

PROGRESS ON ALCHEMIST ACES: TECHNOLOGY FOR NEXT GENERATION SPACE TRANSPORTATION

Andrew M. Crocker*, Adam M. Wuerl**, Jason E. Andrews[†], and Dr. Dana G. Andrews^{††}

Andrews Space, Inc.
505 5th Ave S, Suite 300
Seattle, WA 98104

<http://www.andrews-space.com>

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	2 nd Generation Reusable Launch Vehicle
ACES	Air Collection and Enrichment System
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
ConOps	Concept of Operations
COTS	Commercial Off The Shelf

DMS	Document Management System
DRM	Design Reference Mission
FAR	Federal Aviation Regulations
FOM	Figure of Merit
GPS	Global Positioning System
GTOW	Gross Takeoff Weight
HTHL	Horizontal Takeoff Horizontal Landing
ICM	Integrated Concept Model
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
R&D	Research & Development
RFDU	Rotating Fractional Distillation Unit
RLV	Reusable Launch Vehicle
RMP	Risk Management Plan
ROCETS	ROCKET Engine Transient Simulation
ROLS	Recoverable Orbital Launch System
SBIR	Small Business Innovation Research
SSTO	Single Stage To Orbit
T/W	Thrust-to-Weight Ratio
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

* Lead Project Manager, Senior Member AIAA

** Engineer, Member AIAA

[†] President, Member AIAA

^{††} Chief Technology Officer, Senior Member AIAA

Copyright © 2003 by Andrews Space, Inc. Published by the American Institute of Aeronautics and Astronautics, Inc. with permission.

Horizontal Takeoff, Horizontal Landing (HTHL) architectures to meet NASA's Next Generation 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.

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.

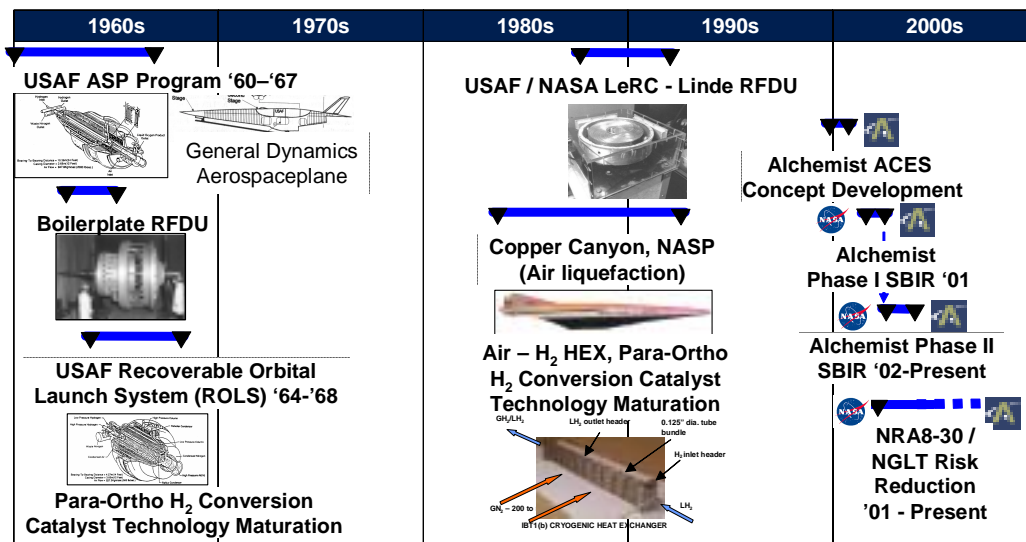


Figure 3 – Summary of Historical ACES Work

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.

While this contract work focused on system configurations that incorporated the rotating, double-column, fractional distillation air separation unit, a vortex tube air separation concept was also briefly evaluated during this contract period.

Phase II SBIR

In 2002, a follow-on contract was awarded to investigate the process and viability of vortex tube air separation for use in Alchemist. In a vortex tube, a two-phase air stream is injected tangentially into a static tube, where it is separated into an oxygen product stream and oxygen-depleted (nitrogen) waste stream. If it is shown to provide similar or better performance than an RFDU, a vortex tube has potential for substitution as an air separator due to its simplicity. The goal of the SBIR project is to move from proof of principle to proof of concept for the vortex tube air separation system. The two primary objectives are (1) creation of a two-phase vortex tube thermodynamic model which can be calibrated and validated with experimental results and design, fabrication, and (2) testing of a modular vortex tube experimental unit. Modeling and testing are both underway as of this publication (Figure 4).



Figure 4 – Vortex Tube Testing

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). In order to ease sharing and remote manipulation of data, Andrews also created a web-based Document Management System (DMS), which has built-in, automatic document configuration control. The DMS is maintained by a data manager and provides automatic notification of data releases and revisions including applicable data received from subcontractors and team members. This secure, ITAR-compliant system accepts and manages any electronic media files and is protected by IT security measures. (See <http://dms.andrews-space.com>).

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 (RMP). This plan was created to establish, track, and mitigate program risks. With the creation of the RMP, 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 5).

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 Alchemist ACES Technologies	Baseline	Current TRL
Integrated Operations (Configuration, Control, etc.)	X	2.5
Heat Exchangers		
Plate/Fin Design with Louvered Cores	X	5
Plate/Fin Design with Vortex Generator Cores	O	3
Fault Tolerant Air / Hydrogen Heat Exchanger	X	3.5
Gaseous Helium Enthalpy Transfer Loop	O	6
Para-to-Ortho LH2 Catalyst (Isothermal)	X	3
Para-to-Ortho LH2 Catalyst (Adiabatic/Industrial)	O	5
Reliable, Flight Weight Heat Exchanger Design	X	5
Cryogenic Dehumidifier / Contamination Removal	X	4
Air Separation - Fractional Distillation		
RFDU w/ Packed Columns (98% purity)	X	3
Vortex Tube	O	2
Air Supply / Propulsion Systems		
Dual Fuel Turbine Engine Operation (JP/LH2)	X	3
Restarting Engines After Exo-atmospheric Flight	X	3
Turbojet Duct Extraction w/ Compression	X	4
Ambient Air Compression	O	5
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 5 – 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.

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. Andrews was asked to brief the NGLT program on Alchemist and the architecture it enables (known as “Gryphon”, shown in Figure 6). Then, 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 contract is primarily designed to cover architecture analyses, but Alchemist configuration studies are involved.

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.

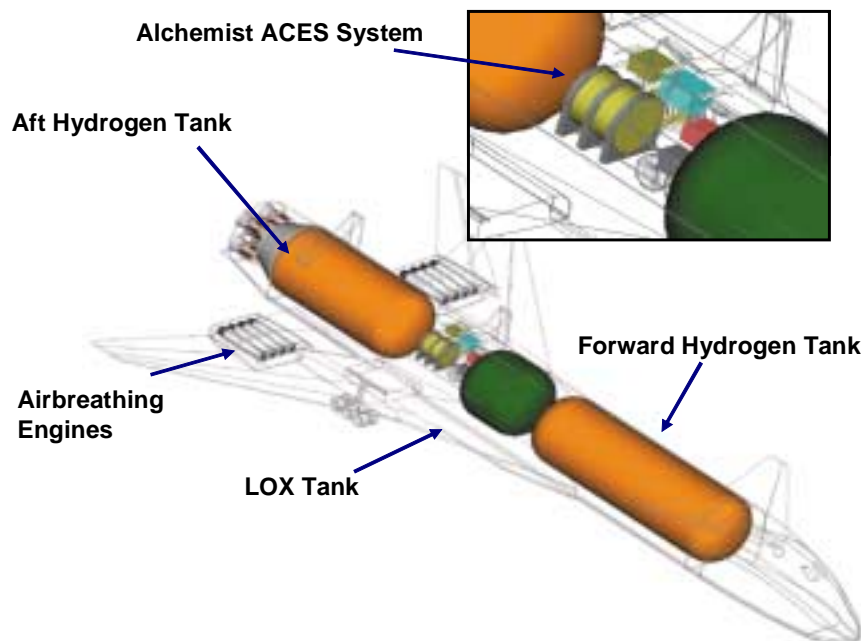


Figure 6 – Gryphon Architecture Subsystem Layout

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.

Under the same contract as the Alchemist study for NGLT SAP, Andrews has been tasked to conduct architecture-specific studies in cooperation with the same multi-center NASA/industry team. These tasks include Gryphon configuration studies, architectural

evolution studies, and aerodynamic evaluations. These tasks will mainly be focused on designing an architecture concept capable of satisfying NGLT Design Reference Missions (DRMs) while at least meeting all Figure of Merit (FOM) thresholds. All architectures will be designed with Alchemist packaged in the first stage fuselage. The ConOps will also include ground turnaround launch processing, engine operation (startup, nominal operation, and shutdown), and top-level fault (i.e., abort) operations, as well as nominal and off-nominal Alchemist operating requirements and updated interface data. 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). Finally, 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 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.

Looking forward

As discussed above, the Alchemist Team has developed a comprehensive risk reduction program, which is focused on demonstration of critical Alchemist component technologies. Early activities will involve component and system modeling to capture off-design and transient effects and understand component and environmental interactions. Then, the Team will design, build, and test Alchemist sub-components, which demonstrate the capability required for all major components in the baseline configuration. Next, the team will assemble and test all major system components. Concentrated development effort will be focused on the RFDU air separator, an integrated air dehumidification system (featuring a fault tolerant air/hydrogen heat exchanger), and a nitrogen liquefier with a para-to-ortho hydrogen conversion catalyst system. The plan culminates in an integrated Air Enrichment System ground demonstration at NASA-Glenn Research Center's Plum Brook Station (Figure 7). Plum Brook's Hypersonic Tunnel Facility will be modified to supply properly conditioned air to for up to one-hour test durations. In this manner, the entire Alchemist thermodynamic cycle will be demonstrated in a low risk, cost effective fashion.

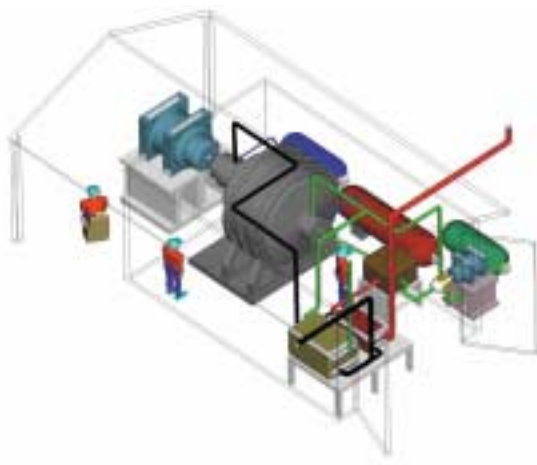


Figure 7 – Notional Schematic of Ground Test at Plum Brook Station

Andrews has established a program plan to go beyond the Alchemist Risk Reduction Program to flight testing. In this extended plan, Air Collection System development, including jet engine modifications and updates, runs in parallel to Air Enrichment System development. These parallel paths are integrated into a flight test vehicle. A number of existing vehicles have been identified as candidates for use.

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. One potential method for allowing this stepping-stone approach is to use LOX/kerosene rocket engines on the smaller, concept demonstration vehicles; this provides commonality with the jet engine fuel and offers near-term handling capability at existing USAF air bases. Upon demonstration of responsiveness, LOX/hydrogen engines can be substituted for maximum vehicle performance (hydrogen also offers commonality with the Alchemist coolant and secondary jet engine fuel), as shown in Figure 8.

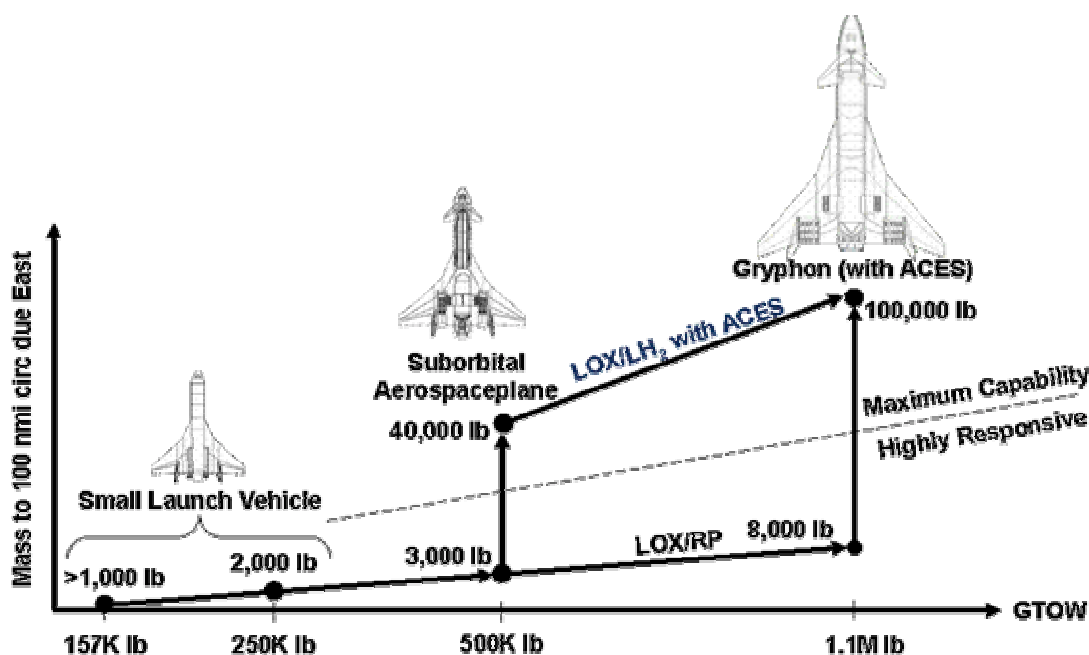


Figure 8 – Stepping-stone Development of Vehicle Capability

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.

During its research of the Alchemist concept, assembled a proven contractor team with specialties in the key component areas. This team downselected to a low risk Alchemist concept baseline, which has been the basis of recent studies. The team also planned a complete risk reduction program for key Alchemist technologies to reduce or eliminate all major system risks prior to full-scale system development. 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.

References

Andrews, D.G. and Andrews, J.E., "Designing for the Future Space Transportation Missions," AIAA Paper 2001-3964, July 2001.

Andrews, J.E. and Andrews, D.G., "Airport-to-Orbit, the Economics of Horizontal RLV Systems," Presentation at 1st AIAA/IAF Symposium on Future Reusable Launch Vehicles, April 2002.

Crocker, A.M., White, S.M., Andrews, J.E., and Andrews, D.G., "Alchemist ACES: Enabling Technology for 2nd and Future Generation Space Transportation," AIAA Paper 2002-4327, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, Indiana, 7-10 July 2002.

Escher, W.J.D. and Doughty, D.L., "Assessment of Cryogenic Hydrogen-Induced Air Liquefaction Technologies," Final Report to Science Applications International Corporation from Astronautics

Corporation of America, U.S. Air Force Contract No. F33615-84-C-0100, Sept. 1986.

Leingang, J.L., Maurice, L.Q., and Carreiro, L.R., "In-Flight Oxidizer Collection Systems for Airbreathing Boosters," *Developments in High-Speed-Vehicle Propulsion Systems*, Vol. 165, AIAA Progress in Aeronautics & Astronautics Series, 1996, pp 333-384.