Communications Corporation
- Lockheed Martin Corporation
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- Sierra Nevada Corporation
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- Triton Systems, Inc
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Vincent Rausch, Chair, served as the Program Manager of the NASA Hyper-X/X-43A program from 1996 through 2004 at the NASA Langley Research Center. In 2004, this program successfully flight-demonstrated two scramjet-powered X-43A research vehicles, at Mach 7 and at Mach 10. In the early 1980s he served as the director for concepts and innovation in the Aeronautical Systems Division, Wright-Patterson AFB, Ohio, where he led the Transatmospheric Vehicle (TAV) system studies, transitioned the DARPA/USAF Teal Dawn project into the Advanced Cruise Missile, led classified studies and analyses, and served as the DARPA agent for Copper Canyon. In 1985, he set up the National Aero-Space Plane (NASP) Program Office and served as its director of operations, and in 1988, he transferred to the Pentagon to establish and lead the joint Air Force, Navy, and NASA NASP Interagency Office. In 1991, he was selected for the position of Assistant Director for Aeronautics (High-Performance Aircraft) at NASA Headquarters. After successful X-43 flights, he led the preliminary design of the Ares 1-X first stage prototype and design concept demonstrator in the Ares I program. He spent 25 years in the USAF, retiring as a colonel in 1991. He currently serves on the flight test review team of the Air Force X-51A.

William H. Heiser is professor emeritus of aeronautics at the United States Air Force Academy, and has served as a visiting professor at Cambridge University and at the University of California, Davis, and began his academic career as an assistant professor at the Massachusetts Institute of Technology. His industrial experience includes serving as head of turbine technology at Pratt and Whitney Aircraft, manager of advanced technology at the General Electric Aircraft Engine Group, and vice president of research at Aerojet General Corporation. He also served as chief scientist at the Air Force Aero Propulsion Laboratory and the Air Force Arnold Engineering Development Center. Dr Heiser is an Honorary Fellow of the American Institute of Aeronautics and Astronautics, a Fellow of the American Association for the Advancement of Science, and a Life Fellow of the American Society of Mechanical Engineers. He has a B.S. degree from Cooper Union, a M.S. degree from the California Institute of Technology, was a Fulbright Exchange Student at the Braunschweig Technische Hochschule, Germany, and holds a Ph.D. degree in mechanical engineering from the Massachusetts Institute of Technology. He currently chairs the technology review for the Air Force high mach number expendable turbine engine and serves on the flight test review team for the X-51A.

Uwe Hueter is a senior engineer in the Missile Defense and Space Operations at Science Applications International Corporation (SAIC) located in Huntsville, Alabama. Uwe has 48 years of experience in aerospace of which the first 42 years were at the NASA's Marshall Space Flight Center in Huntsville, AL. His experience includes 20 years in flight hardware development and 28 years in launch vehicle design supporting many NASA programs, such as Saturn, Skylab, Spacelab, and Space Station, as well as various advanced space transportation initiatives and the Constellation program. After retiring from NASA in 2004, Uwe joined SAIC in Huntsville where he has been supporting NASA in the earth-to-orbit transportation systems under the exploration initiative activities and supporting DoD for reusable access-to-space and high-speed air responsive vehicle technologies. Uwe has authored 35 technical papers and received many NASA awards including the Silver Snoopy Award, Exceptional Service Medal, and Exceptional Achievement Medal.

Jay P. Penn is a distinguished engineer with over 31 years of experience in the aerospace industry and currently heads the Reusable Launch Vehicle Office at the Aerospace Corporation. He began his career as a flight control engineer at the NASA Johnson Space Center and has supported numerous defense and commercial space launch customers around the world as an expert in space systems, technologies, planning, and program management. He has experience across the acquisition, development, test and operations phases of expendable and reusable space launch systems and architectures as well as satellite and constellation design and orbit transfer. Recent projects include the Joint NASA/DARPA Manned Geosynchronous Servicing study, the DARPA F6 Fractionated Satellite Program, and DARPA's FAST High Performance Solar Array development efforts; some of his many past projects include the Reusable Booster System, the Evolved Expendable Launch Vehicle, the Military Spaceplane, Space Maneuver Vehicle roadmap planning activities, SLI Gen 2 and 3 activities, DC-X /XA, and the X-30. Mr Penn participated in an independent assessment of the X-33 and X-37 programs, provided technical support to the National Reconnaissance Office in advanced spacelift planning, requirements definition, and studies, led Aerospace Corporation's support to the successful DARPA Orbital Express Advanced Technology Demonstration and their Space Solar Power system engineering activities. He has published extensively on related topics. Mr Penn received a B.S. degree in mechanical engineering from Rutgers University.

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GLOSSARY (Acronyms and Abbreviations)

AAR	air-augmented rocket
ABLV	air breathing launch vehicle
ACES	air collection and enrichment system
AHP	analytical hierarchy process
AIAA	American Institute of Aeronautics and Astronautics
AMSC	Advanced Manned Spaceflight Capability
ATK	Alliant Techsystems
ATS	access to space
AVATAR	aerobic vehicle for hypersonic aerospace transportation
CAV	common aero vehicle
CFD	computational fluid dynamics
CONOP	concept of operation
CONUS	continental United States
DARPA	Defense Advanced Research Projects Agency
DCTJ	deeply cooled turbojet
DDT&E	design, development, test, and evaluation
DMRSJ	dual-mode ramjet/scramjet
DRM	design reference mission
EDL	entry, descent, and landing
FASST	flexible aerospace system solution for transformation
FOM	figure of merit
FT	flight test system concept
FY	fiscal year
GEM	ground effect machine
GEO	geosynchronous orbit
HEDM	high-energy density material (propellant)
HLS	Horizontal Launch Study
HOTOL	horizontal takeoff and landing
HRST	highly reusable space transportation
HSCT	High-Speed Civil Transport
HSDTV	hypersonic technology demonstrator vehicle
HTHL	horizontal take-off, horizontal landing
HTPB	hydroxyl-terminated polybutadiene
ICBM	intercontinental ballistic missile
ICM	integrated concept model
IHPRPT	integrated high payoff rocket propulsion technology
IOC	initial operational capability
IRAD	industrial research and development
ISR	intelligence, surveillance, and reconnaissance
JSS	Joint System Study
LACE	liquid air cycle engine

lb	pound
LCC	lifecycle cost
LE	leading edge
LEO	low Earth orbit
LH2	liquid hydrogen
LOM	loss of mission
LOX	liquid oxygen
LSOS	low-speed operating system
MAKS	multipurpose aerospace system
MAUT	multi-attribute utility theory
MDO	multidisciplinary optimization
MHD	magnetohydrodynamics
MIPCC	Mass Injection Pre-Compressor Cooling
MIS	modular insertion stage
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
NGLT	Next Generation Launch Technology program
OSC	Orbital Sciences Corporation
PD	point design system concept
PDE	pulse detonation engine
PDRE	pulse detonation rocket engine
POST	program to optimize simulated trajectories
psf	pounds per square foot
PWR	Pratt Whitney Rocketdyne
q	dynamic pressure
QFD	Quality Function Deployment
RASCAL	rapid access small cargo affordable launch
RASV	reusable aerodynamic space vehicle
RBCC	rocket based combined cycle
ROSETTA	reduced order simulation for evaluating technologies and transportation architectures
RP	rocket propellant
RTA	revolutionary turbine accelerator
SCA	shuttle carrier aircraft
SERJ	supercharged ejector ramjet
SMV	space maneuver vehicle
SSTO	single stage to orbit
TAV	Trans-Atmospheric Vehicle
TBCC	turbine based combined cycle
TM	technical memorandum
TRL	technology readiness level
TSTO	two stage to orbit
V	velocity
VTO	vertical takeoff
VTOHL	vertical takeoff horizontal landing
X	experimental