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GRYPHON: A FEASIBLE HORIZONTAL TAKEOFF NEXT GENERATION ARCHITECTURE CONCEPT

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Abstract

NASA's Next Generation Launch Technology (NGLT) program recently funded studies of the Gryphon launch architecture. Gryphon combines existing technologies with moderate propulsion advancements and a design for operations approach into a unique, aircraft-like architecture. A joint NASA/industry team was assembled by NGLT's Systems Analysis Project to assess the Gryphon concept and produce a conceptual design to specific performance, reliability, safety, and life cycle cost goals while meeting NASA and DoD requirements. The effort demonstrated the fundamental feasibility of the architecture. This paper describes the study, outlines the architecture's features and benefits, and highlights the critical issues identified for further study.

Acronyms

ACES	Air Collection and Enrichment System
CFD	Computational Fluid Dynamics
DRM	Design Reference Mission
FOM	Figure of Merit
GTOW	Gross Takeoff Weight
HTHL	Horizontal Takeoff Horizontal Landing
IVHM	Integrated Vehicle Health Management
L/D	Lift-to-Drag Ratio
LEO	Low Earth Orbit
LOM	Loss of Mission
LOP	Loss of Payload
LOV	Loss of Vehicle
LOX	Liquid Oxygen
NGC	Northrop Grumman Corporation
NGLT	Next Generation Launch Technology
POD	Point of Departure
R&D	Research & Development
RLV	Reusable Launch Vehicle
SAP	Systems Analysis Project
SBIR	Small Business Innovation Research
SLI	Space Launch Initiative
TAT	Turn Around Time
TPS	Thermal Protection System
TSTO	Two Stage To Orbit

Introduction to Gryphon

Horizontal Takeoff, Horizontal Landing (HTHL) architectures typically either use highly advanced technologies (such as hypersonic propulsion, advanced materials, etc.) or are incapable of delivering substantial payloads to orbit. The Gryphon Two-Stage-to-Orbit (TSTO) HTHL architecture, however, meets NASA and DoD payload requirements without significant technology advancements. This is made possible by an in-flight propellant collection system, the Alchemist™ Air Collection and Enrichment System (ACES), developed by Andrews Space, Inc. Alchemist ACES generates liquid oxygen (LOX) through separation of atmospheric air, which allows Gryphon to take off without LOX on board, minimizing vehicle takeoff weight.[1,2] Studies have shown that ACES, previously proposed for hypersonic combined cycle reusable launch vehicles (RLVs), is a higher payoff, lower-risk technology if LOX generation is performed while the vehicle cruises subsonically.[3] This enables RLVs that operate with existing airbreathing and rocket propulsion systems, creating a paradigm shift in space operations.

Mission Operations

Figure 1 shows a nominal Gryphon trajectory. Both vehicle stages use liquid hydrogen and oxygen engines for rocket-powered flight. The second stage,

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which consists of either an orbiter or an upper stage rocket, rides "piggyback" on the booster. Fueled with hydrogen and jet fuel, the vehicle takes off (point 1 in the figure) and climbs using jet engines. Military-derived turbofans are used due to the requirements for high thrust at altitude and supersonic performance. At altitude, the vehicle can either cruise for thousands of miles or begin generating LOX. Alchemist ACES uses the refrigerative capacity of liquid hydrogen to generate LOX (stored in the tanks) and returns gasified hydrogen at high pressure to the turbofan engines, where it is burned to generate thrust (point 2). The LOX collection duration (which depends on the rate of collection and quantity required for the mission) allows the vehicle to cruise to the desired launch point and address all azimuths from a single operating base. Once LOX tanking is completed, the vehicle assumes the desired heading, rocket engines fire in a predetermined sequence to minimize risk, and the combined stages begin a rapid climb (point 3). The turbofan engines are shut down below Mach 2, their inlets are covered, and they are thermally conditioned for restart. At Mach 2, the vehicle is above 40,000 ft and the dynamic pressure is below 40 psf. At approximately Mach 5, the first stage throttles back to match the acceleration of the second stage, and the stages separate (point 4). The first stage then shuts down its rocket engines and, using its attitude control system, rotates to high angle of attack for reentry. The first stage reenters, unpowered at first, then restarts the turbofan engines (point 5) for a powered landing (point 6). The second stage proceeds to its desired orbit and begins payload operations (point 7). Gryphon can operate out of any air field or base to which hydrogen can be transported and can fly worldwide burning conventional jet fuels.

Background

The Gryphon architecture concept was conceived at Andrews Space and initially studied under internal R&D funds. Then, a Phase I SBIR and a Space Launch Initiative (SLI) contract focused on the Alchemist technology to allow further investigation of the concept. When Northrop Grumman Corporation (NGC) included the concept in its architecture studies during SLI, it received additional technical scrutiny. After NASA's 2nd and 3rd Generation RLV programs were merged, Andrews briefed the new NGLT program on Alchemist and Gryphon. Upon the creation of the NGLT Systems Analysis Project (SAP), an integrated, multi-center, cooperative NASA/industry team was set up to study the Gryphon architecture as one of several promising concepts. Early successful progress allowed Gryphon to garner additional funding for continued study.

Study Approach

Because early conceptual design and analyses had already been completed by Andrews, the NGLT SAP study was focused on (1) identifying and assessing fundamental issues of feasibility and (2) generating a credible architecture design. Some of the key feasibility questions were as follows:

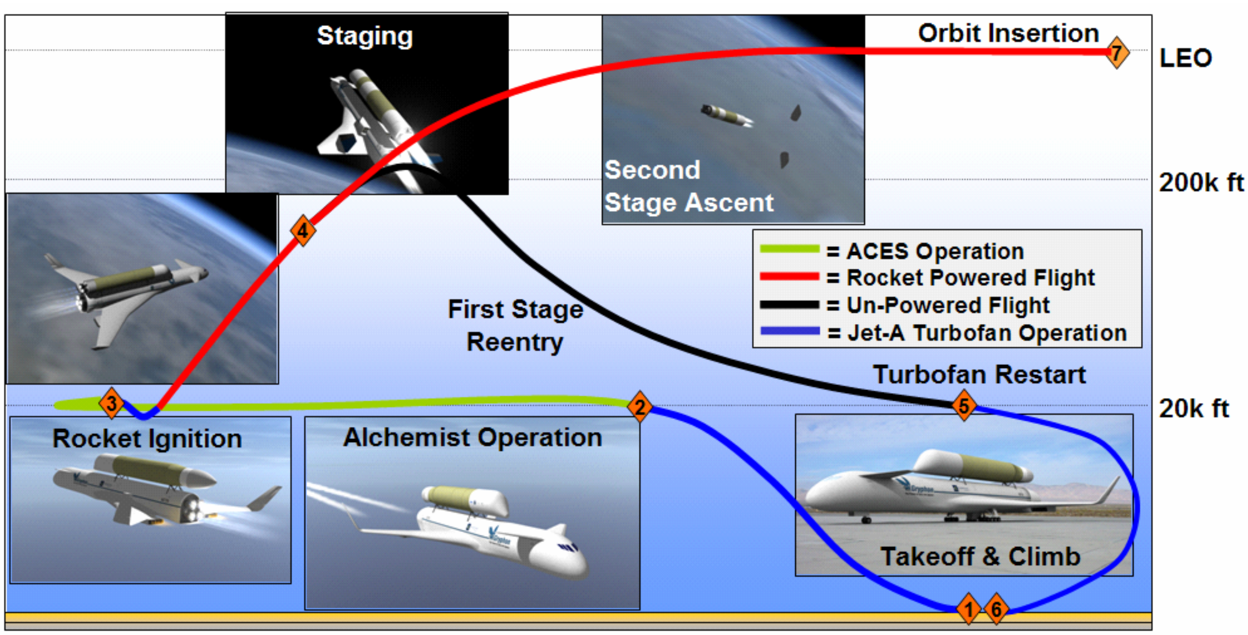

Figure 1. Nominal Gryphon Mission Profile

- **Performance**: *What is the payload capacity with Gross Take Off Weight (GTOW) < 1.4 Mlb?* The payload capability of HTHL vehicles has traditionally been limited by runway load capacity (allowable takeoff and/or abort landing weight). Gryphon circumvents this threshold by taking off without LOX. The latest large commercial airliner (Airbus 380) tops out near 1.4 Mlb, so this was used as a design constraint.
- **Weights and Sizing**: *Can weights and sizing analyses be independently confirmed?* Only Andrews and NGC had estimated Gryphon weights and geometry prior to the NGLT study. NASA and other industry partners provided tools and experts for new analyses.
- **Aerodynamics**: *Can high subsonic lift-to-drag (L/D) be achieved during air collection?* Alchemist LOX collection takes a significant portion of total Gryphon flight time. Low L/D over this period would require additional jet thrust, increasing fuel and overall vehicle weight.
- **Alchemist**: *Evaluate its feasibility, maturity, and risk*. Although considerable work was completed on ACES-related technologies since the 1950s,[2] questions of integration risk remained.
- **Thermal Protection**: *Can it be verified that the booster needs no thermal protection system (TPS)?* Initial studies by Andrews suggested that the booster stage structure did not reach temperatures beyond structural limits. Avoiding use of booster TPS could provide substantial operations and cost benefits to the architecture.
- **Operations**: *Can the vehicle be designed to use existing infrastructure?* Benefits of using existing runways and operations sites required further study.
- **Safety**: *Can significant safety and reliability improvements be realized?* Claims of substantial reductions in loss of vehicle, among other Figures of Merit (FOMs), had been made by both Andrews and NGC. Detailed evaluations by NASA experts were desired, including abort scenarios throughout the mission envelope, component-level studies, etc.
- **Cost**: *What is the estimated life cycle cost?* With the Space Shuttle as the baseline, NASA experts were to use NASA tools to verify cost predictions.

Study Participants

Numerous disciplines were required to generate and analyze Gryphon conceptual designs and evaluate trade alternatives. These included vehicle system design (structures, propulsion, various subsystems), performance and sizing (including trajectory analysis), aerodynamic analysis, thermal analysis, operations analysis, reliability and safety assessment, life cycle cost estimation, technology assessment, and system integration. Analysts with the skills needed for this effort were located across the country at NASA centers (Ames Research Center, Glenn Research Center, Johnson Space Center, Langley Research Center, Marshall Space Flight Center), various industry sites (Andrews Space, Northrop Grumman, and Boeing), and consultants (SAIC, Sverdrup).

Study Process

The architecture study process used, as shown in Figure 2, had several iteration loops:

- Vehicle synthesis loop – Focused on vehicle “closure” (demonstrating that the vehicle can meet customer performance requirements)
- Operations concept development loop – Development of an operations and maintenance concept
- Life cycle assessment loop – Assessment of the architecture’s safety, reliability, cost, and technology maturity
- Outer loop – Design improvements / iterations to meet program goals

The study process benefited from the broad involvement of industry and the various NASA centers; however, the rapid pace of the activity made communications difficult. A weekly teleconference was conducted to coordinate the progress of the participants and maintain the focus of the development. Workshops were occasionally held to stimulate design cooperation and ease collaboration. Periodic reviews were held to document study results for program management and update the design requirements. The effort to pool the expertise in this manner was highly beneficial to the team and lead to a strong, well integrated product.

The initial point of departure (POD) vehicle and operations concept was based on customer requirements and provided by Andrews. This POD was analyzed by the team, which performed trade studies and executed the study process resulting in an optimized concept. Over the span of a year, in which milestones were driven by several formal program technical reviews, the team completed multiple iterations of the study process. The team arrived at an architecture design it deemed feasible and identified specific areas for further work.

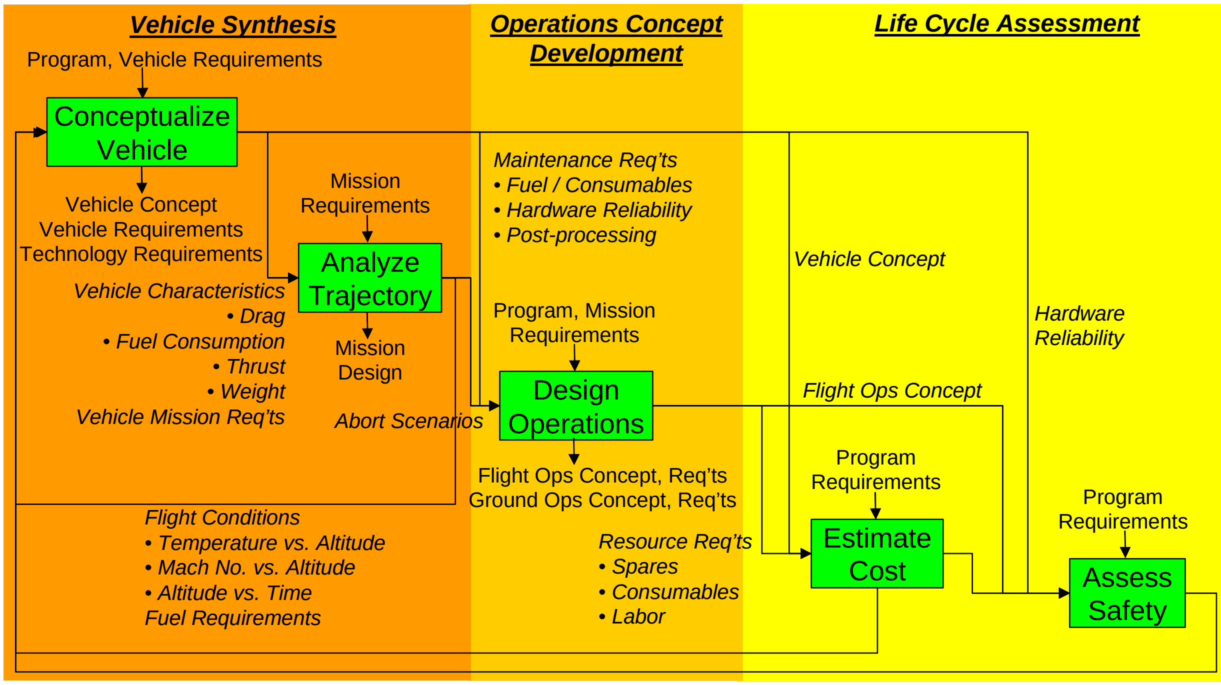

Figure 2. Top-level NGLT Gryphon Study Process

Study Results

Design Approach

The broad goals of the NGLT program required the development of launch vehicle technologies that reduce life cycle costs and improve safety/reliability substantially when compared to Shuttle. NGLT SAP was tasked with evaluating architecture concepts upon which potential RLV technologies could be assessed. Although the requirements changed throughout the effort, the main performance objective was to size the architecture to deliver 40 mT (metric tons) to LEO. From the beginning, the team employed a “design for operations” philosophy, which dramatically influenced the architecture design. This philosophy was consistent with previous efforts at Andrews and allowed the team to take full advantage of the concept’s discriminating features. Existing technologies, manufacturing processes, and vehicle systems—such as airframe materials, propellant tanks, jet engines, and rocket engines—were incorporated wherever possible. Expensive and time-consuming Shuttle maintenance procedures such as thermal protection system inspection and replacement were eliminated by tailoring the first stage’s flight trajectory. Other Shuttle operations were dramatically improved by inherent vehicle differences or proper design such as common fluids, standard connections, etc. The fuselage and propellant tanks were designed for tank replacement.

Horizontal takeoff and landing inherently enables the vehicle to operate at facilities with 12,000 ft runways within the continental U.S. This also allows operation in inclement weather and enables increased flight rates without additional infrastructure such as launch pads.

Safety of the vehicle was increased by maximizing abort opportunities throughout the trajectory, resulting in a design capable of aborting throughout the entire operational envelope assuming that multiple critical faults could be detected and not become catastrophic.

The vehicle concept of operations evolved through the design study, resulting in the overall approach shown in Figure 3. Major operations shown include: (1) processing of the major flight elements (stages) in an element processing facility, (2) mating flight elements and payload in a payload processing and integration facility, (3) fueling and vehicle checkout prior to takeoff at a propellant handling facility, (4) takeoff and eventual landing of the vehicle utilizing a runway. A logistics facility is used to coordinate and stage all hardware utilized (5), and a base support, engineering support and administration facility provides for mission planning, launch staff, maintenance staff, etc. (6).

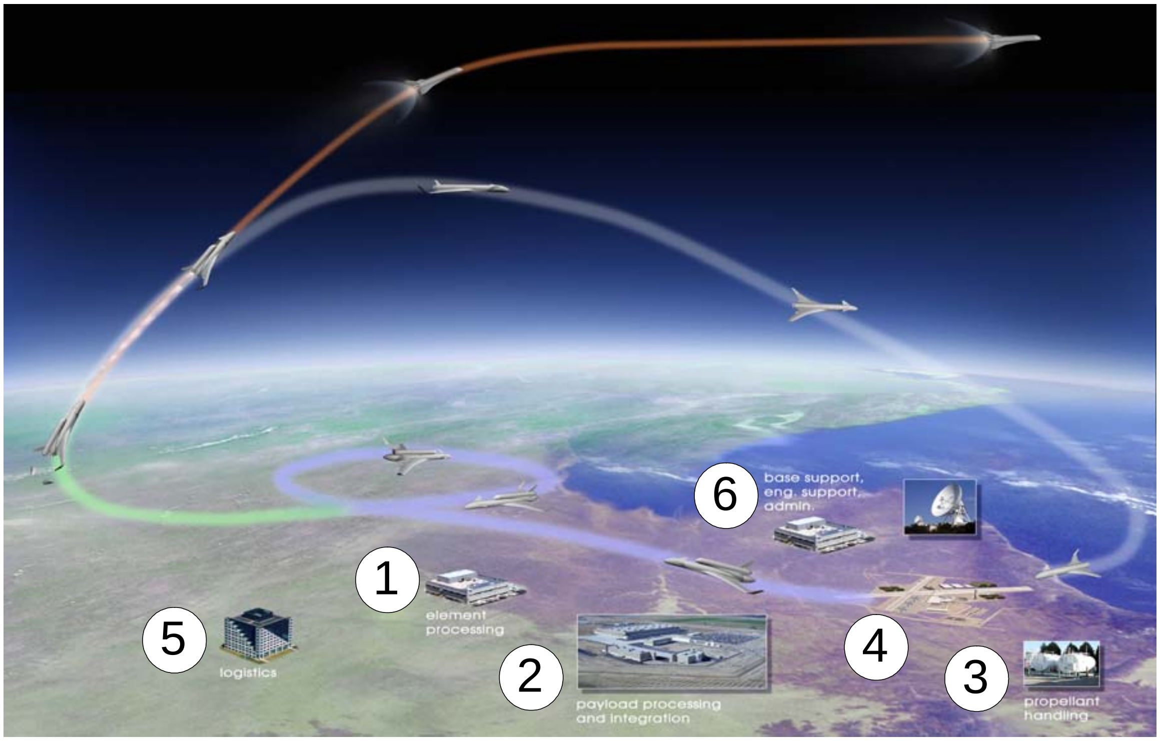

Figure 3. Basic Gryphon Architecture Concept of Operations

Architecture Benefits and Advantages

A key accomplishment of the effort was analytical verification of architecture benefits and development of validation plans for each feature. Table 1 characterizes the unique advantages of the Gryphon architecture identified by the team and outlines the required actions necessary to demonstrate and prove each attribute.

Gryphon enables launch vehicle cost savings by reducing both initial (non-recurring) and recurring costs. A key benefit of Alchemist ACES is that it minimizes GTOW, resulting in a significantly smaller and lighter first stage system. This reduces vehicle development and manufacturing costs by simplifying the design and shrinking the size of key elements such as propulsion system (rocket and jet engines), the landing gear, the rocket propellant tanks, and the wing. Initial cost is further reduced by minimizing the vehicle support and infrastructure requirements. HTHL operations allow an RLV to address all markets from a single operating base located at an existing airport. This significantly reduces the dedicated infrastructure requirements and operations cost over conventional vertical takeoff solutions.

Recurring costs are reduced by decreasing the vehicle's turn around time (TAT). Reduced TAT means fewer vehicles are required to achieve the same flight rate and that less money is spent to ready the vehicle for its next launch. The bulk of the TAT reduction is achieved by eliminating or substantially reducing the two largest drivers in the Space Shuttle's between-flight maintenance: thermal protection system (TPS) inspection/repair/ waterproofing and rocket engine maintenance. The optimal staging Mach number for a TSTO vehicle with ACES is low enough (less than Mach 6) that the first stage does not require TPS. Secondly, when compared to a vertical rocket with similar payload capability, the Gryphon requires less total thrust. This results in fewer rocket engines running at lower throttle settings and reduces rocket engine maintenance. Remaining TAT reductions are made possible by aircraft-like horizontal processing, the ability to self-ferry between launch sites, and an integrated vehicle health management system, which reduces the need to disassemble the vehicle for inspection.

Gryphon also reduces development and operational risk. Technical development risk is reduced because Gryphon does not require the use of any low technology readiness level (TRL) systems, such as hypersonic propulsion or hot structures. Alchemist ACES is the Gryphon system with the lowest TRL, but the key features have already been experimentally demonstrated. Programmatic risk is reduced because the Gryphon can use a traditional airplane test program, where dozens of subsonic flights can be performed to demonstrate system operations and reliability before rocket powered flight occurs. In comparison, the Shuttle had only a few taxi and air drop tests before its first flight to orbit.

By merging the reduced thrust needs (which allows smaller, higher reliability rockets) and improved abort options, properly configured HTHL architectures can be significantly safer than VTHL options. Robust abort modes eliminate rocket dead-zones during rocket ascent (regions where the loss of rocket propulsion leads to loss of the vehicle). During ascent, the jet engines remain on until all the rocket engines have ignited, to ensure ignition and proper operation. After jet engine shutdown, any non-catastrophic rocket engine failure is recoverable by re-starting the jet engines and flying back for a powered landing.

Finally, the Gryphon architecture is flexible. During air collection, Gryphon can cruise to a desired launch point. This allows it to address all launch azimuths from a single facility, widen launch windows, and avoid bad weather. The modular upper stage approach allows the vehicle to address a number of missions while maintaining a common first stage, eliminating the need for the everything-for-everyone design compromises that hampered the Shuttle program.

Table 1. Unique Advantages of Gryphon with Alchemist ACES

	Unique Benefits of Gryphon	Enabling Feature of Architecture	Required to Demonstrate Capability: Design / Analysis	Required to Demonstrate Capability: Testing
Low Cost	Low GTOW	Alchemist ACES	ACES design/modeling Control System Development ACES/Vehicle integrated performance analysis	ACES ground test Integrated flight test
		Efficient Subsonic Cruise	Aerodynamic Validation	Wind tunnel testing
	Quick Turn-around Time and Reduced Fleet Size	No TPS or hot structures	Aerothermal Validation Abort scenario modeling	Wind tunnel testing Structural materials testing
		Horizontal Processing	HTHL Design	--
		Self-ferry	Cruises on turbofans	Initial flight tests
		Reduced Vehicle and Engine Maintenance	Integrated Vehicle Health Management Systems Rocket engines designed for maintainability/operability	IVHM testing Ground test of rocket engines to prove maintainability
	Minimal Infrastructure	No launch pad	HTHL Design	--
		Self-ferry to launch site	Cruises on turbofans	Initial flight tests
		No LOX production facility	--	--
Low Risk	Progressive Flight Test	Test cruise w/o ACES Test ACES w/o rockets Test rockets w/o orbit	Cruises on turbofans Rocket failure aborts	Conduct flight tests to validate systems incrementally
	Aircraft Safety and Reliability	Turbofan Operations	--	--
		Enhanced Abort Options	Model abort modes and vehicle recovery after rocket failure	Flight test aborts
		Increased rocket engine safety	Run at lower throttle or use more reliable rocket engines	Demonstrate higher rocket engine reliability
	Few Low TRL Systems	No hot structures	Aerothermal Validation	--
		No TBCC / RBCC engines	Existing propulsion	--
		No low TRL systems	Some ACES testing	ACES ground test
High Flexibility	All Weather Operations	Rocket Ignition at Altitude Cruise away from weather	--	Qualify rocket engines for air-start
	Supports Variety of Missions	Common Booster with interchangeable upper stages	Assess capabilities of upper stage options	--
	Launch Time Flexibility All Azimuth Capability	Sufficient cruise range to reach desired ignition point	Detailed overflight and range safety analysis	--
			Design vehicle with sufficient flyback range	--

Concept Design

The Gryphon architecture consists of a common booster, or first stage, capable of supporting a variety of upper stage options, which are specifically designed to address civil, commercial, and defense missions. The booster (see Figure 4) is fully reusable and houses the Alchemist ACES, jet engines, and rocket propulsion systems. Liquid hydrogen is stored in separate tanks (for center of gravity control) and is used as ACES coolant and rocket fuel. Oxidizer collected during cruise is stored in LOX tanks located on the booster near the center of gravity and on the upper stage. Jet fuel is stored on the booster in wet wing tanks; the jet engines are located on the wing trailing edge. Alchemist ACES is located in the booster nose to increase vehicle stability, decrease center of gravity travel during flight, and reduce complexity, by physically separating ACES from the other propulsion systems.

The Gryphon outer mold line and control surfaces are optimized for efficient subsonic flight, which is crucial to vehicle performance. Actuating canards provide pitch stability and control while winglets provide lateral stability. The upper stage is mounted to the booster via hard points located on the dorsal side of the fuselage. Dorsally located propellant crossfeeds allow for of the filling second stage LOX tank during ACES operations and the topping off the second stage tank during the parallel burn.

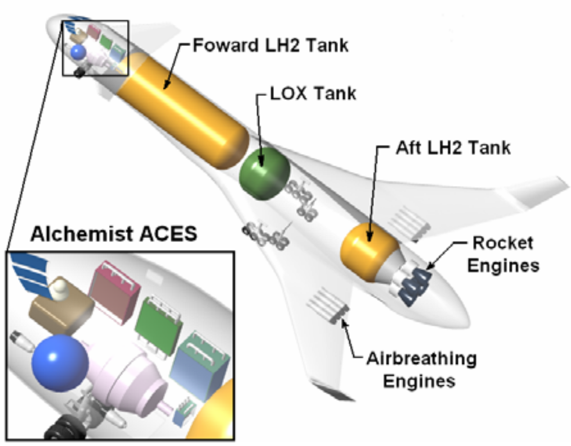

Figure 4. Gryphon Architecture Subsystem Layout

Architecture Feasibility

Prior to the NGLT program, Andrews conducted vehicle level analysis of the Gryphon architecture in support of its study of Alchemist ACES. NGLT built on this previous effort to answer the configuration's fundamental design and feasibility questions. The study ultimately determined that the Gryphon is a credible and viable RLV concept.

- **Performance**: *What is the payload capacity with GTOW < 1.4 Mlb?* The Gryphon launch vehicle is capable of delivering a 40 mT payload to LEO at a GTOW of < 1.3 Mlb. Variable upper stages allow payload tailoring. The GTOW is < 1.0 Mlb to deliver 56,000 lbs to the ISS and <1.4 Mlb to deliver 100 klb to LEO. The architecture is capable of performing all NGLT-specified DRMs (NASA and DoD, including heavy lift). The booster is the size of a large commercial aircraft (such as the A380) and has a balanced field length of 10,000 ft enabling operations from almost all major airport runways.
- **Weights and Sizing**: *Can weights and sizing analyses be independently confirmed?* NASA-GRC independently confirmed Gryphon weights and sizing using the NASA SIZER tool. The final booster was sized to work with multiple upper stages and included a 25% dry weight margin. Weight growth during the NGLT analysis effort was minimal and was primarily the result of conscious choices to trade increased structural weights for improvements in vehicle reliability, safety, operability, and cost.
- **Aerodynamics**: *Can high subsonic lift-to-drag (L/D) be achieved during air collection?* Andrews, NASA-Ames, and Analytical Methods, Inc. optimized the vehicle for aerodynamic performance using CFD and analytically verified subsonic L/Ds over 10. Control surfaces were redesigned to provide static stability over the entire flight regime.
- **Alchemist**: *Evaluate its feasibility, maturity, and risk.* Andrews built on its previous work and improved its steady-state thermodynamic models of Alchemist ACES. Proposals were submitted to perform ACES risk reduction in two critical areas: dual fuel turbofan operation, and advanced (transient) ACES modeling. A complete ACES risk reduction program was developed that would increase the system TRL to level 6.
- **Thermal Protection**: *Can it be verified that the booster needs no thermal protection system (TPS)?* NASA-Ames validated that the booster does not require a thermal protection system. Re-entry trajectories and staging mach number were tailored such that the maximum temperature during flight stayed below structural temperature limits. Heat load during reentry was heat sinked into the vehicle's thermal mass. The material stack-up for a Titanium heat shield was designed to protect the vehicle nose.

- **Operations**: *Can the vehicle be designed to use existing infrastructure?* Infrastructure requirements were minimized by designing for operability and by eliminating systems with high infrastructure overhead. Gryphon's horizontal integration and capability to self-ferry eliminates the need for Shuttle elements like the crawler, Vehicle Assembly Building, Orbiter Processing Facility, and launch pad. Additionally, IVHM and line replaceable units improve TATs and simplify maintenance because faults are detected during flyback and defective units are switched out quickly and checked out automatically. It was estimated that the booster could be turned around (ready for next flight) within one week.
- **Safety**: *Can significant safety and reliability improvements be realized?* Safety and reliability were maximized through vehicle design. The flight profile was tailored to mitigate the impact of rocket engines failures. Operating the jet engines through rocket ignition drastically reduces the impact of rocket engine infant mortality and start failures on loss of mission (LOM) and loss of vehicle (LOV) probabilities. Strategic placement of the ignition point and robust abort modes were identified that enable the complete vehicle (including payload) to return to base safely after non-catastrophic failures. The inclusion of high reliability rocket engines, especially on the second stage where abort modes are more limited, vastly increased safety and reliability. LOM, LOV, and loss of payload (LOP) probabilities were calculated to be below the thresholds set by the NGLT program.
- **Cost**: *What is the estimated life cycle cost?* Initial estimates for development and operational costs were based on the vehicle design and operations concept and NGLT groundrules and assumptions (fees, contingency, program support, etc.). Cost tool parametrics were based on historical data. Booster development costs were estimated at $15 billion and production costs were estimated at $4 billion per vehicle. Operational costs were estimated at $2000-$3000 per pound to orbit, depending on the type of upper stage.

Technology Needs

NGLT was established as a technology development program, with the vehicle analysis tasks providing the justification and framework for advancing various launch vehicle technologies. In addition to the vehicle design and validation effort, the team also identified a list of key technologies required to enable the concept. When possible, backup or alternative technologies were also identified. Table 2 lists several key technologies and the supporting rationale.

Lastly, the architecture analysis effort identified several critical issues that require further study. Several of these issues were directly related to Alchemist ACES, which was identified as a critically enabling technology. ACES has received limited funding for development and demonstration testing.

- Ground testing of previously demonstrated Alchemist ACES component technologies integrated with a fault-tolerant control system to demonstrate key performance parameters such as collection ratio, LOX purity and yield, and reliability. Test data will be used to corroborate detailed system models and validate the performance numbers used in trajectory simulations.
- Wind tunnel validation of Gryphon CFD models and subsonic aerodynamic performance. Wind tunnel simulation of dynamic separation events.
- Verification of control/trim margin through detailed aerodynamic modeling and six degree of freedom trajectory simulations.
- Finite element analysis of vehicle structure.
- Thermal analysis of the vehicle in all phases of flight.
- Analytical modeling of shock impingement during ascent and reentry to assess localized heating effects.

Table 2. Identified Technology Needs

Technology	Criticality	Rationale
Alchemist ACES	Critically Enabling	Enables heavy lift horizontal takeoff < 1.4 Mlb GTOW
LOX/LH2 Rocket Engines	Critically Enabling	Air start, increased reliability, and reduced engine processing required for low operations cost
Airbreathing Turbofan Engines	Critically Enabling	Air restart and environment required for architecture feasibility
Thermal Protection System	Critically Enabling (DoD)	Minimal TPS processing for orbiter required for mission rates and operational cost
Long-life Fuel Tanks	Enabling	Lighter weight improves GTOW; increased life reduces life cycle cost
IVHM	Enabling	Condition-based maintenance required for low operations cost
Propellant Delivery System	Enhancing	Densified propellants and crossfeed further reduce architecture GTOW

Summary

The Gryphon launch vehicle architecture is an attractive solution to the nation's need for a system to replace the Shuttle. An NGLT study was performed by an experienced and multidisciplinary team using state-of-the-art tools and methods. The team validated and updated previous design choices, verified the architecture's key benefits, and set the stage for the risk mitigation and hardware testing phase that precedes full-scale development. Technologies applicable to every aspect of the system were assessed for their TRL and applicability to the Gryphon system. The study verified the feasibility of the concept and identified a logical approach for the development of the system.

For further study, wind tunnel testing is recommended to validate aerodynamic analysis. Finite element analysis and detailed thermal analysis is required to ensure structural integrity of all vehicle stages. Additionally, Alchemist ACES must be verified experimentally to reduce programmatic risk.

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