ASTRID Rocket Flight Test

Our recent ground launch of the world's smallest pump-fed rocket developed at LLNL shows that our new technology can propel a miniature rocket fast enough to intercept theater ballistic missiles. We now envision cost-effective uses for the new propulsion system in commercial aerospace vehicles, exploration of the planets, and defense applications.

FOR more than 5 years, the Laboratory has been developing a new kind of liquid rocket propulsion system with support from the Department of Defense's Ballistic Missile Defense Organization. Our lightweight propulsion technology, which won an R&D 100 award in 1992, features miniature pumps that can react to thrust changes within a millisecond to meet a range of vehicle-control requirements. The thrust-on-demand, pumped-propulsion technology for spacecraft is described in more detail in the March 1993 issue of *Energy and Technology Review.* This year, we flight tested the special engine for the first time with the ground launch of the world's smallest pump-fed rocket.

Why a New Propulsion System?

The performance of small liquid propulsion systems for spacecraft has always been limited by the absence of pumps. Small propulsion systems that run their tanks and engine at about the same pressure, using no pumps in the process, represent a compromise. Their performance is constrained because designers have to settle on an intermediate value between the high pressure required so that thrusters can be small and lightweight and the low pressure required so that the fuel tanks can remain thin-walled and lightweight. Pumps would give the high pressures that are desired without the added weight needed for high-pressure tanks.

Small rocket systems now operate by adding a high-pressure inert gas to pressurize the propellant tank to slightly above thruster pressure. All spacecraft to date—including communication satellites and planetary spacecraft such as Viking, Voyager, Magellan, Galileo, Clementine, and the Mars Observer—use propellant tanks that operate at a higher pressure than the thrust chambers. Such a pressure-fed system is simple and generally reliable, but, once again, the performance is limited. In particular, tanks designed for standard spacecraft pressures of about 2 MPa (300 psi) can store and deliver 10 to 20 times their own mass in propellant. Thrusters designed to be fed from such moderately pressurized tanks typically can lift 10 to 20 times their own weight.

In contrast, our new approach—a unique propulsion system that is designed around pairs of reciprocating pumps that stroke alternately (Figure 1)—allows spacecraft to go faster and farther with less total weight than was previously possible. Low-pressure tanks compatible with our technology can hold about 50 times their own mass in propellant, and our engine (including pumps and high-pressure thrusters) can deliver thrust equal to 50 times its own weight. Figure 2 compares ASTRID with examples of existing rocket-propulsion systems. In addition to the weight of tanks and engines, this graph takes into account accessory propulsion hardware, which is found on both ASTRID and pressure-fed spacecraft. Our advance in rocketry means that it is now possible to plan a variety of missions in space with smaller and lighter propulsion packages than were feasible before.

About the ASTRID Vehicle

We just completed a year-long project, which culminated in the first flight test of our new rocket engine. Many of the propulsion components we tested in the rocket evolved over a 5-year development effort that had its origins in the Brilliant Pebbles program, which focused on new miniature interceptors. Owing in

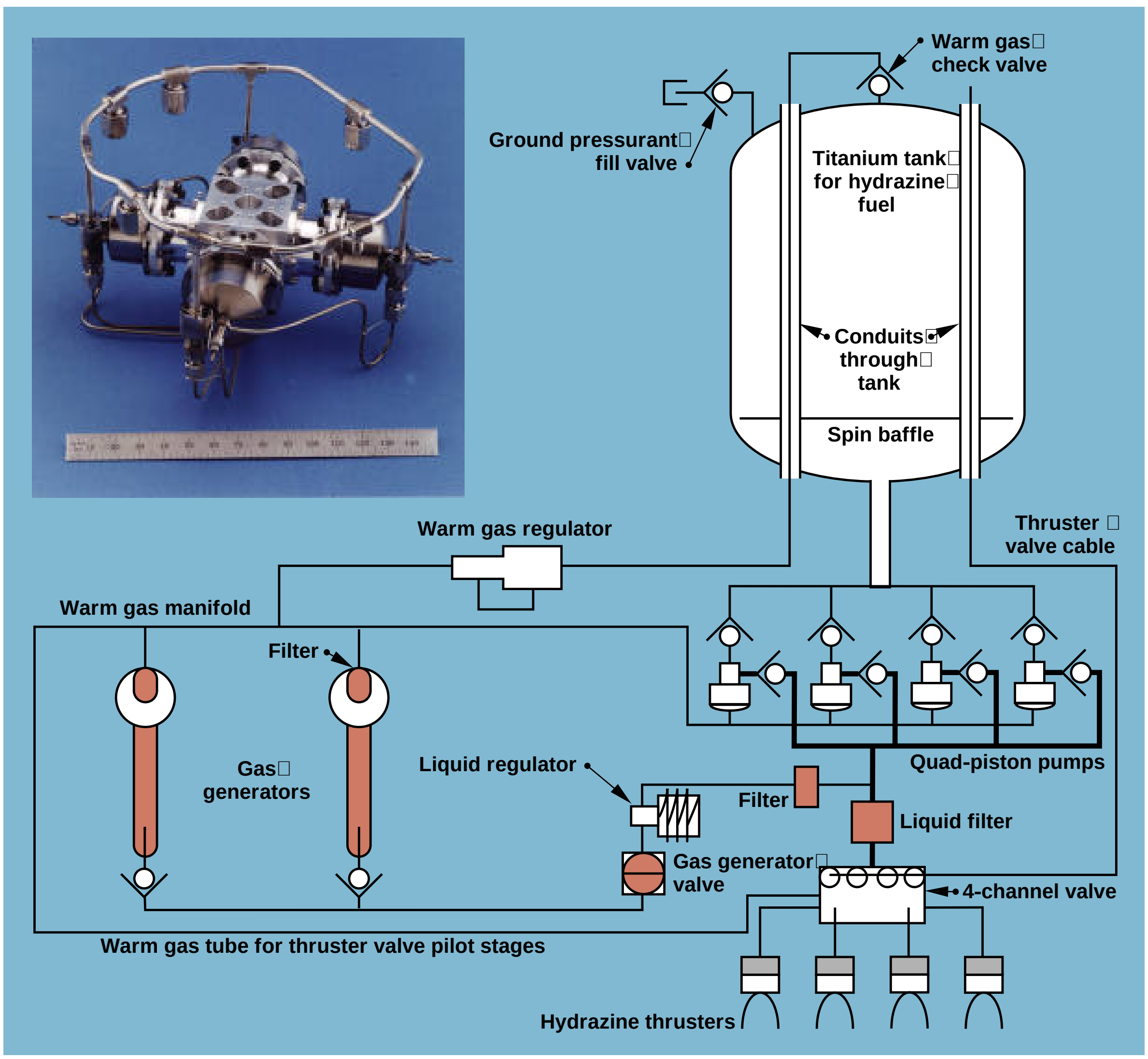


Figure 1. Our new thrust-on-demand propulsion system uses four reciprocating free-piston pumps and monopropellant hydrazine. The quad-piston pumpset (inset) delivers its own mass (365 g) in hydrazine each second at a pressure of 7 MPa (1000 psi).

part to this history, our project was named the advanced, single-stage technology, rapid-insertion demonstration, or ASTRID for short.

We built the ASTRID rocket (Figure 3) to demonstrate the feasibility of a small, high-velocity interceptor vehicle that would also be equipped with a navigation system and side-mounted thrusters for steering. Such interceptors were intended to be carried aloft and launched from unmanned, high-altitude aircraft called RAPTORs, which were being developed in parallel by the Laboratory's Theater Missile Defense Program to safeguard our military, our allies, and their population centers from hostile attacks by theater ballistic missiles. (See the article beginning on p. 1 for a description of one of the RAPTOR prototypes, called Pathfinder.)

The ASTRID project culminated in a successful demonstration of the ability of our new propulsion system to function in atmospheric flight. To minimize risks, we kept the ASTRID vehicle quite simple for the flight test. For example, we built a monopropellant machine using components already tested. Monopropellant systems are simpler and require fewer parts than the pumped bipropellant (fuel plus oxidizer) system ultimately envisioned. For added simplicity and reduced cost, we opted for a fin-guided, roll-stabilized vehicle and did not employ active flight control.

We built two complete vehicles. Vehicle assembly and most of the parts fabrication was done at LLNL; other parts were purchased. We used the first vehicle for 10- and 30-second static fire tests on the ground in November and December 1993. The second ASTRID rocket—with its innovative pumped-propulsion technology—was launched from Vandenberg Air Force Base on the morning of February 4, 1994.

As shown in Figure 4, the test rocket was 1.9 m long and had a diameter of 0.16 m. The empty mass of the ASTRID flight vehicle was 8.25 kg. Of this mass, the lightweight propulsion components weighed less than 3 kg. The airframe was basically built around the lightweight, 15.3-liter fuel tank made from a titanium alloy. We designed the tank with a large safety margin for pressure (about a factor of 4) and avoided 90% of the

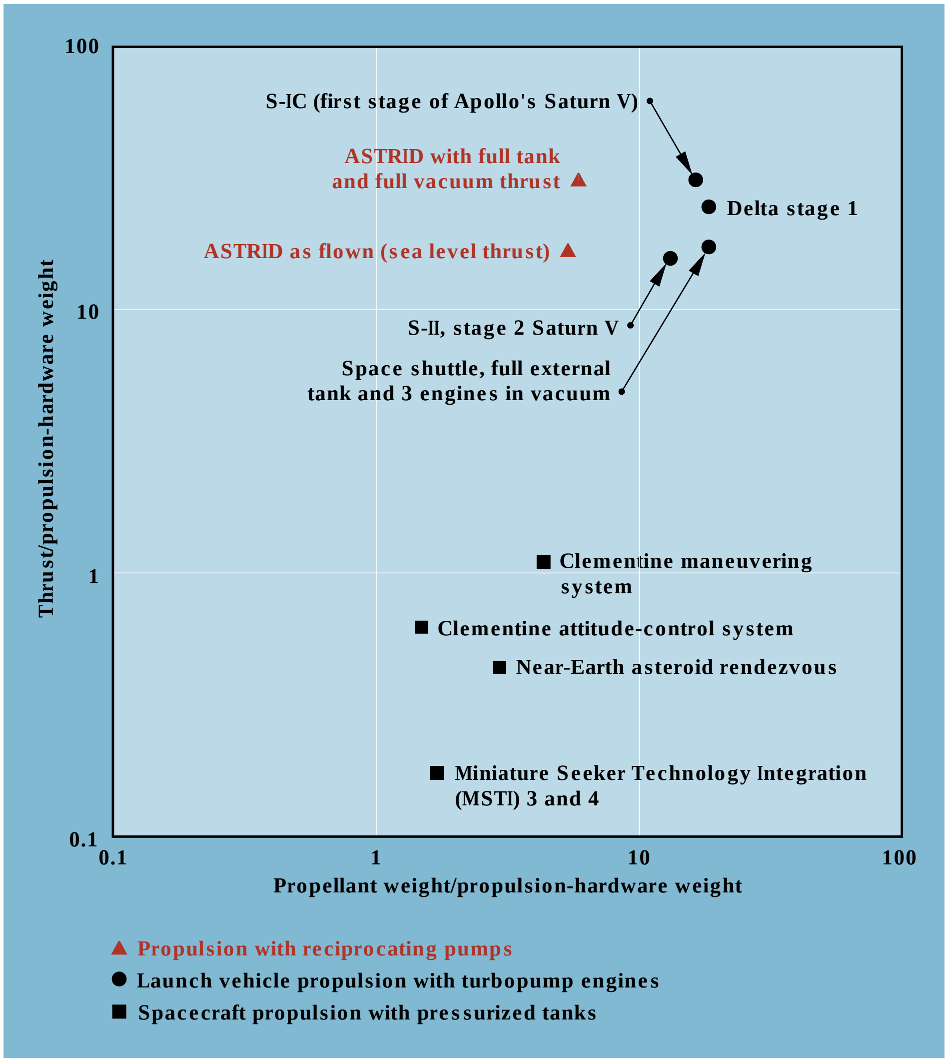


Figure 2. ASTRID compared with examples of existing rocket propulsion systems. Both propellant weight and thrust are normalized to total propulsion hardware weight (including tanks and engines) because rocket systems must provide both propellant storage and thrust with as little hardware as possible. Note that pressure-fed spacecraft systems are generally found in the lower portion of the graph, whereas high-performance, launch-vehicle propulsion systems (fed by turbopumps) fall toward the upper right. ASTRID lies near the upper right of the graph, which indicates that the LLNL piston pumps can support launch-vehicle performance capability on a small scale. ASTRID's 2.6 kg of propulsion hardware stored 12.7 kg of propellant before the flight, and delivered 440 N of thrust.

pressure safety documentation normally required for spacecraft tanks. Prior to flight, we loaded the fuel tank with 12.7 kg of industry-standard monopropellant fuel, high-purity hydrazine (N_2H_4).

The ASTRID avionics were housed in the fiberglass nose of the rocket. These components consisted of sensors for vibration, acceleration, airspeed, and system pressures; a controller to demonstrate the thrust-on-demand capability of the propulsion system; and an encoder and transmitter to relay the in-flight data.

The Launch and Flight

At first, we proposed to make ASTRID an inertially guided vehicle. However, to reduce the cost and complexity associated with flight electronics, we decided to eliminate active control altogether. This decision enabled us to focus on our primary test objective: to demonstrate the propulsion technology in the conditions of free flight. In a parallel activity at the Nevada Test Site, the engineering issues related to actively guiding an agile, small interceptor were being addressed.

We launched the vehicle, as shown in Figure 5, under essentially windless conditions from an 18.3-m-long (60-ft) rail that was set at an angle of 80 deg from horizontal. After the rocket left the rail (Figure 6), fixed fins on the aft section provided aerodynamic stability and guided the rocket in a gravity-turn trajectory. The four fins were canted to induce roll—that is, to rotate the vehicle just after it left the rail. Through roll-rate stabilization, any slight asymmetries associated with aerodynamics, thrust, structure, or mass distribution are averaged out.

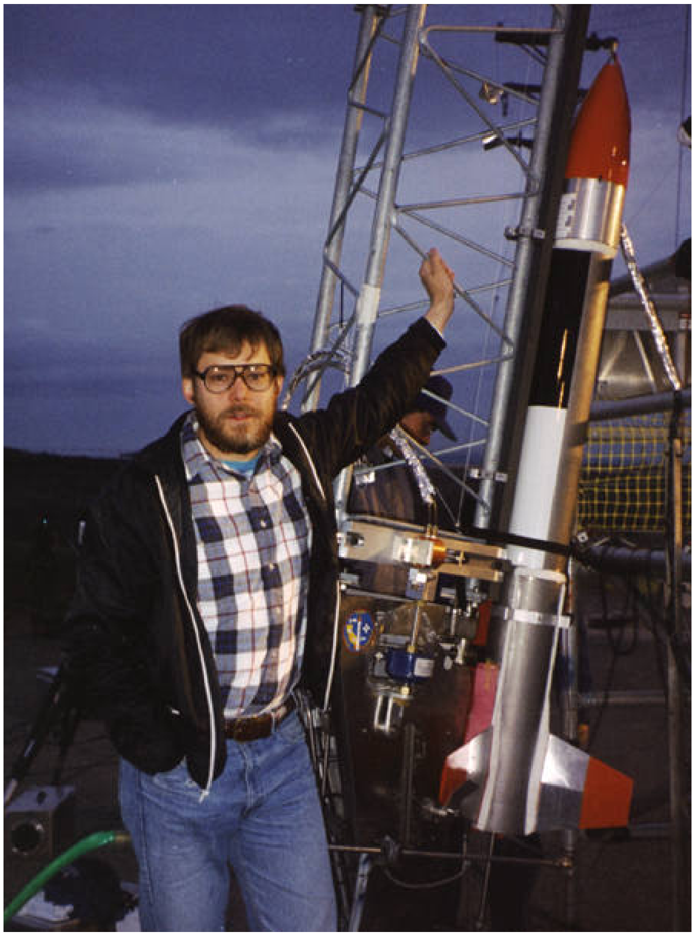


Figure 3. **The pump-fed ASTRID rocket. Standing next to the rocket prior to sunrise before launch at Vandenberg Air Force Base is the inventor of the propulsion system, John C. Whitehead.**

During the 1-minute flight, our engine enabled the ASTRID vehicle to soar 2 km up and to reach nearly the speed of sound (Mach 1, which is 300 meters per second) before splashing down in the Pacific Ocean about 8 km downrange. The test clearly demonstrated the ability of our new propulsion system to function in atmospheric flight.

The speed attained was limited because ASTRID was launched from sea level for this experiment. A vehicle flying in this densest part of the atmosphere is subjected to severe aerodynamic drag. Had the launch taken place in the upper atmosphere from an aircraft such as RAPTOR, ASTRID would have gone about six times as fast (in excess of 2 kilometers per second).

Results

From the ASTRID flight, we obtained a large quantity of data, including measurements of axial acceleration, thrust level, vibration, trajectory, velocity, airspeed, and roll rate. However, the primary objective of ASTRID was to demonstrate how reciprocating rocket pumps would perform in flight and to make two key pressure measurements. These measurements indicated that the pumps boosted the pressure of the fuel delivered to the thrusters, as expected, to more than 10 times tank pressure throughout the powered flight.

An obvious concern related to using pumps is vibration. Among other things, vibration could adversely affect sensitive inertial guidance instruments that might be used in future applications. We found that vibration both along and transverse to the axis of the ASTRID vehicle was not unusually high during launch, and the magnitude of vibration peaks decreased during free flight.

Following ignition, the rocket was released after a short holding time of 8.3 seconds. The rail ascent itself took 1.7 seconds, and the powered flight time from the rail top was 27.7 seconds. Data from accelerometers clearly indicate that the thrusters operated for 37.6 seconds.

Operation and shutdown of the propulsion system performed as expected, with no major problems or

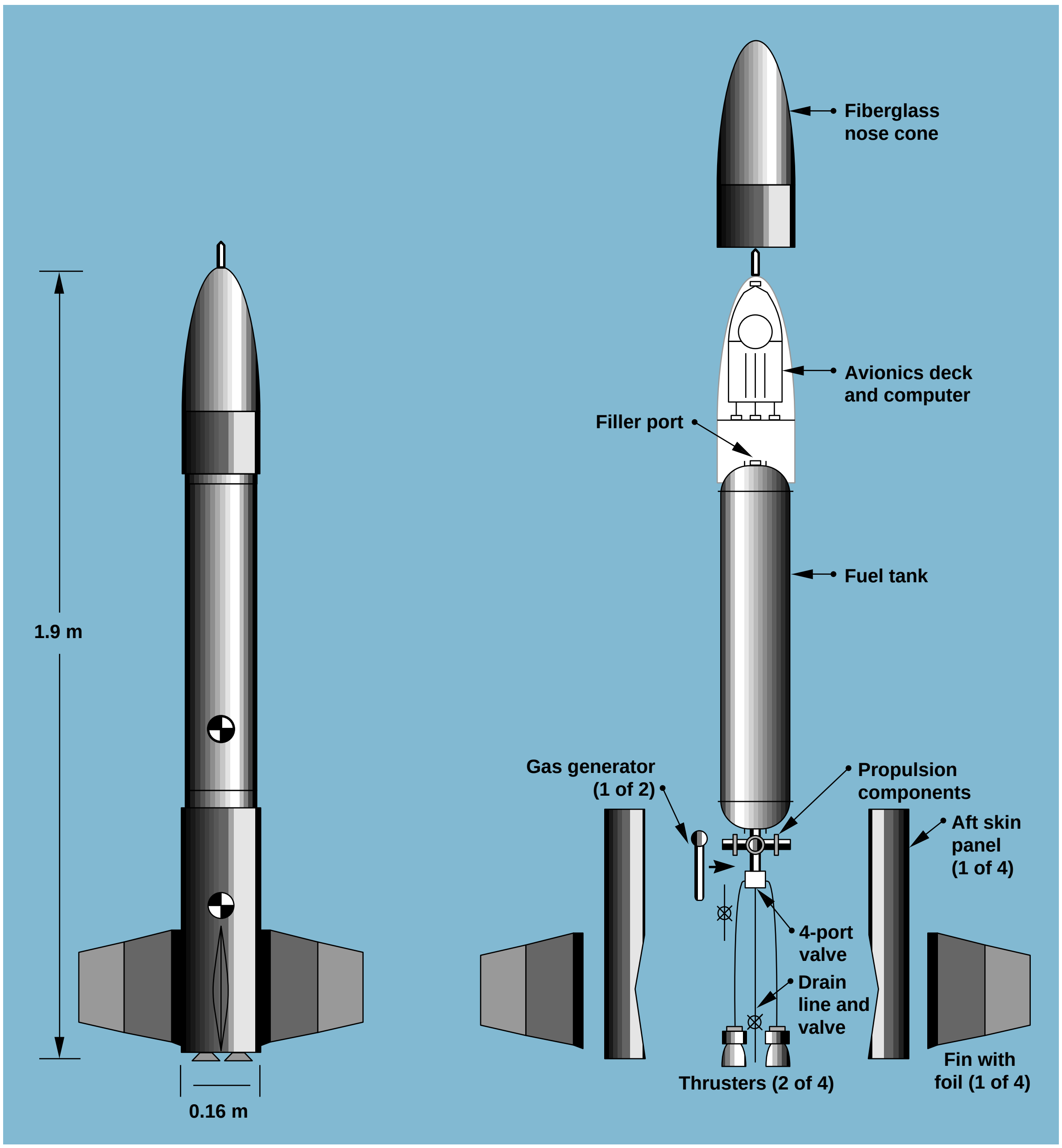


Figure 4. The 1.9-m-long, pump-fed ASTRID rocket. The fiberglass nose houses avionics for sensing, control, and transmitting data back to the ground. The forward section of the vehicle, between nose cone and tank, is an aluminum shell containing pressure transducers and hardware for filling the fuel tank. The titanium fuel tank occupies just about half of the vehicle's length and serves as the center body. The components associated with propulsion occupy only about half of the aft skirt. The four fins, made of lightweight Kevlar, provide aerodynamic stability.

surprises occurring during the flight test. Our preliminary analysis of the data shows that the thrust level was initially just over 440 N and was about 420 N during ascent on the rail and flight. This thrust is within the predicted range. The maximum roll rate of 4.1 revolutions per second (rps) also compares well with the design rate of 4.5 rps.

Collaborations and Future Plans

The ASTRID flight test was a truly collaborative effort involving more than 40 LLNL technicians, engineers, and scientists and a well-coordinated team of outside collaborators. This group built the rocket, developed the data-acquisition systems, performed all fielding operations, and analyzed the data. Organizations that made critical contributions to developing and testing the pump-fed rocket include:

- Olin Aerospace Company (formerly Rocket Research Company).
- Moog, Inc.
- Ball Aerospace Company.
- Johns Hopkins Applied Physics Laboratory (APL).
- Vandenberg Air Force Base.
- Catto Aircraft Inc.

We envision a variety of potential uses for the miniature propulsion system we have developed and successfully flight tested. For example, we have worked for more than six years with Olin Aerospace Company, whose engineers developed the thrusters for ASTRID. We will explore the possibility of commercializing our technology with this company and others for possible use on spacecraft and launch vehicle upper stages.

Our propulsion system can be used in an upper stage to boost a satellite from low Earth orbit (at an altitude of a few hundred kilometers, where the Space Shuttle circles Earth) to geosynchronous orbit (at an altitude of about 35,000 km above Earth, where a satellite remains “stationary” over one geographic location). Once in orbit, the system can be used to make hard maneuvers and adjust the orbit.

Our new technology provides more propulsive capability per unit mass of propulsion system hardware than any other means available today for small liquid systems. In particular, our pumped propulsion can make missions to the moon and planets much more economical than in the past.

A mission to make a soft Mars landing and retrieve rock and soil samples would benefit greatly from the high performance, low mass, and thrust-on-demand features of this system. The precision-throttling capability conferred by the responsive pumps would facilitate control of the descent vehicle’s landing. Then, after landing and sample collection, a vehicle would need to be launched for the return flight to Earth. Our new technology provides the required launch-vehicle performance on a small scale.

Figure 5. ASTRID ascends the launch rail on February 4, 1994. The glow of the four thrust chambers can be seen, but the plume is invisible because hydrazine fuel decomposes cleanly and at a lower temperature than other rocket propellants.

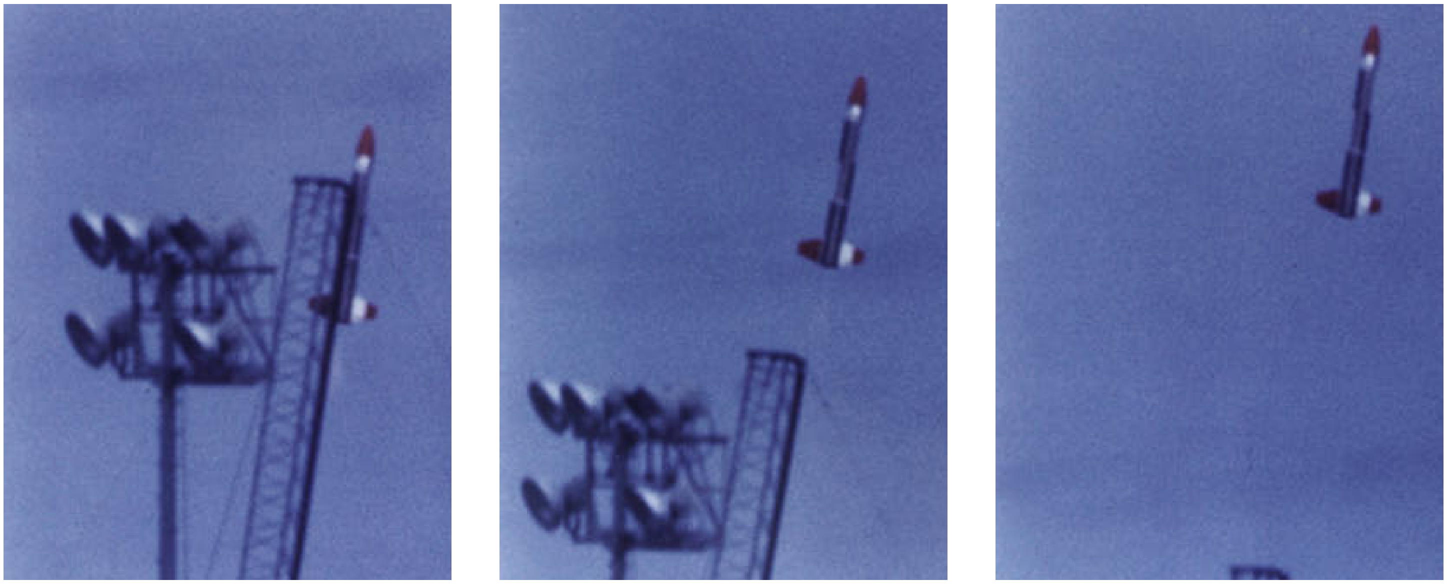
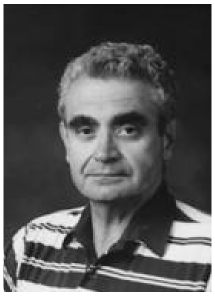


Figure 6. **Sequence of three photos taken of the ASTRID flight test. At *t* = 1.7 seconds after launch, ASTRID leaves the launch rail at Vandenberg Air Force Base on its way to spashdown about a minute later in the Pacific Ocean.**

On another front, several ongoing defense programs can benefit from our technology, particularly those that require small defensive missiles that are highly maneuverable. We plan to explore these and other potential applications for the new pumped-propulsion technology in the future.

Work funded by the Pentagon's Ballistic Missile Defense Organization. BMDO is the successor to the Strategic Defense Initiative Organization.

Key words: advanced single-stage technology rapid insertion demonstration (ASTRID); RAPTOR; rocket propulsion.



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