DARPA's RASCAL: Status, Challenges, and Accomplishments

Jacob Lopata
The Space Launch Corporation
18881 Von Karman Avenue, 17th Floor, Irvine, CA 92612; (949) 486-0880
lopata@spacelaunch.com

Preston Carter
Defense Advanced Research Projects Agency
3701 North Fairfax Drive, Arlington, VA 22203; (703) 696-7500
phcarter@darpa.mil

In March 2002, the Defense Advanced Research Projects Agency (DARPA) initiated the Rapid Access Small Cargo Affordable Launch (RASCAL) program and established the goal of creating a launch system capable of responsively and routinely placing small payloads into orbit at significantly reduced cost. RASCAL is a highly responsive, economical launch system capable of placing a 150 kg payload into an easterly low-Earth-orbit at a recurring cost below $10,000/kg. The RASCAL system consists of a reusable aircraft as the launch platform for a two-stage expendable rocket vehicle (ERV). A significant feature of the RASCAL aircraft is the ability for exo-atmospheric flight using a propulsion enhancement known as Mass Injection Pre-Compressor Cooling, or MIPCC. As we approach the end of Phase II in the fall of 2004, a design configuration update and discussion of major technological challenges and successes is provided. Specific discussions of system performance and risk mitigation testing are included.

INTRODUCTION

In March 2002, the Defense Advanced Research Projects Agency (DARPA) initiated the Rapid Access Small Cargo Affordable Launch (RASCAL) program and established the goal of creating a launch system capable of responsively placing payloads into orbit at significantly reduced cost. Once operational, the RASCAL system will have the ability to covertly launch a tactical satellite within hours of threat identification from any number of existing airfields in CONUS.

The RASCAL system consists of two major subsystems; a reusable aircraft incorporating enhanced air-breathing propulsion and a two-stage expendable rocket vehicle. The RASCAL aircraft utilizes heritage turbojet propulsion with a 'bolt-on' propulsion modification known as Mass Injection Pre-Compressor Cooling, or MIPCC. This propulsion enhancement allows for increased Mach number and altitude operations without exceeding the normal operating envelope of the turbojet engines.

Carried internally to the RASCAL aircraft, the two-stage Expendable Rocket Vehicle, or ERV, consists of a hybrid motor first stage and a solid motor second stage. The ERV also incorporates a smart guidance and propulsion stage called the Head-End-Module, or HEM, that provides all guidance and control for the ERV from release to payload insertion. The ERV, which is deployed exo-atmospherically at a dynamic pressure of less than 1 psf, has a simple thrust bearing structure and requires no payload shroud. Limiting the ERV to exo-atmospheric flight greatly simplified the ERV design resulting in significantly reduced recurring costs compared to traditional air and ground launched rockets.

In order to accomplish an exo-atmospheric release of the ERV, the RASCAL aircraft must perform a high Mach 'zoom-climb maneuver'. In this maneuver, the RASCAL aircraft accelerates in level flight using MIPCC to a velocity in excess of Mach 3 before initiating a wings level, 4 g 'pull-up'. During this maneuver the vehicle climbs near vertically until the dynamic pressure drops below 1 psf.

By injecting water and then oxygen upstream of the compressors, the turbojet engines in the RASCAL aircraft will operate to altitudes in excess of 90,000 ft during the zoom-climb maneuver. Beyond this altitude the engines are shut down in a controlled manner and the vehicle enters a ballistic coast up to the point of ERV release (Figure 1).

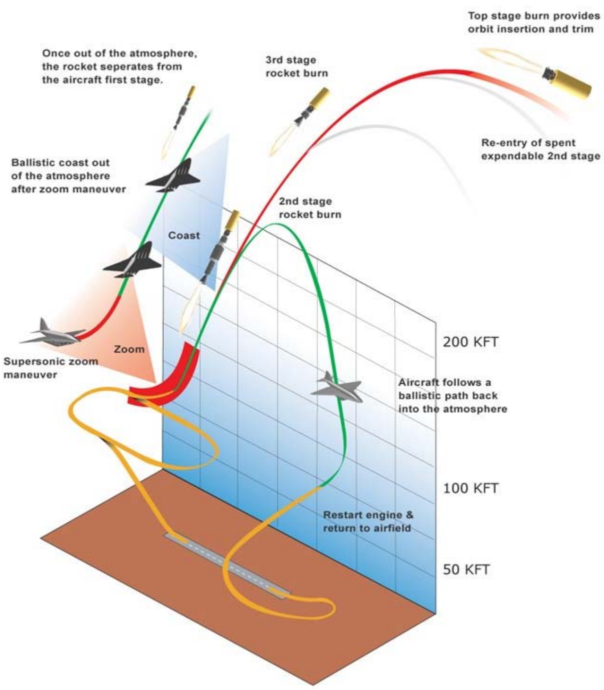

Figure 1. A Typical RASCAL Zoom-Climb Maneuver

The RASCAL program is currently more than half way through Phase II, an 18-month design and risk mitigation phase that commenced in March of 2003 with the selection of The Space Launch Corporation (SLC) of Irvine, California as prime contractor, with Scaled Composites as the lead subcontractor for the RASCAL aircraft.

Phase II of the RASCAL program will provide for a better understanding of MIPCC through continued analytical studies of engine cycle and evaporative cooling models. Ultimately ground testing of an F100-class engine at simulated Mach numbers up to 3.5 and altitudes up to 100,000 ft will be conducted at a DARPA funded test bench constructed in Mojave, California.

Phase III, which is scheduled to begin in October of 2004, will serve as the construction, test, and demonstration phase of the RASCAL program, with flight tests scheduled to begin in CY '05. The flight test program is scheduled to culminate with the launch of at least two orbital payloads in CY '07.

SYSTEM CONFIGURATION AND PERFORMANCE

Through the course of phase II, the RASCAL system design evolved from an aircraft with a twin tail, single delta wing planform incorporating a bottom loading ERV bay between dual twin-engine pods to an aircraft with a double delta wing/chine configuration incorporating a single tail and a top loading ERV bay (Figure 2).

Figure 2. Final RASCAL System Configuration

The 3-stage launch system (1st stage aircraft and 2-stage rocket vehicle) operates at speeds and altitudes in excess of Mach 3 and 180,000 ft respectively. The system is capable of placing up to 110 kg into a 500 km sun-synchronous orbit or 150 kg into a 500 km orbit inclined at 28.5° to the equator, exceeding the government's initial payload requirement by 32%.

The realization of this final configuration was the result of a significant, integrated design effort coupling structural, aero, propulsion, and trajectory analyses for both the RASCAL aircraft and ERV. In parallel with the design effort, a series of subsystems tests are currently being conducted to reduce programmatic and technical risk through the validation of analytical models.

THE RASCAL AIRCRAFT

The RASCAL aircraft is a low wing supersonic aircraft with a 59 ft wingspan, 102 ft length, and a 2100 ft^2 wing area. The 100,000 lb gross weight vehicle incorporates four F100-PW-200 turbojet engines, all with water and liquid oxygen MIPCC spray bars upstream of the engine compressors (Figure 3). In terms of overall size, the RASCAL aircraft is comparable to another Mach 3 aircraft, the SR-71 (Figure 4).

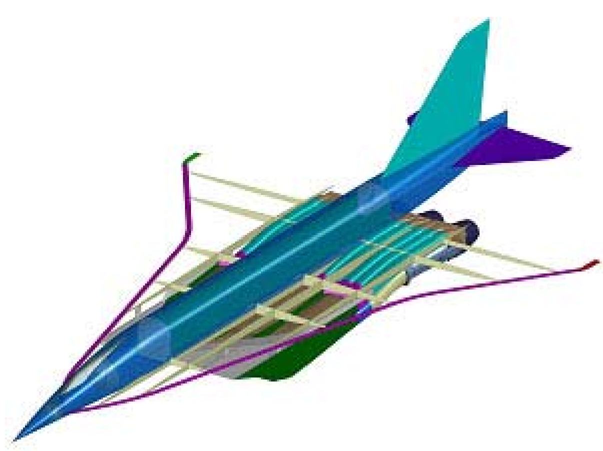

Figure 3. The Mach 3 RASCAL Aircraft

The aircraft will have accommodations for a single pilot but will be capable of conversion for remote piloted or autonomous operations. The aircraft will operate from conventional airfields with a runway length of only 2500 m and be capable of quick turnarounds in order to maximize mission sortie rate. And unlike ground-launched systems, which have a launch event that can be observed from the ground, missions utilizing the RASCAL aircraft can be accomplished covertly, over water from extremely high altitude.

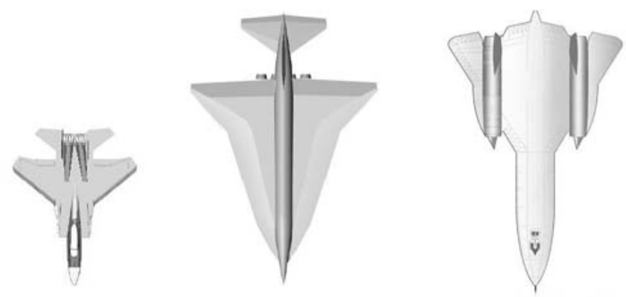

Figure 4. Aircraft Size Comparison: An F-15, the RASCAL Aircraft, and the SR-71

Over the course of the past 17 months, significant progress has been made in the development of the RASCAL aircraft. In addition to the latest design configuration, which meets all government performance requirements, subsystem risk mitigation testing has taken place that has validated the design approach of the contractor team. The testing that has been accomplished to date involves the ground testing of MIPCC and sub-scale inlet test in a supersonic wind tunnel.

In the 4th quarter of 2003, construction on the DARPA funded MIPCC Test Bench (MTB) was completed with the goal of ground testing a complete MIPCC system using the engine that will eventually power the RASCAL aircraft – an F100-PW-200. This test bench has the ability to flow both water and liquid oxygen into a manifold upstream of a turbojet engine and create simulated flight conditions up to a velocity of Mach 3.5.

The simulation of high-speed flight conditions on the ground is accomplished by filling a large steel plenum with the exhaust of a turbojet engine (Figure 5). The hot exhaust from this source engine is supplemented with liquid air and oxygen to obtain a flow with a temperature, pressure, and composition similar to high Mach flight. The outflow from the plenum is fed directly into the MIPCC duct of the test engine where water and liquid oxygen are injected according to a predetermined schedule.

Figure 5. J79 Source Engine Feeding into the Plenum at the MIPCC Test Bench in Mojave

In March of this year, initial shakedown runs using a J85 engine were performed at the MTB as a precursor to testing with a F100-PW-200 engine. During these initial runs, both water and liquid oxygen were injected into the J85 MIPCC duct with promising results. The initial data indicated that with both water and oxygen injection, a 2-fold increase in engine thrust could be achieved (Figure 6).

The F100-PW-200 engine to be used in testing at Mojave was procured from Pratt & Whitney Serviceable Military Assets in San Antonio, TX, earlier this year. It was subsequently checked out and trimmed at Edwards Air Force Base in California before delivery to The Space Launch Corporation in Mojave for integration into the MTB along with the MIPCC duct (Figure 7). MIPCC testing with the F100 engine is due to be completed this summer.

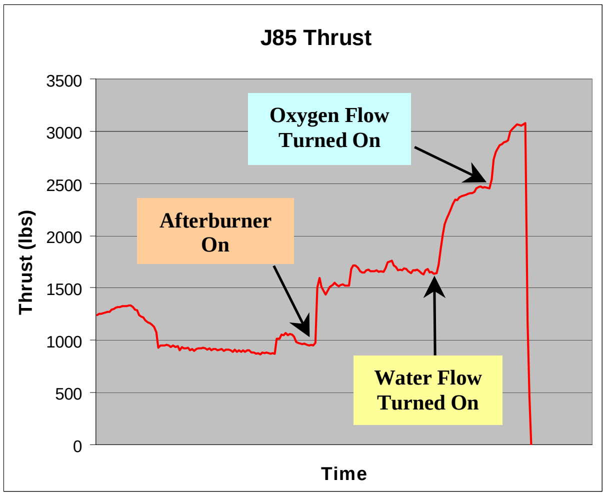

Figure 6. Thrust Profile for the J85 Engine with the Addition of MIPCC (Inlet Condition: M=1.7 at 40kft)

In addition to MIPCC, testing is underway in a supersonic wind tunnel with a 10% scale model of a single RASCAL supersonic inlet. This model, which includes movable ramps, is being used to validate the inlet design of the RASCAL aircraft with respect to the internal handling of large amounts of bypass air. In order to obtain enough airflow during the zoom maneuver at altitudes approaching 100,000 ft, the inlets for the RASCAL aircraft were designed with a very large capture area.

Figure 7. The MIPCC Duct Test Article for the F100 Engine (top) with Water and Liquid Oxygen Spray Bars Visible Inside the Duct (left)

At low altitude these large inlets swallow much more air than is required by the engines. Traditionally this excess air would be allowed to “spill” off around the inlet. Allowing spillage significantly increases the drag associated with the propulsion system so the design team opted for an internal bypass system to handle the excess air while at low altitude. A bypass system of this kind has never been attempted until now and the validation of the inlet design at sub-scale is considered a major risk mitigation step. The model is also being used to validate the self-start capability of the inlet as well as the CFD model used to design the inner and outer mold lines of the inlet (Figure 8).

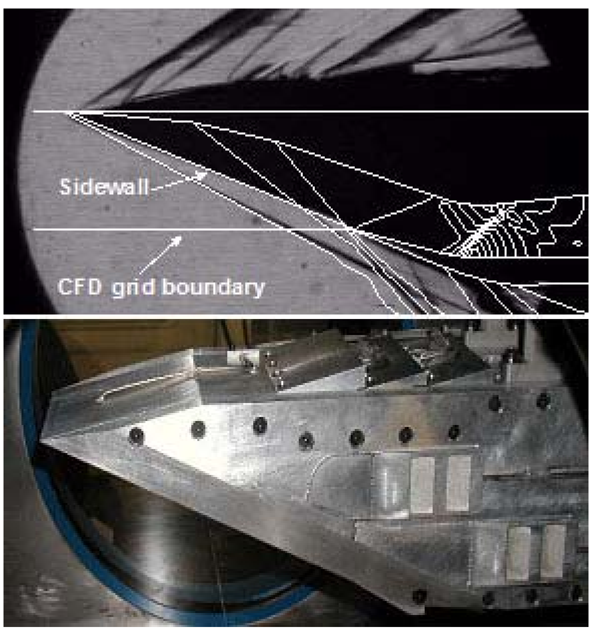

Figure 8. High-Speed (Mach 2.5) Schlieren Image with Superimposed CFD Shock Train Demonstrating a Successful Self-Start (top), and the Sub-Scale Inlet Model in the Tri-Sonic Wind Tunnel (bottom)

THE RASCAL EXPENDABLE ROCKET VEHICLE

The RASCAL ERV is a simple, two-stage vehicle employing a hybrid rocket motor (solid fuel and liquid oxidizer) for the first stage, a solid rocket motor for the second stage, and a small guidance and propulsion stage called the Head-End-Module, or HEM (Figure 9). Representing 75% of the recurring cost of the RASCAL system, the design for the ERV was optimized with respect to cost from both an engineering and operational perspective.

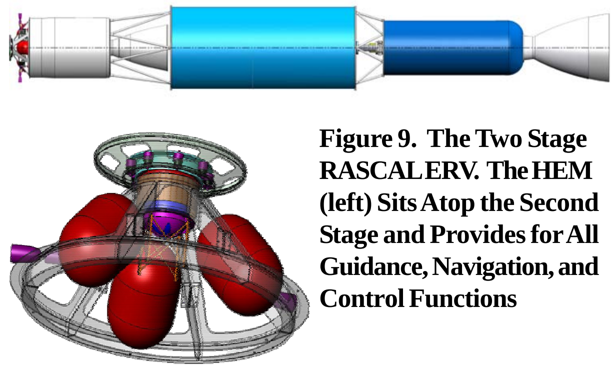

Figure 9. The Two Stage RASCAL ERV. The HEM (left) Sits Atop the Second Stage and Provides for All Guidance, Navigation, and Control Functions

A certain degree of cost savings result from the ability to launch the ERV exo-atmospherically. As the dynamic pressure after release from the RASCAL aircraft is never greater than 1 psf, the ERV was designed with simple thrust structures that do not need to account for atmospheric forces. As a result, the ERV structure is simple, lightweight, and low cost. In addition, the low dynamic pressure negates the need for a payload shroud which further reduces ERV cost and weight.

The hybrid first stage is a 30,000 lbf motor that utilizes storable, non-toxic propellants (98% H_2O_2 and aluminized HTPB). This stage incorporates an innovative pressurization system that eliminates the need for separate pressurant tanks and valves, simplifying the design of the first stage motor and significantly reduces recurring cost.

A full-scale heavy weight prototype of the first stage motor is due to be tested at The Space Launch Corporation’s test facility in Mojave, CA this fall. To date, significant sub-scale hybrid motor testing has occurred that is providing burn rate data critical to the design of the full scale motor (Figure 10).

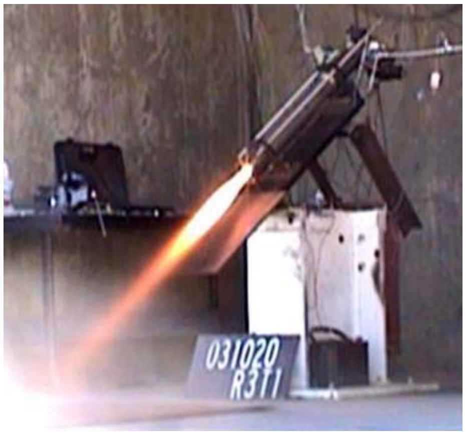

Figure10. Sub-Scale Motor Testing to Acquire Burn Rate Data for the Design of the Heavy Weight Hybrid Rocket Motor

The solid propellant second stage is a new Alliant Techsystems design that includes a number of new technologies and production processes in order to reduce recurring cost. Non-traditional filament wound composite case materials, throat materials and manufacturing techniques are currently being investigated as means to reduce the cost of solid motor production by a factor of 10 compared to traditional space motors. A full scale heavy weight test of the stage 2 motor is due to be conduced by ATK in Elkton, MD before the end of Phase II to validate key technologies and motor ballistic design.

At the top of the ERV stack is the Head-End-Module, or HEM. The HEM is being designed by The Space Launch Corporation and is the true brain of the ERV. The HEM provides all command and control functions for the ERV eliminating the need for avionics or thrust vector control on the individual stages, thereby simplifying and significantly reducing the cost of the ERV. The HEM also serves as an upper stage providing for final payload insertion and 300 m/s of additional delta-V reserve for on orbit maneuvering.

The HEM is actually much more than a smart upper stage. From a functional standpoint, the HEM is being designed as a satellite bus that will be able to support various payloads by incorporating modular subsystem add-ons. Analogous to a "Heath Kit", these modular subsystems will allow the user community to quickly build a HEM bus to meet the needs of a specific payload, whether that payload is a imaging sensor, a transponder, or any number of space test payloads.

Examples of available add-ons are solar panels, sensors for fine pointing, and thermal control devices. With the ability to support individual payloads directly without the need for a separate satellite bus, the ERV will provide a complete turn key solution for the user community at the lowest possible total mission cost.