vehicle to orbit with a single stage of engines that would automatically adapt to changing atmospheric pressure. But the X-33, which will not itself achieve orbit, pushes the limits of current construction techniques. And some observers now doubt whether it will be able to provide NASA with enough information for a promised year 2000 decision on whether the agency should continue to rely on current shuttles until after 2020 or instead phase out those expensive workhorses around 2012.

Difficulties in building the engines have delayed the first flight of the X-33 by six months, until the end of this year. And Daniel R. Mulville, NASA's chief engineer, maintains that a further "year or two" of development will most likely be needed after flight tests are completed in late 2000 before a decision on building a full-

Highways of Light

by Leik N. Myrabo

Today's spacecraft carry their source of power. The cost of space travel could be drastically reduced by leaving the fuel and massive components behind and beaming high-intensity laser light or microwave energy to the vehicles. Experiments sponsored over the past year by the National Aeronautics and Space Administration and the U.S. Air Force have demonstrated what I call a lightcraft, which rides along a pulsed infrared laser beam from the ground. Reflective surfaces in the craft focus the beam into a ring, where it heats air to a temperature nearly five times hotter than the surface of the sun, causing the air to expand explosively for thrust.

Using an army 10-kilowatt carbon dioxide laser pulsing 28 times per second, Franklin B. Mead of the U.S. Air Force Research Laboratory and I have successfully propelled spin-stabilized miniature lightcraft measuring 10 to 15 centimeters (four to six inches) in diameter to altitudes of up to 30 meters (99 feet) in roughly three seconds. We have funding to increase the laser power to 100 kilowatts, which will enable flights up to a 30-kilometer altitude. Although today's models weigh less than 50 grams (two ounces), our five-year goal is to accelerate a one-kilogram microsatellite into low-Earth orbit using a custom-built, one-megawatt ground-based laser—expending just a few hundred dollars' worth of electricity.


LEIK N. MYRABO

MINIATURE LIGHTCRAFT demonstration vehicle has already flown to a height of 30 meters in tests, powered by a 10-kilowatt laser. Larger designs should be able to accelerate to orbit.

Current lightcraft demonstration vehicles are made of ordinary aircraft-grade aluminum and consist of a forward aeroshell, or covering, an annular (ring-shaped) cowl and an aft part consisting of an optic and expansion nozzle. During atmospheric flight, the forward section compresses the air and directs it to the engine inlet. The annular cowl takes the brunt of the thrust. The aft section serves as a parabolic collection mirror that concentrates the infrared laser light into an annular focus, while providing another surface against which the hot-air exhaust can press. The design offers automatic steering: if the craft starts to move outside the beam, the thrust inclines and pushes the vehicle back.

A one-kilogram lightcraft will accelerate this way to about Mach 5 and reach 30 kilometers' altitude, then switch to onboard liquid hydrogen for propellant as air becomes scarce. One kilogram of hydrogen should suffice to take the craft to orbit. A version 1.4 meters in diameter should be able to orbit microsatellites of up to 100 kilograms by riding a 100-megawatt laser beam. Because the beams we use are pulsed, this power might be achieved fairly easily by combining the output from a group of lasers. Such lasers could launch communications satellites and de-orbit them when their electronics become obsolete.

Lightcraft with different geometries can move toward their energy source rather than away from it—or even sideways. These variant vehicles have potential for moving cargo economically around the planet. Lightcraft could also be powered by microwaves. Microwaves cannot achieve such high power densities as lasers, so the vehicles would have to be larger. But microwave sources are considerably less expensive and easier to scale to very high powers.

I have also designed more sophisticated beamed-energy craft, operating on a different principle, that could transport passengers. These craft would be better for carrying larger cargoes because they can produce thrust more efficiently.

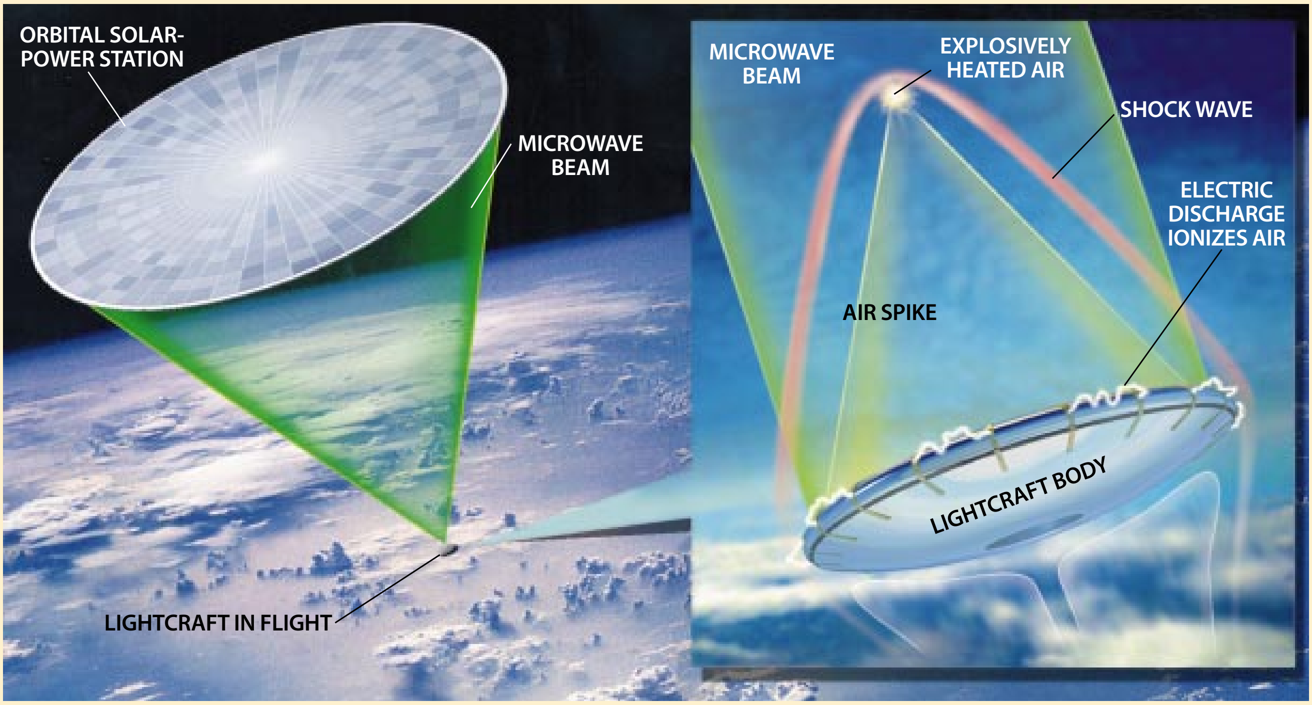
A mirror in the craft focuses some of the incoming beamed energy at a point one vehicle-diameter ahead of the vehicle. The intense heat creates an "air spike" that diverts oncoming air past the vehicle, decreasing drag and reducing the heating of the craft.

This craft taps some additional beamed energy to generate powerful electric fields around the rim, which ionizes air. It also uses superconducting magnets to create strong magnetic fields in that region. When ionized air moves through electric and magnetic fields in this configuration, magnetohydrodynamic forces come into play that accelerate the slipstream to create thrust.

By varying the amount of energy it reflects forward, the lightcraft can control the airflow around the vehicle. I demonstrated reduction of drag by an air spike in April 1995 in a hypersonic shock tunnel at Rensselaer Polytechnic Institute, though with an electrically heated plasma torch rather than with laser power. Tests aimed at generating magnetohydrodynamic thrust, using a 15-centimeter-diameter device, have just begun. A person-size lightcraft of this type driven by microwaves or by a 1,000-megawatt pulsed laser should be able to operate at altitudes up to 50 kilometers and to accelerate easily to orbital velocities.

Lightcraft could revolutionize transportation if they are driven from orbiting solar-power stations. But the cost of assembling the orbital infrastructure eventually must be reduced below a few hundred dollars per kilogram. It now costs about size single-stage-to-orbit vehicle. (Lockheed Martin, however, which calls its design the VentureStar, says it will be ready to commit by the end of 2000.) One problem: the world does not have a large enough autoclave to cure the VentureStar's all-composite liquid-hydrogen tank. More effort is also needed on the metallic tiles that will protect the craft from the heat of reentry.

The VentureStar was billed as a potential national launch system, notes Marcia S. Smith of the Congressional Research Service. Yet the timing could be awkward, as the first VentureStar would not carry humans. NASA has recently asked industry to study the options for carrying to orbit both human and nonhuman cargo early next century. Some potentially useful tricks are being explored with a smaller experimental vehicle known as



NASA AND TOM MOORE

ORBITING solar-power station (*upper left*) could beam microwave energy to an ascending lightcraft (*right*) powered by magnetohydrodynamic thrust. The lightcraft focuses the microwave energy to create an "air spike" that deflects oncoming air. Electrodes on the vehicle's rim ionize air and form part of the thrust-generating system.

$20,000 to put a kilogram of payload in orbit by means of the space shuttle, about 100 times too much.

I think we can bridge the gap by making the first orbital power station one that is specialized for enabling cheap access to space. Imagine a one-kilometer-diameter structure built like a giant bicycle wheel and orbiting at an altitude of 500 kilometers. Its mass would be about 1,010 metric tons, and it would slowly spin to gain gyroscopic stability. Besides the structural "spokes," the wheel would have a disk made from 55 large, pie-slice segments of 0.32-millimeter-thick silicon carbide. Completely covering one side of the silicon carbide would be 30 percent efficient, thin-film solar photovoltaic cells capable of supplying 320 megawatts of electricity. (Such devices are expected within a decade.) On the other side would be 13.2 billion miniature solid-state transmitters, each just 8.5 millimeters across and delivering 1.5 watts of microwave power.

Today's heavy-lift chemical rockets could loft this entire structure over about 55 launches, at an affordable cost of perhaps $5.5 billion. The station would be ringed by an energy storage device consisting of two superconducting cables, each with a mass of 100 metric tons, that could be charged up with counterflowing electric currents. (This arrangement would eliminate the titanic magnetic torque that would be produced by a single cable.)

During two orbits of Earth, the station would completely charge this system with 1,800 gigajoules of energy. It would then beam down 4.3 gigawatts of microwave power onto a lightcraft at a range of about 1,170 kilometers. Torquing forces produced by shifting small amounts of current from one cable to the other would crudely point the power station, but fine control would come from a beacon mounted on the lightcraft. It would send a signal that would coordinate the individual transmitters on the power station to create a spot 10 meters in diameter at the launch site. The vehicle could reach orbit in less than five minutes, subjecting occupants to no more than three g's of acceleration, about the same that shuttle astronauts experience. Or the solar-power station could unload all its energy in a 54-second burst that should offer a nearly vertical 20-g boost to geostationary orbit or even to escape velocity.

The first orbital solar-power station will pave the way for a whole industry of orbital stations, launched and assembled from specialized lightcraft. Within decades, a fleet of these will make feasible rapid, low-cost travel around the globe, to the moon and beyond.

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