takes off and lands horizontally. Pioneer Rocketplane in Vandenberg, Calif., is developing a lightweight, two-seater vehicle powered by a rocket engine as well as conventional turbofan engines. The plane, with a payload and attached second stage in its small shuttle-style cargo bay, takes off from a runway with its turbofans and climbs to 6,100 meters (20,000 feet). There it meets a fuel tanker that supplies it with 64,000 kilograms (140,000 pounds) of liquid oxygen. After the two planes separate, the oxygen is used to fire up the smaller plane's rocket engine and take it to Mach 15 and 113 kilometers' altitude, at which point it can release its payload and second stage. A fail-safe mechanism for the cryogenic oxygen transfer is the main technical challenge, says the company's vice president for business development, Charles J. Lauer.

Kelly Space and Technology is also developing a horizontal takeoff plane for satellite launches, but one that can handle larger payloads, up to 32,000 kilograms. Kelly's Astroliner, which looks like a smaller version of the shuttle, has to be towed to 6,100 meters. At that altitude, its rocket engines are tested, and a decision is made either to zip up to 122,000

## Air-Breathing Engines

**by Charles R. McClinton**

For years, engineers have dreamed of building an aircraft that could reach hypersonic speeds, greater than Mach 5, or five times the speed of sound. Propelled by a special type of air-breathing jet engine, a high-performance hypersonic craft might even be able to "fly" into orbit—a possibility first considered more than four decades ago. Recently, as the technology has matured and as the demand for more efficient Earth-to-orbit propulsion grows, scientists have begun seriously considering such systems for access to space.

Air-breathing engines have several advantages over rockets. Because the former use oxygen from the atmosphere, they require less propellant—fuel, but no oxidizer—resulting in lighter, smaller and cheaper launch vehicles. To produce the same thrust, air-breathing engines require less than one seventh the propellant that rockets do. Furthermore, because air-breathing vehicles rely on aerodynamic forces rather than on rocket thrust, they have greater maneuverability, leading to higher safety: flights can be aborted, with the vehicle gliding back to Earth. Missions can also be more flexible.

But air-breathing engines for launch vehicles are relatively immature compared with rocket technology, which has continually evolved, with refinements and re-refinements, over the past 40 years. Hypersonic air-breathing propulsion is just now finally coming of age.

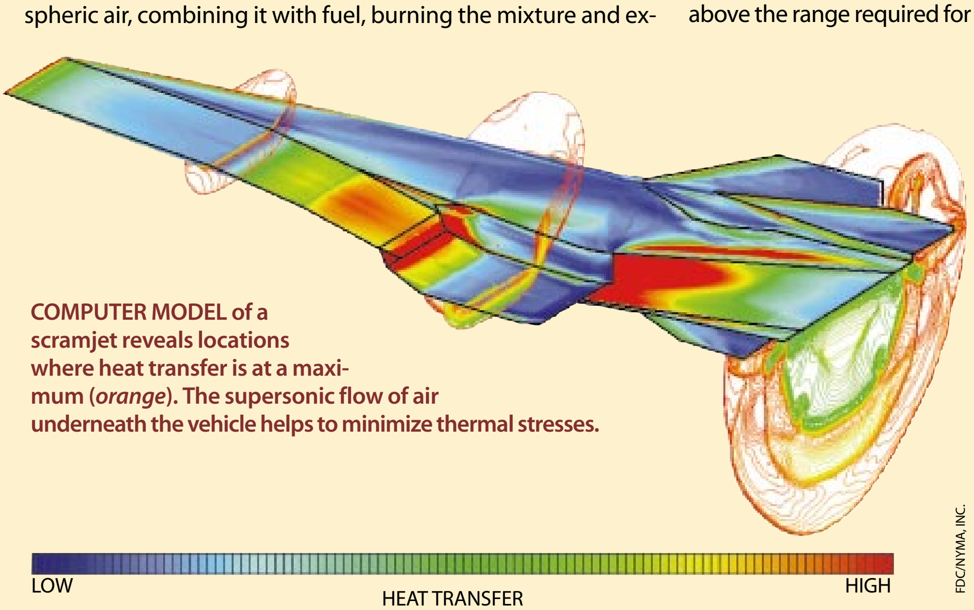
Of course, jet engines—which work by compressing atmospheric air, combining it with fuel, burning the mixture and expanding the combustion products to provide thrust—are nothing new. But turbojet engines, such as those found on commercial and fighter aircraft, are limited to Mach 3 or 4, above which the turbine and blades that compress the air suffer damage from overheating.

Fortunately, at such high supersonic speeds a turbine is not required if the engine is designed so that the air is "ram"-compressed. Such an engine has an air inlet that has been specially shaped to slow and compress the air when the vehicle is moving rapidly through the atmosphere. Because ramjets cannot work unless the vehicle is traveling at high speeds, they have been integrated in the same engine housing with turbojets, as in the French Griffon II experimental aircraft, which set a speed record of 1,640 kilometers per hour (1,020 miles per hour) around a course in 1959. Ramjets have also been combined with rockets in surface-to-air and air-to-surface missiles. But ramjets are limited to about Mach 6, above which the combustion chamber becomes so hot that the combustion products (water) decompose.

To obtain higher speeds, supersonic-combustion ramjets, or scramjets, reduce the compression of the airflow at the inlet so that it is not slowed nearly as much. Because the flow remains supersonic, its temperature does not increase as dramatically as it does in ramjets. Fuel is injected into the supersonic airflow, where it mixes and must burn within a millisecond. The upper speed limit of scramjets has yet to be determined, but theoretically it is above the range required for orbital velocity (Mach 20 to 25). But at such extreme speeds, the benefits of scramjets over rockets become small and possibly moot because of the resulting severe structural stresses.

Hypersonic air-breathing engines can operate with a variety of fuel sources, including both hydrogen and hydrocarbons. Liquid hydrogen, which powers the U.S. space shuttle, is the choice for space launch because it can be used to cool the engine and vehicle before being burned. Hydrocarbons cannot be utilized so efficiently and are limited to speeds less than about Mach 8.

For a scramjet-powered craft, which must be designed to capture large quantities of air, the




COMPUTER MODEL of a scramjet reveals locations where heat transfer is at a maximum (*orange*). The supersonic flow of air underneath the vehicle helps to minimize thermal stresses.

meters or to fly back to the launch site. The first two vehicles should cost close to $500 million, and Kelly is now lining up investors.

Other companies are being more technologically adventurous. One of the most intriguing is Rotary Rocket in Redwood City, Calif., which is building a crewed rocket that would take off and land vertically. The most innovative feature of the design, called the Roton, is its engine. Oxidizer and fuel are fed into 96 combustors inside a horizontal disk seven meters in diameter that is spun at 720 revolutions per minute before launch. Centrifugal force provides the pressure for combustion, thereby eliminating the need for massive, expensive turbo pumps and allowing the vehicle's single stage to go all the way to orbit. The Roton descends with the aid of foldaway helicopter blades that are spun by tiny rockets on their tips, like a Catherine wheel. Rotary Rocket says it will be able to deliver payloads to low-Earth orbit for a tenth of today's typical launch price. The first orbital flight is scheduled for 2000; the company has already tested individual combustors, and atmospheric flights are supposed to take place this year. The de-

distinction between engine and vehicle blurs. The oncoming flow is deflected mainly by the underside of the craft, which increases the pressure of the diverted air. Generally, the change is great enough to cause a pressure discontinuity, called a shock wave, which originates at the ship's nose and then propagates through the atmosphere. Most of the compressed air between the bottom of the vehicle and the shock wave is directed into the engine. The air gets hotter as its flow is slowed and as fuel is burned in the combustion region. The end product of the reaction expands through both an internal and an external nozzle, generating thrust. The high pressures on the underside of the vehicle also provide lift.

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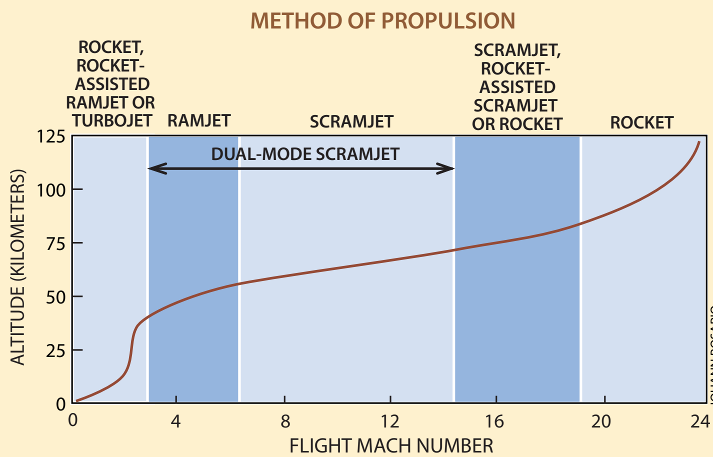
To broaden the scramjet's operating range, engineers have designed vehicles that can fly in either scram or ram mode. The dual-mode operation can be achieved either by constructing a combustor of variable geometry or by shifting the fuel flow between injectors at different locations.

Because neither scramjets nor ramjets can operate efficiently when they are traveling below Mach 2 or 3, a third type of propulsion (perhaps turbojet or rocket) is required for takeoff. So-called rocket-based combined-cycle engines, which could be used in a space vehicle, rely on a rocket that is integrated within the scramjet combustor to provide thrust from takeoff through subsonic, low-supersonic and then ramjet speeds. Ramjet operation is then followed by scramjet propulsion to at least Mach 10 or 12, after which the rocket is utilized again to supplement the scramjet thrust. Above Mach 18, the rocket by itself propels the vehicle into orbit and enables it to maneuver in space. The National Aeronautics and Space Administration is currently testing several variations of such a system.

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**SCRAMJETS (*top*) are designed to capture large quantities of air underneath the craft for burning with a fuel source, such as liquid hydrogen. Dual-mode scramjet engines could be combined with rockets (*graph*) in a vehicle that would, in essence, "fly" into space.**

First, though, much work remains to validate scramjets. Sophisticated computational fluid-dynamic and engineering design methods have made it possible to develop a launch vehicle that has a scramjet built into its structure. Challenges remaining include developing lightweight, high-temperature materials, ensuring rapid and efficient fuel mixing and combustion, and minimizing the buildup of undesirable heat.

In the 1970s the NASA Langley Research Center demonstrated basic scramjet technology with models of hypersonic vehicles and a wind tunnel. Additional ground tests of prototype engines have been performed elsewhere in the U.S. as well as in England, France, Germany, Russia, Japan and Australia, with other related research under way in countries such as China, Italy and India. Today scientists routinely conduct ground tests of scramjet engines at simulated speeds up to Mach 15. In flight tests the Russians have demonstrated ramjet operation of a dual-mode scramjet up to Mach 6.4.

To date, though, no vehicle has flown under scramjet power. But this ultimate test is nearing reality. Through its Hyper-X research program at Langley and Dryden Flight Research Center, NASA is currently building the X-43A, a 3.6-meter-long aircraft that will demonstrate scramjet flight at Mach 7 and Mach 10 within the next three years. If all goes well, the tests will pave the way for future uses of scramjet propulsion, possibly in a vehicle designed for hypersonic flight into space.

*CHARLES R. MCCLINTON, technology manager of the Hyper-X Program at the NASA Langley Research Center in Hampton, Va., has been intrigued and captivated by the technical challenges of hypersonic air-breathing propulsion since the 1960s.*