WEAPONS goes hypersonic

DARPA's step-by-step pursuit of futuristic aerospace vehicle technologies may someday yield sustained air-breathing cruise speeds of Mach 7 or more

by **John Croft**
Contributing writer

Steven Walker's project has all the ingredients of a science fiction novel—rockets, ramjets, scramjets, single-stage-to-orbit shuttles, hypersonic cruisers, and unmanned drones that skip along the atmosphere's roof like flat stones on a smooth pond.

There is nothing fictional about the project's ultimate goal, however: to provide the Dept. of Defense with a family of vehicles that can express-deliver "conventional" munitions to a hostile location anywhere on Earth in 2 hr or less, hitting within 10 ft or less of a target at an impact speed of 4,000 ft/sec.

Walker is a program manager at DARPA, and his project is called Force Application and Launch from the Continental U.S. (FALCON).

As it matures, FALCON promises to offer a plethora of juicy design and fabrication challenges for the aerospace community in the area of high-speed mechanics and the problems such speed entails. Walker's project and follow-on efforts will have to advance the state of the art in thermal control, engines, communications, and countless other flight systems. FALCON's gift to the future, in addition to a more potent and efficient military, could in theory include commercial flights from Washington to Singapore with just one in-flight movie.

DARPA created FALCON as the first step in a "long-view" plan to provide the Dept. of Defense with a reusable hypersonic cruise vehicle (HCV) by 2025. The desired traits of the cruiser are still largely the stuff of science fiction: The HCV is to take off and land on a conventional military runway, carrying a 12,000-lb payload

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of gliding weapons pods called Common Aero Vehicles, cruise missiles, and "small-diameter bombs" or other munitions. The program manager envisions a build program similar in size to that of the B-2 bomber, with a total fleet size measured in tens or twenties.

Faster than a speeding Blackbird

The cruiser's objective is to deliver the munitions to a target 9,000 mi. away—the other side of the Earth—in less than 2 hr and have "reusability consistent with airplane-like operations," according to DARPA. Basic mathematics says this will require an average speed of 4,500 mph, or roughly Mach 6. A vehicle is considered hypersonic at speeds above Mach 5.

The world's fastest vehicle in the horizontal-takeoff, horizontal-landing category, at least as far as the civilian world knows, is the turboramjet-powered SR-71, which cruises at more than Mach 3 for 3,200 mi. at altitudes greater than 85,000 ft. Even the rocket-propelled X-15's top recorded speed—Mach 6.7—could pale in comparison to what is expected of the HCV.

More than doubling the Blackbird's capabilities will require some ingenuity. The agency states in its FALCON proposal materials that the government "seeks to open up the design space and provide a catalyst for exploring 'clean sheet of paper' system design philosophies and global strike mission scenarios, especially for far-term approaches."

If the HCV is to have the ultimate in operational characteristics—adequate payload, full reusability, global coverage in two hours, and a horizontal takeoff and landing—it is almost a certainty the vehicle will have to fly at hypersonic speeds and use a scramjet engine.

According to NASA and others, a hypersonic vehicle must have an air-breathing engine that creates thrust by scooping in atmosphere and mixing it with fuel, rather than carrying an oxidizer along as a rocket does, in order to optimize its payload. And to achieve and maintain hypersonic cruise speeds, the vehicle will most likely have to incorporate a supersonic combustion engine (scramjet). The requirements set the stage for the huge amount of research, development, and testing that awaits FALCONers of today and tomorrow. Just ask NASA.

The turboramjet-powered SR-71, or Blackbird, cruises at more than Mach 3.

The X-43A (above, beneath the B-52 wing) was part of NASA's Hyper-X propulsion program. As a follow-on, Boeing's Phantom Works was designing the X-43C at right.

Hyper-X activities

In March, following a failure in 2001, NASA launched its second X-43A hypersonic research vehicle, which flew successfully for 11 sec. The work flight capped a seven-year development effort as part of the agency's Hyper-X program to study propulsion and related technologies for air-breathing hypersonic aircraft in flight. The flight test in 2001 yielded zero data when the Pegasus booster became unstable during its boost phase and the vehicle had to be destroyed. NASA has one more flight scheduled for the X-43A, sometime later this year.

Just getting the X-43A's engine started takes great effort—the 12.3-ft-long lifting body, attached to the front end of an Orbital Sciences Pegasus booster, is dropped from under the wing of a B-52 cruising at 40,000 ft; the booster fires and accelerates the vehicle to 100,000 ft and Mach 7, after which the gaseous-hydrogen-powered scramjet fires for several seconds.

NASA's follow-on vehicle, the X-43C, was being designed by Boeing Phantom Works and Allied Aerospace. Unfortunately, however, for budgetary reasons, NASA Administrator Sean O'Keefe announced the cancellation of the X-43C program earlier this year. (See "Speeding into oblivion?," page 3.)

Hyper-X followed in the footsteps of the 1980s-era X-30 National Aerospace Plane, a joint Air Force-NASA program that developed and demonstrated scramjet engines and high-temperature materials, but ultimately faded away. The X-30 was designed to take off and land on standard runways and cruise between any two points on the Earth in 2 hr, at cruise speeds up to Mach 12, using a scramjet fueled with liquid hydrogen and atmospheric oxygen.

The X-30 National Aerospace Plane program was a precursor to the Hyper-X vehicles.

Walker says its demise in 1993 in part resulted from trying to do too much too soon in the push for a reusable hypersonic system: "They weren't willing to do a stair-step approach." Other contemporary programs include the Navy and Air Force efforts to test hypersonic engines on missiles, according to Walker.

Realistic goals

For FALCON, Walker started with somewhat more meager goals, using tried and true rocket technology to loft hypersonic gliders to the upper reaches of the atmosphere or into LEO, while steadily building toward the technologies that could make for a realizable, reusable HCV. By using rockets, the military in theory can achieve its global reach goal by 2010 using hypersonic gliders instead of hypersonic cruisers, and information from the gliders will help with the HCV development. Walker earned a doctorate in aerodynamics and airframe/propulsion integration from Notre Dame and is the former program manager for the Air Force's Office of Scientific Research for Hypersonics.

In November 2003, DARPA elected 11 winners from 29 contractors bidding for two tasks in the initial phase of the FALCON program. Task 1, awarded to nine companies, is a six-month study to develop conceptual designs, performance predictions, and demonstration plans for a small launch vehicle (SLV). Task 2—awarded to four contractors, two of which won Task 1 contracts—is a study of the HCV and various military payloads that can be placed atop the SLV to meet the global reach goal quickly.

If nothing else, DARPA's performance objectives for the SLV should provide an incentive for manufacturers to reduce launch rates on the commercial side. The agency is asking for a $5-million vehicle that can place a 2-ft×2-ft×3-ft, 1,000-lb payload into a 100-mi. circular orbit at an inclination of 28.5°, launching within 24 hr of an alert status. For nonstandard launches, the booster must have the flexibility to carry payloads from 220 lb to 2,200 lb for no more than $7,500/lb. Though proven launch vehicles built by U.S. manufacturers generally cost three or more times the $5-million base price DARPA seeks, the potential for bulk orders should bring costs down in and of itself.

Elon Musk, CEO of Space Exploration Technologies in El Segundo, Calif., had to do very little to meet the intent of Task 1. Though unproven, Musk's Falcon launcher (which he is now calling Falconus to prevent confusion), comes in at $6 million, with performance numbers that match DARPA's desires quite nicely: 1,400 lb to a 125-mi. circular orbit at launch-site inclination, a per-pound-to-orbit cost of $4,000. Musk's first launch is scheduled for sometime this spring, six months later than originally planned. [See "Changing the low-cost launch game," February, page 39.]

Musk plans to offer his baseline Falconus and is asking for no associated development costs—that is, unless DARPA wants to make changes. As for meeting the $5-million price tag, Musk says DARPA's plan to buy in bulk—20 boosters a year for 10 years—will bring his costs in line. Musk bristles at the implication that the naming of his rocket had anything to do with the defense project. "Ours was named after the Millennium Falcon in *Star Wars*," he retorts. "There's no connection." In addition to Musk's company, six others won Task 1 contracts valued at $340,000-$540,000.

Gliding toward global reach

While the SLV is an enabler in FALCON's 2010 efforts, it is what the SLV will carry that is of more interest to the Defense Dept. As part of Task 2, contractors are investigating how to build what the military is calling the Common Aero Vehicle, or CAV, a 2,000-lb hypersonic glider with a variety of munitions that would be launched into a suborbital trajectory by the SLV or similar booster on a moment's notice.

Initially the CAV will carry and dispense a 1,000-lb fused "penetrator" designed to strike "deeply buried" targets at 4,000 ft/sec (2,727 mph, or Mach 3.5), with 3-m accuracy, in the space of an hour from launch to impact. DARPA wants the CAV to be able to glide 3,000 mi. along-track and 800 mi. cross-track in 800 sec, in order to hammer mobile and relocating targets. Also in the plan is an enhanced CAV, or ECAV, which is supposed to glide for 9,000 mi. along-track and 3,000 mi. across-track over 3,000 sec.

Except for propulsion, CAVs will require many of the same technological advances needed

Designing the SLV was a Task 1 activity.

An enhanced CAV is meant to glide for 9,000 mi. along-track and 3,000 mi. across-track over 3,000 sec.

for the hypersonic cruiser—such as leading-edge materials, boundary layer modeling, thermal protection, optimized trajectory, and high L/D—though perhaps with a tougher outer shell to keep the payloads from "melting" at reentry speeds as high as Mach 25 (orbital velocity).

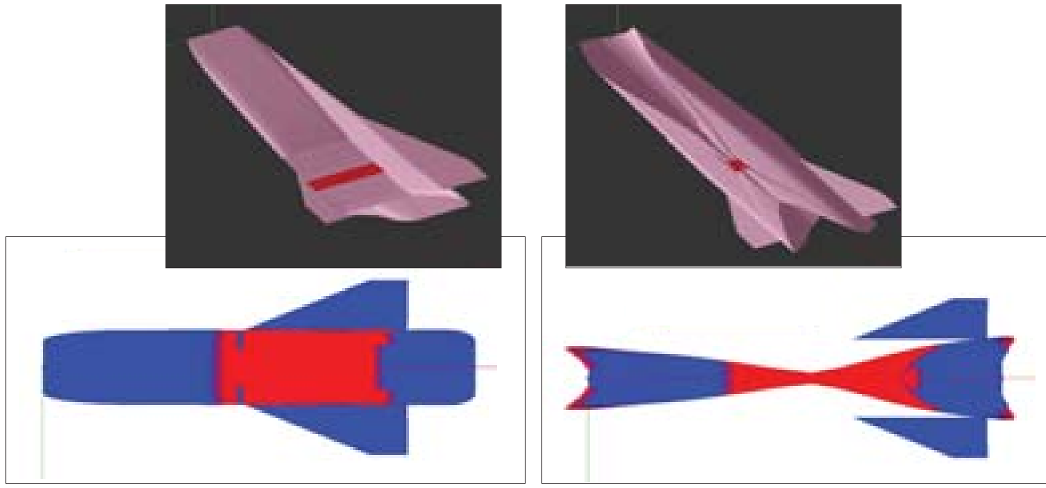
Dennis Poulos, program manager for Northrop Grumman, winner of a Task 2 contract, says the CAV is basically a reentry "shell" that will allow the military to strike globally by deploying conventional weapons through space. "Today, we have to deploy forces, or use B-2 bombers," he says.

HCV challenges

Though the CAV is "probably our primary interest," says Poulos, the company continues to work with engine manufacturers such as Pratt & Whitney, General Electric, and Aerojet to come up with potential designs for the more daunting hypersonic cruiser. Along with finding a long-term funding source and surmounting the obvious obstacles to proving out scramjets, Poulos says the HCV faces "major" challenges in areas of high-temperature structures, thermal protection, and communications systems that can handle plasma fields at Mach 8 cruise.

Walker is encouraging Task 2 contractors to come up with out-of-the-box solutions to such problems. In the thermal area, this includes looking at trajectories where the HCV would skip along the outer edges of the atmosphere to help cool the vehicle, allowing for a lighter thermal protection system (TPS). "If a skipping trajectory will work and you can get away with 20% less weight on the TPS, you can put that weight into fuel," he says.

Dissipating internally generated heat presents a monumental problem as well. Ajay P. Kothari, CEO of College Park, Md.-based AstroX, sees internal thermal problems as the key obstacle for the boxy 2D designs that NASA and others continue to test as part of the Hyper-X



The required active cooling area for the 2D shape (left) is quite different from that of the inward-turning hypersonic vehicle shape (red indicates active cooling).

program. Kothari's company has been analyzing hypersonic issues since 1987 and is currently working as a subcontractor to Seattle-based Andrews Space, a winner of both Task 1 and Task 2 contracts worth $2 million.

With hydrocarbon scramjets operating at Mach 7 (or hydrogen-powered vehicles at Mach 9), Kothari's simulations show that the adiabatic wall temperatures just aft of the scramjet's throat can reach 5,000-6,000 K. This heat must be removed via active cooling, using either onboard liquid fuel or some other means. If a 2D inlet is used, Kothari says, the vehicle must carry extra fuel simply to cool a large surface area surrounding the chamber.

Kothari advocates a 3D "inward-turning" design that simulations show can reduce the surface area that must be cooled by about 40%, though the overall mechanical design could be more complicated. With hypersonic vehicles, the structure is used not only to create aerodynamic forces but also to form an inlet for the engines on the front side and a nozzle for the exhaust on the back side.

By allowing for a lighter vehicle, Kothari says, the AstroX design could enable an otherwise undoable horizontal-takeoff/horizontal-landing, single-stage-to-orbit design for a futuristic space shuttle. Such a vehicle would take off with rocket propulsion, switch to a ramjet at Mach 3, transition to a scramjet at Mach 9, and return to rocket propulsion for the trip from Mach 15 to orbital velocity at Mach 25.

Getting away from a 2D design could be in line with DARPA's thinking as well. "We've told contractors we want to them to look at different scramjet technologies," Walker says, including the shape of the vehicle and alternative fuel injection concepts. Walker says axisymmetric, or round, structures as opposed to 2D could lead to better performance by lowering skin friction and allowing for higher inlet temperatures, assuming the analyses under way in Task 1 come to the same conclusion.

DARPA's open-mindedness is good news for Livingston Holder Jr., vice president of space systems for Andrews Space. Holder says that what his company lacks in clout, it makes up for in its ability to pursue bold new ideas. The five-year-old, 30-employee company is relatively obscure in the mega-corporate aerospace world. "Big companies tend to want to do everything in-house," says Holder. "We are able to look at what we need to get the job done, then pick and choose who we want to work with to get [it] done." Andrews is teamed with AstroX for hypersonic design, Scaled Composites for rapid prototyping, and Aerojet for propulsion and thermal protection as well as Raytheon for air-to-air weapons systems and munitions delivery systems.

Like the other aerospace firms, Andrews hopes to survive FALCON's down-select cut this summer, when DARPA and Walker will choose which companies will take the most promising results from phase one and move into a 30-36-month second phase, where contractors will develop and build prototype hardware for the launch vehicle and common aero vehicle, while continuing to study the HCV.

"That's a big step," says Holder.

Falcon Task 1 Contractors	
Air Launch LLC	Reno, Nevada
Andrews Space	Seattle, Washington
Exquadrum	Victorville, California
KT Engineering	Huntsville, Alabama
Lockheed Martin, Michoud Operations	New Orleans, Louisiana
Microcosm	El Segundo, California
Orbital Sciences	Dulles, Virginia
Schafer	Chelmsford, Massachusetts
Space Exploration Technologies	El Segundo, California

Falcon Task 2 Contractors	
Andrews Space	Seattle, Washington
Boeing Company	St. Louis, Missouri
Lockheed Martin	Palmdale, California
Northrop Grumman	El Segundo, California