Results of QuickReach™ Small Launch Vehicle Propulsion Testing and Next Steps to Demonstration Flights

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ABSTRACT

For the past four years, AirLaunch LLC has been developing the QuickReach™ Small Launch Vehicle (SLV) under the DARPA/U.S. Air Force Falcon SLV program. The company has successfully completed Phases 1, 2A and 2B of the program. Phase 2C began in June 2007 and continues through fall of 2008.

Phase 2C focuses on propulsion characterization of AirLaunch's innovative liquid oxygen (LOX)/propane vapor pressurization (VaPak) propulsion system used on the second stage of its QuickReach™ SLV. Phase 2C Milestones include upgrades to hardware, instrumentation, and test stands; and a series of test fires on the Horizontal Test Stand (HTS) to gather data on engine performance and on the Vertical Test Stand (VTS) to more comprehensively characterize second stage performance.

The QuickReach™ booster is designed to deliver 1,000 pounds to low earth orbit for $5 million per launch, with less than 24-hour response time. AirLaunch's approach achieves responsiveness by flying the two-stage, pressurized QuickReach™ system inside an unmodified C-17A or other large cargo aircraft.

AirLaunch has also been exploring applications of its second stage propulsion system to other launch vehicles, configurations, and markets. An air-launched rocket enables new concepts of operations (CONOPS) that lead to Operationally Responsive Spacelift (ORS) capability.

This paper shares the results of Phase 2C to date and identifies various applications of AirLaunch's propulsion technology and vehicle configurations to enable the earliest possible flight demonstration.

Introduction

AirLaunch has completed Phases 1 through 2B of the joint Defense Advanced Research Projects Agency (DARPA) / Air Force Falcon Small Launch Vehicle (SLV) program. This program originated with a call for proposals in June 2003, resulting in awards to 9 companies in September 2003 to conduct 6-month Phase 1 design studies for an SLV. In September 2004, DARPA held another open competition and selected 4 companies for further Phase 2A studies and demonstrations leading to a SLV Preliminary Design Review. In October 2005, the program selected AirLaunch LLC for contract continuance through Phase 2B, with a $17.8 million value. AirLaunch completed Phase 2B in April 2007. Phase 2C began in June 2007, with a contract value of $7.6M and a focus on propulsion.

The Falcon program is governed by a Memorandum of Agreement (MOA) signed by DARPA and the Air Force in May 2003 with DARPA managing the Falcon SLV program and the Air Force funding the program from what is now the Operational Responsive Space (ORS) budget line. Phase 2C is jointly funded by DARPA and the Air Force. The intent has been to develop operational responsive space launch vehicles as called for in the U.S. Space Transportation Policy.

Responsive space would allow the government to react quickly and use small satellites equipped with sensors to monitor and provide communication for urgent military needs. Having a quick reaction launch system that can launch specialized small satellites will provide the warfighter with real-time data and communication during time-urgent situations. AirLaunch's system achieves responsiveness by launching from an unmodified C-17 or other large cargo aircraft.

QuickReach™ Small Launch Vehicle Overview

The QuickReach™ SLV is designed to meet the needs of the DARPA/Air Force Falcon SLV program: deliver 1,000 pounds to low earth orbit (LEO), for $5M per flight, with response time of less than 24 hours. It is an air-launched, two-stage, liquid fueled rocket, used with an unmodified C-17A transport aircraft and compatible with other transports with similar capacity, such as the An-124 or C-5A. Satellite launch missions are conducted with a single QuickReach™ loaded in the aircraft along with airborne support equipment.

Launching from altitude provides unique opportunities to operate a simple, low-cost system with the high performance characteristics of most two stage launch vehicles. AirLaunch opted to launch from a cargo aircraft at altitude to provide increased performance and take advantage of the innovative liquid oxygen and propane vapor pressurization (VaPak) propulsion system that QuickReach™ employs.

Air launching leverages the low atmospheric pressure at altitude (30,000+ feet) which allows a pressure-fed launch vehicle to use high area ratio nozzles while operating at relatively low engine chamber pressures. AirLaunch's approach provides weight and specific impulse (Isp) performance that is competitive with high-pressure turbopump-fed systems without the associated safety, cost, or complexity issues.

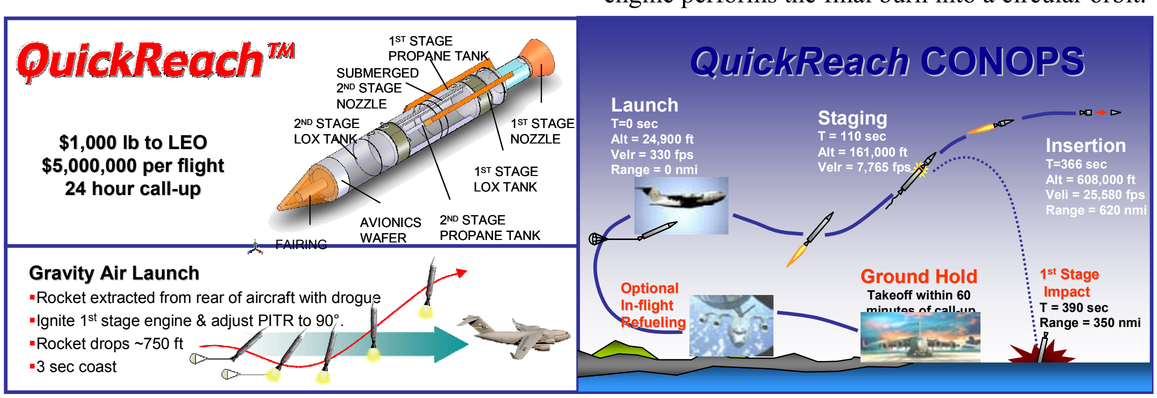
QuickReach™ can be loaded onto the aircraft in 20 minutes, and then fly to a nominal launch point ~200 miles off the coast. The aircraft climbs to ~30K–35K feet where it cruises to the desired drop point. The aircraft can loiter before launching for several hours. If a dangerous situation arises on-board, emergency extraction may be triggered by the loadmaster anytime during flight. During an emergency extraction all rocket components and propellants are extracted from the carrier aircraft in less than 30 seconds.

The carrier aircraft is flown to a "drop box," an approximately 1 x 1 mile area over the open ocean. Several minutes prior to launch the aircraft deck angle is established at ~6 degrees nose up, cabin pressure is equalized with atmospheric pressure, and the aft cargo door is opened. Fifteen seconds before launch, a small drogue parachute attached to the first stage nozzle is deployed. Upon launch command, the rocket is released and gravity pulls the launch vehicle out of the aircraft, assisted by the drogue chute. The drogue chute dampens the pitch rate imparted by the cargo door ledge and after about 3 seconds the launch vehicle's pitch attitude is 70 to 80 degrees above the horizon.

The Stage One engine ignites when the launch vehicle is 200+ feet from the aircraft, with the launch vehicle descending at 100 feet per second (fps) and traveling 50 fps aft relative to the aircraft. At the point of ignition, the parachute is released by having its risers burned off. The launch vehicle needs another 500 feet of altitude to arrest its descent; then the rocket flies to a vertical heading and continues in this attitude until it re-crosses the launch altitude more than 1,000 ft behind the launch aircraft ~15 seconds after extraction.

Initially the first stage engine operates on liquid combustion and tanks are pressurized using the VaPak mode. Once the liquid has been depleted, the vehicle transitions to vapor burn mode, and both tank and engine chamber pressure drop rapidly.

Following separation, the second stage ignites under VaPak operation. The payload fairing is released when the environment outside of the vehicle is no longer harmful to the payload. The second stage burn is designed to transition to vapor operation prior to completion of the initial burn. This allows the second stage to restart following the coast to apogee, with only vapor in the propellant tanks, which eliminates propellant settling concerns. Lastly the second stage engine performs the final burn into a circular orbit.



The QuickReach™ Small Launch Vehicle Provides Extraordinary Capability with Ordinary Technology

Program Overview

Phase 2C of the QuickReach development program focuses on propulsion characterization of AirLaunch's innovative liquid oxygen (LOX)/propane vapor pressurization (VaPak) propulsion system used on the second stage. Phase 2C Milestones include upgrades to hardware, instrumentation, and test stands; and a series of test fires on the Horizontal Test Stand (HTS) to gather data on engine performance and on the Vertical Test Stand (VTS) to more comprehensively characterize second stage performance.

At the time this paper is written, AirLaunch has completed upgrades to the test stand facilities and data acquisition systems, developed and tested a water-cooled test article of the 2^{nd} stage engine for extensive engine performance testing, and completed construction of the integrated stage 2 test article.

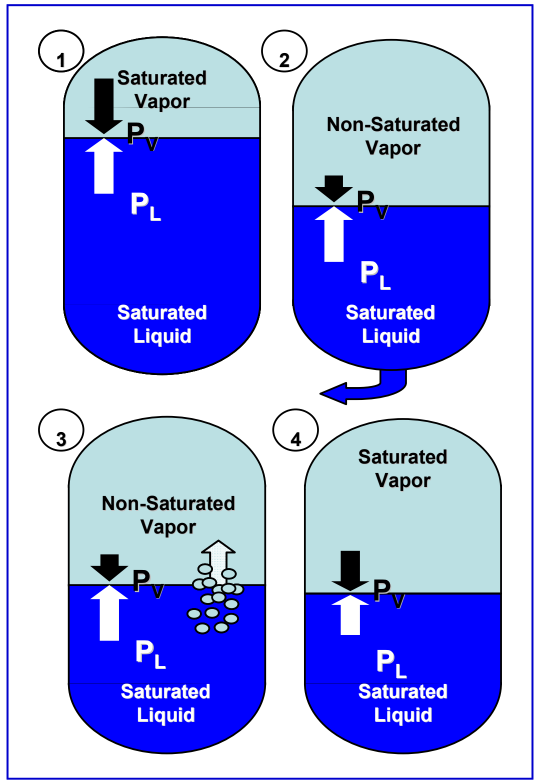
Propulsion Test Program

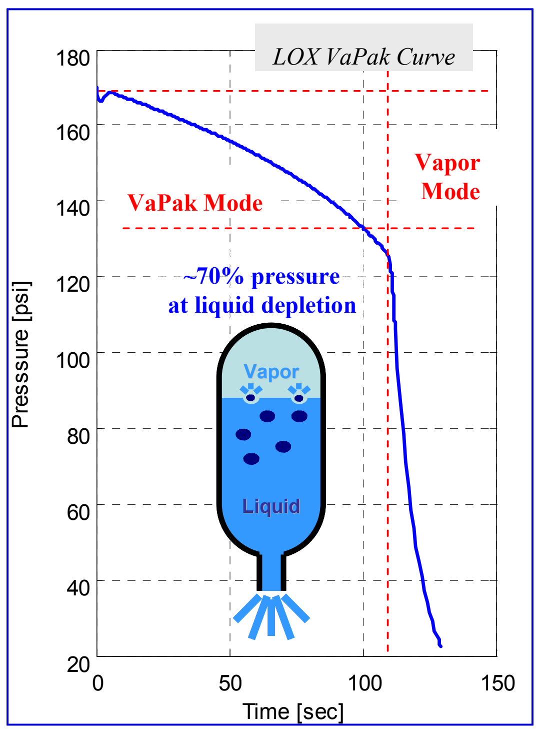
The focus of Phase 2C program activities is on propulsion aspects and associated performance impacts to the system as a whole.

~~VaPak Propulsion Technology~~

Conceived in 1960 by Aerojet, VaPak combines the simplicity and reliability of a solid rocket with the performance of a liquid propellant design. The VaPak process leverages the energy stored in the saturated propellant to force propellants out of the tanks. Initially, propellant exists as saturated liquid and vapor at equal pressure. When liquid is removed from the tank, the pressure in the vapor phase drops below the saturation point; as a result the liquid boils and the released gas re-pressurizes the vapor phase. The behavior can be tailored by selection of initial propellant loading conditions, making the system very adaptable to changing requirements and easy to scale. No pumps of any kind are used in a VaPak propulsion system. At the completion of the VaPak process (when all liquid has been expelled from the tank), approximately 70% of the initial tank pressure is still present. The remaining vapor can also be used as propellant, significantly reducing the weight of propellant residuals. The inherent pressure drop of the system provides lower burn-out accelerations and precise final orbit injection.

VaPak systems hold the promise of low complexity propulsion systems for highly reliable and cost-effective vehicle designs. VaPak eliminates costly components such turbo-pumps, gas generators, high pressure bottles, or complex valving used in a typical pump-fed launch vehicle. In conjunction with appropriate engine design, the resulting systems are equally useable for trans-atmospheric or in space operations.





The VaPak Technology employed by the QuickReach SLV enables Performance and significantly reduces System Complexity.

~~Testing Approach~~

The Horizontal Test Stand (HTS) is used for engine development and engine performance model validation. Hot fires on the HTS have a duration of approximately 20 seconds. The stand is heavily instrumented and equipped with a special tank pressurization system that enables operation of the engine at constant inlet conditions throughout the entire burn duration. This allows for operation of the engine at a fixed point along the variable chamber pressure curve it will see during flight operations. The data gathered at the HTS will be used to calibrate the engine performance predictions of the analytical model.

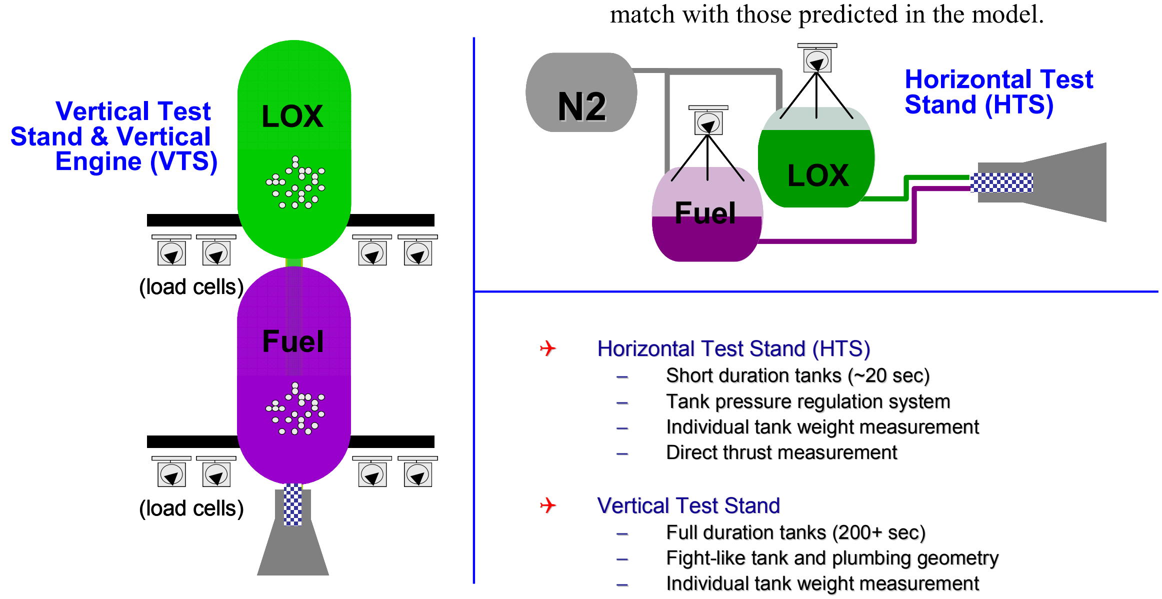
The second component of the test activities takes place on the Vertical Test Stand (VTS). In Phase 2C, the VTS uses a flight-geometry test article, allowing for multiple long-duration tests in as flight-like a configuration as possible. Propellant tank geometry, propellant feed lines, tank insulation, and the injector / thrust chamber assembly are all identical to the specifications of the flight vehicle. Instrumentation on the VTS is not as extensive as on the HTS, to prevent interference with flight-like operation of the test article. Hot-fire burn duration on the VTS will be as projected on the second stage of the flight system (~250-300 sec).

There are three components of the vehicle performance model that require validation through test data to establish confidence in system payload performance predictions: (1) engine performance, (2) VaPak (feed system) performance, and (3) integrated stage performance. Each model component validation goal is shown together with the anticipated test setup and associated key parameters being captured.

The engine performance model is based on the industry standard JANNAF Two Dimensional Kinetics code. The model produces engine performance predictions (thrust, specific impulse, etc.) as a function of oxidizer-fuel ratio (OF), chamber pressure (Pc), and system specifications. The purpose of the test series is to determine the lower bound of the engine performance map as produced by the model. Historically, the TDK code has produced engine performance models within 98%-101% of the engine performance measured on the test stand. The data from this test series will be used to recalibrate the engine performance model for both the test and the flight configuration, within the lower bound of achievable testing accuracy.

The second component of the integrated performance model to be validated is the VaPak performance model (propellant feed/pressurization system performance). It is modeled using an idealized enthalpy balance approach; the model also does account for non-ideal effects such as startup-transients, thermal energy exchange between the tanks and their environment, and the impact of flow-work in propellant feed lines. These effects are incorporated in the form of engineering correction factors to the idealized model, and are calibrated with test data from the VTS.

The third component of the performance model validation effort is integrated stage performance. The integrated stage performance model combines the engine performance model and the VaPak performance model by use of a mass-flow balance. The model is validated when the history of tank pressure vs. time and chamber pressure vs. time, as observed on the VTS, match with those predicted in the model.



The AirLaunch Propulsion Test Program for Phase 2C is conducted on complementary Facilities.

Horizontal Test Stand (HTS) Activities

A number of significant modifications have been made during Phase 2C, including a new thrust structure, larger propellant tanks with an improved weighing system that will yield much more accurate mass flow data, and an updated sensor and instrumentation suite (including a built-in system for calibrating all transducers). These modifications address the lessons learned in obtaining accurate measurements on the HTS during Phase 2B. The upgraded instrument suite provides for higher-fidelity measurements of chamber pressure, and propellant temperatures and pressures, and thus will allow more accurate determination of propellant flow rates. The upgraded test stand is sited in the Protoflight East Test Area, collocated with the Vertical Test Stand, in Mojave, CA.

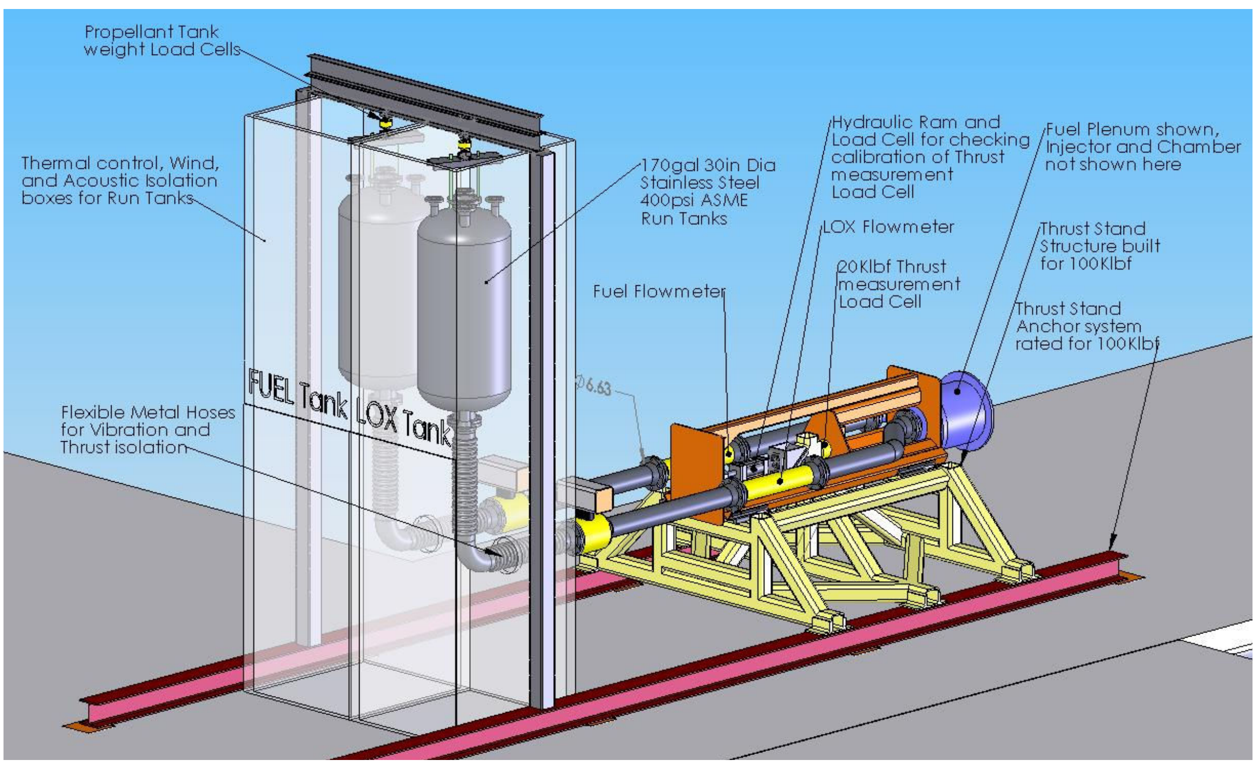
Test Article

The ablative chamber used on the flight system is also used on the VTS. However, to reduce the number of variables (throat area variation) and increase the rate at which test can be conducted, a water cooled chamber with flight-like geometry (but a truncated nozzle) is used for all HTS testing.

The chamber/nozzle unit consists of two mild steel pipe drums with a liner section fabricated of spun Inconel 718 that slips into the drum, and has a series of drilled holes that act as orifices for water jets. The water sprays onto the Inconel liner, cooling it. Water fills the plenum area and exits through a series of outlets distributed evenly around the plenum. Another outlet is located in about the middle of the chamber area in order to drain the chamber plenum between hot fire tests. Water flow rate through the system is 3,000 gallons per minute.

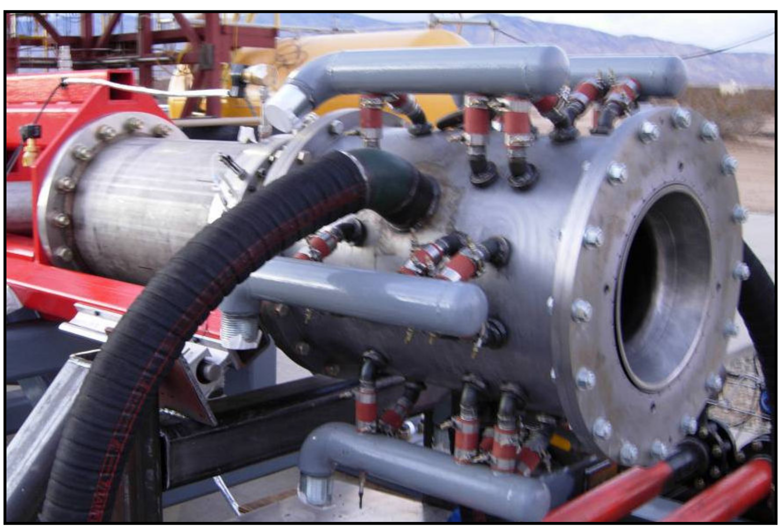
Results of Phase 2C Tests to Date

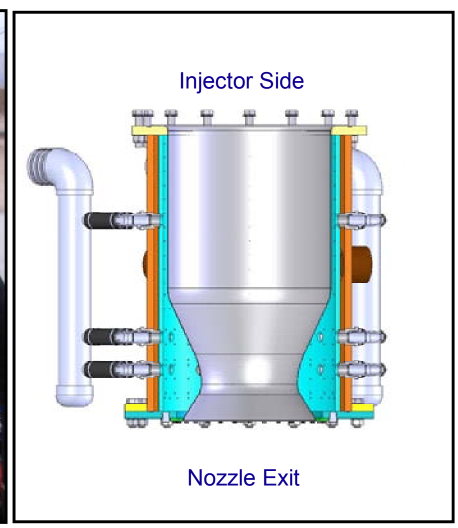
AirLaunch has conducted four hot-fire tests and several cold-flow tests on the HTS to date in Phase 2C. Initial tests were aimed at shaking down the new facility and data acquisition system, as well as verifying operation of the water cooled chamber (see next page). Results indicate excellent durability for the updated test article and data acquisition has been significantly improved over 2B activities. Engine performance characterization tests are expected to be conducted over the summer.



The AirLaunch developed Horizontal Test Stand (HTS) enables Rapid Engine Performance Evaluation.

AirLaunch passed the Horizontal Test Stand (HTS) Readiness Review Milestone in early 2008. The new HTS is on the left; the Vertical Test Stand is on the right, shown with the flight-weight Integrated Stage 2 test article used in Phase 2B.





Use of the Water-Cooled Test Engine enables Rapid and Repeated Testing of the Engine at Minimum Cost.

Vertical Test Stand (VTS) Activities

In Phase 2C, AirLaunch has also modified the Vertical Test Stand (VTS) and the system test article. These modifications improve engine and stage performance; increase confidence in the measurements taken during testing; and incorporate lessons learned from Phase 2B testing regarding combustion stability, mass flow measurement, and mixture ratio variation throughout the burn.

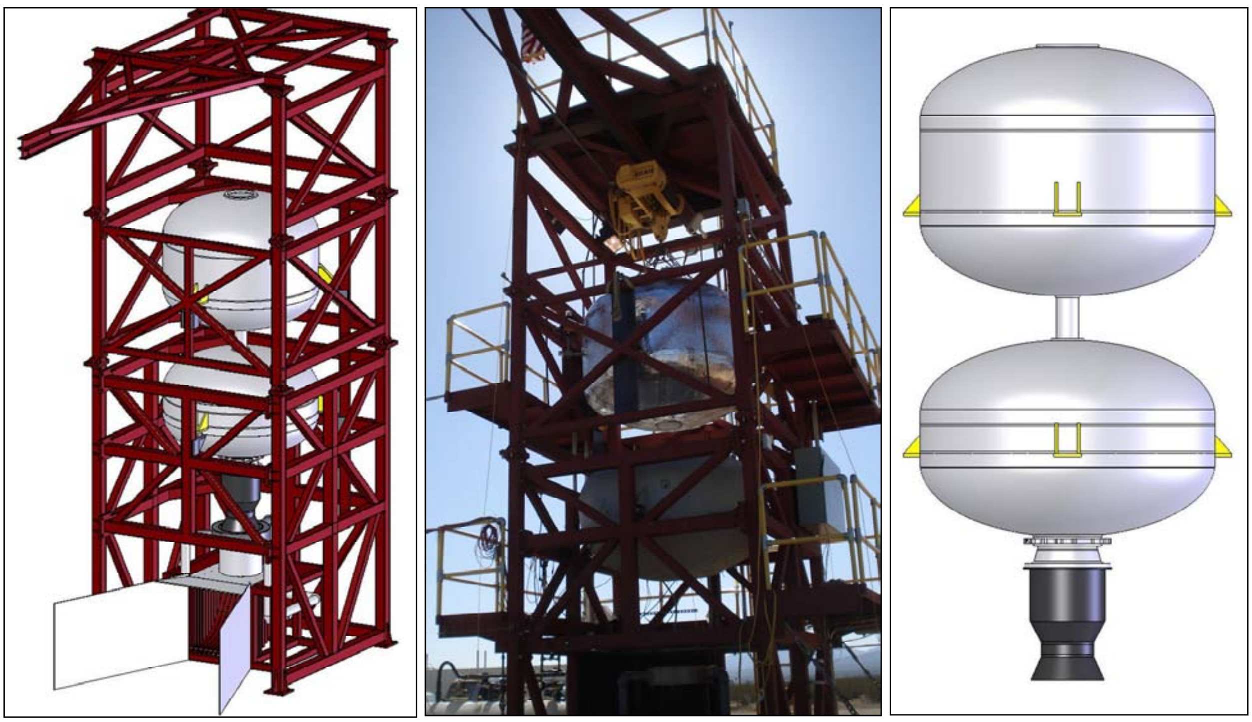
Changes made to the vertical test stand structure include attachment of new crossbars to mount the Test Stage 2 (TS2) higher in the test stand than it was during Phase 2B. This change accommodates insertion of an L* extension (for improved engine performance) and inclusion of a LOX isolation valve external to the LOX propellant tank.

Secondly, the flame deflector panels were reoriented inward to avoid flame impingement on the newly collocated horizontal test stand.

~~Test Article~~

The 2nd stage design has been modified by eliminating the common bulkhead used during Phase 2B, addressing difficulties in propellant thermal management encountered in the previous phase. Physically separating the two tanks also provides the capability to separately weigh the tanks, permitting a better measurement of propellant mass and mixture ratio during testing.

The upgraded VTS hardware is now in place. Hot fire tests on the VTS with the new 2nd stage test article configuration are anticipated to commence in late summer/early fall, following the HTS test series.



The AirLaunch updated Vertical Test Stand (VTS) and Full Size Stage 2 Test Article are nearing completion.

Flight Applications

As part of Phase 2C, AirLaunch is evaluating various applications of AirLaunch's propulsion technology and vehicle configurations. For example, at the end of Phase 2C, the company will have a well-characterized and tested, restartable second stage liquid engine, with performance of ~25,000 pounds thrust. Such an engine may be applied as an upper stage for other launch systems.

In addition, the company is exploring other aircraft options in addition to the C-17. AirLaunch received its Gravity Air Launch (GAL) patent on March 4, 2008. This system is compatible with other cargo aircraft such as the C-5 and An-124.

The company's "Trapeze Lanyard" (t/LAD) extraction methodology is patent pending, and can be used for deploying the QuickReach™ vehicle from underneath an aircraft, such as a DC-10 or 747.

This concept was explored as part of t/Space's bid to NASA's Commercial Orbital Transportation Systems (COTS) program.

The definition of Phase 2C of the Falcon SLV program is still in progress. AirLaunch's goal is to identify a path that leads to the earliest possible demonstration flight with opportunities for small payloads and rideshare.

Summary

AirLaunch has made significant progress in its development of the QuickReach™ SLV. Phase 2C of the program is well underway and focuses on propulsion system improvements and performance verification.

The QuickReach™ SLV uses a VaPak based propulsion system, which is validated on two test facilities. The Horizontal Test Stand (HTS) is used for engine performance tuning and validation testing, while the Vertical Test Stand (VTS) is used for integrated 2nd Stage testing. HTS facility upgrades have been completed, including the design, construction, and shakedown testing of the new water-cooled chamber for rapid engine testing. VTS facility upgrades have also been completed, and a new test article with updated tank configuration is in place for testing to commence in mid 2008.

In Phases 1, 2A and 2B, AirLaunch completed 2 stage separation tests; assembly of the integrated LOX/propane tankset for stage two and the vertical test stand; over 50 engine test firings of the 2nd stage engine on the Horizontal Test Stand and 5 test fires of its Integrated Stage 2 on the Vertical Test Stand; assembly of the payload fairing and payload fairing separation test; series of ground drop tests and 3 record- setting C-17 drop tests with a simulated full-scale, full-weight QuickReach™ rocket (at 66 feet long and 72,000 pounds); and an Incremental Critical Design Review.

The QuickReach™ SLV is designed to meet the needs of the DARPA/Air Force Falcon SLV program: deliver 1,000 pounds to low earth orbit (LEO), for $5M per flight, with response time of less than 24 hours. Operationally responsive space would allow the government to react quickly and use small satellites equipped with sensors to monitor and provide communication for urgent military needs. Having a quick reaction launch system that can launch specialized small satellites will provide the warfighter with real-time data and communication during time-urgent situations. AirLaunch's system achieves responsiveness by launching from an unmodified C-17 or other large cargo aircraft.

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