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ACES: PROPULSION TECHNOLOGY FOR NEXT GENERATION SPACE TRANSPORTATION

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Abstract

Andrews Space has developed the "Alchemist" Air Collection and Enrichment System (ACES), a dual-mode propulsion system that enables safe, economical launch systems that take off and land horizontally. Alchemist generates liquid oxygen through separation of atmospheric air using the refrigeration capacity of liquid hydrogen. The key benefit of Alchemist is that it minimizes vehicle takeoff weight. All internal and NASA-funded activities have shown that ACES, previously proposed for hypersonic combined cycle RLVs, is a higher payoff, lower-risk technology if LOX generation is performed while the vehicle cruises subsonically.

Andrews Space has developed the Alchemist concept from a small system study to viable Next Generation launch system technology, conducting not only feasibility studies but also related hardware tests, and it has planned a detailed risk reduction program which employs an experienced, proven contractor team. Andrews also has participated in preliminary studies of an evolvable Next Generation vehicle architecture—enabled by Alchemist ACES—which could meet civil, military, and commercial space requirements within two decades.

Acronyms

2GRLV	2nd Generation Reusable Launch Vehicle
3DOF	Three Degrees of Freedom
ACES	Air Collection and Enrichment System
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
ConOps	Concept of Operations
COTS	Commercial Off The Shelf
DRM	Design Reference Mission
FOM	Figure of Merit
GPS	Global Positioning System
GTOW	Gross Takeoff Weight
HTHL	Horizontal Takeoff Horizontal Landing
IOC	Initial Operational Capability
I_{sp}	Specific Impulse
ISS	International Space Station
L/D	Lift-to-Drag Ratio
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
NASP	National Aerospace Plane
NGC	Northrop Grumman Corporation
NGLT	Next Generation Launch Vehicle
NRA	NASA Research Announcement
OTIS	Optimal Trajectory by Implicit Simulation
R&D	Research & Development
RFDU	Rotating Fractional Distillation Unit
RLV	Reusable Launch Vehicle
ROCETS	ROCket Engine Transient Simulation
ROLS	Recoverable Orbital Launch System
SBIR	Small Business Innovation Research
SSTO	Single Stage To Orbit
TPS	Thermal Protection System
TSTO	Two Stage To Orbit
USAF	United States Air Force
VTHL	Vertical Takeoff Horizontal Landing

Introduction to ACES

Andrews Space has developed an In-flight Propellant Collection System, the "Alchemist" Air Collection and Enrichment System (ACES), which generates liquid oxygen (LOX) through separation of atmospheric air. Since it allows vehicles to take off without LOX on board—minimizing vehicle takeoff weight—the ACES technology is critical for Horizontal Takeoff, Horizontal Landing (HTHL) architectures to meet NASA's Next Generation

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safety, economic, and operational goals in the near term. 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. This enables RLVs that operate with existing airbreathing and rocket propulsion systems, creating a paradigm shift in space operations. Alchemist ACES, as proposed by Andrews, has only moderate technical risk, because key elements have been demonstrated during previous programs.

Mission Operation / Profile

During a typical mission for an ACES-driven, HTHL Two-Stage-to-Orbit (TSTO) architecture, both stages use liquid hydrogen and oxygen engines for rocket powered flight. The second stage, which consists of either an orbiter or an upper stage, rides “piggyback” on the first stage (Figure 1). The vehicle, fueled with hydrogen and jet fuel, takes off and climbs using military-derived turbofan engines, which are used due to the requirements for high thrust at altitude (low bypass ratio) and engine augmentation (afterburners). At altitude, the RLV can either cruise for thousands of miles or begin generating LOX. Alchemist ACES uses the refrigerative capacity of liquid hydrogen to generate at least 95% pure LOX (which is stored in the tanks) and supplies the gasified hydrogen at high pressure to the turbofan engines, where it is burned to generate thrust. Also, the liquid nitrogen generated during Alchemist operation may be used to chill the cryogenic tanks, and remaining nitrogen is used for tank inerting. 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.

Figure 1 – TSTO with Orbiter.

Once LOX tanking is finished, the RLV assumes the proper heading, all rocket engines fire, and the combined stages begin a rapid climb. The turbofan engines are shut down slightly above Mach 1, their inlets are covered, and they are thermally conditioned for restart. By the time the system reaches Mach 2, it is already above 100,000 feet and the dynamic pressure is below 100 pounds per square foot. At approximately Mach 6, the propellant crossfeeds disconnect, the first stage throttles back to match the acceleration of the second stage, and the stages separate. The first stage then shuts down its engines and, using its Attitude Control System, rotates to high angle of attack (between 30 and 60 degrees) for re-entry. The second stage proceeds to its desired orbit and begins payload operations as required. The first stage re-enters, unpowered at first, then restarts the turbofan engines for a powered landing. If necessary, the vehicle may rendezvous with an aerial tanker to load additional jet fuel to return to base.

An RLV using Alchemist can operate out of any air field or base to which hydrogen can be transported and can fly worldwide burning conventional jet fuels. For NASA missions, an Alchemist-powered TSTO configuration the size and weight of a Boeing 747 can deliver the same pressurized cargo to the International Space Station (ISS) as the current Space Shuttle. For United States Air Force (USAF) missions, a similarly sized vehicle, comprised of a single-stage Space Operations Vehicle (SOV), can accelerate to 18,500 feet per second relative velocity to launch replacement GPS satellites or a Space Maneuvering Vehicle (SMV) to high inclination orbit, deploy three Common Aero Vehicles (CAVs), or conduct over flight reconnaissance operations.

ACES Operating Description

Andrews has named its subsonic variant of ACES “Alchemist” since it turns air into rocket propellant. As mentioned above, Alchemist (Figure 2) generates liquid oxygen while cruising subsonically. Air collected from the atmosphere is separated into its constituents by using a fractional distillation process and the refrigeration capacity of liquid hydrogen stored on-board the first stage. Alchemist is comprised of two functionally distinct sections, an Air Collection & Pre-Cooling System and an Air Enrichment System. The Collection & Pre-Cooling portion supplies the specified mass flow rate of air to the Enrichment System at the required pressure and temperature. The Enrichment System cryogenically cools and liquefies the air and separates the oxygen utilizing the liquid hydrogen enthalpy.

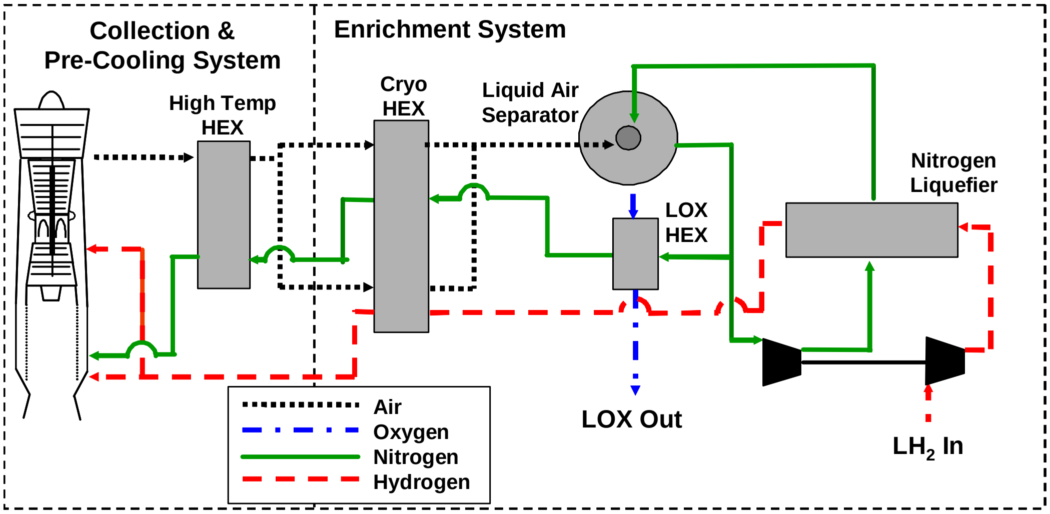


Figure 2 - Baseline Air Collection and Enrichment System Fluid Flow Schematic.

Alchemist first compresses air to a moderate pressure using turbofan engine bypass air and/or dedicated shaft driven compressors (optimizing configuration studies are still in progress). Next, the pressurized air is cooled to room temperature in a series of heat exchangers. It is dehumidified and cooled to its dew point in the primary cryogenic heat exchangers, which have switchable connections to vent moisture and other contaminates (such as CO_2) to the atmosphere. The air then enters a rotating double-column, fractional distillation separator, which separates the saturated air vapor into liquid oxygen (of at least 95% purity) and oxygen-depleted air vapor (98+% nitrogen). The Rotating Fractional Distillation Unit (RFDU) uses the same distillation cycle used in large industrial units, except it uses centrifugal force instead of gravity to drive the mixing of the vapor and liquid phases. The purified oxygen exiting the RFDU proceeds through a LOX Subcooler before being stored in an on-board tank for rocket engine usage. Most of the oxygen-depleted air is recycled through the system heat exchangers to cool the incoming air before exhausting through a nozzle to provide residual thrust to the vehicle during ACES operation. The remaining nitrogen is compressed slightly and recycled through a nitrogen liquefier, which supplies the coolant stream (reflux) to the RFDU that is required to separate and liquefy the oxygen from the incoming air stream. Liquid hydrogen from vehicle cryogenic tanks is used to liquefy waste nitrogen from the RFDU. A para-to-ortho catalyst is used to convert the hydrogen coolant stream to equilibrium conditions and thereby provide additional cooling capacity from the endothermic reaction. The “waste” hydrogen is then used as a fuel source for the flight engines and compression system.

History of ACES

Several historical launch vehicle development programs recognized the importance of airplane-like operations and designed their systems with airplane features. They also realized the key benefit of ACES (or any air liquefaction approach): it minimizes HTHL vehicle GTOW, resulting in a small first stage system. This allows a TSTO vehicle to optimize by staging at a higher mach number, lowering total Delta V requirements and resulting in a smaller RLV requiring less total thrust. Because of these advantages, considerable work on ACES-related concepts was completed.

In the late 1950s and early 1960s, several airbreathing launch studies and technology development projects were undertaken. In particular, the USAF involved dozens of subsystem manufacturers and government laboratories in its Aerospaceplane Program to develop a hypersonic airplane (Figure 3). While the program was focused on maximizing vehicle performance, hypersonic airbreathing propulsion was technically uncertain, so an ACES system was included in some vehicle designs. For example, General Dynamics designed a 700,000 lbm GTOW vehicle that could deliver a 23,000 lbm payload to 300 nmi polar orbit; this required a Mach 8 hypersonic airplane with an ACES system that collected LOX supersonically. In component-centered research related to the vehicle effort, Union Carbide’s Linde Division demonstrated a boilerplate RFDU and para-to-ortho hydrogen conversion catalyst studies were conducted at various sites. In 1964-68, the USAF studied the Recoverable Orbital Launch System (ROLS), which produced another RFDU design. There was a lull between the late 1960s and early 1980s in the U.S., although some work was completed abroad (especially Japan). The National AeroSpacePlane (NASP) of the 1980s and early 90s was an airbreathing scramjet Single Stage to Orbit (SSTO) concept, basically a second attempt at work started in the 1960s. This program supported several hardware demonstrations of LACE (consisting essentially of a rocket-type thrust chamber and an air liquefaction heat exchanger—an "airbreathing rocket"), advanced versions of LACE, and key aspects of ACES. This included further work conducted at Linde through an USAF/NASA-LeRC contract to demonstrate advanced RFDU technologies, while additional air/hydrogen heat exchanger and hydrogen conversion catalyst projects were completed elsewhere. Still, these ACES-related programs focused chiefly on performance rather than safety, reliability, and cost. Because they were interested in performance first, they carried too much technical risk (primarily in hot structures and advanced combined cycle propulsion systems), which lead to high development costs.

There are several major differences between Andrews' Alchemist ACES configuration and previous air liquefaction systems. First, whereas early ACES configurations were designed to amass LOX as rapidly as possible, Alchemist collects LOX at *subsonic* speeds utilizing a subsonic wing design (high lift-to-drag ratio, or L/D) and existing jet engines. This relieves the technical requirements on the ACES system, allowing Commercial Off-The-Shelf (COTS) technologies or simpler development projects. Collecting subsonically also makes use of air at low ambient temperatures, which significantly reduces the amount of hydrogen needed as a heat sink and therefore reduces operations costs and vehicle empty weight. Second, during LOX collection, the Alchemist vehicle system has specific impulse values from 6,000 to 10,000 sec, because it runs on jet engines only. Previous systems employed less fuel-efficient combined cycles while generating LOX. Alchemist's low fuel consumption allows collection of LOX over hours rather than minutes. A reduced collection rate results in a smaller, lighter ACES that can be packaged more easily inside an RLV. Also, in the Alchemist baseline, gaseous hydrogen mass flow requirements match turbofan fuel flow requirements, so all the hydrogen can be "recycled" (burned) in the engines instead of being dumped overboard. Finally, the longer collection period is also advantageous for the mission because the cruise duration provides range to avoid weather problems and fly to an optimum launch point.

Alchemist ACES History

Phase I SBIR

In 2001, Andrews was awarded a NASA Phase I Small Business Innovation Research (SBIR) contract to verify Alchemist ACES feasibility and identify and address potential showstoppers. Specific tasks included verifying the feasibility of the air extraction/reinsertion approach, improving the fidelity of the computational model, identifying and addressing any potential issues, and optimizing the interaction between the turbofan engines and the liquefaction/separation systems. Also, Andrews performed initial sizing of system components then developed Computer Aided Design (CAD) models and physically integrating them into the airframe.

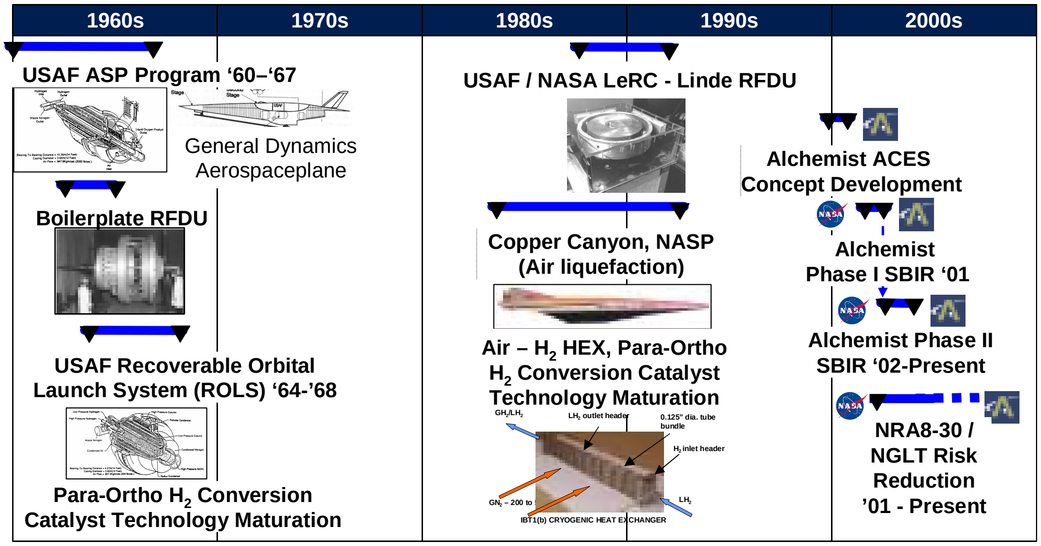


Figure 3 – Summary of Historical ACES Work.

Specific accomplishments of this contract included turbofan performance simulation, computational system model development, conceptual design and vehicle integration, and business case development. Pratt & Whitney modified existing engine performance codes to account for Alchemist air extraction/reinsertion. This allowed the selection of air extraction rates, thrust levels, and operational altitudes to maximize system performance, flexibility, and safety. Several key improvements were incorporated in Alchemist system models. Also, additional safety requirements and margins were factored into the models as a result of discussions with experts in heat exchangers, air separators, and turbomachinery. The Alchemist system components (including the air separation unit, heat exchangers, turbomachinery, air extraction/reinsertion system, etc.) were sized (weight and volume) in accordance with the requirements identified in the Alchemist thermodynamic system model. CAD models of these components were developed and integrated into the flight vehicle to validate the feasibility of the overall RLV configuration. Finally, Andrews assessed the business opportunities enabled by utilizing the Alchemist technology.

NRA8-30

Based on SBIR results and the overall potential of Alchemist, Andrews Space was awarded a contract under NASA's Space Launch Initiative (NASA Research Announcement 8-30). This activity was focused on the development of technologies for a 2nd Generation Reusable Launch Vehicle (2GRLV). Andrews' technology focus under NRA8-30 was on propulsion, as Alchemist research was funded under the propulsion Technical Area (TA-8). The specific objectives of the program were to model and analyze multiple Alchemist system cycles, evaluating various system designs; quantify risks to the system and individual components, involving both operations and implementation; derive preliminary operating requirements and specifications at the component level; and select a preferred system design to carry forward into the next phase of work.

One of the key accomplishments of the program was the assembly and integration of an experienced, proven contractor team. The team included traditional aerospace contractors, such as Hamilton Sundstrand (for controls and air separator design and development) and Pratt & Whitney (for turbomachinery and air collection system design and development), as well as smaller firms with particular expertise in key areas, such as Creare (heat exchangers) and Universal Technologies Corporation (air separation system consulting).

Andrews also developed several key documents as part of the program. First, a detailed Concept of Operations (ConOps) document was created to describe the vision vehicle system that is enabled by Alchemist, as well as the manner in which it may be deployed, operated, and maintained. Andrews also developed a detailed Risk Management Plan. This plan was created to establish, track, and mitigate program risks. With its creation, Alchemist technical and programmatic risks were identified, and several were reduced and/or eliminated.

The integrated Team planned a complete risk reduction program for key Alchemist technologies, including a part-flow-scale, integrated ground demonstration of the Air Enrichment System and key technologies for the Air Collection System. This program will take the key technologies of Alchemist to TRL 6 within approximately four years and will reduce or eliminate all major risks, including the highest risk, integration and operation of the system (Figure 4).

The Alchemist Team performed an initial vehicle-subsystem integration analysis, including CAD modeling and packaging of Alchemist within the first stage vehicle. Due to the close interaction with the propulsive jet engines, packaging the air collection system of ACES is a crucial integration issue. The Team also performed an initial architecture cost analysis of the TSTO RLV system.

The key analysis, however, was detailed thermodynamic modeling of Alchemist and its subsystems. The Team used legacy aerospace tools (such as ROCket Engine Transient Simulation, or ROCETS, and other Fortran component codes) and modern, industry-standard tools (MATLAB and Simulink, MatrixX, and National Institute of Standards and Technology fluid property databases). Using this toolset, the Team analyzed multiple Alchemist configurations and component options, including various air collection methods (air extraction from a jet engine core, air extraction from a turbofan bypass duct with additional compression, and use of dedicated air compressors).

Key Technologies	Baseline	Current TRL
Integrated Operations (Configuration, Control, etc.)	X	2.5
Heat Exchangers		
Plate/Fin Design with SOTA Core	X	5
Plate/Fin Design with Advanced Core	O	3
Air / Hydrogen Heat Exchanger	X	3.5
Gaseous Helium Enthalpy Transfer Loop	O	6
Reliable, Flight Weight Heat Exchanger Design	X	5
Cryogenic Dehumidifier / Contamination Removal	X	4
Air Separation		
Rotating Fractional Distillation Unit	X	3
Vortex Tube	O	2
Air Supply / Propulsion Systems		
Dual Fuel Turbine Engine Operation	X	3
Restarting Engines After Exo-atmospheric Flight	X	3
Turbojet Duct Extraction w/ Compression	X	4
Ambient Air Compression	O	5
Jet Engine Core Extraction	O	2
Turbomachinery		
Liquid Hydrogen Pump	X	6
Dedicated Air Compressor	X	6
Auxilliary Power Units	X	8

Baseline Technology = X
Optional (Fall Back) Technology = O

Figure 4 – Alchemist ACES Key Technology Risks.

At the component level, the Team investigated a number of different design options, with the goal of minimizing overall risk to the vehicle while providing the required performance with margin. The Team evaluated multiple air separation methods [RFDU, including design trades such as trays vs. packed columns, vortex tube (from the SBIR research), and paramagnetic separation)] and numerous methods for enthalpy transfer (para-to-ortho hydrogen conversion catalysis, refrigeration, air/hydrogen heat exchangers vs. an air/helium plus helium/hydrogen approach, and wing skin heat exchangers). Component studies included a detailed weights analysis; the Team used "conservative" estimations for subsystem weights. In addition to the technical effects, an Analytical Hierarchy Process (AHP) was used to evaluate the cost-to-benefit ratios of optional technologies.

Finally, the Team identified low risk, performance enhancing options for each component and thereby downselected to a preferred Alchemist baseline. The functional and physical component requirements were initially identified by component. Given that baseline, the Team used MatrixX to create a preliminary animated graphical model of the system in operation, which required a preliminary control system analysis. The graphical model enacted startup to full power, full duration operation, and shutdown, as well as several key abort scenarios. Future off-design, transient, and control system models will be able to use these preliminary results.

Architecture Studies

Similar to the Alchemist system, Gryphon was initially studied under internal R&D funds at Andrews. The ACES Phase I SBIR allowed further investigation of the concept. However, not until Northrop Grumman Corporation (NGC) included the vehicle concept in its architecture studies during the Space Launch Initiative (NRA8-30 TA-1) did it receive technical scrutiny elsewhere within industry. As part of NGC's independent analysis, the Alchemist Team was invited to a Non-Advocate Review of Alchemist ACES at NGC in order for a panel of industry experts to assess the concept's viability. The Alchemist Team presented an overview of the Gryphon concept and the benefits Alchemist provides, a historical perspective on ACES, and technical details on Gryphon and Alchemist, followed by detailed coverage of each of the Alchemist subsystem areas (delivered by the Team members). The Team concluded with an overview of the integrated Alchemist development approach. Overall, the non-advocate review team agreed that Alchemist was feasible and could be ready to support 2GRLV, assuming sufficient funding for technology risk mitigation.

Upon completion of its analyses, NGC determined that Gryphon competes well with other concepts in most payload classes. They found that the architecture provides synergy for NASA and USAF missions and also found its blend of aircraft and rocket design philosophies advantageous due to avoidance of dead zones during ascent. NGC analysts also identified several key lessons learned during their studies as well. First, they realized the importance of obtaining detailed aerodynamic analysis results early. Next, they learned that the Gryphon trajectory is difficult to analyze, especially with traditional space vehicle tools, because it has both the flight path of a rocket and the cruise performance of an airplane, which means that it has to be analyzed as two complex systems. Therefore, the system cannot be constrained to Vertical Takeoff groundrules. Finally, the NGC team suggested that, as the major enabling technology for the Gryphon TSTO HTHL vehicle, the Alchemist technology requires early and full value funding if it is to be ready for Full Scale Development in the 2GRLV timeframe.

Next Generation Launch Technology Program

At the end of the Alchemist study contract under the Space Launch Initiative, the 2GRLV and 3rd Generation RLV programs were merged into the Next Generation Launch Technology (NGLT) program. As a continuation of the NRA8-30 work, Andrews was contracted to support NGLT's technology and architecture evaluation efforts, participating on an integrated, multi-center NASA-industry team under the NGLT Systems Analysis Project (SAP). This team is focused on the architecture enabled by Alchemist, known as "Gryphon" (Figure 5).

In this contract, Andrews continues to develop MATLAB-based thermodynamic cycle models of Alchemist for all air collection configurations and is conducting performance assessments and exploring the benefits of advanced technology items. Andrews is also continuing with its system optimization studies to investigate the impact of various Alchemist operating parameters on key technical measures, such as collection ratio and system weight. This list of operating parameters includes: mass flow rate split between heat exchangers, heat exchanger effectiveness, hydrogen turbomachinery outlet pressure, RFDU inlet pressure and rotation rate, etc.

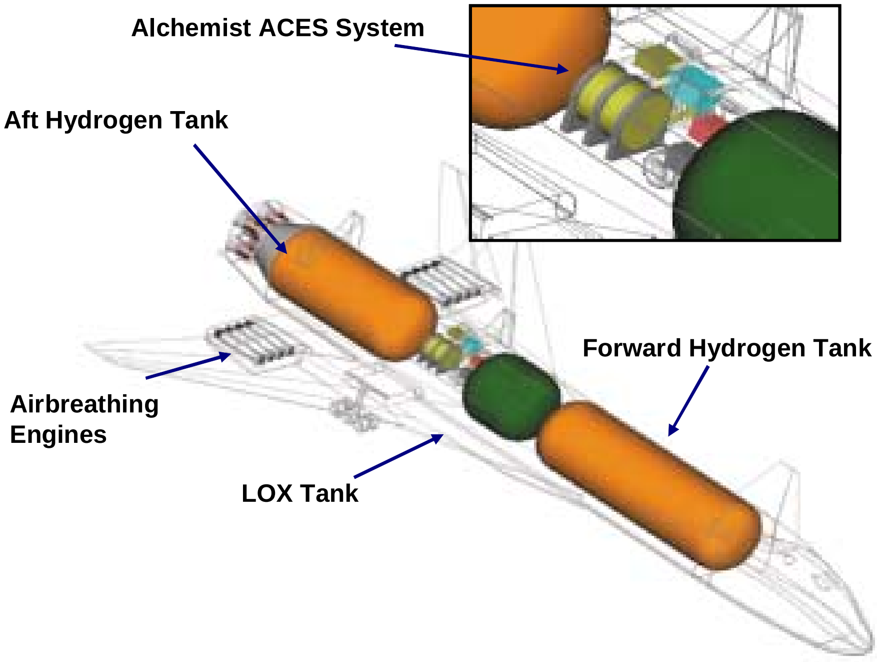


Figure 5 – Gryphon Architecture Subsystem Layout.

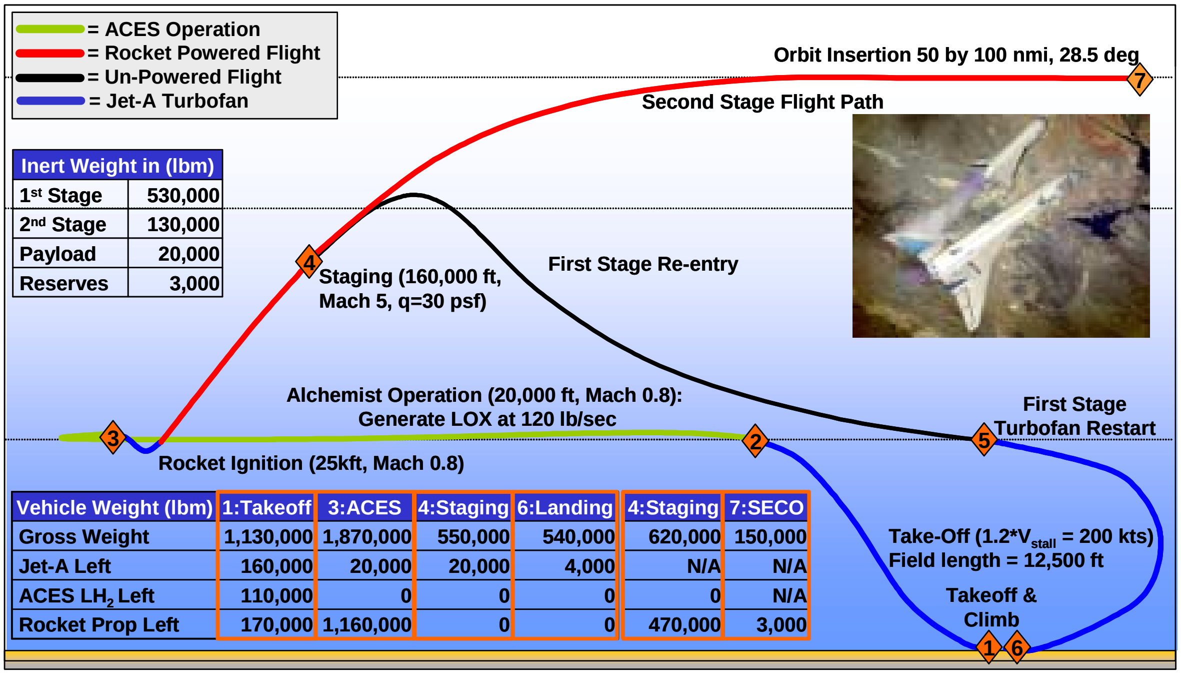
Andrews is also participating in architecture-specific tasks, including Gryphon configuration studies and architectural evolution studies. These tasks are mainly focused on designing an architecture concept capable of satisfying NGLT Design Reference Missions (DRMs) while at least meeting all Figure of Merit (FOM) thresholds. The team will develop the architecture ConOps, which will include ground turnaround launch processing, engine operation (startup, nominal operation, and shutdown), and top-level fault (i.e., abort) operations. Evolution studies will involve the evaluation of customer mission needs over time; Andrews will quantitatively illustrate the ability of ACES-based architectures to evolve and satisfy different customer needs in the near-term (e.g., with an IOC of 2015 or earlier), mid-term (IOC of about 2020), and far-term (IOC of 2025 or later).

Configuration studies are centered on the conceptual design of a TSTO architecture with Alchemist packaged in the first stage fuselage (as shown in Figure 5) to allow horizontal takeoff without oxidizer. Key analyses being conducted are trajectory analysis, weights and sizing, aerodynamics, aerothermal, structures, vehicle subsystems, reliability/safety, operations, and life cycle cost.

The team uses the industry-standard trajectory analysis tool OTIS (Optimal Trajectories by Implicit Simulation) to conduct optimized takeoff, LOX collection, ascent, flyback, and re-entry simulations. The simulations presently use three degrees of freedom (3DOF) are currently un-trimmed. Trim and 6DOF will shortly follow. The trajectories are integrated and branched, however, allowing the full mission profile to be optimized at one time. Figure 6 is a representative flight profile generated by OTIS.

Multiple weights and sizing tools are being employed by the team to arrive at a closed vehicle solution with the OTIS trajectory. Andrews' LVDesTool and NASA-Glenn's SIZER code have provide independent but consistent results (see bottom left of Figure 6). These tools provide bookkeeping of all subsystems, propellants, and fluids based on top-level loading and packaging analyses and inputs from other disciplines.

Since aerodynamic performance (especially subsonic) plays such a crucial role in the performance of the architecture, Andrews is leading a team to conduct an aerodynamic evaluation of vehicle configurations using both linear impact methods and Computational Fluid Dynamics (CFD). The analyses will determine basic aerodynamic coefficients (center of lift, Mach drag rise, longitudinal and directional stability derivatives, interference drag, etc.) at subsonic and transonic flight conditions. The analysis will demonstrate that the vehicle satisfies all takeoff/landing speeds, glide path, and runway length requirements as well as top-level stability requirements. CFD is used with semi-empirical drag increments to enhance first-order understanding of the vehicle (Figure 7).



Inert Weight in (lbm)	
1st Stage	530,000
2nd Stage	130,000
Payload	20,000
Reserves	3,000

Vehicle Weight (lbm)	1:Takeoff	3:ACES	4:Staging	6:Landing	4:Staging	7:SECO
Gross Weight	1,130,000	1,870,000	550,000	540,000	620,000	150,000
Jet-A Left	160,000	20,000	20,000	4,000	N/A	N/A
ACES LH_2 Left	110,000	0	0	0	0	N/A
Rocket Prop Left	170,000	1,160,000	0	0	470,000	3,000

Figure 6 – Representative Gryphon Nominal Mission Profile.

Figure 7 – Aerodynamic Pressure Contours on Gryphon First Stage.

Aerothermal loads are being analyzed using both one-dimensional and CFD-based two-dimensional/three-dimensional engineering methods for items such as thermal protection system (TPS) sizing. A key study is determining whether or not the first stage requires expensive and operationally-intensive TPS. Figure 8 is an example of these results; temperature profiles of the windward, lateral, and leeward surfaces are shown versus time.

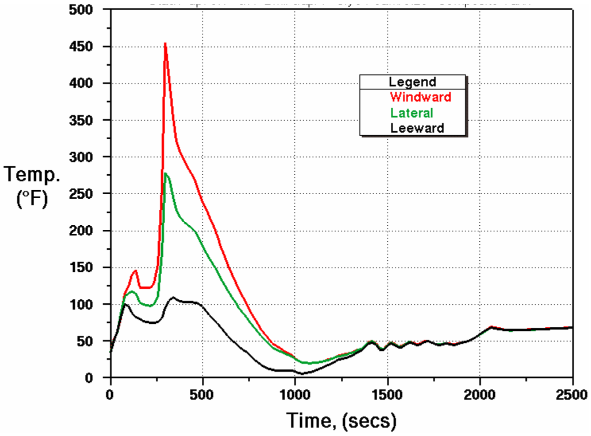


Figure 8 – Example Aerothermal Analysis of Gryphon First Stage.

Structural bending loads analysis is based on the theory of beams, shell, etc. using design experience from both aircraft and Space Shuttle-like systems.

Pro/Engineer is used to develop the detailed vehicle geometry based on weights and sizing results. External and major internal components, such as propellant tanks, the payload bay, propulsion systems, Alchemist, etc. are modeled for packaging with volume, area, and key linear dimensions.

For vehicle subsystems, the team is conducting functional requirements definition and evaluation and one-dimensional modeling of some subsystems, while others are receiving quantitative thermal and fluid analyses and component weights estimations. As the key enabling technology, Alchemist is the focus of most subsystem analysis.

For reliability, safety, maintainability, and operations analyses, propulsion, TPS, and other subsystems are estimated from relevant aircraft and space vehicle historical data and are adjusted for differing operational requirements or advanced technology increments.

Weight-based cost estimating relationships are also derived from aircraft and space vehicle historical data with adjustments for technology complexity. Then economic theory and business case analyses are used to determine the life cycle cost.

In addition to analysis of the architecture baseline, key trades are being performed. Engine-out capability and thrust requirements are being determined to evaluate jet and rocket engine types for use. Various trajectory trades are in work, such as the variation of payload with staging Mach number. Also, tank and primary structure materials trades are key to optimizing weight on a robust vehicle design.

Looking forward: Technology Development

In addition to Alchemist-specific technology development, studies and development are required for the TSTO HTHL vehicle enabled by Alchemist. There are no existing spacecraft that take off horizontally like an airplane then fly to Mach 6 or beyond. Therefore, a number of key technologies must be demonstrated before a full-scale Alchemist can be integrated into a vehicle. For propulsion alone there are several issues: for example, interactions between airbreathing and rocket engines in flight, air-starting rocket engines, and restarting jet engines after exoatmospheric flight. The HTHL vehicle should also exhibit air basing logistics and rapid turnaround, among other key factors, in order to demonstrate a highly responsive spacecraft. Then, Alchemist and other key technologies can be added to achieve maximum payload capability to orbit.

Summary

ACES has been studied as a potential performance-enhancing technology for launch systems for over four decades. Starting with an SBIR and continuing through today, Andrews Space developed the Alchemist ACES concept, which is an enabling technology for economical Next Generation launch systems that take off and land horizontally. The key advantage of Alchemist is LOX generation during subsonic cruise. This allows HTHL launch systems with low GTOW values to use existing airbreathing and rocket propulsion. The combination of an HTHL approach and the ability to use existing or COTS technologies enables a safer, more reliable, and lower cost architecture. Analysis on both Alchemist and the vehicle it enables is proceeding under NASA funding.

Since key elements of the system have been demonstrated during previous programs, the key technology development for Alchemist is integration and control of its components in a ground testbed. Andrews has also extended this plan through flight testing. Therefore, with sufficient funding, this enabling technology can be demonstrated and ready to support Next Generation launch systems.

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