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X-30

OUT OF THIS WORLD IN A SCRAMJET

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The National Aerospace Plane program aims to wing its way into orbit instead of rocketing straight up like a space shuttle. The technology to achieve this efficient route to space lies at, or beyond, the ragged edge of knowledge about scramjet propulsion, hypersonic shapes, and ultra-high-heat-resistant materials.

By STUART F. BROWN

Like lugging ice cubes to Antarctica; that's how some engineers view rockets. What they're referring to is the inefficiency of a vehicle that carries a heavy load of oxygen in its lower stages as it blasts through Earth's atmosphere, which is full of oxygen free for the taking.

Theoreticians have long toyed with a sensible, yet technically formidable notion: build a reusable "air breather" that derives oxygen and aerodynamic lift from the atmosphere on its way to space, rather than bulldozing through with brute force as rockets do. In the 1960s, NASA, the Air Force, and the Navy conducted research into hydrogen-fueled scramjet engines to power such a craft, but the inquiry slowed to a snail's pace when NASA selected liquid-fueled rockets for its manned flight programs.

Since the early 1980s, when the National Aerospace Plane (NASP) program was secretly begun by the Defense Advanced Research Projects Agency (DARPA), concentrated scientific and engineering work has been under way at scores of government and industrial labs around the country. The focus is again on developing the exotic technologies needed to take off from a runway and fly into space.

Now funded by the Air Force and NASA, the partly declassified NASP program is a pure research effort designed to build and flight test an experimental hypersonic plane called the X-30. Big cost reductions are the payoff such a single-stage-to-orbit (SSTO) craft might provide; the lion's share of the savings would result from the much smaller number of people and ground facilities required to

PHOTO COURTESY OF NASP NATIONAL

launch, land, and service an airplanelike vehicle. Estimates range from one-tenth to one one-hundredth of the space shuttle's cost per pound of payload delivered to low Earth orbit.

Lessons learned from flying the X-30 could be applied to a future generation of aerospace planes built to launch and retrieve satellites or to ferry crews to an orbiting space station. Potential military missions include surveillance, testing and servicing space-based Star Wars (Strategic Defense Initiative) antimissile hardware, even streaking around the globe to attack an adversary. The NASP program *isn't* geared to developing the "Orient Express" high-speed airliner that former President Reagan referred to in his 1986 state-of-the-union address ["Spaceplanes," May '86].

Travel light and fast, or stay home

For an aircraft to fly into low Earth orbit (about 100 miles up), it must accelerate to orbital velocity—the electrifying speed of 17,500 mph (Mach 25). To put this rate of travel into perspective, the X-15 rocket plane became the only aircraft to nudge into hypersonic flight (greater than six times the speed of sound) when it set the current absolute speed record of Mach 6.7 in 1967 (see "X" Stands for Experimental). The goal of going more than three times faster qualifies the NASP program as one of the most audacious engineering ventures under way.

A brutally unforgiving equation underlies SSTO flight: It's easy to run out of fuel on the way up, yet increasing the size of the fuel tank quickly drives the design into a downward spiral of diminishing returns. Rocket designers have it easy by comparison. They can gain extended range by using multiple stages that are discarded as their fuel supply is exhausted.

"The X-30 needs to be as small as possible to keep its weight at an absolute minimum yet large enough to carry sufficient fuel to get to orbit," says Dr. Robert R. Barthelemy, the Air Force civilian scientist who manages the NASP program at Wright-Patterson Air Force Base in Dayton, Ohio. "Engine efficiency has to be very high—about 95 percent—to get as much energy as possible from each pound of fuel, which is just baggage until you actually burn it. If we don't achieve this efficiency within 1 or 2 percent and keep the vehicle's empty weight at less than 25 percent of its takeoff weight, we'll never get to orbit."

The rest of the world hasn't overlooked the benefits of affordable access to space from ordinary airport runways. Although the U.S. NASP is by far the best-funded aerospace-plane effort and is founded on a superior base of knowledge about hypersonic technologies, British, German, and Japanese programs are also under way. The French, too, are studying entry into the field.

The foreign program closest in concept to the NASP is a Japanese plan to develop an aerospace plane propelled by liquefied-air rocket and scramjet engines to achieve SSTO operation from a runway. Analysts feel that the Japanese government

"X" STANDS FOR EXPERIMENTAL

The X-15 (top) and X-24B rocket planes proved in the 1960s and 1970s that hypersonic flight and the wingless lifting body were workable ideas. Their shape and construction influence the X-30's design.

A radical aircraft concept like the NASP doesn't materialize out of the blue—it stands on the shoulders of pioneering machines that have flown before it. A pair of earlier research aircraft bearing the charismatic X designation, the North American X-15 and Martin Marietta X-24B rocket planes, yielded a wealth of knowledge essential to planning the X-30.

The X-15's still unmatched sprint up to Mach 6.7 was combined with an ability to climb as high as 354,000 feet into the near reaches of space, where it passed from conventional aerodynamic flight control to a reaction-type control system using small nose and wing-tip thruster jets. A then-exotic metal alloy called Inconel-X, which could withstand frictional heating to 1,200°F, was used to fabricate the X-15's skin. Areas of the plane expected to reach 2,000°F peak temperatures were treated with an ablative heat-shield coating.

The dangers of heat are not just theoretical. When the X-15 took off in late 1967 for what was to be its fastest flight, a model of a hypersonic scramjet was attached to its underside. "Aerodynamic overheating severely damaged the plane," says Johnny G. Armstrong, manager of hypersonic projects at Edwards Air Force Base in California. "A shock wave formed upstream of the scramjet and totally overheated an Inconel instrument tube, which fell off the airplane while it was in the landing pattern," he recalls, displaying the twisted and discolored part.

The X-24 series of lifting-body planes proved that a supersonic craft with low lift and high drag could land safely on a runway. The X-24B flew at speeds up to Mach 1.8, and repeatedly demonstrated unpowered precision landings. "They showed a more graceful way to come back from space than swimming around in the ocean," says Armstrong.

"Flight testing the X-30 is going to be incremental, adding speed a bit at a time, because we just can't predict local hot spots, and they can eat up the airplane. The computational-fluid-dynamics guys can do a good job of predicting temperatures for the overall acreage of the airplane, but not in these little areas. We have three NASA SR-71 Blackbirds here that we can use to keep a close eye on the X-30 up to about Mach 3."—*S. F. B.*

A classified NASP research engine is readied for a low-speed Mach 2.7 run in a test facility at Marquardt Co. in Van Nuys, Calif. The engine's exhaust outlet (at right) and inlet duct (behind the engineer) were kept covered by security officials when the photo was taken. The long, rectangular engine is almost obscured by monitoring instruments and cooling water pipes. The largest test engine built to date, it is slightly smaller than the proposed X-30 propulsion units. NASP engines have been run at up to Mach 8 in this cell.

KEN ROGERS

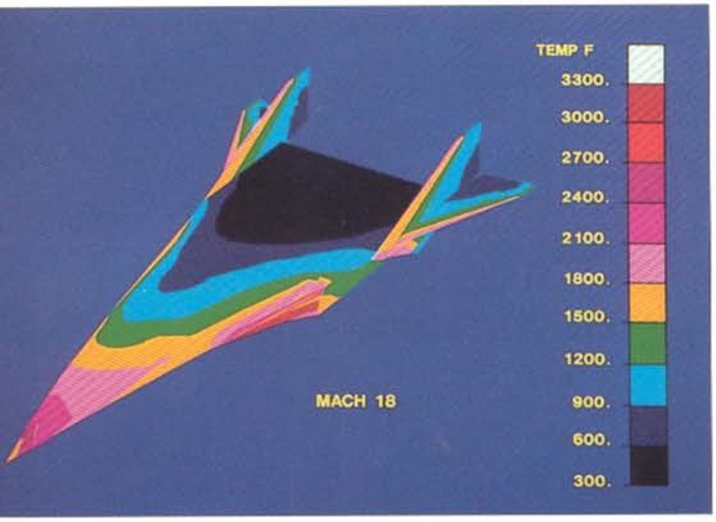
has not yet decided how to structure the necessary research, and at what pace to proceed.

The most advanced program in terms of research and development accomplishment is Germany's push to develop its two-stage-to-orbit Saenger II launch system. The Saenger's crewless first stage would be about the size of a Boeing 747 airliner and use a turboramjet engine (a hybrid design incorporating both turbine and ramjet elements) to accelerate from a runway takeoff to about Mach 6.8. A much smaller piloted second stage would then separate from its perch atop the first and climb to orbit using rocket propulsion. Both reusable stages would return to land on European runways, the first stage controlled remotely by operators on the ground.

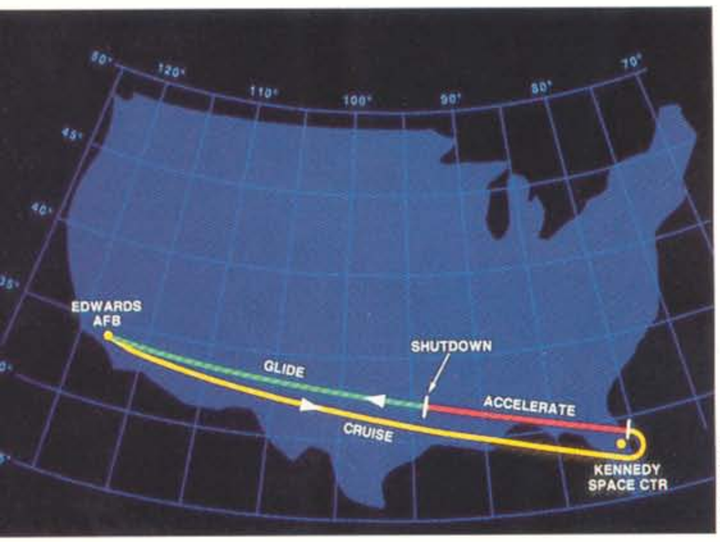
The modestly funded British Aerospace HOTOL program involves plans to develop an unmanned, reusable SSTO vehicle. The original concept (see Aerospace Planes: The Global Competition) involved ground launch from a runway-mounted rocket sled and climb powered by a classified Rolls-Royce RB-545 engine that breathes atmospheric air at low altitudes and then switches to an on-board liquid-oxygen supply to sustain rocket combustion from about 85,000 feet to orbit. A recent study focused on air-launching the HOTOL from a gigantic Soviet An-225 transport plane. If this method is adopted, the craft may rely instead on Soviet-developed traditional rocket technology.

If funding from Washington and the pace of technological progress hold up, construction of a pair of X-30 aircraft will begin in 1993, with the first flight planned for 1997. But until then, the X-30 is only a gleam in a test pilot's eye.

Technicians (above) at Wyle Laboratories in Norco, Calif., close an environmental chamber containing an 8-foot-long composite NASP fuselage and hydrogen-tank section. It is designed to withstand cryogenic (-420°F), thermal (1,300°F), and mechanical stresses that would be encountered in flight. Safe handling of hydrogen (right) is a must.



U.S. AIR FORCE



U.S. AIR FORCE

A computational fluid dynamics image (top) of a NASP-type aircraft flying at Mach 18. The colors are keyed to local airframe temperatures generated by atmospheric friction. The actual shape of the NASP remains classified. The test-flight plan (above) shows how a Mach 12 hypersonic run would traverse the continental United States twice in one hour.

Heat is the scary monster waiting to gobble up ultrafast flying machines. As an aircraft accelerates into supersonic flight, its skin warms up from atmospheric friction.

The Mach 2 Concorde airliner and the Mach 3.2 SR-71 spyplane are built using metal alloys that can take high heat while remaining sufficiently strong. At the much higher Mach numbers into which the NASP program will venture, the temperature, pressure, and mechanical stress conditions are so unfamiliar that they are virtually impossible to simulate accurately in earthbound laboratories. Only one thing is certain—they will be severe. "We just don't know much at all about scramjet flight above Mach 12. There's no way to find out if this will work other than to build the airplane and fly it," says the Barthelemy.

"Unobtanium" unnecessary

The hypersonic velocities anticipated for the X-30 will heat certain areas of the aircraft to more than 5,000°F, far beyond the melting points of traditional heat-tolerant alloys. As recently as five years ago, many people familiar with advanced composite materials were dismissing the NASP as a craft that could only be built from "unobtanium." But rapid strides in research and development over the past three years ["Hot Jets," June '90] have entirely changed the outlook, according to Dr. Terry Ronald, the program's deputy director for materials.

"It became clear in 1987 that the materials part of the program was a critical issue and that the rate at which we were working wasn't going to get the job done," Ronald says. "We set up a consortium of contractors and greatly accelerated the pace of high-temperature-materials work. We feel pretty encouraged now. Some of our test samples are surviving simulations for the projected life of the vehicle, which is measured in hundreds of hours."

A key breakthrough has been keeping carbon-carbon composite from succumbing to its Achilles heel: burning up in the presence of oxygen. The composite's tolerance for extremely high temperatures makes it the material of choice for heat shields to protect hot areas of the X-30's airframe. Researchers were bedeviled by problems with silicon-carbide ceramic coatings that were designed to keep out oxygen, but had chronic cracking problems due to the different thermal-expansion rates of the two materials. "The solution lay in putting additional coatings between them to accommodate the expansion differences," Ronald explains. "We also added layers of a glass-forming material that oxidizes and flows to seal any cracks that might develop. Finally, we added inhibitors to the carbon

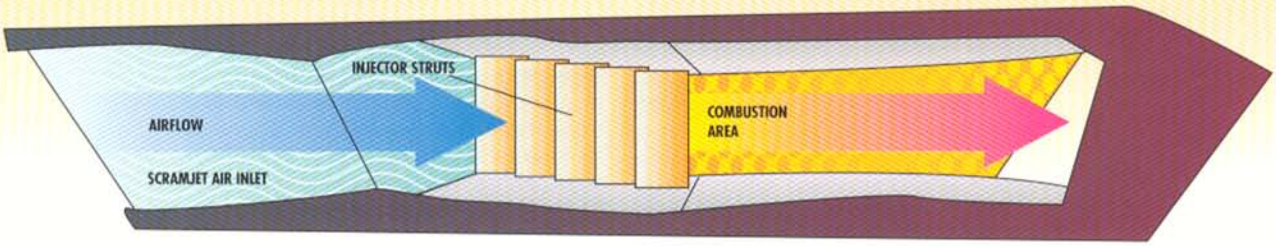
AEROSPACE PLANES: THE GLOBAL COMPETITION

Nations regard developing independent means of getting into space as not only a matter of prestige and security, but also as an economic engine that can advance their technological prowess and spawn new industries early in the next century. Some strategists believe that the rest of the world will pool its resources to build a craft to rival the U.S. NASP. The table summarizes technical goals of the four major programs.

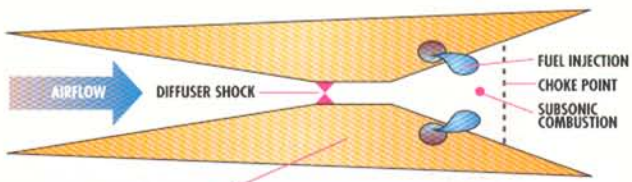
AEROSPACE PLANE CHARACTERISTICS	U.S.	U.K.	GERMANY	JAPAN
AIR-BREATHING ENGINE SPEED LIMIT (MACH SPEEDS)	15-20	5	4-4.7	6-12
AIR-BREATHING UPPER ALTITUDE LIMIT (FEET; 1ST STAGE ONLY)	150,000	85,000	85,000	120,000
HIGHEST TEMPERATURES TO WITHSTAND (° F)	5,000	2,700	2,000	4,000
ANTICIPATED FIRST TEST FLIGHT	1997	2000	2005	2006
USE OF SCRAMJET	YES	NO	NO	YES
USE OF ACTIVE COOLING SYSTEM	YES	NO	NO	YES
HYPERSONIC CRUISE CAPABILITY	YES	NO	YES (1st STAGE ONLY)	YES
SINGLE STAGE TO ORBIT	YES	YES	NO	YES
POWERED LANDING CAPABILITY	YES	NO	YES (1st STAGE ONLY)	YES

SOURCE: CONGRESSIONAL RESEARCH SERVICE

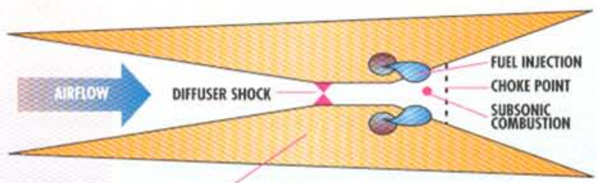
PROPULSION FROM ZERO TO (MAYBE) MACH 25



A scramjet engine (above) designed to run at speeds of Mach 6 and higher consists of a rectangular, open-ended duct with a convergent inlet throat, or diffuser. Air entering the inlet is slowed, compressed, and heated as it passes through the narrowing throat, but still travels at supersonic speed. Fuel enters through openings in the injector struts. Mixing and combustion occur downstream of the struts. The exhaust gases expand and accelerate as they exit through the widening aft end, producing thrust.

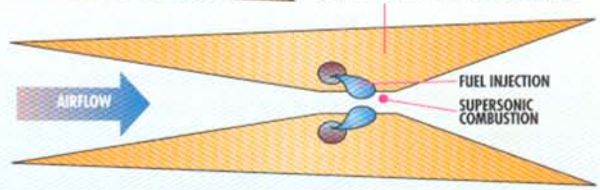


The dual-mode NASP propulsion system being developed by Pratt & Whitney and Rocketdyne slows the inlet air to subsonic speeds before injecting hydrogen gas. The decelerating airflow reaches subsonic speed at the choke point, where combustion occurs. This is the ramjet operating mode. Back pressure created by the compression process in the tapered inlet, or diffuser, causes a shock wave to form.



As flight speeds approach Mach 5, the choke point moves upstream in the exhaust nozzle. The engine sustains subsonic combustion by switching to a second set of fuel injectors located farther upstream in the flow path.

Above Mach 6, the engine functions in its scramjet mode. Immense inlet pressures eliminate the diffuser shock from the flow path. A third set of fuel injectors even farther upstream initiates combustion in the supersonic flow that exists throughout the engine.



← SUPERSONIC SPEEDS → ← HYPERSONIC SPEEDS →

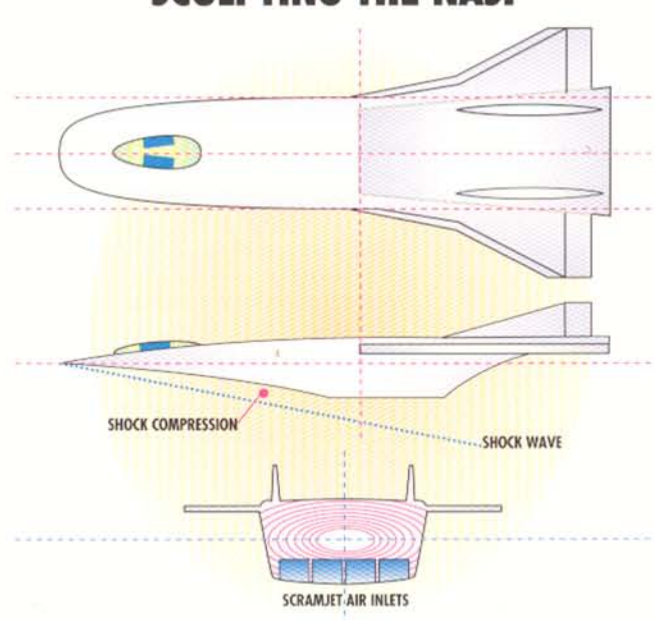
matrix itself to cause any oxygen that did get through the outer layers to form something innocuous that won't hurt the material. This is really a self-healing notion."

The X-30's stressed skin will be made largely from a new metal-matrix composite consisting of special titanium alloys reinforced with ceramic fibers. Coated carbon-carbon heat-shield panels will then be attached over much of the aircraft's surface. Areas where aerodynamic heating is most severe, such as the nose tip, fuselage leading edges, and inside the engines, will be actively cooled: Cold hydrogen gas will be piped through a maze of internal passages that are formed inside sheets of high-thermal-conductivity composite made from carbon fibers embedded in a copper-alloy matrix.

The success of the materials-development consortium led NASP managers to extend the team approach to the entire program. The five major contracting companies—General Dynamics, McDonnell Douglas, Pratt & Whitney, and Rockwell Corp.'s North American Aviation and Rocketdyne divisions—were melded into a cooperative arrangement wherein each partner assumes responsibility for developing a major chunk of the X-30, and shares its lessons learned with the other four.

"We set ourselves the goal that each of the five companies in this partnership will have a significant enough design and manufacturing role that any of them will be a competitive force in the field of hypersonics before we're done. You can't do this by creating a monopoly for one company," says Chuck Anderson, deputy for program inte-

SCULPTING THE NASP



The broad fuselage shape seen in the plan view at top provides the large underbody area needed to generate lift and accommodate multiple scramjets. The stubby wings provide flight control, but little lift. In the side view (middle), the shock wave forming at the craft's nose adds compression energy to the inlet airflow. The underbody contours are closely guarded secrets.

gration. "This approach has worked very well for the Japanese. It's a way of being a leader in a technological area by building a competitive environment on a large enough base of people. We want to maintain our lead in aerospace."

Scram!

The thrust needed to push an X-30 into double-digit Mach numbers will come from a hybrid ramjet-scramjet propulsion system. Ramjets are surprisingly uncomplicated devices that have been used for decades to power missiles. A classic ramjet consists of a pinched tube with fuel injectors inside and a cone (pointed end forward) in the front end. This cone slows incoming supersonic air to subsonic speed, thereby compressing and heating it for efficient combustion. The resulting exhaust gases expand out the widening aft end of the tube at a velocity higher than that of the inlet air, producing thrust.

Ramjets function well from slightly above Mach 1 to around Mach 6, where they become extremely hot and inefficient due to the drag created by compressing the fast-moving airstream. To go beyond Mach 6, a ram-type engine must be able to mix fuel with air flowing through it at *supersonic* speeds, then complete the burning process in a fleeting instant—a feat engineers like to compare to lighting a match in a hurricane. This variant is called a supersonic-combustion ramjet, or scramjet ["Mach 25 Scramjets," Apr. '86].

The mere millisecond or so available for burning inside a scramjet makes a chemically fast-reacting fuel mandatory. Hydrogen fits the bill. The light element has a major shortcoming, however. Its low density dictates that enough liquid hydrogen to fuel an air-breathing SSTO craft occupies a very large volume. Fortunately, liquid hydrogen can be chilled to the point that it becomes a half-solid, half-liquid slush. Using denser slush hydrogen as fuel promises to reduce the aircraft's takeoff weight by as much as 30 percent from that of a liquid-fueled design. Still, peeling away the X-30's skin would reveal insides dominated by a huge cryogenic fuel tank.

Updated versions of ramjet-scramjet designs developed in the 1960s under Air Force contracts are the heart of the NASP propulsion system, says ram-engine expert Robert D. Wilson, director of aero-propulsion at Marquardt Co. in Van Nuys, Calif. The long, rectangular engines are able to shift from ramjet into scramjet mode without mechanically altering the internal path through which the airstream flows (see Propulsion From Zero to (Maybe) Mach 25). "You could build two separate engines to do all this stuff, but it wouldn't be worth the weight penalty," he observes. The trick to making the same engine run under quite different conditions is using sets of fuel injectors situated at different points along its internal walls. A control system automatically varies the fuel-injection point in concert with the location of the engine's combustion area, which shifts upstream in the flow path as flight speeds increase.

From three to five of these ram-scram modules will be ganged together to form the X-30's main source of propulsion. Researchers at various labs report that experimental ramjet and scramjet engines so far have generally come close to their predicted performance goals, though the thrust levels achieved in testing remain classified. Much of the research on hypersonic flight and propulsion has been conducted at NASA's Langley Research Center in Langley, Va., where work has continued at low funding levels since the 1960s.

Not much air up there

Anyone who has hiked in tall mountains has experienced Earth's atmosphere thinning rapidly with altitude. How then is an air-breathing craft going to fly to the edge of space without "suffocating"? This much is known: Scramjets will run in deathly thin air. "When you're going 17,000 miles per hour, molecules can be pretty far apart, yet you're still gathering a lot of them up each second," says Tim Geohegan, the program's combustor analytical design coordinator.

The upper limits for speed and altitude of the scramjet-powered portion of an aerospace plane's flight are a great unknown. Morsels of insight into conditions at Mach 10 to Mach 17 have been gleaned from testing small scramjet and airframe models in pulse-type wind tunnels that can momentarily generate hypersonic airflow by uncorking huge tanks of high-pressure compressed air.

"It will probably go Mach 17," Barthelemy predicts, "but will it go Mach 18, or 22, or 25? We just don't know. The high end of the scramjet mode is the uncertain one. That's where you're starting to experience an increasingly small difference between thrust and drag. Eventually the drag will get worse than the thrust produced—that's the point where you just have to turn on a rocket for a final push to orbit. But there's no way to know in advance at what speed this will occur."

The X-30's modest-size restartable rocket engine will also be used to push it out of orbit and into a descent trajectory for an unpowered glide back to Earth. Should things go badly during the first approach to a runway landing, the two-member crew will be able to make a go-around and second approach, a luxury space shuttle pilots don't have.

Rockwell Corp's space systems division in Downey, Calif., has built an engineering simulator to help develop the X-30's cockpit design. "An X-30 approach will be very similar to a space shuttle approach, and pretty close to an X-15's," says Air National Guard Maj. Gen. Joe H. Engle, an engineering consultant involved in Rockwell's project who has flown both vehicles back from space. "An X-30 landing wouldn't be too strange at all for a shuttle pilot, or for any pilot for that matter. The approach is quite steep, and it's impressive the first several times. But after enough simulator practice, the timing becomes very natural. Once you leave the outer glide slope, you have about 25 seconds before you run out of lift and speed and have to touch down. You develop a kind of internal clock—time stretches out a bit, and you just know when those 25 seconds are up and the main landing gear touches the runway. Climbing in an X-30 will be uneventful by comparison."

Starting from a standstill

Questions about how the X-30 may behave at hypersonic speeds would remain purely academic if the plane couldn't get off the ground. The element of the propulsion system that moves the craft from a dead standstill to somewhere near Mach 3 is one of the most highly classified areas of the program, so engineers will discuss it only in the vaguest terms.

How might the secret system work? One version under development "uses no turbojets or any kind of rotating equipment in any of the flow paths," says Phil Maddox, project engineer for the low-speed oxidizer element of the program at Rockwell Corp.'s Rocketdyne division. His reference may be to a liquid-air cycle engine, which uses liquid-hydrogen heat exchangers to liquefy atmospheric air entering the inlet duct. The liquid air and liquid hydrogen are then mixed and burned in a rocket-type combustion chamber. Such engines were built and tested a number of years ago. Various pulse-type ramjet engines (like those powering German buzz bombs in World War II) are also known to be able to get a vehicle moving from zero mph. In addition, though they might not prove to be the most attractive solution from the standpoint of weight, turbine engine designs are still being considered in the ongoing "trade studies" scrutinizing the advantages and shortcomings of many combinations of propulsion hardware.

The plane *is* the engine

Designers speak of the planned X-30 as having an "integrated" airframe and propulsion system. They mean this literally. No longer can the engines be thought of as discrete bolt-in modules like those found in rockets or conventional jet aircraft. "The whole bottom of the vehicle is truly an inseparable part of the propulsion system," says Bill Imfeld, NASP director of engineering at Wright-Patterson.

The underbody performs two key functions. First, it provides lift. The X-30 belongs to a category of aircraft known as lifting bodies. Developed through extensive flight research in the 1960s, lifting bodies are blunt, essentially wingless craft. The most familiar lifting body is the space shuttle, which uses its contoured underbody to develop enough lift to keep from dropping like a stone on its steep, unpowered glide back from orbit.

The second role of the X-30's underbody is to perform a large share of the inlet-air compression and exhaust-expansion work by which the scramjets produce thrust. At supersonic and hypersonic velocities, shock waves trailing back from the aircraft's nose interact with the curvature of the forward underbody to trap a portion of the airstream, squeeze it—thereby raising its temperature—and force it into the scramjets. Further compression occurs in the tapered inlet ducts before hydrogen is added and combustion occurs.

As the hot exhaust stream (composed largely of water vapor) roars out the back ends of the scramjets, the crescent shape of the aft underbody controls the rate at which the gases expand to optimize the thrust developed. In effect, the underbody beneath the X-30's tail fins will behave like half of a rocket's exhaust nozzle sliced lengthwise.

With the lifting-body airframe and the propulsion system so fundamentally a part of each other and with all the unknowns regarding the temperature and pressure levels that ultra-high-Mach velocities will create on the X-30's skin and inside its scramjets, it's a wonder designers have a clue about how to begin sculpting a shape that might work. They wouldn't without supercomputers.

The NASP program would have been unthinkable before the advent of powerhouse computers able to churn quickly through millions of calculations used in the young discipline of computational fluid dynamics (CFD) to model aerodynamic events of previously imponderable complexity ["Winging it into Space," May '89]. Dr. Joe Shang, technical manager of the computational aerodynamics group at Wright-Patterson, is only one part of a network of supercomputer-equipped researchers contributing to the NASP program that has included three-quarters of the CFD specialists in the country. "We are able to see things, such as heat-transfer information, that you cannot see any other way. A possible hot spot can be avoided this way," he explains.

CFD and flight testing will dovetail intimately if an X-30 finally rolls out onto a runway at Edwards Air Force Base and takes to the skies. When the cautiously structured test program unfolds and flight speeds push past about Mach 8, CFD and flying will begin to play leapfrog with each other. As the airplane pushes notch by notch into the little-understood conditions at high Mach numbers and altitudes, data pouring in from its sensors will be incorporated into the CFD data base—which can then be used to make meaningful predictions about what to expect during the next flight into the unknown.

Uncertain, expensive, exciting

At this point, the NASP effort is a collection of research-and-development projects—some more mature than others—sharply focused on an extremely demanding goal. Barthelemy summarizes his program's evolution this way: "At first the NASP idea was an airplane nicknamed 'the pig' because it had everybody's favorite system in it and it weighed one million pounds. I really think that sometimes you have to go through this phase and then realize what a monster you're talking about and get back to basics. Now we've got an airplane roughly the size of the shuttle orbiter that should weigh 340,000 pounds at takeoff. The entire program to build and fly the plane could cost $5 billion to $10 billion. We want to go around the Earth at least once to claim we've gotten to orbit. If we can show that getting something into space really can be much less expensive, there's a market to be developed. A lot more things will start going into space." PS