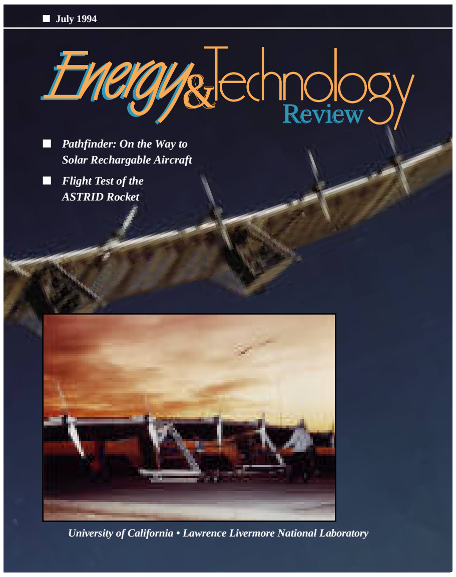
July 1994

Energy & Technology Review

- *Pathfinder: On the Way to Solar Rechargable Aircraft*
- *Flight Test of the ASTRID Rocket*

University of California • Lawrence Livermore National Laboratory



About the Cover

Pathfinder, serving as our flying testbed for designing a solar-rechargeable airplane, embodies technologies and engineering practices essential for achieving “virtually eternal” flight at high altitude. Derived from an airframe that flew nearly a decade ago, the Pathfinder expresses today’s advances in electric motors, solar arrays, and power conditioning. Last fall and winter, the Pathfinder completed a low-altitude flight test series at the Rogers Dry Lake Bed, Edwards Air Force Base in California, and is being enhanced to attempt a high-altitude series. For more information, see the article on p. 1.

About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, in response to new national needs, we have added other major programs, including technology transfer, laser science (fusion, isotope separation, materials processing), biology and biotechnology, environmental research and remediation, arms control and nonproliferation, advanced defense technology, and applied energy technology. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computing science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. Please address any correspondence concerning *Energy and Technology Review* (including name and address changes) to Mail Stop L-3, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, or telephone (510) 422-4859.

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Pathfinder and the Development of Solar Rechargeable Aircraft

Recent flight tests of the Pathfinder (shown above) demonstrated the potential benefits of solar-rechargeable aircraft. Since the Pathfinder is nonpolluting and very smooth flying, it offers a unique platform for high-altitude surveillance and atmospheric sensing.

SATELLITES have shrunk the world to the size of the proverbial global village. They track weather and the traffic patterns of ships and aircraft, and monitor our environment. Defense satellites provide high-resolution images of objects on the ground to protect our troops and allies. Telecommunication satellites have interwoven business sectors, corporations, and markets into global networks.

Nevertheless, orbiting satellites may not be the best choice for all applications requiring a high vantage point. Satellites and their payloads are expensive, and launching them by rocket is expensive and risky. They must operate in the extreme conditions of space, bombarded by radiation and with no airflow to cool their electronics. Only valuable, long-term missions would seem to justify the expense and risk of a satellite. Even then, satellites are not always the best choice. They typically cannot hop to a new orbit, and some uses, such as local and global communications, require a large number of satellites to ensure adequate coverage. There is clearly a large potential role for high-altitude, atmospheric vehicles that can stay aloft for very long periods (weeks or months) and can roam virtually anywhere.

Relocatable Satellites in the Atmosphere

High-altitude, long-endurance, unmanned air vehicles are less costly than satellites in every way. They take off and land rather than having to be launched. They can vary their flight paths like any other aircraft, providing continuous local coverage and then relocating hundreds of kilometers in a single day. An airplane powered by the sun during the day and by an on-board rechargeable energy-storage system at night can, in principle, stay aloft for weeks or months at a time. Because the energy is renewable (see Figure 1), only the wear of components limits flight duration. Equipped with the proper sensors or cameras, a single aircraft flying at an altitude of 20 to 25 km could scan some 200,000 km^2 at a time (this area is roughly equivalent to the size of Nebraska). These aircraft could perform a variety of environmental, commercial, and scientific services:

- Spot the beginning and monitor the evolution of natural disasters on all scales, from hurricanes and river floods to forest fires.
- Monitor pollution, toxic gas releases, and effluents from volcanic eruptions.
- Monitor the spread of an oil spill to aid containment and cleanup efforts.
- Monitor agricultural conditions (crop health, blight, pestilence, soil erosion, and irrigation) and help measure harvests.
- Map resources such as minerals, oil, and geothermal power.
- Monitor oceanic thermal currents.
- Measure high-altitude ozone levels and other atmospheric phenomena for studies of global warming.

For military applications, such planes could be sent aloft over areas of known or suspected hostile activity to perform high-resolution surveillance or to work as “aerial mines.” That is, they could detect the launch and ascent of a hostile theater ballistic missile, such as a SCUD, and release a small, agile, high-velocity interceptor to smash into it while it is still over enemy territory.[1] Such planes could have been used to great effect in the Gulf War.

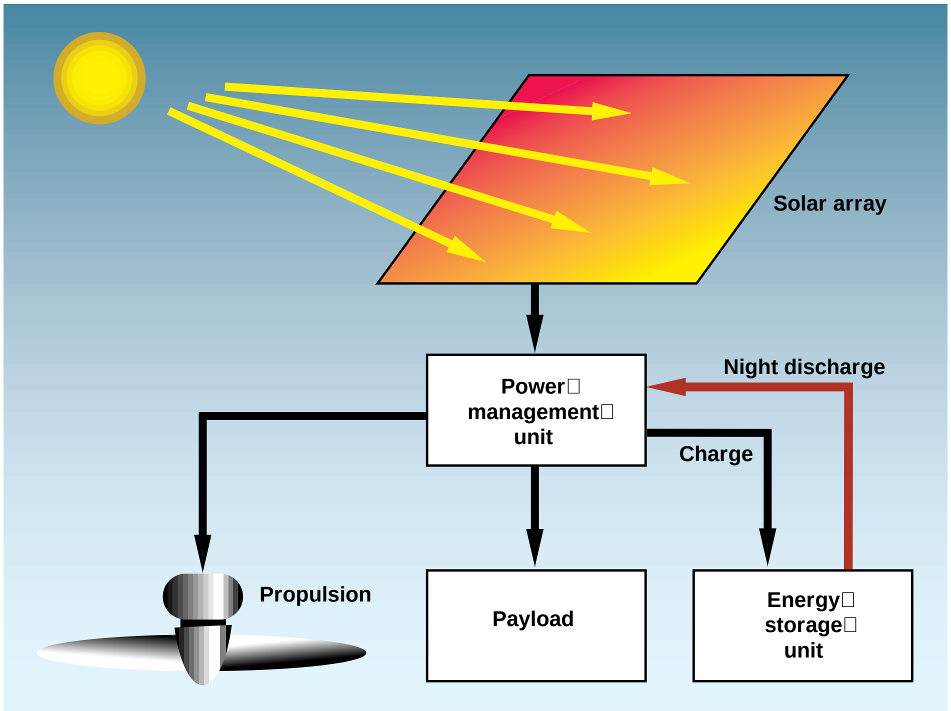


Figure 1. A simplified schematic of solar-rechargeable, round-the-clock flight. Less than half the sunlight striking the solar cells powers the motors; a larger fraction is stored on board. As the solar energy striking the cells falls below a certain minimum, the aircraftÕs power-management unit begins drawing on the stored energy for the ÒnightÓ portion of the flight.

A Flying Wing Design

The first steps toward developing a solar rechargeable airplane were taken in the early 1980s, with the development of HALSOL (high-altitude solar vehicle). AeroVironment, Inc., of Monrovia, California, designed, built, and tested an experimental prototype aircraft.[2] The goal of the unmanned plane was to fly day and night, at high altitudes (above 20 km), for very long periods in temperate and tropical latitudes (i.e., too far from either pole to capitalize on its seasonal 24-hr sunlight). Such an airplane would have to collect at least twice the solar energy needed for daytime flight and store the surplus for use at night.

Compared with internal-combustion aircraft, solar-powered aircraft require a large area of wing per unit weight of the craft (i.e., a “low wing loading”). Moreover, the higher the desired operating altitude, the more power is needed to sustain flight. Therefore, the wing area must be increased in order to collect more sunlight.

Conditions at the desired operating altitudes required an aircraft with very large wings—too large for a conventional cantilever design, in which the wing is projected from a large central mass, the fuselage. The new aircraft required a design in which the solar collection area could be increased without forcing an increase in the thickness of the spar (the main structural element of the wing). The weight is distributed as evenly as possible across the wingspan (i.e., it is a “span-loaded” design). Thus, HALSOL was a flying wing, resembling a 30 m × 2.6 m plank flying sideways. For a description of the operating conditions at high altitudes, see the box on p. 8.

The 200-kg HALSOL made nine flights under battery power (to avoid risking expensive solar arrays during early experimental flights) over a two-month period in 1983. The tests validated the plane's aerodynamic and structural properties, its mechanical performance, and its flight behavior. However, available batteries had inadequate specific energy (energy available per unit weight) for nighttime use, and the more promising alternative—namely, fuel cells—was an immature technology. The HALSOL program was terminated and the vehicle was mothballed in 1983.

Pathfinder

The next steps followed nearly 10 years later, in 1992, when LLNL teamed with AeroVironment to identify affordable current and near-term technologies that could be engineered into the design of a solar rechargeable aircraft. To do so quickly and with modest resources, we had to capitalize on the lessons learned during the development of HALSOL.

Under the sponsorship of the Ballistic Missile Defense Organization, we obtained the mothballed vehicle, upgraded its airframe (as described under "Technology Advances"), and equipped it with today's technology for propulsion and vehicle control. The metamorphosed aircraft was renamed Pathfinder, and it serves as our flying testbed for critically testing factors affecting solar rechargeable flight at high altitude. Figure 2 shows Pathfinder at rest and in flight.

Like HALSOL, Pathfinder spans 30 m and has a 2.6 m chord (the distance from the wing's leading edge to its trailing edge). The wing's spar is a hollow tube made of carbon fiber composite. The wing is assembled from five modules for flexibility in flight conditions and for ease of ground transport, and carries eight motors.

If, for the sake of simplicity, we imagine Pathfinder flying a steady course in broad daylight at some 20 km altitude, we can give a basic description of what Pathfinder does: it gathers electric current from the solar cells on its wings and converts it to the rotary motion of the propellers (with occasional adjustments of the elevators as needed). This simple description masks an engineering challenge, which requires a sophisticated control-system design. External conditions at the solar panels, such as the intensity and angle of the sunlight and the density and temperature of the air, determine the amount of available electrical energy. Air density and velocity also determine what power the motors require to maintain a steady course.

A human pilot negotiates among these conditions by reading instruments that give the needed information and then, on the basis of training and experience, manipulating the controls to adjust the plane's behavior. In an unmanned vehicle, an integrated system of sensors and electronic controls performs all the tasks of collecting and measuring information, interpreting it, and feeding the correct

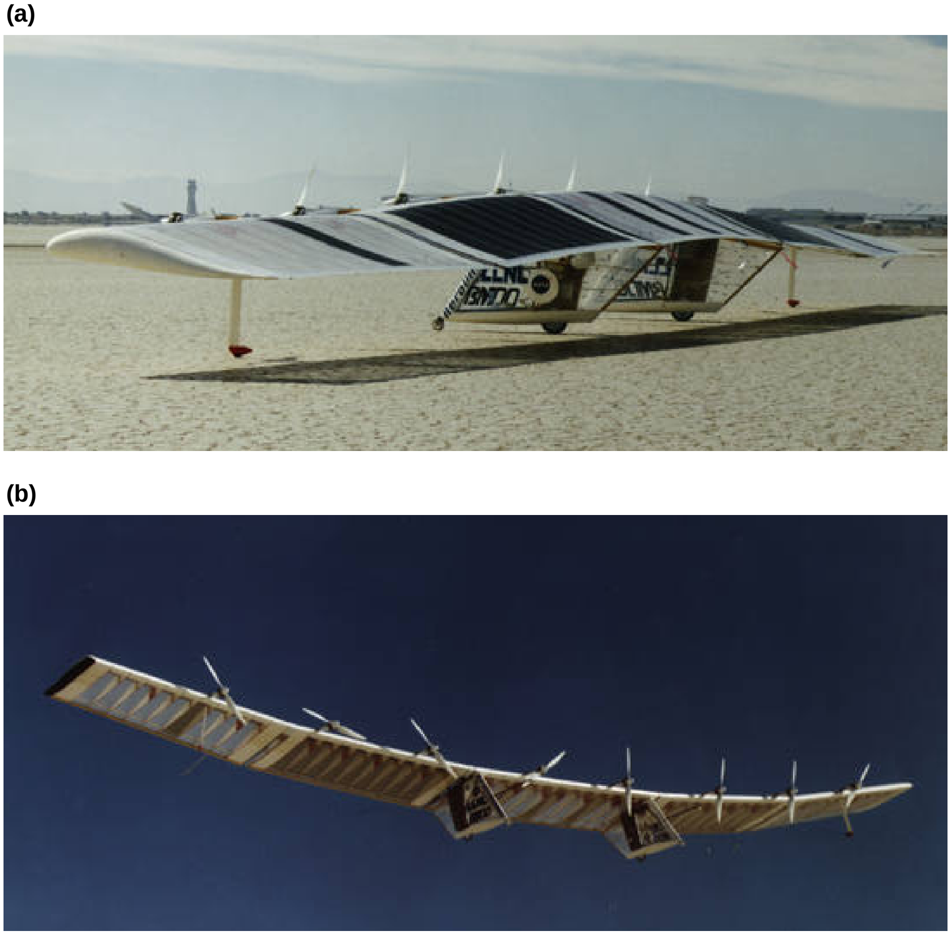


Figure 2. (a) Pathfinder on Rogers Dry Lake Bed before flight. The dark areas are the solar cells. Compare the slight droop of the wing with its position in (b), which shows Pathfinder in flight (altitude ~60 m). The upward curve of the wing results from lift, and this curvature of the wing puts its structural components in the condition of least load. However fragile Pathfinder might look, its flexibility and light weight allow it to withstand high wind gusts as it climbs to high altitude.

amount of power to each motor. In the near decade between the mothballing of HALSOL and the fitting of Pathfinder, all the technologies that contribute to such a control system advanced significantly.

Technology Advances

In addition to the sensors and electronic controls, solar-photovoltaic-array and motor technologies advanced considerably. AeroVironment, by virtue of its involvement with General Motors on solar-powered and electric automobile projects (called SunRaycer and Impact, respectively), became expert in designing electric motors and power-control systems. Electronic component technologies leapt forward even more strikingly. The following descriptions highlight the ways in which Pathfinder was modified from its predecessor.

Structural Design. Pathfinder's wing surfaces are skinned with new structural polymers that are stronger and more resistant to the sun's ultraviolet light. Although the aircraft is deceptively flimsy in appearance, it can withstand 4-*g* shocks on landing and 5-*g* loads in flight. It is also designed to handle the strong gusts that it might encounter near a jet stream. The span-loaded design evenly distributes gust loads; when it encounters turbulence at high altitude, it responds much like an air mattress riding the ocean's waves.

Solar Cells. The silicon solar cells are extremely thin and lightweight, yet are affordable. Compared to the best cells available ten years ago, today's cells have two to five times the specific power (power available per unit weight) and a unit cost (dollars per unit of available power) that is nearly a factor of ten lower. During its low-altitude flight testing, the wing was equipped with nearly 19 m^2 of solar cells (up to 60 m^2 is possible) that are more efficient and lighter. More than 90% of the area of the solar arrays collects light; less than 10% is area between cells or structural support.

Figure 3. A wing section of Pathfinder in the shop after nine solar arrays were installed.

Figure 3 shows a wing section with solar arrays installed. Siemens Solar Industries and LLNL teamed to produce the modules at very low cost for early flight testing on Pathfinder. Later in the program, LLNL developed and flew even lighter-weight modules and also developed a technique for laminating modules to ease their handling and increase protection.

Motor Design. Because moving parts wear more rapidly in the partial vacuum at high altitudes and may fail, we employed two solutions: redundancy and extreme simplicity. Pathfinder's 8 propeller pods and 26 elevators provide enough redundancy to ensure adequate propulsion and control for recovering the aircraft if some parts fail. On the other hand, we radically redesigned the motor and propeller assembly to reduce the number of moving parts.

Because the brushes in conventional electric motors arc and wear rapidly at high altitude, Pathfinder uses lightweight, brushless DC motors with rare-earth, permanent magnets to rotate the propeller. This electronically commutated design eliminated more than 100 moving parts from each propeller pod, leaving only three moving parts: two bearings and a lightweight spider armature on which the propeller is mounted. (LLNL made the motor housings and spider armatures.) The new design also reduces the drag-inducing frontal area of the motor cowling. Figure 4 shows the Pathfinder motor assembled and disassembled.

To improve cooling efficiency, we moved the heat-producing power components to the outside of a nickel-plated aluminum motor housing and radially splayed the cooling fins.

Propellers. A plane must negotiate flight environments that vary in combinations of wind force, air temperature, and air density, while undergoing different performance demands, such as climbing, accelerating, and level cruising. Conventional propeller-driven planes adapt at least partially by using variable-pitch propellers. (The blade can change its angle to the direction of its travel, its pitch; at one extreme, it can cut through the air cleanly like a knife edge or, at the other extreme, present a broad surface like a Ping-Pong paddle being swung.)

The HALSOL motors had variable-pitch propellers, but the Pathfinder motors use fixed-pitch propellers. The pitch is set before takeoff to what is optimal at the aircraft's cruising altitude, and motor speed compensates for the pitch deficiencies at other altitudes. This change to fixed pitch allowed us to significantly reduce the number of parts, as described above, by eliminating the gearbox and control mechanisms to vary pitch and the complex pitch-control analog circuit. The new fixed-pitch, ground-adjustable propellers are lighter, stronger, and more reliable than their variable-pitch predecessors.

Flight Testing

Between October 1993 and January 1994, the Pathfinder, remotely controlled from a ground station, flew 10 low-altitude test flights using both battery and solar power. These flight tests took place at Rogers Dry Lake Bed, NASA Dryden Flight Center, in California.

All technology upgrades were validated. We quantitatively assessed the controllability of the airplane through precise measurements of lift, velocity, power, and angle of attack, and are using the collected data to refine the dynamic control model. The flight series met all objectives, along with a few bonuses:

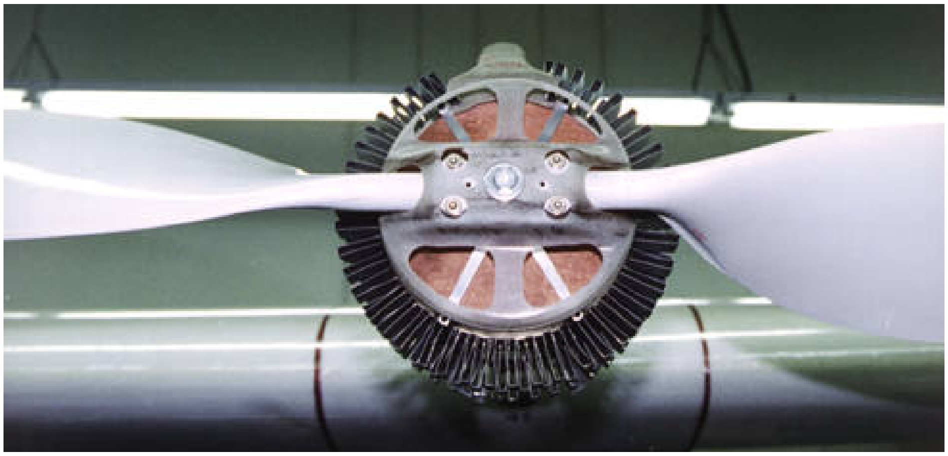
- One flight was exclusively solar powered.
- We obtained high-resolution images from an on-board camera that was mounted directly to the airframe, demonstrating the remarkably low levels of vibration of the aircraft during flight.
- We measured the dust levels above the Rogers Dry Lake Bed using a sensitive particulate counter. Because the aircraft is nonpolluting, it will be an ideal platform for many environmental measurements.

After the entire available wing area—60 m^2 of the 75 m^2 total (15 m^2 must be free of cells to keep the wing near the leading edge aerodynamically clean)—is covered with solar panels currently being fabricated, the plane will be able to ascend to more than 20 km. Simulations indicate that Pathfinder could stay aloft for several days above the Arctic Circle during the Arctic summer, even without an energy-storage system.

Future Work: Storing and Recycling Energy

We have analyzed and designed a rechargeable energy-storage system

(a)



(b)

Figure 4. Two views of a Pathfinder motor: with propeller assembly (a) and without (b), showing its internal components and the radial cooling fins. There are only three moving parts in the entire assembly, as compared to more than 100 in the previous generation design.

that makes night flight possible. The next stage in the development program would be to build this system, install it in the aircraft, and test the system's performance and durability at altitude. Rechargeable battery technology falls far short of our needs, but an energy storage system based on fuel-cell technology could meet our requirement for high specific energy. Figure 5 gives a schematic overview of a solar-rechargeable propulsion system.

Fuel Cells

A battery and a fuel cell both store energy in the form of reactants and produce power through electrochemical reactions in cells. Unlike a battery, which is self-contained (all its components for storing energy and producing power are within a sealed volume), the fuel cell stores one or both of its reactants externally. The energy capacity of a system using a fuel cell can be made larger simply by storing more fuel.

The fuel cell brings hydrogen and oxygen gases together in a controlled reaction to produce electrical power and water during nighttime. During daylight hours, electrolytic cells recharge the system by decomposing the same water (by electrolysis) into hydrogen and oxygen gases that are then stored at high pressure in tanks in the wing. The reactants are recycled each day.

This type of system is called a regenerative fuel cell. The system can be designed to use separate electrochemical cells to create electricity and to electrolyze water, or to use the same cells to perform both functions (at a very small sacrifice in efficiency). The second type is a reversible system called a unitized regenerative fuel cell. Figure 6 shows a conceptual design of this type of fuel cell.

Weight Considerations

The weight of the entire energy-storage system is critical because it represents from a third to nearly half the total weight of the aircraft and payload. Since a unitized regenerative fuel cell uses the same components for creating electricity and for electrolysis, it can be significantly lighter than a system using separate fuel and electrolytic cells. It also has simpler plumbing and thermal management requirements.

Combining a small fuel cell stack with large-volume, lightweight tanks should yield high specific energy and energy capacity. Although unitized regenerative fuel cells require additional development time and cost, the suggested benefits of less storage-system weight and complexity and greater reliability argue in their favor. However, prototyping the energy-storage system with discrete components (i.e., separate electrolyzer and fuel cell stacks) allows the earliest opportunity to develop and test, in a laboratory setting, the hardware and software related to the energy and power-management system.

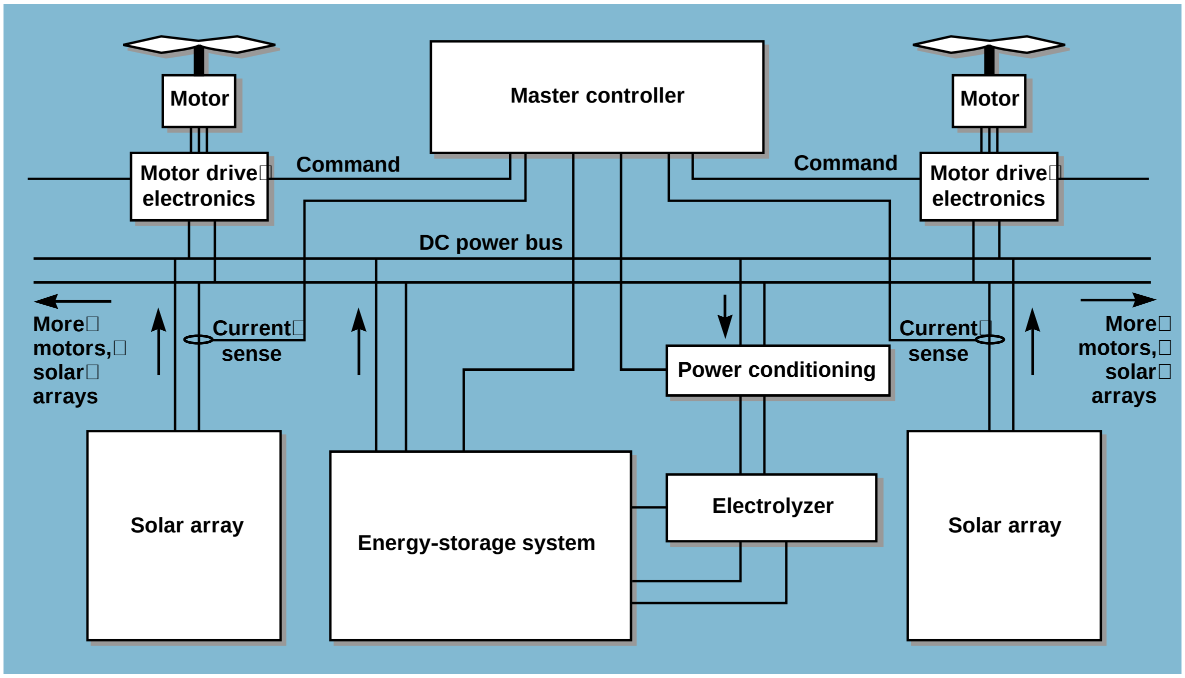


Figure 5. A schematic of the propulsion system of a solar-rechargeable aircraft. Figure 6 shows the components of the energy-storage system.

Possible Design

The LLNL /AeroVironment team concluded that the reactant gases (hydrogen and oxygen) can be stored under pressure within the hollow wing spar. However, a permeation barrier is needed because the fiber composites that make up the spar are fairly permeable to pressurized hydrogen gas. The conventional barrier of thin-walled aluminum would add unwanted weight to the spar. Therefore, we have pursued the development of a bladder liner consisting of a sandwich of metal-coated polymer membranes that has extremely low loss rates of pressurized hydrogen and oxygen gases. One or two bladders (one each for hydrogen and oxygen) could be installed in each spar segment. Using a polymer bladder instead of an aluminum liner could reduce the weight by more than 20 kg, and using the spar as tankage may save an additional 20 kg. (Forty kilograms is a sizable percentage of the ~100-kg payload capacity.) Thus, any savings in vehicle weight can be traded for increased payload weight.

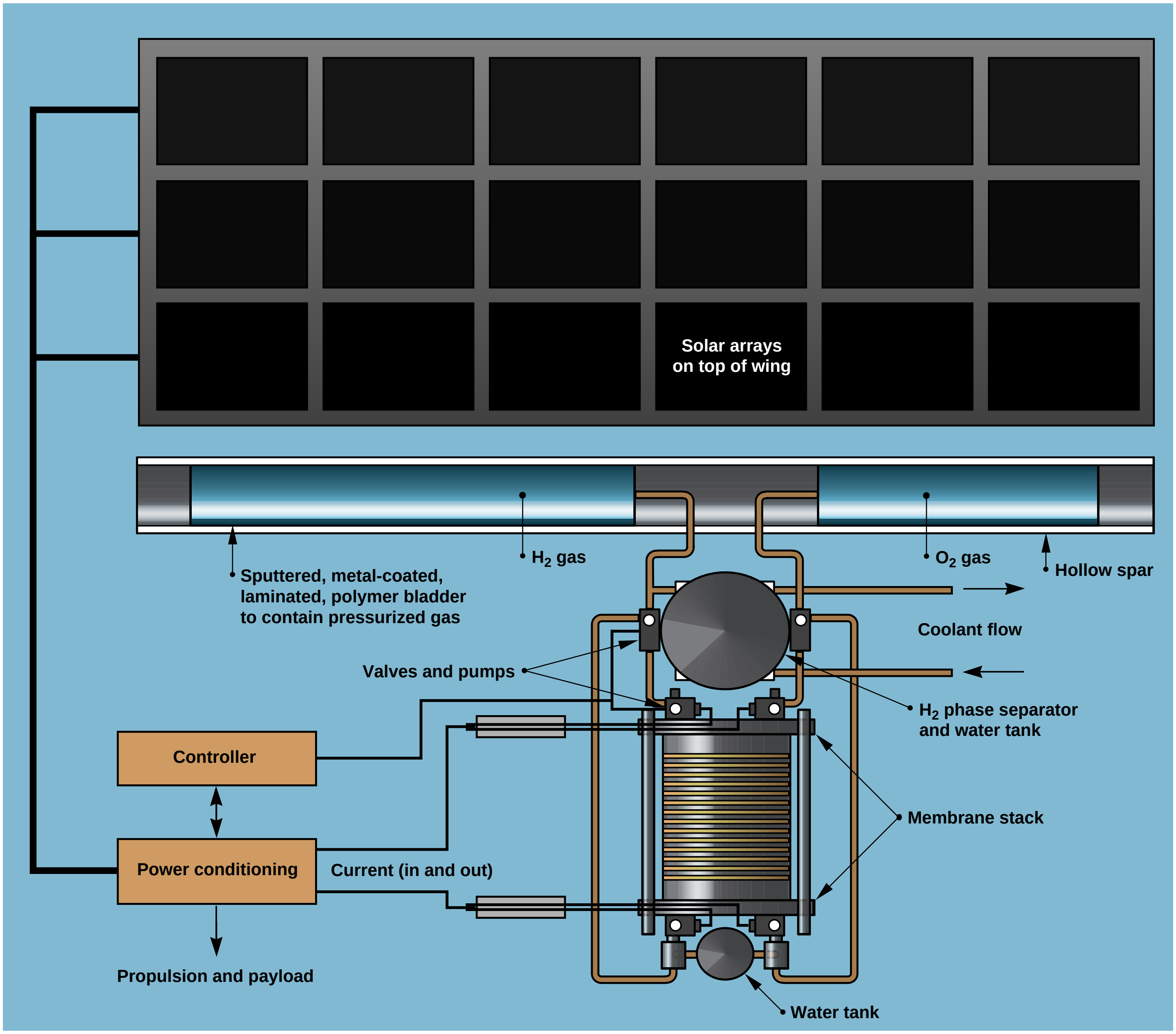
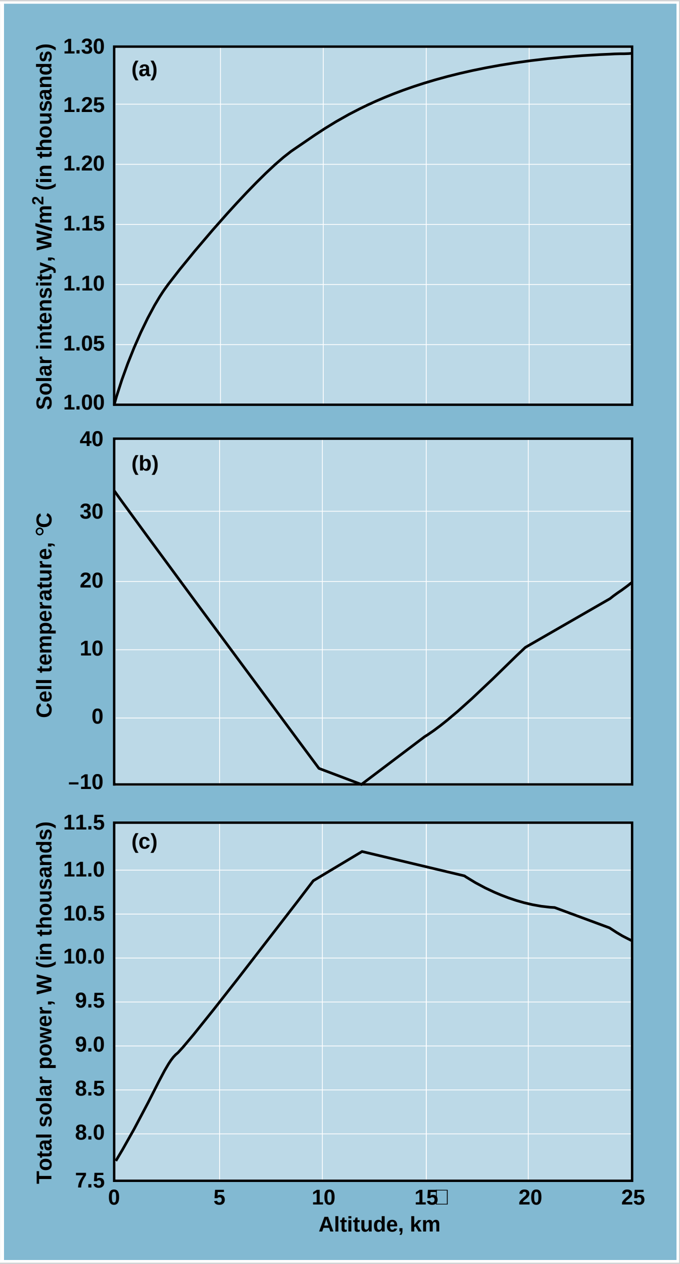


Figure 6. Rendering of a generic unitized regenerative fuel cell subsystem, including storage of reactant gases in the wing spar.

High-Altitude Solar Flight: The Balancing Act



As a solar-powered aircraft gains altitude, its environment gradually changes in ways that significantly affect its need for power and the amount of power available. The intensity of sunlight increases with altitude, and air temperature and density decrease. With no losses to atmospheric absorption and scattering, sunlight in space is about 35% more intense than at Earth's surface. Air temperature averages about 15°C at sea level and drops to –45°C at 30 km. The electric power available from the solar panels is nearly proportional to the intensity of sunlight, and is inversely proportional to the temperature of the solar cells.

The figure to the left shows the factors that must be balanced for high-altitude, solar-powered flight. As shown in (a), solar intensity increases with altitude. However, the ever-thinning atmosphere supplies progressively less airflow to cool the solar cells (b), which produce less power as their temperatures increase (c).

Thus, as the aircraft rises through the dense but gradually thinning lower atmosphere, from sea level to 12 km, increasing sunlight intensity and gradually cooler air produce a rapid increase in electrical power available from the solar panels. This power is about 45% higher at 12 km than at sea level. However, at altitudes above 12 km, power from the panels gradually decreases as panel temperature increases; the thinner air provides less flow over the panel surface to cool the cells. Electric power from crystalline silicon cells decreases 0.5% for every degree Celsius in temperature rise.

The decreased air density not only causes a drop in solar-cell efficiency, it requires more power from the motors to maintain sufficient lift (the upward force on a wing created by the greater air pressure under the wing than above it). For example, a wing needs about 400% more power to maintain level flight at an altitude of 20 km than it requires to cruise at sea level, and 550% at 25 km. At the same time, the electrical power available from the panels has increased less than 45% since the aircraft left sea level, and is slowly decreasing with additional altitude.

This combination of factors leads to a fairly inflexible altitude ceiling, where the rapidly increasing demand for power exceeds the relatively fixed electrical power available from the wing. Factors such as the plane's total weight, the total area of the solar panels, and the efficiency of the solar cells fix the altitude where this occurs. Pathfinder's ceiling occurs at 20 to 25 km.

To have adequate power to maintain lift in the thin upper atmosphere while recharging the energy-storage system, a plane must have a larger solar collection area than Pathfinder's. Pathfinder is capable of reaching a peak altitude of 20 to 25 km, but it can cruise there only during daylight conditions. A solar-rechargeable aircraft will require twice Pathfinder's wingspan to operate continuously at 20 km or higher while carrying a 100-kg-class or heavier payload and the energy-storage system. Doubling the wingspan to 60 m while keeping the same 2.6 m chord will double the solar collection area. (Still larger wing spans are possible but may be unwieldy for ground handling.)

Summary

Some assignments, both civilian and military, are better performed by unmanned, long-endurance, solar-rechargeable aircraft high in the atmosphere than by satellites in low-Earth orbits. These aircraft would have more flexible flight paths and would be far less costly than satellites to design, build, and operate. LLNL has been working for the Department of Defense's Ballistic Missile Defense Organization to develop unmanned aircraft to protect our military forces and our allies from attack by theater ballistic missiles.

In collaboration with AeroVironment, Inc., we developed a lightweight flying wing, called Pathfinder, that uses present-day technologies in photovoltaics, power electronics, aerodynamics, and guidance and control. Because of its light weight, 30-m wingspan, and intended high peak altitude (20–25 km), Pathfinder is span loaded; that is, the weight of all components is distributed as evenly as possible across the five modules that make up its wing. Flight tests have proven the soundness of the concepts and components.

We have analyzed and designed a rechargeable energy-storage system that makes night flight possible, thus making flight durations of months possible. The technology, which is based on fuel cells, has been developed for other applications. Our challenge is to fit the application to the constraints of a span-loaded aircraft operating at high altitudes. The design must minimize total system weight while distributing the weight of the components as uniformly as practical across the span. The preferred approach is a unitized regenerative fuel cell system, in which the fuel-cell components that produce electric power and water also perform the reverse process of electrolysis, breaking the water into gaseous hydrogen and oxygen for storage. However, a system with separate components, though heavier, may offer a nearer-term, more-affordable option.

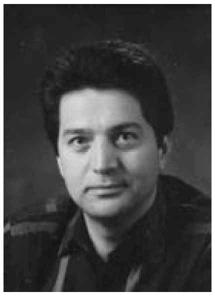
Although Pathfinder is capable of reaching a peak altitude of 20 to 25 km, it cannot cruise there in the absence of sunlight. An aircraft capable of performing day/night missions at that altitude, especially with the added weight of the energy-storage system, must have larger dimensions than Pathfinder for more solar-collection capability. LLNL, together with AeroVironment, is designing such a plane—a high-altitude, extremely long-endurance, solar-rechargeable airplane. We are teaming with industry to identify affordable near-term technologies that could be applied to reduce weight, increase reliability, and maintain adequate efficiency of components. The tasks ahead involve applying good system-integration practices to ensure low wingloading and high reliability needed for a multiweek mission, and to develop an aircraft that can be handled readily on the ground and in the air.

Work funded by the Department of Defense's Ballistic Missile Defense Organization.

Key Words: fuel cells—rechargeable, regenerative, unitized regenerative; HALSOL; high-altitude unmanned flight; Pathfinder; solar aircraft.

Notes

1. This concept motivated the RAPTOR/TALON Program at LLNL. RAPTOR stands for Responsive Aircraft Program for Theater Operations; TALON stands for Theater Application Launch On Notice. The Ballistic Missile Defense Organization within the Department of Defense put LLNL in charge of the program.
2. AeroVironment, Inc., established preeminence in the field of solar flight in 1980, when its Gossamer Penguin became the first manned solar-powered plane to fly, and again in 1981, when its Solar Challenger made aviation history by safely ferrying its pilot 262 km, from Paris, France, to Kent, England, at altitudes exceeding 3 km.



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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

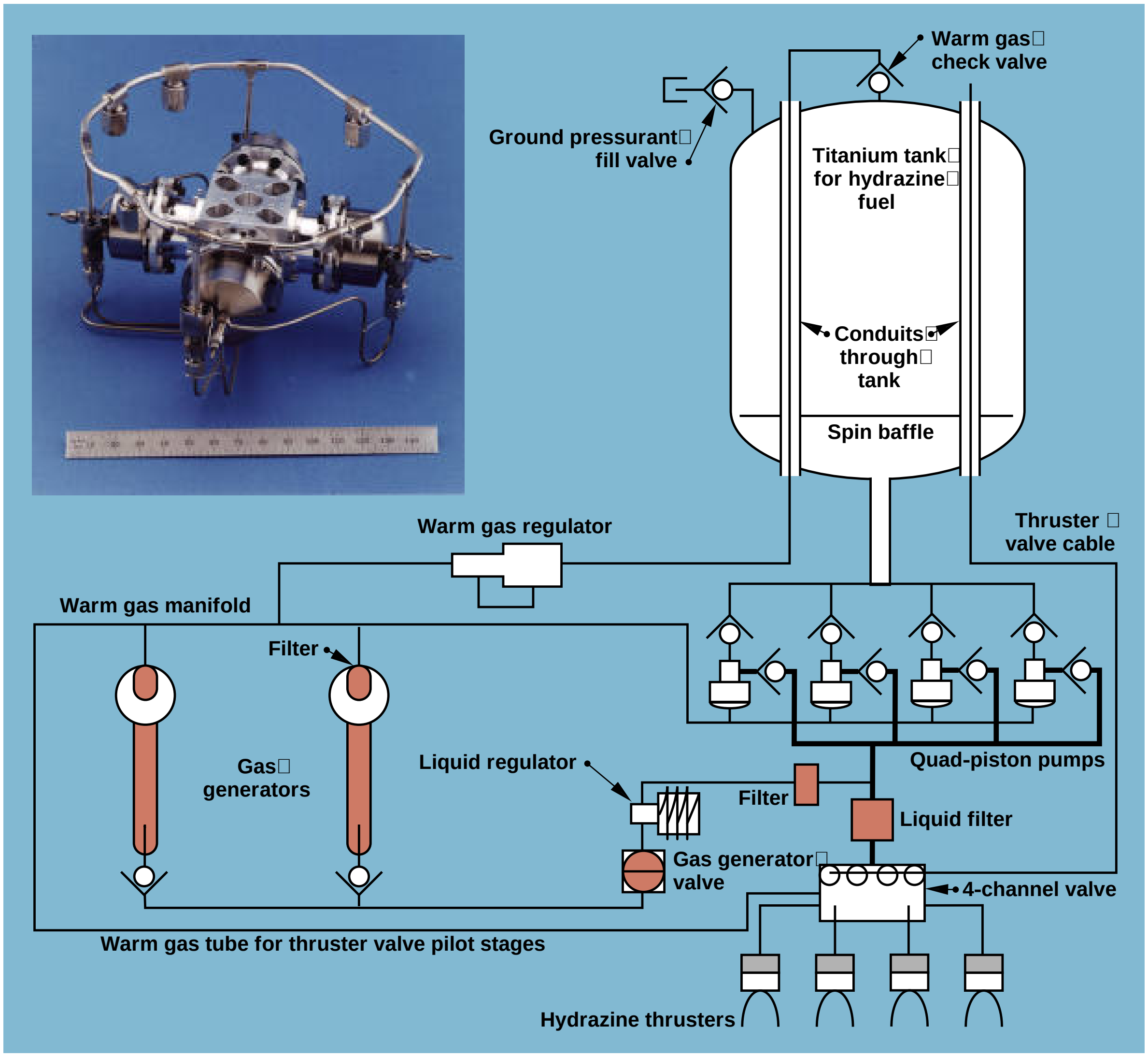


Figure 1. Our new thrust-on-demand propulsion system uses four reciprocating free-piston pumps and monopropellant hydrazine. The quad-piston pumpset (inset) delivers its own mass (365 g) in hydrazine each second at a pressure of 7 MPa (1000 psi).

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

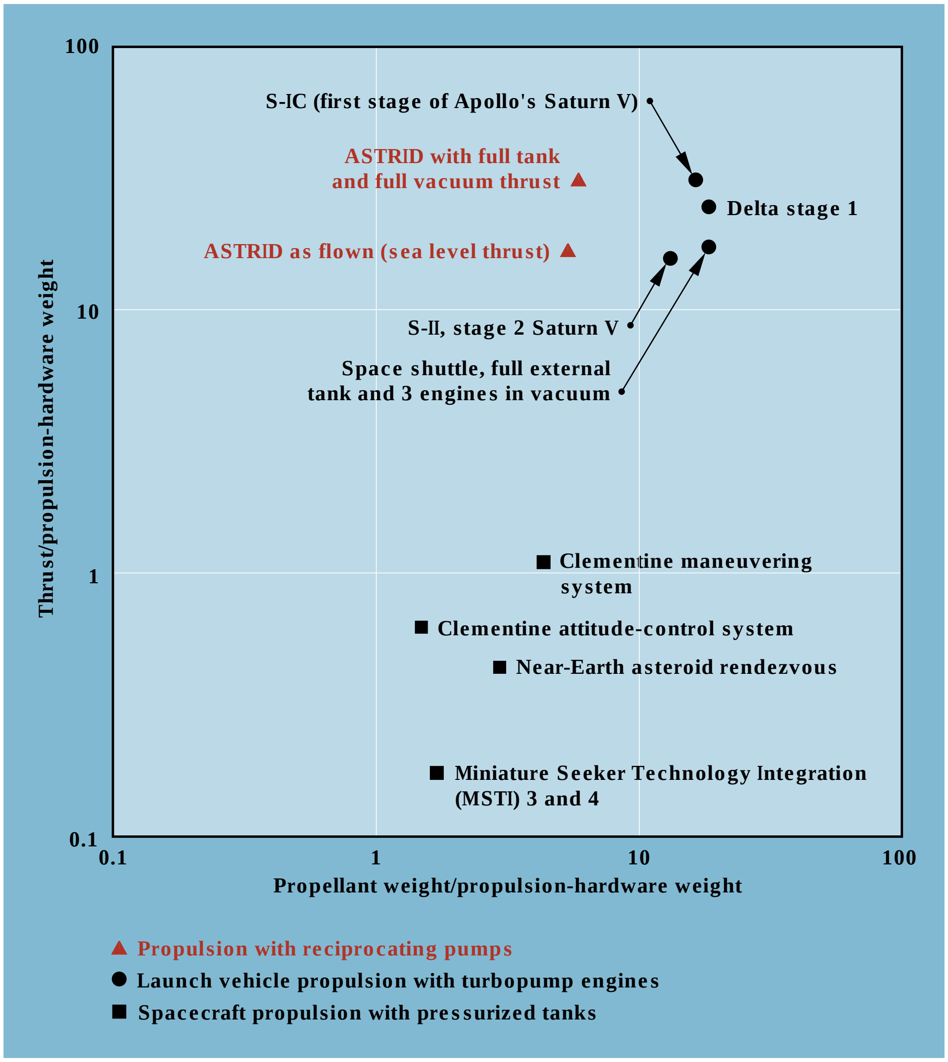


Figure 2. ASTRID compared with examples of existing rocket propulsion systems. Both propellant weight and thrust are normalized to total propulsion hardware weight (including tanks and engines) because rocket systems must provide both propellant storage and thrust with as little hardware as possible. 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.

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

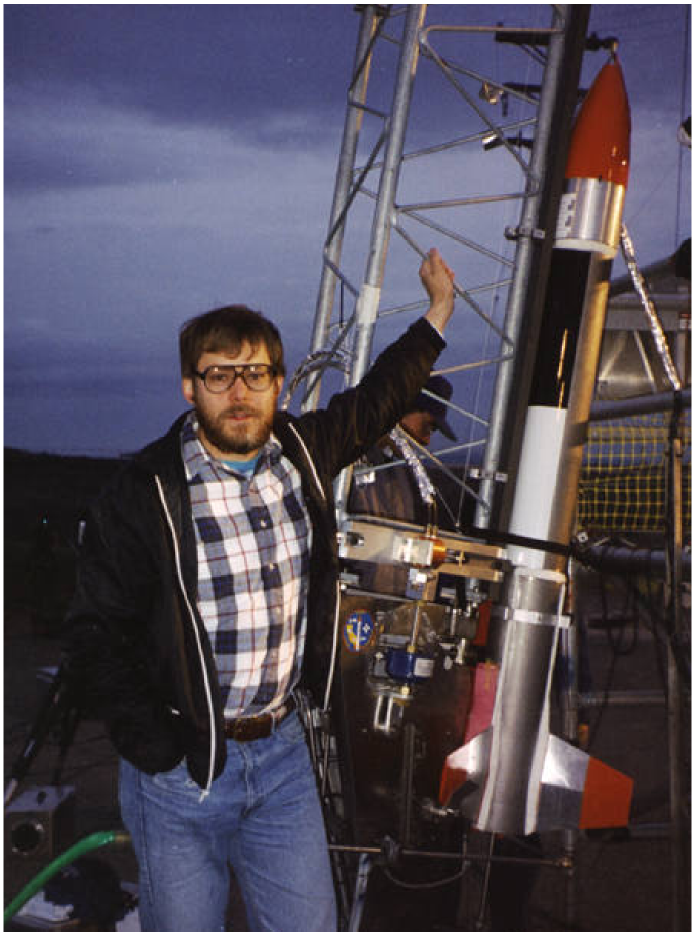


Figure 3. **The pump-fed ASTRID rocket. Standing next to the rocket prior to sunrise before launch at Vandenberg Air Force Base is the inventor of the propulsion system, John C. Whitehead.**

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

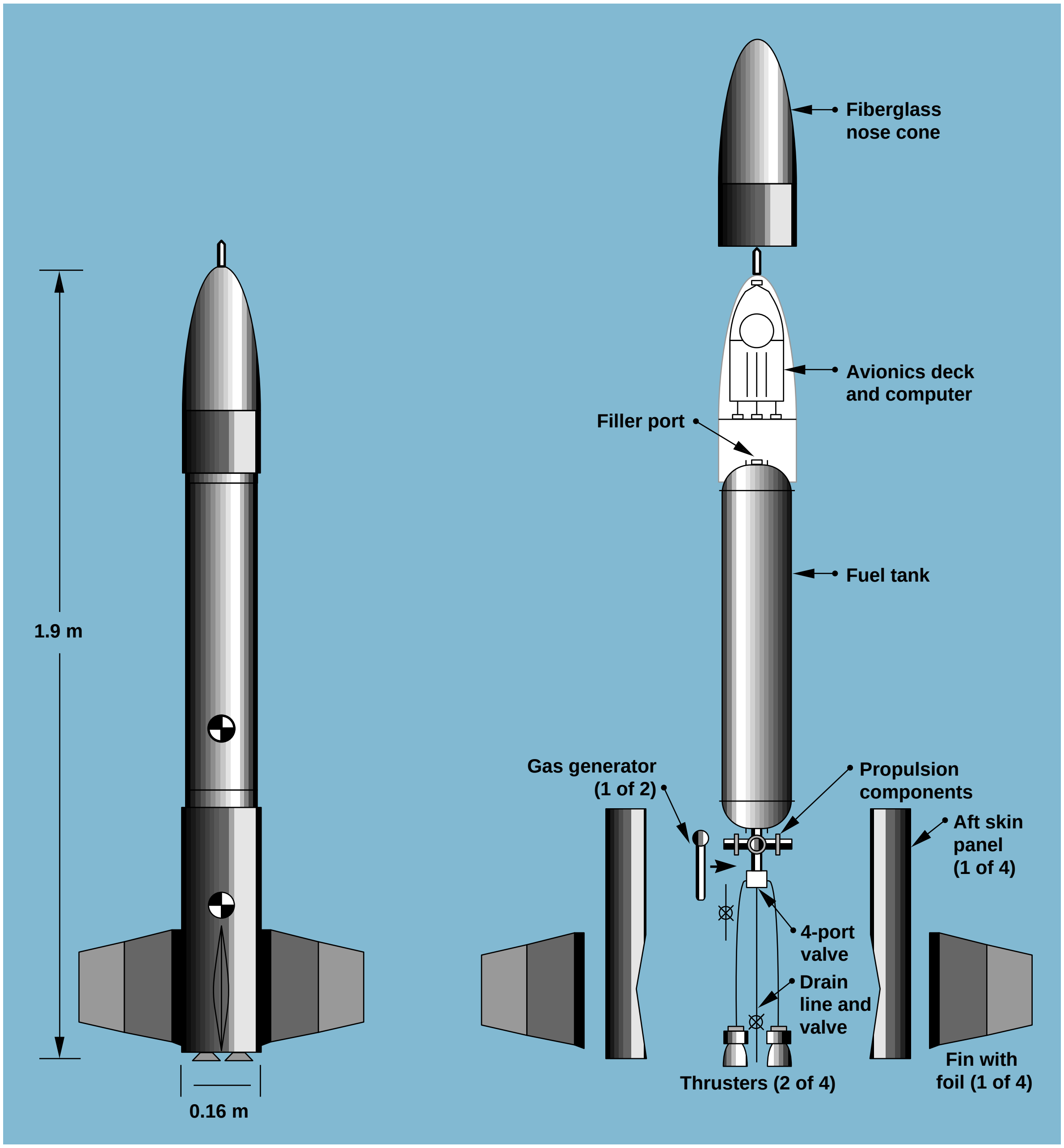


Figure 4. The 1.9-m-long, pump-fed ASTRID rocket. The fiberglass nose houses avionics for sensing, control, and transmitting data back to the ground. The forward section of the vehicle, between nose cone and tank, is an aluminum shell containing pressure transducers and hardware for filling the fuel 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.**

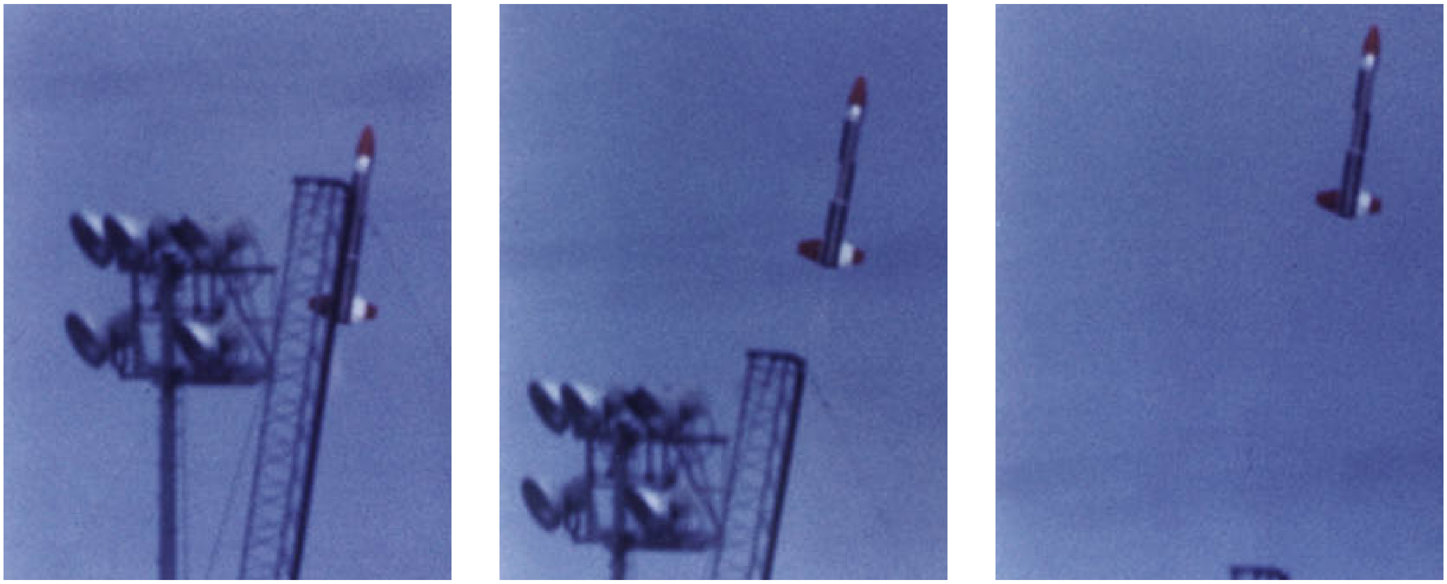
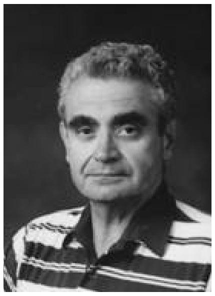


Figure 6. **Sequence of three photos taken of the ASTRID flight test. At t = 1.7 seconds after launch, ASTRID leaves the launch rail at Vandenberg Air Force Base on its way to spashdown about a minute later in the Pacific Ocean.**

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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Abstracts

Pathfinder and the Development of Solar Rechargeable Aircraft

For many military, civilian, and commercial applications, unmanned aircraft flying at high altitude with long endurance offer advantages over satellites. These advantages include substantially lower costs for design, construction, and launch. Such aircraft may function as reusable, relocatable, geostationary satellites operating within the atmosphere. We are working for the Ballistic Missile Defense Organization to develop unmanned aircraft platforms for protecting our military forces and our allies from attack by theater ballistic missiles. A team of engineers from AeroVironment, Inc., and LLNL have designed and recently completed flight testing of a solar-powered airplane called Pathfinder. The Pathfinder is a flying testbed for proving key technologies, critical system integration approaches, and flight control issues essential to achieving solar rechargeable flight at high altitude. Fuel cell technology has been demonstrated to the point that unitized rechargeable fuel cells are possible. Such an energy-storage system weighs less than a third the weight of the best rechargeable batteries available. The next step would be to build a plane like Pathfinder that has wing dimensions that can accommodate the weight of the rechargeable energy-storage system while enabling it to operate continuously at altitudes (20 to 25 km).

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ASTRID Rocket Flight Test

On February 4, 1994, we successfully flight tested the ASTRID rocket from Vandenberg Air Force Base. The technology for this rocket originated in the Brilliant Pebbles program and represents a five-year development effort. This rocket demonstrated how our new pumped-propulsion technology—which reduced the total effective engine mass by more than one half and cut the tank mass to one fifth previous requirements—would perform in atmospheric flight. This demonstration paves the way for potential cost-effective uses of the new propulsion system in commercial aerospace vehicles, exploration of the planets, and defense applications.

Contact: John C. Whitehead (510) 423-4847, Lee C. Pittenger (510) 422-9909, or Nicholas J. Colella (510) 423-8452 (LLNL)/ (412) 268-6537 (Carnegie Mellon University).