HRE. An aircraft of this type indeed took shape before long, with the designation X-30. However, it did not originate purely as a technical exercise. Its background lay in presidential politics.

The 1980 election took place less than a year after the Soviets invaded Afghanistan. President Jimmy Carter had placed strong hope in arms control and had negotiated a major treaty with his Soviet counterpart, Leonid Brezhnev. But the incursion into Afghanistan took Carter by surprise and destroyed the climate of international trust that was essential for Senate ratification of this treaty. Reagan thus came to the White House with arms-control prospects on hold and with the Cold War once more in a deep freeze. He responded by launching an arms buildup that particularly included new missiles for Europe.[29]

Peace activist Randall Forsberg replied by taking the lead in calling for a nuclear freeze, urging the superpowers to halt the "testing, production and deployment of nuclear weapons" as an important step toward "lessening the risk of nuclear war." His arguments touched a nerve within the general public, for within two years, support for a freeze topped 70 percent. Congressman Edward Markey introduced a nuclear-freeze resolution in the House of Representatives. It failed by a margin of only one vote, with Democratic gains in the 1982 mid-term elections making passage a near certainty. By the end of that year half the states in the Union adopted their own freeze resolutions, as did more than 800 cities, counties, and towns.[30]

To Reagan, a freeze was anathema. He declared that it "would be largely unverifiable…. It would reward the Soviets for their massive military buildup while preventing us from modernizing our aging and increasingly vulnerable forces." He asserted that Moscow held a "present margin of superiority" and that a freeze would leave America "prohibited from catching up."[31]

With the freeze ascendant, Admiral James Watkins, the Chief of Naval Operations, took a central role in seeking an approach that might counter its political appeal. Exchanges with Robert McFarlane and John Poindexter, deputies within the National Security Council, drew his thoughts toward missile defense. Then in January 1983 he learned that the Joint Chiefs were to meet with Reagan on 11 February. As preparation, he met with a group of advisors that included the physicist Edward Teller.

Trembling with passion, Teller declared that there was enormous promise in a new concept: the x-ray laser. This was a nuclear bomb that was to produce intense beams of x-rays that might be aimed to destroy enemy missiles. Watkins agreed that the broad concept of missile defense indeed was attractive. It could introduce a new prospect: that America might counter the Soviet buildup, not with a buildup of its own but by turning to its strength in advanced technology.

Watkins succeeded in winning support from his fellow Joint Chiefs, including the chairman, General John Vessey. Vessey then gave Reagan a half-hour briefing at

the 11 February meeting, as he drew extensively on the views of Watkins. Reagan showed strong interest and told the Chiefs that he wanted a written proposal. Robert McFarlane, Deputy to the National Security Advisor, already had begun to explore concepts for missile defense. During the next several weeks his associates took the lead in developing plans for a program and budget.[32]

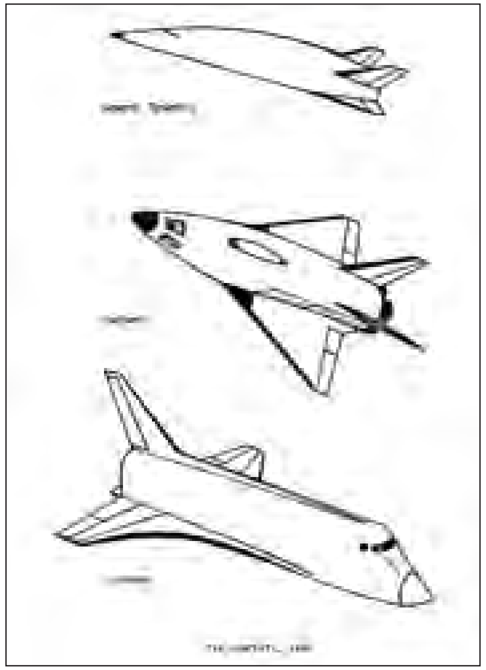
On 23 March 1983 Reagan spoke to the nation in a televised address. He dealt broadly with issues of nuclear weaponry. Toward the end of the speech, he offered new thoughts:

> "Let me share with you a vision of the future which offers hope. It is that we embark on a program to counter the awesome Soviet missile threat with measures that are defensive. Let us turn to the very strengths in technology that spawned our great industrial base and that have given us the quality of life we enjoy today.
>
> What if free people could live secure in the knowledge that their security did not rest upon the threat of instant U.S. retaliation to deter a Soviet attack, that we could intercept and destroy strategic ballistic missiles before they reached our own soil or that of our allies?…
>
> I call upon the scientific community in our country, those who gave us nuclear weapons, to turn their great talents now to the cause of mankind and world peace, to give us the means of rendering these nuclear weapons impotent and obsolete."[33]

The ensuing Strategic Defense Initiative never deployed weapons that could shoot down a missile. Yet from the outset it proved highly effective in shooting down the nuclear freeze. That movement reached its high-water mark in May 1983, as a strengthened Democratic majority in the House indeed passed Markey's resolution. But the Senate was still held by Republicans, and the freeze went no further. The SDI gave everyone something new to talk about. Reagan's speech helped him to regain the initiative, and in 1984 he swept to re-election with an overwhelming majority.[34]

The SDI brought the prospect of a major upsurge in traffic to orbit, raising the prospect of a flood of new military payloads. SDI supporters asserted that some one hundred orbiting satellites could provide an effective strategic defense, although the Union of Concerned Scientists, a center of criticism, declared that the number would be as large as 2,400. Certainly, though, an operational missile defense was likely to place new and extensive demands on means for access to space.

Within the Air Force Systems Command, there already was interest in a next-generation single-stage-to-orbit launch vehicle that was to use the existing Space Shuttle Main Engine. Lieutenant General Lawrence Skantze, Commander of the



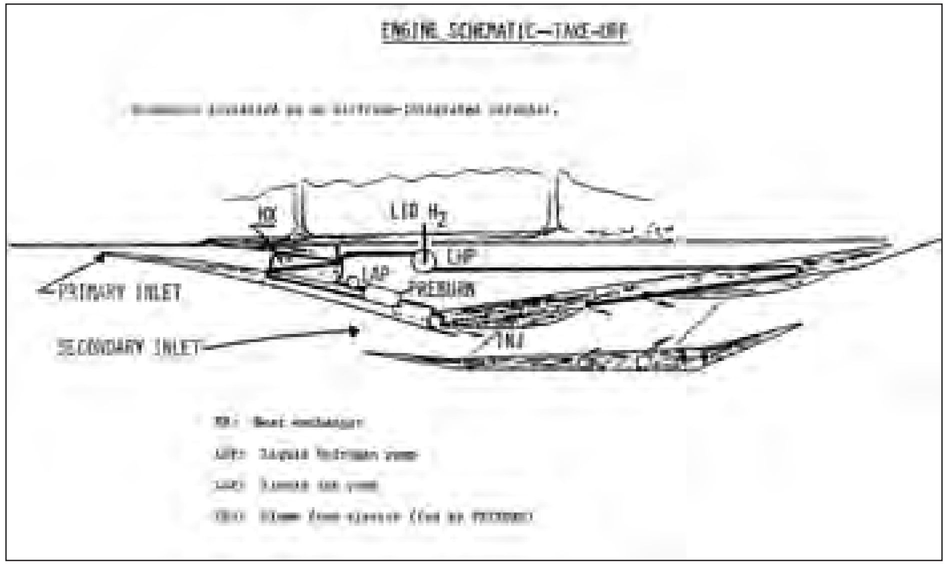
Transatmospheric Vehicle concepts, 1984. (U.S. Air Force)

Air Force Systems Command's Aeronautical Systems Division (ASD), launched work in this area early in 1982 by directing the ASD planning staff to conduct an in-house study of post-shuttle launch vehicles. It then went forward under the leadership of Stanley Tremaine, the ASD's Deputy for Development Planning, who christened these craft as Transatmospheric Vehicles. In December 1984 Tremaine set up a TAV Program Office, directed by Lieutenant Colonel Vince Rausch.[35]

Moreover, General Skantze was advancing into high-level realms of command, where he could make his voice heard. In August 1982 he went to Air Force Headquarters, where he took the post of Deputy Chief of Staff for Research, Development, and Acquisition. This gave him responsibility for all Air Force programs in these areas. In October 1983 he pinned on his fourth star as he took an appointment as Air Force Vice Chief of Staff. In August 1984 he became Commander of the Air Force Systems Command.[36]

He accepted these Washington positions amid growing military disenchantment with the space shuttle. Experience was showing that it was costly and required a long time to prepare for launch. There also was increasing concern for its safety, with a 1982 Rand Corporation study flatly predicting that as many as three shuttle orbiters would be lost to accidents during the life of the program. The Air Force was unwilling to place all its eggs in such a basket. In February 1984 Defense Secretary Caspar Weinberger approved a document stating that total reliance on the shuttle "represents an unacceptable national security risk." Air Force Secretary Edward Aldridge responded by announcing that he would remove 10 payloads from the shuttle beginning in 1988 and would fly them on expendables.[37]

Just then the Defense Advanced Research Projects Agency was coming to the forefront as an important new center for studies of TAV-like vehicles. DARPA was already reviving the field of flight research with its X-29, which featured a forward-swept wing along with an innovative array of control systems and advanced materials. Robert Cooper, DARPA's director, held a strong interest in such projects and saw them as a way to widen his agency's portfolio. He found encouragement during



Anthony duPont's engine. (GASL)

1982 as a group of ramjet specialists met with Richard De Lauer, the Undersecretary of Defense Research and Engineering. They urged him to keep the field alive with enough new funds to prevent them from having to break up their groups. De Lauer responded with letters that he sent to the Navy, Air Force, and DARPA, asking them to help.[38]

This provided an opening for Tony duPont, who had designed the HRE. He had taken a strong interest in combined-cycle concepts and decided that the scramlace was the one he preferred. It was to eliminate the big booster that every ramjet needed, by using an ejector, but experimental versions weren't very powerful. DuPont thought he could do better by using the HRE as a point of departure, as he added an auxiliary inlet for LACE and a set of ejector nozzles upstream of the combustor. He filed for a patent on his engine in 1970 and won it two years later.[39]

In 1982 he still believed in it, and he learned that Anthony Tether was the DARPA man who had been attending TAV meetings. The two men met several times, with Tether finally sending him up to talk with Cooper. Cooper listened to duPont and sent him over to Robert Williams, one of DARPA's best aerodynamicists. Cooper declares that Williams "was the right guy; he knew the most in this area. This wasn't his specialty, but he was an imaginative fellow."[40]

Williams had come up within the Navy, working at its David Taylor research center. His specialty was helicopters; he had initiated studies of the X-wing, which was to stop its rotor in midair and fly as a fixed-wing aircraft. He also was interested in high-speed flight. He had studied a missile that was to fight what the Navy called the "outer air battle," which might use a scramjet. This had brought him into discussions with Fred Billig, who also worked for the Navy and helped him to learn his hypersonic propulsion. He came to DARPA in 1981 and joined its Tactical Technologies Office, where he became known as the man to see if anyone was interested in scramjets.[41]

Williams now phoned duPont and gave him a test: "I've got a very ambitious problem for you. If you think the airplane can do this, perhaps we can promote a program. Cooper has asked me to check you out." The problem was to achieve single-stage-to-orbit flight with a scramjet and a suite of heat-resistant materials, and duPont recalls his response: "I stayed up all night; I was more and more intrigued with this. Finally I called him back: 'Okay, Bob, it's not impossible. Now what?'"[42]

DuPont had been using a desktop computer, and Williams and Tether responded to his impromptu calculations by giving him $30,000 to prepare a report. Soon Williams was broadening his circle of scramjet specialists by talking with old-timers such as Arthur Thomas, who had been conducting similar studies a quarter-century earlier, and who quickly became skeptical. DuPont had patented his propulsion concept, but Thomas saw it differently: "I recognized it as a Marquardt engine. Tony called it the duPont cycle, which threw me off, but I recognized it as our engine. He claimed he'd improved it." In fact, "he'd made a mistake in calculating the heat capacity of air. So his engine looked so much better than ours."

Thomas nevertheless signed on to contribute to the missionary work, joining Williams and duPont in giving presentations to other conceptual-design groups. At Lockheed and Boeing, they found themselves talking to other people who knew scramjets. As Thomas recalls, "The people were amazed at the component efficiencies that had been assumed in the study. They got me aside and asked if I really believed it. Were these things achievable? Tony was optimistic everywhere: on mass fraction, on air drag of the vehicle, on inlet performance, on nozzle performance, on combustor performance. The whole thing, across the board. But what salved our conscience was that even if these weren't all achieved, we still could have something worth while. Whatever we got would still be exciting."[43]

Williams recalls that in April 1984, "I put together a presentation for Cooper called 'Resurrection of the Aerospaceplane.' He had one hour; I had 150 slides. He came in, sat down, and said Go. We blasted through those slides. Then there was silence. Cooper said, 'I want to spend a day on this.'" After hearing additional briefings, he approved a $5.5-million effort known as Copper Canyon, which brought an expanded program of studies and analyses.[44]

Copper Canyon represented an attempt to show how the SDI could achieve its access to space, and a number of high-level people responded favorably when Cooper asked to give a briefing. He and Williams made a presentation to George Keyworth, Reagan's science advisor. They then briefed the White House Science Council. Keyworth recalls that "here were people who normally would ask questions for hours. But after only about a half-hour, David Packard said, 'What's keeping us? Let's do it!'" Packard was Deputy Secretary of Defense.[45]

During 1985, as Copper Canyon neared conclusion, the question arose of expanding the effort with support from NASA and the Air Force. Cooper attended a classified review and as he recalls, "I went into that meeting with a high degree of skepticism." But technical presentations brought him around: "For each major problem, there were three or four plausible ways to deal with it. That's extraordinary. Usually it's—'Well, we don't know exactly how we'll do it, but we'll do it.' Or, 'We have *a* way to do it, which may work.' It was really a surprise to me; I couldn't pick any obvious holes in what they had done. I could find no reason why they couldn't go forward."[46]

Further briefings followed. Williams gave one to Admiral Watkins, whom Cooper describes as "very supportive, said he would commit the Navy to support of the program." Then in July, Cooper accompanied Williams as they gave a presentation to General Skantze.

They displayed their viewgraphs and in Cooper's words, "He took one look at our concept and said, 'Yeah, that's what I meant. I invented that idea.'" Not even the stars on his shoulders could give him that achievement, but his endorsement reflected the fact that he was dissatisfied with the TAV studies. He had come away appreciating that he needed something better than rocket engines—and here it was. "His enthusiasm came from the fact that this was all he had anticipated," Cooper continues. "He felt as if he owned it."

Skantze wanted more than viewgraphs. He wanted to see duPont's engine in operation. A small version was under test at GASL, without LACE but definitely with its ejector, and one technician had said, "This engine really does put out static thrust, which isn't obvious for a ramjet." Skantze saw the demonstration and came away impressed. Then, Williams adds, "the Air Force system began to move with the speed of a spaceplane. In literally a week and a half, the entire Air Force senior command was briefed."

Initial version of the duPont engine under test at GASL. (GASL)

Later that year the Secretary of Defense, Caspar Weinberger, granted a briefing. With him were members of his staff, along with senior people from NASA and the military service. After giving the presentation, Williams recalls that "there was silence in the room. The Secretary said, 'Interesting,' and turned to his staff. Of course, all the groundwork had been laid. All of the people there had been briefed, and we could go for a yes-or-no decision. We had essentially total unanimity around the table, and he decided that the program would proceed as a major Defense Department initiative. With this, we moved immediately to issue requests for proposal to industry."[47]

In January 1986 the TAV effort was formally terminated. At Wright-Patterson AFB, the staff of its program office went over to a new Joint Program Office that now supported what was called the National Aerospace Plane. It brought together representatives from the Air Force, Navy, and NASA. Program management remained at DARPA, where Williams retained his post as the overall manager.[48]

In this fashion, NASP became a significant federal initiative. It benefited from a rare alignment of the political stars, for Reagan's SDI cried out for better launch vehicles and Skantze was ready to offer them. Nor did funding appear to be a problem, at least initially. Reagan had shown favor to aerospace through such acts as approving NASA's space station in 1984. Pentagon spending had surged, and DARPA's Cooper was asserting that an X-30 might be built for an affordable cost.

Yet NASP was a leap into the unknown. Its scramjets now were in the forefront but not because the Langley research had shown that they were ready. Instead they were a focus of hope because Reagan wanted SDI, SDI needed better access to space, and Skantze wanted something better than rockets.

The people who were making Air Force decisions, such as Skantze, did not know much about these engines. The people who did know them, such as Thomas, were well aware of duPont's optimism. There thus was abundant opportunity for high hope to give way to hard experience.

The Decline of NASP

NASP was one of Reagan's programs, and for a time it seemed likely that it would not long survive the change in administrations after he left office in 1989. That fiscal year brought a high-water mark for the program, as its budget peaked at $320 million. During the spring of that year officials prepared budgets for FY 1991, which President George H. W. Bush would send to Congress early in 1990. Military spending was already trending downward, and within the Pentagon, analyst David Chu recommended canceling all Defense Department spending for NASP. The new Secretary of Defense, Richard Cheney, accepted this proposal. With this, NASP appeared dead.

NASP had a new program manager, Robert Barthelemy, who had replaced Williams. Working through channels, he found support in the White House from Vice President Dan Quayle. Quayle chaired the National Space Council, which had been created by law in 1958 and that just then was active for the first time in a decade. He

X-30 concept of 1985. (NASA)

used it to rescue NASP. He led the Space Council to recommend proceeding with the program under a reduced but stable budget, and with a schedule slip. This plan won acceptance, giving the program leeway to face a new issue: excessive technical optimism.[49]

During 1984, amid the Copper Canyon activities, Tony duPont devised a conceptual configuration that evolved into the program's baseline. It had a gross weight of 52,650 pounds, which included a 2,500-pound payload that it was to carry to polar orbit. Its weight of fuel was 28,450 pounds. The propellant mass fraction, the ratio of these quantities, then was 0.54.[50]

The fuel had low density and was bulky, demanding high weight for the tankage and airframe. To save weight, duPont's concept had no landing gear. It lacked reserves of fuel; it was to reach orbit by burning its last drops. Once there it could not execute a controlled deorbit, for it lacked maneuvering rockets as well as fuel and oxidizer for them. DuPont also made no provision for a reserve of weight to accommodate normal increases during development.[51]

Williams's colleagues addressed these deficiencies, although they continued to accept duPont's optimism in the areas of vehicle drag and engine performance. The new concept had a gross weight of 80,000 pounds. Its engines gave a specific impulse of 1,400 seconds, averaged over the trajectory, which corresponded to a mean exhaust velocity of 45,000 feet per second. (That of the SSME was 453.5 seconds in vacuum, or 14,590 feet per second.) The effective velocity increase for the X-30 was calculated at 47,000 feet per second, with orbital velocity being 25,000 feet per second; the difference represented loss due to drag. This version of the X-30 was designated the "government baseline" and went to the contractors for further study.[52]

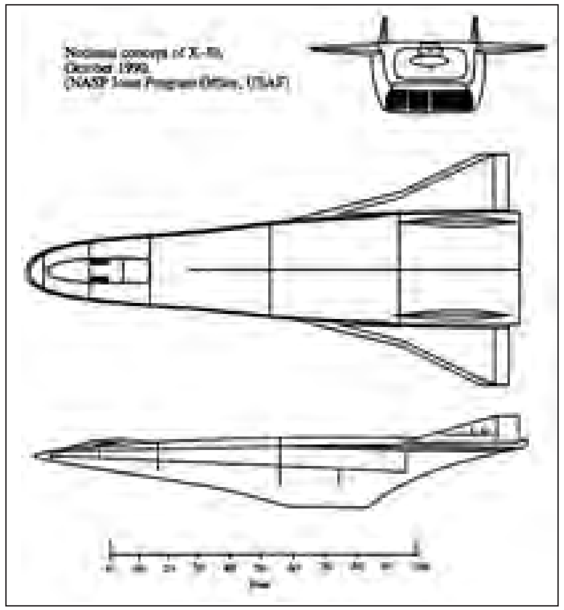
The initial round of contract awards was announced in April 1986. Five airframe firms developed new conceptual designs, introducing their own estimates of drag and engine performance along with their own choices of materials. They gave the following weight estimates for the X-30:

Rockwell International	175,000 pounds
McDonnell Douglas	245,000
General Dynamics	280,000
Boeing	340,000
Lockheed	375,000

A subsequent downselection, in October 1987, eliminated the two heaviest concepts while retaining Rockwell, McDonnell Douglas, and General Dynamics for further work.[53]

What brought these weight increases? Much of the reason lay in a falloff in estimated engine performance, which fell as low as 1,070 seconds of averaged specific impulse. New estimates of drag pushed the required effective velocity increase during ascent to as much as 52,000 feet per second.

A 1989 technical review, sponsored by the National Research Council, showed what this meant. The chairman, Jack Kerrebrock, was an experienced propulsion specialist from MIT. His panel included other men of similar background: Seymour Bogdonoff of Princeton, Artur Mager of Marquardt, Frank Marble from Caltech. Their report stated that for the X-30 to reach orbit as a single stage, "a fuel fraction of approximately 0.75 is required."[54]



X-30 concept of 1990, which had grown considerably. (U.S. Air Force)

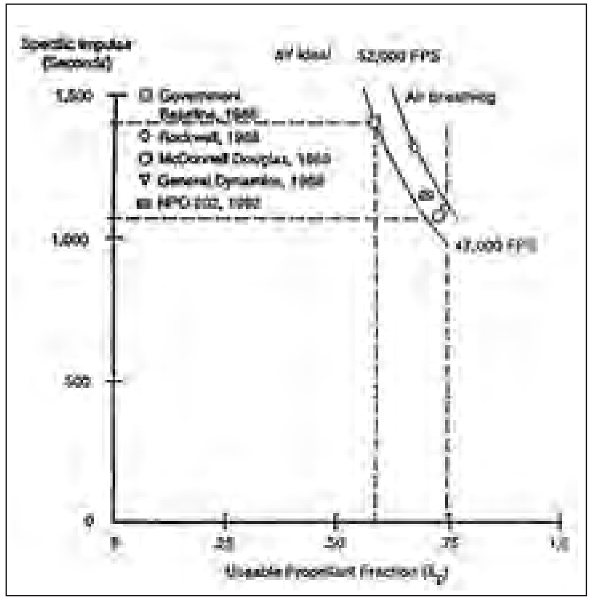
One gains insight by considering three hydrogen-fueled

rocket stages of NASA and calculating their values of propellant mass fraction if both their hydrogen and oxygen tanks were filled with NASP fuel. This was slush hydrogen, a slurry of the solid and liquid. The stages are the S-II and S-IVB of Apollo and the space shuttle's external tank. Liquid hydrogen has 1/16 the density of liquid oxygen. With NASP slush having 1.16 times the density of liquid hydrogen,[55] the propellant mass fractions are as follows:[56]

S-IVB, third stage of the Saturn V	0.722
S-II, second stage of the Saturn V	0.753
External Tank	0.868

The S-II, which comes close to Kerrebrock's value of 0.75, was an insulated shell that mounted five rocket engines. It withstood compressive loads along its length that resulted from the weight of the S-IVB and the Apollo moonship but did not require reinforcement to cope with major bending loads. It was constructed of aluminum alloy and lacked landing gear, thermal protection, wings, and a flight deck.

How then did NASP offer an X-30 concept that constituted a true hypersonic airplane rather than a mere rocket stage? The answer lay in adding weight to the fuel, which boosted the propellant mass fraction. The vehicle was not to reach orbit entirely on slush-fueled scramjets but was to use a rocket for final ascent. It used tanked oxygen—with nearly 14 times the density of slush hydrogen. In addition, design requirements specified a tripropellant system that was to burn liquid methane during the early part of the flight. This fuel had less energy than hydrogen, but it too added weight because it was relatively dense. The recommended mix called for 69 percent hydrogen, 20 percent oxygen, and 11 percent methane.[57]



Evolution of the X-30. The government baseline of 1986 had Isp of 1,400 seconds, delta-V to reach orbit of 47,000 feet per second, and propellant mass fraction of 0.54. Its 1992 counterpart had less Isp, more drag, propellant mass fraction of 0.75, and could not reach orbit. (NASP National Program Office)

In 1984, with optimism at its height, Cooper had asserted that the X-30 would be the size of an SR-71 and could be ready in three years. DuPont argued that his concept could lead to a "5-5-50" program by building a 50,000-pound vehicle in five years for $5 billion.[58] Eight years later, in October 1990, the program had a new chosen configuration. It was rectangular in cross section, with flat sides. Three scramjet engines were to provide propulsion. Two small vertical stabilizers were at the rear, giving better stability than a single large one. A single rocket engine of approximately 60,000 pounds of thrust, integrated into the airframe, completed the layout. Other decisions selected the hot structure as the basic approach to thermal protection. The primary structure was to be of titanium-matrix composite, with insulated panels of carbon to radiate away the heat.[59]

This 1990 baseline design showed little resemblance to its 1984 ancestor. As revised in 1992, it no longer was to fly to a polar orbit but would take off on a due-east launch from Kennedy Space Center, thereby gaining some 1,340 feet per second of launch velocity. Its gross weight was quoted at 400,000 pounds, some 40 percent heavier than the General Dynamics weight that had been the heaviest acceptable in the 1987 downselect. Yet even then the 1992 concept was expected to fall short of orbit by some 3,000 feet per second. An uprated version, with a gross weight of at least 450,000 pounds, appeared necessary to reach orbital velocity. The prospective program budget came to $15 billion or more, with the time to first flight being eight to ten years.[60]

During 1992 both the Defense Science Board (DSB) and Congress's General Accounting Office (GAO) conducted major program reviews. The immediate issue was whether to proceed as planned by making a commitment that would actually build and fly the X-30. Such a decision would take the program from its ongoing phase of research and study into a new phase of mainstream engineering development.

Both reviews focused on technology, but international issues were in the background, for the Cold War had just ended. The Soviet Union had collapsed in 1991, with communists falling from power while that nation dissolved into 15 constituent states. Germany had already reunified; the Berlin Wall had fallen, and the whole of Eastern Europe had won independence from Moscow. The western border of Russia now approximated that of 1648, at the end of the Thirty Years' War. Two complete tiers of nominally independent nations now stood between Russia and the West.

These developments greatly diminished the military urgency of NASP, while the reviews' conclusions gave further reason to reduce its priority. The GAO noted that program managers had established 38 technical milestones that were to be satisfied before proceeding to mainstream development. These covered the specific topics of X-30 design, propulsion, structures and materials, and use of slush hydrogen as a fuel. According to the contractors themselves, only 17 of those milestones—fewer than half—were to be achieved by September 1993. The situation was particularly worrisome in the critical area of structures and materials, for which only six of 19 milestones were slated for completion. The GAO therefore recommended delaying a commitment to mainstream development "until critical technologies are developed and demonstrated."[61]

The DSB concurred, highlighting specific technical deficiencies. The most important involved the prediction of scramjet performance and of boundary-layer transition. In the latter, an initially laminar or smoothly flowing boundary layer becomes turbulent. This brings large increases in heat transfer and skin friction, a major source of drag. The locations of transition thus had to be known.

The scramjet-performance problem arose because of basic limitations in the capabilities of ground-test facilities. The best of them could accommodate a complete engine, with inlet, combustor, and nozzle, but could conduct tests only below Mach 8. "Even at Mach 8," the DSB declared, "the scramjet cycle is just beginning to be established and consequently, there is uncertainty associated with extrapolating the results into the higher Mach regime. At speeds above Mach 8, only small components of the scramjet can be tested." This brought further uncertainty when predicting the performance of complete engines.

Boundary-layer transition to turbulence also demanded attention: "It is essential to understand the boundary-layer behavior at hypersonic speeds in order to ensure thermal survival of the airplane structure as designed, as well as to accurately predict the propulsion system performance and airplane drag. Excessive conservatism in boundary-layer predictions will lead to an overweight design incapable of achieving [single stage to orbit], while excessive optimism will lead to an airplane unable to survive in the hypersonic flight environment."

The DSB also showed strong concern over issues of control in flight of the X-30 and its engines. These were not simple matters of using ailerons or pushing throttles. The report stated that "controllability issues for NASP are so complex, so widely ranging in dynamics and frequency, and so interactive between technical disciplines as to have no parallels in aeronautical history…the most fundamental initial requirements for elementary aircraft control are not yet fully comprehended." An onboard computer was to manage the vehicle and its engines in flight, but an understanding of the pertinent forces and moments "is still in an embryonic state." Active cooling of the vehicle demanded a close understanding of boundary-layer transition. Active cooling of the engine called for resolution of "major uncertainties…connected with supersonic burning." In approaching these issues, "very great uncertainties exist at a fundamental level."

The DSB echoed the GAO in calling for extensive additional research before proceeding into mainstream development of the X-30:

> We have concluded [that] fundamental uncertainties will continue to exist in at least four critical areas: boundary-layer transition; stability and controllability; propulsion performance; and structural and subsystem weight. Boundary-layer transition and scramjet performance cannot be validated in existing ground-test facilities, and the weight estimates have insufficient reserves for the inevitable growth attendant to material allowables, fastening and joining, and detailed configuration issues.… Using optimistic assumptions on transition and scramjet performance, and the present weight estimates on material performance and active cooling, the vehicle design does not yet close; the velocity achieved is short of orbital requirements.[62]

Faced with the prospect that the flight trajectory of the X-30 would merely amount to a parabola, budget makers turned the curve of program funding into a parabola as well. The total budget had held at close to $250 million during FY 1990 and 1991, falling to $205 million in 1992. But in 1993 it took a sharp dip to $140 million. The NASP National Program Office tried to rescue the situation by proposing a six-year program with a budget of $2 billion, called Hyflite, that was to conduct a series of unmanned flight tests. The Air Force responded with a new technical group, the Independent Review Team, that turned thumbs down on Hyflite and called instead for a "minimum" flight test program. Such an effort was to address the key problem of reducing uncertainties in scramjet performance at high Mach.

The National Program Office came back with a proposal for a new program called HySTP. Its budget request came to $400 million over five years, which would have continued the NASP effort at a level only slightly higher than its allocation of $60 million for FY 1994. Yet even this minimal program budget proved to be unavailable. In January 1995 the Air Force declined to approve the HySTP budget and initiated the formal termination of the NASP program.[63]

In this fashion, NASP lived and died. Like SDI and the space station, one could view it as another in a series of exercises in Reaganesque optimism that fell short. Yet from the outset, supporters of NASP had emphasized that it was to make important contributions in such areas as propulsion, hypersonic aerodynamics, computational fluid dynamics, and materials. The program indeed did these things and thereby laid groundwork for further developments.

1 AIAA Paper 93-2329.

2 *Johns Hopkins APL Technical Digest*, Vol. 13, No. 1 (1992), pp. 63-65.

3 Hallion, *Hypersonic*, pp. 754-55; Harshman, "Design and Test."

4 Waltrup et al., "Supersonic," pp. 42-18 to 42-19; DTIC AD-386653.

5 Hallion, *Hypersonic*, pp. VI-xvii to VI-xx; "Scramjet Flight Test Program" (Marquardt brochure, September 1965); DTIC AD-388239.

6 Hallion, *Hypersonic*, pp. VI-xiv, 780; "Report of the USAF Scientific Advisory Board Aerospace Vehicles Panel," February 1966.

7 Hallion, *Hypersonic*, p. 780.

8 NASA SP-2000-4518, p. 63; NASA SP-4303, pp. 125-26.

9 AIAA Paper 93-2328; interoffice memo (GASL), E. Sanlorenzo to L. Nucci, 24 October 1967.

10 Mackley, "Historical"; DTIC AD-393374.

11 *Journal of Aircraft*, January-February 1968, p. 3.

12 Author interviews, Louis Nucci, 13 November 1987 and 24 June 1988 (includes quotes). Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

13 Author interviews, Arthur Thomas, 24 September 1987 and 24 June 1988 (includes quotes). Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

14 Author interviews: Fred Billig, 27 June 1987 and Louis Nucci, 24 June 1988. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

15 Hallion, *Hypersonic*, pp. 756-78; Miller, *X-Planes*, pp. 189-90.

16 Author interview, Anthony duPont, 23 November 1987. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

17 Hallion, *Hypersonic*, pp. 774-78; "Handbook of Texas Online: Ordnance Aerophysics Laboratory," internet website.

18 Hallion, *Hypersonic*, pp. 142-45; Miller, *X-Planes*, pp. 190-91, 194-95; NASA SP-4303, pp. 121-22; author interview, William "Pete" Knight, 24 September 1987. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

19 NASA SP-2000-4518, pp. 59-60.

20 Hallion, *Hypersonic*, pp. 792-96; AIAA Paper 93-2323; NASA TM X-2572.

21 Hallion, *Hypersonic*, pp. 798-802; AIAA Paper 93-2323; NASA TM X-2572.

22 Hallion, *Hypersonic*, pp. 802-22 (quote, p. 818); Mackley, "Historical."

23 Waltrup et al., "Supersonic," pp. 42-13 to 42-14; NASA SP-292, pp. 157-77; NASA TM X-2895; *Astronautics & Aeronautics*, February 1978, pp. 38-48; AIAA Paper 86-0159.

24 AIAA Papers 70-715, 75-1212.

25 AIAA Papers 79-7045, 98-2506.

26 AIAA Paper 79-7045.

27 AIAA Paper 86-0159 (quotes, p. 7).

28 Ibid. (quotes, pp. 1, 7); AIAA Paper 98-2506.

29 Malia, *Soviet*, pp. 378-80; Walker, *Cold War*, pp. 250-57.

30 Fitzgerald, *Way Out*, pp. 179-82, 190-91 (quotes, p. 180).

31 "Address by the President to the Nation." Washington, DC: The White House, 23 March 1983.

32 Baucom, *Origins*, pp. 184-92; Broad, *Teller's War*, pp. 121-24; Fitzgerald, *Way Out*, pp. 195-98, 200-02.

33 "Address by the President to the Nation." Washington, DC: The White House, 23 March 1983.

34 Fitzgerald, *Way Out*, p. 225.

35 Schweikart, *Quest*, pp. 20-22; Hallion, *Hypersonic*, pp. 1336-46; AIAA Paper 84-2414; *Air Power History*, Spring 1994, 39.

36 "Biography: General Lawrence A. Skantze." Washington, DC: Office of Public Affairs, Secretary of the Air Force, August 1984.

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38 Miller, *X-Planes*, ch. 33; author interview, Robert Cooper, 12 May 1986. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

39 U.S. Patent 3,690,102 (duPont). Also author interview, Anthony duPont, 23 November 1987. Folder 18649, NASA Historical Collection, NASA History Division, Washington, D.C. 20546.

40 Author interviews, Robert Cooper, 12 May 1986 (includes quote); Anthony duPont, 23 November 1987. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

41 Schweikart, *Quest*, p. 20; author interview, Robert Williams, 1 May 1986 and 23 November 1987. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

42 Author interviews, Robert Williams, 1 May 1986 and 23 November 1987. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

43 Author interviews, Arthur Thomas, 24 September 1987 and 22 July 1988. Folder 18649, NASA Historical Reference Collection, NASA History Divison, Washington, D.C. 20546.

44 Author interview, Robert Williams, 1 May 1986. Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

45 Author interview, George Keyworth, 23 May 1986. Folder 18469, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

46 Author interview, Robert Cooper,12 May 1986. Folder 18469, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

47 Ibid.; author interview, Robert Williams, 1 May 1986. Folder 18469, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

48 Schweikart, *Quest*, pp. 47-51; Hallion, *Hypersonic*, pp. 1345-46, 1351, 1364-65.

49 Schweikart, *Quest*, pp. 161-62.

50 AIAA Paper 95-6031.

51 Schweikart, *Quest*, pp. 29, 199.

52 AIAA Paper 95-6031. SSME: Rocketdyne Report RI/RD87-142.

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54 Air Force Studies Board, *Hypersonic* (quote, p. 5).

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8

Why NASP Fell Short

NASP was founded on optimism, but it involved a good deal more than blind faith. Key technical areas had not been properly explored and offered significant prospects of advance. These included new forms of titanium, along with the use of an ejector to eliminate the need for an auxiliary engine as a separate installation, for initial boost of a scramjet. There also was the highly promising field of computational fluid dynamics (CFD), which held the prospect of supplementing flight test and work in wind tunnels with sophisticated mathematical simulation.

Still NASP fell short, and there were reasons. CFD proved not to be an exact science, particularly at high Mach. Investigators worked with the complete equations of fluid mechanics, which were exact, but were unable to give precise treatments in such crucial areas as transition to turbulence and the simulation or modeling of turbulence. Their discussions introduced approximations that took away the accuracy and left NASP with more drag and less engine performance than people had sought.

In the field of propulsion, ejectors had not been well studied and stood as a topic that was ripe for deeper investigation. Even so, the ejectors offered poor performance at the outset, and subsequent studies did not bring substantial improvements. This was unfortunate, for use of a highly capable ejector was a key feature of Anthony duPont's patented engine cycle, which had provided technical basis for NASP.

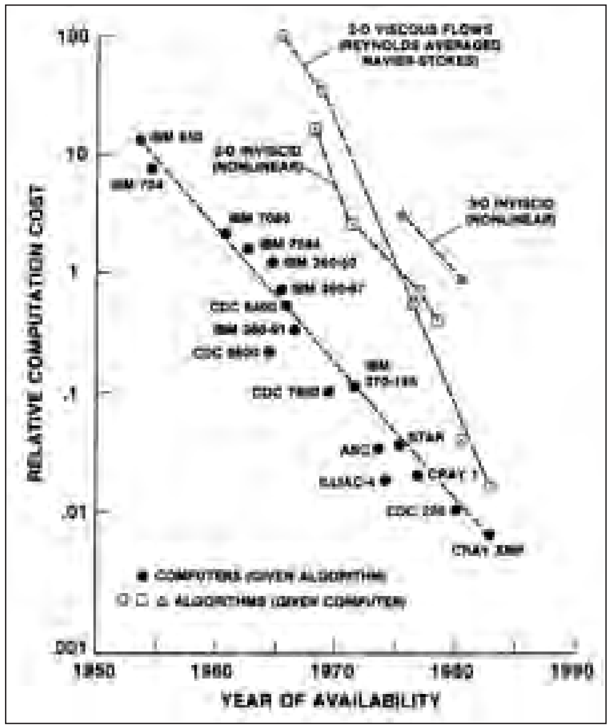
With drag increasing and engine performance falling off, metallurgists might have saved the day by offering new materials. They indeed introduced Beta-21S titanium, which approached the heat resistance of Rene 41, the primary structural material of Dyna-Soar, but had only half the density. Yet even this achievement was not enough. Structural designers needed still more weight saving, and while they experimented with new types of beryllium and carbon-carbon, they came up with no significant contributions to the state of the art.

Aerodynamics

In March 1984, with the Copper Canyon studies showing promise, a classified program review was held near San Diego. In the words of George Baum, a close associate of Robert Williams, "We had to put together all the technology pieces to make it credible to the DARPA management, to get them to come out to a meeting in La Jolla and be willing to sit down for three full days. It wasn't hard to get people out to the West Coast in March; the problem was to get them off the beach."

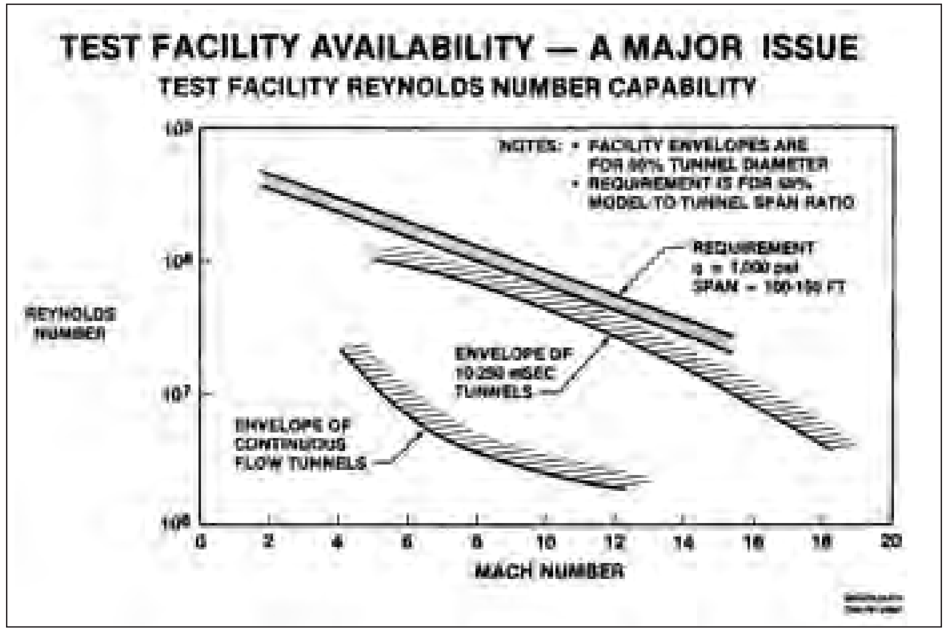
One of the attendees, Robert Whitehead of the Office of Naval Research, gave a talk on CFD. Was the mathematics ready; were computers at hand? Williams recalls that "he explained, in about 15 minutes, the equations of fluid mechanics, in a memorable way. With a few simple slides, he could describe their nature in almost an offhand manner, laying out these equations so the computer could solve them, then showing that the computer technology was also there. We realized that we could compute our way to Mach 25, with high confidence. That was a high point of the presentations."[1]

Whitehead's point of departure lay in the fundamental equations of fluid flow: the Navier-Stokes equations, named for the nineteenth-century physicists Claude-Louis-Marie Navier and Sir George Stokes. They form a set of nonlinear partial differential equations that contain 60 partial derivative terms. Their physical content is simple, comprising the basic laws of conservation of mass, momentum, and energy, along with an equation of state. Yet their solutions, when available, cover the entire realm of fluid mechanics.[2]



Development of CFD prior to NASP. In addition to vast improvement in computers, there also was similar advance in the performance of codes. (NASA)

An example of an important development, contemporaneous with Whitehead's presentation, was a 1985 treatment of flow over a complete X-24C vehicle at Mach 5.95. The authors, Joseph Shang and S. J. Scheer, were at the Air Force's Wright Aeronautical Laboratories. They used a Cray X-MP supercomputer and gave lift and drag coefficients:[3]



Availability of test facilities. Continuous-flow wind tunnels are far below the requirements of realistic simulation of full-size aircraft in flight. Impulse facilities, such as shock tunnels, come close to the requirements but are limited by their very short run times. (NASA)

	C_D	C_L	L/D
Experimental data	0.03676	0.03173	1.158
Numerical results	0.03503	0.02960	1.183
Percent error	4.71	6.71	2.16

(Source: AIAA Paper 85-1509)

In that year the state of the art permitted extensive treatments of scramjets. Complete three-dimensional simulations of inlets were available, along with two-dimensional discussions of scramjet flow fields that covered the inlet, combustor, and nozzle. In 1984 Fred Billig noted that simulation of flow through an inlet using complete Navier-Stokes equations typically demanded a grid of 80,000 points and up to 12,000 time steps, with each run demanding four hours on a Control Data Cyber 203 supercomputer. A code adapted for supersonic flow was up to a hundred times faster. This made it useful for rapid surveys of a number of candidate inlets, with full Navier-Stokes treatments being reserved for a few selected choices.[4]

CFD held particular promise because it had the potential of overcoming the limitations of available facilities. These limits remained in place all through the NASP era. A 1993 review found "adequate" test capability only for classical aerodynamic experiments in a perfect gas, namely helium, which could support such work to Mach 20. Between Mach 13 and 17 there was "limited" ability to conduct tests that exhibited real-gas effects, such as molecular excitation and dissociation. Still, available facilities were too small to capture effects associated with vehicle size, such as determining the location of boundary-layer transition to turbulence.

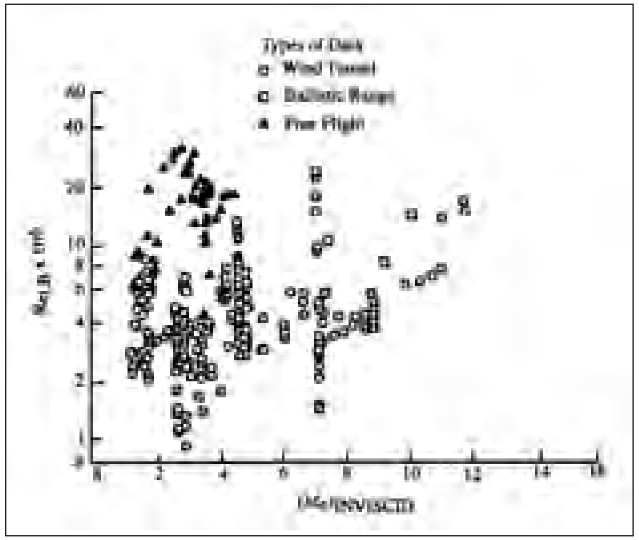
For scramjet studies, the situation was even worse. There was "limited" ability to test combustors out to Mach 7, but at higher Mach the capabilities were "inadequate." Shock tunnels supported studies of flows in rarefied air from Mach 16 upward, but the whole of the nation's capacity for such tests was "inadequate." Some facilities existed that could study complete engines, either by themselves or in airframe-integrated configurations, but again the whole of this capability was "inadequate."[5]

Yet it was an exaggeration in 1984, and remains one to this day, to propose that CFD could remedy these deficiencies by computing one's way to orbital speeds "with high confidence." Experience has shown that CFD falls short in two areas: prediction of transition to turbulence, which sharply increases drag due to skin friction, and in the simulation of turbulence itself.

For NASP, it was vital not only to predict transition but to understand the properties of turbulence after it appeared. One could see this by noting that hypersonic propulsion differs substantially from propulsion of supersonic aircraft. In the latter, the art of engine design allows engineers to ensure that there is enough margin of thrust over drag to permit the vehicle to accelerate. A typical concept for a Mach 3 supersonic airliner, for instance, calls for gross thrust from the engines of 123,000 pounds, with ram drag at the inlets of 54,500. The difference, nearly 80,000 pounds of thrust, is available to overcome skin-friction drag during cruise, or to accelerate.

At Mach 6, a representative hypersonic-transport design shows gross thrust of 330,000 pounds and ram drag of 220,000. Again there is plenty of margin for what, after all, is to be a cruise vehicle. But in hypersonic cruise at Mach 12, the numbers typically are 2.1 million pounds for gross thrust—and 1.95 million for ram drag! Here the margin comes to only 150,000 pounds of thrust, which is narrow indeed. It could vanish if skin-friction drag proves to be higher than estimated, perhaps because of a poor forecast of the location of transition. The margin also could vanish if the thrust is low, due to the use of optimistic turbulence models.[6]

Any high-Mach scramjet-powered craft must not only cruise but accelerate. In turn, the thrust driving this acceleration appears as a small difference between two quantities: total drag and net thrust, the latter being net of losses within the engines. Accordingly, valid predictions concerning transition and turbulence are matters of the first importance.



Experimentally determined locations of the onset of transition to turbulent flow. The strong scatter of the data points defeats attempts to find a predictive rule. (NASA)

NASP-era analysts fell back on the "e^N method," which gave a greatly simplified summary of the pertinent physics but still gave results that were often viewed as useful. It used the Navier-Stokes equations to solve for the overall flow in the laminary boundary layer, upstream of transition. This method then introduced new and simple equations derived from the original Navier-Stokes. These were linear and traced the growth of a small disturbance as one followed the flow downstream. When it had grown by a factor of 22,000—e^{10}, with N = 10—the analyst accepted that transition to turbulence had occurred.[7]

One can obtain a solution in this fashion, but transition results from local roughnesses along a surface, and these can lead to results that vary dramatically. Thus, the repeated re-entries of the space shuttle, during dozens of missions, might have given numerous nearly identical data sets. In fact, transition has occurred at Mach numbers from 6 to 19! A 1990 summary presented data from wind tunnels, ballistic ranges, and tests of re-entry vehicles in free flight. There was a spread of as much as 30 to one in the measured locations of transition, with the free-flight data showing transition positions that typically were five times farther back from a nose or leading edge than positions observed using other methods. At Mach 7, observed locations covered a range of 20 to one.[8]

One may ask whether transition can be predicted accurately even in principle because it involves minute surface roughnesses whose details are not known a priori and may even change in the course of a re-entry. More broadly, the state of transition was summarized in a 1987 review of problems in NASP hypersonics that was written by three NASA leaders in CFD:

> Almost nothing is known about the effects of heat transfer, pressure gradient, three-dimensionality, chemical reactions, shock waves, and other

> influences on hypersonic transition. This is caused by the difficulty of conducting meaningful hypersonic transition experiments in noisy ground-based facilities and the expense and difficulty of carrying out detailed and carefully controlled experiments in flight where it is quiet. Without an adequate, detailed database, development of effective transition models will be impossible.[9]

Matters did not improve in subsequent years. In 1990 Mujeeb Malik, a leader in studies of transition, noted "the long-held view that conventional, noisy ground facilities are simply not suitable for simulation of flight transition behavior." A subsequent critique added that "we easily recognize that there is today no reasonably reliable predictive capability for engineering applications" and commented that "the reader…is left with some feeling of helplessness and discouragement."[10] A contemporary review from the Defense Science Board pulled no punches: "Boundary layer transition…cannot be validated in existing ground test facilities."[11]

There was more. If transition could not be predicted, it also was not generally possible to obtain a valid simulation, from first principles, of a flow that was known to be turbulent. The Navier-Stokes equations carried the physics of turbulence at all scales. The problem was that in flows of practical interest, the largest turbulent eddies were up to 100,000 times bigger than the smallest ones of concern. This meant that complete numerical simulations were out of the question.

Late in the nineteenth century the physicist Osborne Reynolds tried to bypass this difficulty by rederiving these equations in averaged form. He considered the flow velocity at any point as comprising two elements: a steady-flow part and a turbulent part that contained all the motion due to the eddies. Using the Navier-Stokes equations, he obtained equations for averaged quantities, with these quantities being based on the turbulent velocities.

He found, though, that the new equations introduced additional unknowns. Other investigators, pursuing this approach, succeeded in deriving additional equations for these extra unknowns—only to find that these introduced still more unknowns. Reynolds's averaging procedure thus led to an infinite regress, in which at every stage there were more unknown variables describing the turbulence than there were equations with which to solve for them. This contrasted with the Navier-Stokes equations themselves, which in principle could be solved because the number of these equations and the number of their variables was equal.

This infinite regress demonstrated that it was not sufficient to work from the Navier-Stokes equations alone—something more was needed. This situation arose because the averaging process did not preserve the complete physical content of the Navier-Stokes formulation. Information had been lost in the averaging. The problem of turbulence thus called for additional physics that could replace the lost

information, end the regress, and give a set of equations for turbulent flow in which the number of equations again would match the number of unknowns.[12]

The standard means to address this issue has been a turbulence model. This takes the form of one or more auxiliary equations, either algebraic or partial-differential, which are solved simultaneously with the Navier-Stokes equations in Reynolds-averaged form. In turn, the turbulence model attempts to derive one or more quantities that describe the turbulence and to do so in a way that ends the regress.

Viscosity, a physical property of every liquid and gas, provides a widely used point of departure. It arises at the molecular level, and the physics of its origin is well understood. In a turbulent flow, one may speak of an "eddy viscosity" that arises by analogy, with the turbulent eddies playing the role of molecules. This quantity describes how rapidly an ink drop will mix into a stream—or a parcel of hydrogen into the turbulent flow of a scramjet combustor.[13]

Like the e^N method in studies of transition, eddy viscosity presents a view of turbulence that is useful and can often be made to work, at least in well-studied cases. The widely used Baldwin-Lomax model is of this type, and it uses constants derived from experiment. Antony Jameson of Princeton University, a leading writer of flow codes, described it in 1990 as "the most popular turbulence model in the industry, primarily because it's easy to program."[14]

This approach indeed gives a set of equations that are solvable and avoid the regress, but the analyst pays a price: Eddy viscosity lacks standing as a concept supported by fundamental physics. Peter Bradshaw of Stanford University virtually rejects it out of hand, declaring, "Eddy viscosity does not even deserve to be described as a 'theory' of turbulence!" He adds more broadly, "The present state is that even the most sophisticated turbulence models are based on brutal simplification of the N-S equations and hence cannot be relied on to predict a large range of flows with a fixed set of empirical coefficients."[15]

Other specialists gave similar comments throughout the NASP era. Thomas Coakley of NASA-Ames wrote in 1983 that "turbulence models that are now used for complex, compressible flows are not well advanced, being essentially the same models that were developed for incompressible attached boundary layers and shear flows. As a consequence, when applied to compressible flows they yield results that vary widely in terms of their agreement with experimental measurements."[16]

A detailed critique of existing models, given in 1985 by Budugur Lakshminarayana of Pennsylvania State University, gave pointed comments on algebraic models, which included Baldwin-Lomax. This approach "provides poor predictions" for flows with "memory effects," in which the physical character of the turbulence does not respond instantly to a change in flow conditions but continues to show the influence of upstream effects. Such a turbulence model "is not suitable for flows with curvature, rotation, and separation. The model is of little value in three-dimensional complex flows and in situations where turbulence transport effects are important."

“Two-equation models,” which used two partial differential equations to give more detail, had their own faults. In the view of Lakshminarayana, they “fail to capture many of the features associated with complex flows.” This class of models “fails for flows with rotation, curvature, strong swirling flows, three-dimensional flows, shock-induced separation, etc.”[17]

Rather than work with eddy viscosity, some investigators used “Reynolds stress” models. Reynolds stresses were not true stresses, which contributed to drag. Rather, they were terms that appeared in the Reynolds-averaged Navier-Stokes equations alongside other terms that indeed represented stress. Models of this type offered greater physical realism, but again this came at the price of severe computational difficulty.[18]

A group at NASA-Langley, headed by Thomas Gatski, offered words of caution in 1990: “…even in the low-speed incompressible regime, it has not been possible to construct a turbulence closure model which can be applied over a wide class of flows…. In general, Reynolds stress closure models have not been very successful in handling the effects of rotation or three-dimensionality even in the incompressible regime; therefore, it is not likely that these effects can be treated successfully in the compressible regime with existing models.”[19]

Anatol Roshko of Caltech, widely viewed as a dean of aeronautics, has his own view: “History proves that each time you get into a new area, the existing models are found to be inadequate.” Such inadequacies have been seen even in simple flows, such as flow over a flat plate. The resulting skin friction is known to an accuracy of around one percent. Yet values calculated from turbulence models can be in error by up to 10 percent. “You can always take one of these models and fix it so it gives the right answer for a particular case,” says Bradshaw. “Most of us choose the flat plate. So if you can’t get the flat plate right, your case is indeed piteous.”[20]

Another simple case is flow within a channel that suddenly widens. Downstream of the point of widening, the flow shows a zone of strongly whirling circulation. It narrows until the main flow reattaches, flowing in a single zone all the way to the now wider wall. Can one predict the location of this reattachment point? “This is a very severe test,” says John Lumley of Cornell University. “Most of the simple models have trouble getting reattachment within a factor of two.” So-called “k-epsilon models,” he says, are off by that much. Even so, NASA’s Tom Coakley describes them as “the most popular two-equation model,” whereas Princeton University’s Jameson speaks of them as “probably the best engineering choice around” for such problems as…flow within a channel.[21]

Turbulence models have a strongly empirical character and therefore often fail to predict the existence of new physics within a flow. This has been seen to cause difficulties even in the elementary case of steady flow past a cylinder at rest, a case so simple that it is presented in undergraduate courses. Nor do turbulence models cope with another feature of some flows: their strong sensitivity to slight changes in conditions. A simple example is the growth of a mixing layer.

In this scenario, two flows that have different velocities proceed along opposite sides of a thin plate, which terminates within a channel. The mixing layer then forms and grows at the interface between these streams. In Roshko’s words, “a one-percent periodic disturbance in the free stream completely changes the mixing layer growth.” This has been seen in experiments and in highly detailed solutions of the Navier-Stokes equations that solve the complete equations using a very fine grid. It has not been seen in solutions of Reynolds-averaged equations that use turbulence models.[22]

And if simple flows of this type bring such difficulties, what can be said of hypersonics? Even in the free stream that lies at some distance from a vehicle, one finds strong aerodynamic heating along with shock waves and the dissociation, recombination, and chemical reaction of air molecules. Flow along the aircraft surface adds a viscous boundary layer that undergoes shock impingement, while flow within the engine adds the mixing and combustion of fuel.

As William Dannevik of Lawrence Livermore National Laboratory describes it, “There’s a fully nonlinear interaction among several fields: an entropy field, an acoustic field, a vortical field.” By contrast, in low-speed aerodynamics, “you can often reduce it down to one field interacting with itself.” Hypersonic turbulence also brings several channels for the flow and exchange of energy: internal energy, density, and vorticity. The experimental difficulties can be correspondingly severe.[23]

Roshko sees some similarity between turbulence modeling and the astronomy of Ptolemy, who flourished when the Roman Empire was at its height. Ptolemy represented the motions of the planets using epicycles and deferents in a purely empirical fashion and with no basis in physical theory. “Many of us have used that example,” Roshko declares. “It’s a good analogy. People were able to continually keep on fixing up their epicyclic theory, to keep on accounting for new observations, and they were completely wrong in knowing what was going on. I don’t think we’re that badly off, but it’s illustrative of another thing that bothers some people. Every time some new thing comes around, you’ve got to scurry and try to figure out how you’re going to incorporate it.”[24]

A 1987 review concluded, “In general, the state of turbulence modeling for supersonic, and by extension, hypersonic, flows involving complex physics is poor.” Five years later, late in the NASP era, little had changed, for a Defense Science Board program review pointed to scramjet development as the single most important issue that lay beyond the state of the art.[25]

Within NASP, these difficulties meant that there was no prospect of computing one’s way in orbit, or of using CFD to make valid forecasts of high-Mach engine performance. In turn, these deficiencies forced the program to fall back on its test facilities, which had their own limitations.

Propulsion

In the spring of 1992 the NASP Joint Program Office presented a final engine design called the E22A. It had a length of 60 feet and included an inlet ramp, cowled inlet, combustor, and nozzle. An isolator, located between the inlet and combustor, sought to prevent unstarts by processing flow from the inlet through a series of oblique shocks, which increased the backpressure from the combustor.

Program officials then constructed two accurately scaled test models. The Subscale Parametric Engine (SXPE) was built to one-eighth scale and had a length of eight feet. It was tested from April 1993 to March 1994. The Concept Demonstrator Engine (CDE), which followed, was built to a scale of 30 percent. Its length topped 16 feet, and it was described as "the largest airframe-integrated scramjet engine ever tested."[26]

In working with the SXPE, researchers had an important goal in achieving combustion of hydrogen within its limited length. To promote rapid ignition, the engine used a continuous flow of a silane-hydrogen mixture as a pilot, with the silane igniting spontaneously on exposure to air. In addition, to promote mixing, the model incorporated an accurate replication of the spacing between the fuel-injecting struts and ramps, with this spacing being preserved at the model's one-eighth scale. The combustor length required to achieve the desired level of mixing then scaled in this fashion as well.

The larger CDE was tested within the Eight-Foot High-Temperature Tunnel, which was Langley's biggest hypersonic facility. The tests mapped the flowfield entering the engine, determined the performance of the inlet, and explored the potential performance of the design. Investigators varied the fuel flow rate, using the combustors to vary its distribution within the engine.

Boundary-layer effects are important in scramjets, and the tests might have replicated the boundary layers of a full-scale engine by operating at correspondingly higher flow densities. For the CDE, at 30 percent scale, the appropriate density would have been 1/0.3 or 3.3 times that of the atmospheric density at flight altitude. For the SXPE, at one-eighth scale, the test density would have shown an eightfold increase over atmospheric. However, the SXPE used an arc-heated test facility that was limited in the power that drove its arc, and it provided its engine with air at only one-fiftieth of that density. The High Temperature Tunnel faced limits on its flow rate and delivered its test gas at only one-sixth of the appropriate density.

Engineers sought to compensate by using analytical methods to determine the drag in a full-scale engine. Still, this inability to replicate boundary-layer effects meant that the wind-tunnel tests gave poor simulations of internal drag within the test engines. This could have led to erroneous estimates of true thrust, net of drag. In turn, this showed that even when working with large test models and with test facilities of impressive size, true simulations of the boundary layer were ruled out from the start.[27]

For takeoff from a runway, the X-30 was to use a Low-Speed System (LSS). It comprised two principal elements: the Special System, an ejector ramjet; and the Low Speed Oxidizer System, which used LACE.[28] The two were highly synergistic. The ejector used a rocket, which might have been suitable for the final ascent to orbit, with ejector action increasing its thrust during takeoff and acceleration. By giving an exhaust velocity that was closer to the vehicle velocity, the ejector also increased the fuel economy.

The LACE faced the standard problem of requiring far more hydrogen than could be burned in the air it liquefied. The ejector accomplished some derichening by providing a substantial flow of entrained air that burned some of the excess. Additional hydrogen, warmed in the LACE heat exchanger, went into the fuel tanks, which were full of slush hydrogen. By melting the slush into conventional liquid hydrogen (LH_2), some LACE coolant was recycled to stretch the vehicle's fuel supply.[29]

There was good news in at least one area of LACE research: deicing. LACE systems have long been notorious for their tendency to clog with frozen moisture within the air that they liquefy. "The largest LACE ever built made around half a pound per second of liquid air," Paul Czysz of McDonnell Douglas stated in 1986. "It froze up at six percent relative humidity in the Arizona desert, in 38 seconds." Investigators went on to invent more than a dozen methods for water alleviation. The most feasible approach called for injecting antifreeze into the system, to enable the moisture to condense out as liquid water without freezing. A rotary separator eliminated the water, with the dehumidified air being so cold as to contain very little residual water vapor.[30]

The NASP program was not run by shrinking violets, and its managers stated that its LACE was not merely to operate during hot days in the desert near Phoenix. It was to function even on rainy days, for the X-30 was to be capable of flight from anywhere in the world. At NASA-Lewis, James Van Fossen built a water-alleviation system that used ethylene glycol as the antifreeze, spraying it directly onto the cold tubes of a heat exchanger. Water, condensing on those tubes, dissolved some of the glycol and remained liquid as it swept downstream with the flow. He reported that this arrangement protected the system against freezing at temperatures as low as –55°F, with the moisture content of the chilled air being reduced to 0.00018 pounds in each pound of this air. This represented removal of at least 99 percent of the humidity initially present in the airflow.[31]

Pratt & Whitney conducted tests of a LACE precooler that used this arrangement. A company propulsion manager, Walt Lambdin, addressed a NASP technical review meeting in 1991 and reported that it completely eliminated problems of reduced performance of the precooler due to formation of ice. With this, the problem of ice in a LACE system appeared amenable to control.[32]

It was also possible to gain insight into the LACE state of the art by considering contemporary work that was under way in Japan. The point of departure in that country was the H-2 launch vehicle, which first flew to orbit in February 1994. It was a two-stage expendable rocket, with a liquid-fueled core flanked by two solid boosters. LACE was pertinent because a long-range plan called for upgrades that could replace the solid strap-ons with new versions using LACE engines.[33]

Mitsubishi Heavy Industries was developing the H-2's second-stage engine, designated LE-5. It burned hydrogen and oxygen to produce 22,000 pounds of thrust. As an initial step toward LACE, this company built heat exchangers to liquefy air for this engine. In tests conducted during 1987 and 1988, the Mitsubishi heat exchanger demonstrated liquefaction of more than three pounds of air for every pound of LH_2. This was close to four to one, the theoretical limit based on the thermal properties of LH_2 and of air. Still, it takes 34.6 pounds of air to burn a pound of hydrogen, and an all-LACE LE-5 was to run so fuel-rich that its thrust was to be only 6,000 pounds.

But the Mitsubishi group found their own path to prevention of ice buildup. They used a freeze-thaw process, melting ice by switching periodically to the use of ambient air within the cooler after its tubes had become clogged with ice from LH_2. The design also provided spaces between the tubes and allowed a high-speed airflow to blow ice from them.[34]

LACE nevertheless remained controversial, and even with the moisture problem solved, there remained the problem of weight. Czysz noted that an engine with 100,000 pounds of thrust would need 600 pounds per second of liquid air: "The largest liquid-air plant in the world today is the AiResearch plant in Los Angeles, at 150 pounds per second. It covers seven acres. It contains 288,000 tubes welded to headers and 59 miles of 3/32-inch tubing."[35]

Still, no law required the use of so much tubing, and advocates of LACE have long been inventive. A 1963 Marquardt concept called for an engine with 10,000 pounds of thrust, which might have been further increased by using an ejector. This appeared feasible because LACE used LH_2 as the refrigerant. This gave far greater effectiveness than the AiResearch plant, which produced its refrigerant on the spot by chilling air through successive stages.[36]

For LACE heat exchangers, thin-walled tubing was essential. The Japanese model, which was sized to accommodate the liquid-hydrogen flow rate of the LE-5, used 5,400 tubes and weighed 304 pounds, which is certainly noticeable when the engine is to put out no more than 6,000 pounds of thrust. During the mid-1960s investigators at Marquardt and AiResearch fabricated tubes with wall thicknesses as low as 0.001 inch, or one mil. Such tubes had not been used in any heat exchanger subassemblies, but 2-mil tubes of stainless steel had been crafted into a heat exchanger core module with a length of 18 inches.[37]

Even so, this remained beyond the state of the art for NASP, a quarter-century later. Weight estimates for the X-30 LACE heat exchanger were based on the assumed use of 3-mil Weldalite tubing, but a 1992 Lockheed review stated, "At present, only small quantities of suitable, leak free, 3-mil tubing have been fabricated." The plans of that year called for construction of test prototypes using 6-mil Weldalite tubing, for which "suppliers have been able to provide significant quantities." Still, a doubled thickness of the tubing wall was not the way to achieve low weight.[38]

Other weight problems arose in seeking to apply an ingenious technique for derichening the product stream by increasing the heat capacity of the LH_2 coolant. Molecular hydrogen, H_2, has two atoms in its molecule and exists in two forms: para and ortho, which differ in the orientation of the spins of their electrons. The ortho form has parallel spin vectors, while the para form has spin vectors that are oppositely aligned. The ortho molecule amounts to a higher-energy form and loses energy as heat when it transforms into the para state. The reaction therefore is exothermic.

The two forms exist in different equilibrium concentrations, depending on the temperature of the bulk hydrogen. At room temperature the gas is about 25 percent para and 75 percent ortho. When liquefied, the equilibrium state is 100 percent para. Hence it is not feasible to prepare LH_2 simply by liquefying the room-temperature gas. The large component of ortho will relax to para over several hours, producing heat and causing the liquid to boil away. The gas thus must be exposed to a catalyst to convert it to the para form before it is liquefied.

These aspects of fundamental chemistry also open the door to a molecular shift that is endothermic and that absorbs heat. One achieves this again by using a catalyst to convert the LH_2 from para to ortho. This reaction requires heat, which is obtained from the liquefying airflow within the LACE. As a consequence, the air chills more readily when using a given flow of hydrogen refrigerant. This effect is sufficiently strong to increase the heat-sink capacity of the hydrogen by as much as 25 percent.[39]

This concept also dates to the 1960s. Experiments showed that ruthenium metal deposited on aluminum oxide provided a suitable catalyst. For 90 percent para-to-ortho conversion, the LACE required a "beta," a ratio of mass to flow rate, of five to seven pounds of this material for each pound per second of hydrogen flow. Data published in 1988 showed that a beta of five pounds could achieve 85 percent conversion, with this value showing improvement during 1992. However, X-30 weight estimates assumed a beta of two pounds, and this performance remained out of reach.[40]

During takeoff, the X-30 was to be capable of operating from existing runways and of becoming airborne at speeds similar to those of existing aircraft. The low-speed system, along with its accompanying LACE and ejector systems, therefore needed substantial levels of thrust. The ejector, again, called for a rocket exhaust to serve as a primary flow within a duct, entraining an airstream as the secondary flow. Ejectors gave good performance across a broad range of flight speeds, showing an effectiveness that increased with Mach. In the SR-71 at Mach 2.2, they accounted for 14 percent of the thrust in afterburner; at Mach 3.2 this was 28.4 percent. Nor did the SR-71 ejectors burn fuel. They functioned entirely as aerodynamic devices.[41]

It was easy to argue during the 1980s that their usefulness might be increased still further. The most important unclassified data had been published during the 1950s. A good engine needed a high pressure increase, but during the mid-1960s studies at Marquardt recommended a pressure rise by a factor of only about 1.5, when turbojets were showing increases that were an order of magnitude higher.[42] The best theoretical treatment of ejector action dated to 1974. Its author, NASA's B. H. Anderson, also wrote a computer program called REJECT that predicted the performance of supersonic ejectors. However, he had done this in 1974, long before the tools of CFD were in hand. A 1989 review noted that since then "little attention has been directed toward a better understanding of the details of the flow mechanism and behavior."[43]

Within the NASP program, then, the ejector ramjet stood as a classic example of a problem that was well suited to new research. Ejectors were known to have good effectiveness, which might be increased still further and which stood as a good topic for current research techniques. CFD offered an obvious approach, and NASP activities supplemented computational work with an extensive program of experiment.[44]

The effort began at GASL, where Tony duPont's ejector ramjet went on a static test stand during 1985 and impressed General Skantze. DuPont's engine design soon took the title of the Government Baseline Engine and remained a topic of active experimentation during 1986 and 1987. Some work went forward at NASA-Langley, where the Combustion Heated Scramjet Test Facility exercised ejectors over the range of Mach 1.2 to 3.5. NASA-Lewis hosted further tests, at Mach 0.06 and from Mach 2 to 3.5 within its 10 by 10 foot Supersonic Wind Tunnel.

The Lewis engine was built to accommodate growth of boundary layers and placed a 17-degree wedge ramp upstream of the inlet. Three flowpaths were mounted side by side, but only the center duct was fueled; the others were "dummies" that gave data on unfueled operation for comparison. The primary flow had a pressure of 1,000 pounds per square inch and a temperature of 1,340°F, which simulated a fuel-rich rocket exhaust. The experiments studied the impact of fuel-to-air ratio on performance, although the emphasis was on development of controls.

Even so, the performance left much to be desired. Values of fuel-to-air ratio greater than 0.52, with unity representing complete combustion, at times brought "buzz" or unwanted vibration of the inlet structure. Even with no primary flow, the inlet failed to start. The main burner never achieved thermal choking, where the flow rate would rise to the maximum permitted by heat from burning fuel. Ingestion of the boundary layer significantly degraded engine performance. Thrust measurements were described as "no good" due to nonuniform thermal expansion across a break between zones of measurement. As a contrast to this litany of woe, operation of the primary gave a welcome improvement in the isolation of the inlet from the combustor.

Also at GASL, again during 1987, an ejector from Boeing underwent static test. It used a markedly different configuration that featured an axisymmetric duct and a fuel-air mixer. The primary flow was fuel-rich, with temperatures and pressures similar to those of NASA-Lewis. On the whole, the results of the Boeing tests were encouraging. Combustion efficiencies appeared to exceed 95 percent, while measured values of thrust, entrained airflow, and pressures were consistent with company predictions. However, the mixer performance was no more than marginal, and its length merited an increase for better performance.[45]

In 1989 Pratt & Whitney emerged as a major player, beginning with a subscale ejector that used a flow of helium as the primary. It underwent tests at company facilities within the United Technologies Research Center. These tests addressed the basic issue of attempting to increase the entrainment of secondary flow, for which non-combustible helium was useful. Then, between 1990 and 1992, Pratt built three versions of its Low Speed Component Integration Rig (LSCIR), testing them all within facilities of Marquardt.

LSCIR-1 used a design that included a half-scale X-30 flowpath. It included an inlet, front and main combustors, and nozzle, with the inlet cowl featuring fixed geometry. The tests operated using ambient air as well as heated air, with and without fuel in the main combustor, while the engine operated as a pure ramjet for several runs. Thermal choking was achieved, with measured combustion efficiencies lying within 2 percent of values suitable for the X-30. But the inlet was unstarted for nearly all the runs, which showed that it needed variable geometry. This refinement was added to LSCIR-2, which was put through its paces in July 1991, at Mach 2.7. The test sequence would have lasted longer but was terminated prematurely due to a burnthrough of the front combustor, which had been operating at 1,740°F. Thrust measurements showed only limited accuracy due to flow separation in the nozzle.

LSCIR-3 followed within months. The front combustor was rebuilt with a larger throat area to accommodate increased flow and received a new ignition system that used silane. This gas ignited spontaneously on contact with air. In tests, leaks developed between the main combustor, which was actively cooled, and the uncooled nozzle. A redesigned seal eliminated the leakage. The work also validated a method for calculating heat flux to the wall due to impingement of flow from primaries.

Other results were less successful. Ignition proceeded well enough using pure silane, but a mix of silane and hydrogen failed as an ignitant. Problems continued to recur due to inlet unstarts and nozzle flow separation. The system produced 10,000 pounds of thrust at Mach 0.8 and 47,000 pounds at Mach 2.7, but this performance still was rated as low.

Within the overall LSS program, a Modified Government Baseline Engine went under test at NASA-Lewis during 1990, at Mach 3.5. The system now included hydraulically-operated cowl and nozzle flaps that provided variable geometry, along with an isolator with flow channels that amounted to a bypass around the combustor. This helped to prevent inlet unstarts.

Once more the emphasis was on development of controls, with many tests operating the system as a pure ramjet. Only limited data were taken with the primaries on. Ingestion of the boundary layer gave significant degradation in engine performance, but in other respects most of the work went well. The ramjet operations were successful. The use of variable geometry provided reliable starting of the inlet, while operation in the ejector mode, with primaries on, again improved the inlet isolation by diminishing the effect of disturbances propagating upstream from the combustor.[46]

Despite these achievements, a 1993 review at Rocketdyne gave a blunt conclusion: "The demonstrated performance of the X-30 special system is lower than the performance level used in the cycle deck…the performance shortfall is primarily associated with restrictions on the amount of secondary flow." (Secondary flow is entrained by the ejector's main flow.) The experimental program had taught much concerning the prevention of inlet unstarts and the enhancement of inlet-combustor isolation, but the main goal—enhanced performance of the ejector ramjet—still lay out of reach.

Simple enlargement of a basic design offered little promise; Pratt & Whitney had tried that, in LSCIR-3, and had found that this brought inlet flow separation along with reduced inlet efficiency. Then in March 1993, further work on the LSS was canceled due to budget cuts. NASP program managers took the view that they could accelerate an X-30 using rockets for takeoff, as an interim measure, with the LSS being added at a later date. Thus, although the LSS was initially the critical item in duPont's design, in time it was put on hold and held off for another day.[47]

Materials

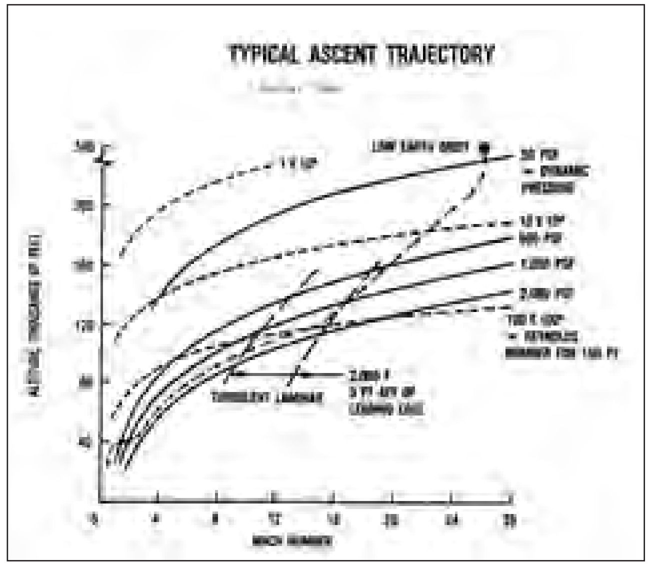
No aircraft has ever cruised at Mach 5, and an important reason involves structures and materials. "If I cruise in the atmosphere for two hours," says Paul Czysz of McDonnell Douglas, "I have a thousand times the heat load into the vehicle that the shuttle gets on its quick transit of the atmosphere." The thermal environment of

the X-30 was defined by aerodynamic heating and by the separate issue of flutter.[48]

A single concern dominated issues of structural design: The vehicle was to fly as low as possible in the atmosphere during ascent to orbit. Re-entry called for flight at higher altitudes, and the loads during ascent therefore were higher than those of re-entry. Ascent at lower altitude—200,000 feet, for instance, rather than 250,000—increased the drag on the X-30. But it also increased the thrust, giving a greater margin between thrust and drag that led to increased acceleration. Considerations of ascent, not re-entry, therefore shaped the selection of temperature-resistant materials.

Yet the aircraft could not fly too low, or it would face limits set by aerodynamic flutter. This resulted from forces on the vehicle that were not steady but oscillated, at frequencies of oscillation that changed as the vehicle accelerated and lost weight. The wings tended to vibrate at characteristic frequencies, as when bent upward and released to flex up and down. If the frequency of an aerodynamic oscillation matched that at which the wings were prone to flex, the aerodynamic forces could tear the wings off. Stiffness in materials, not strength, was what resisted flutter, and the vehicle was to fly a "flutter-limited trajectory," staying high enough to avoid the problem.

The mechanical properties of metals depend on their fine-grained structure. An ingot of metal consists of a mass of interlaced grains or crystals, and small grains give higher strength. Quenching, plunging hot metal into water, yields small grains but often makes the metal brittle or hard to form. Alloying a metal, as by adding small quantities of carbon to make steel, is another traditional practice. However, some additives refuse to dissolve or separate out from the parent metal as it cools.



Ascent trajectory of an airbreather. (NASA)

To overcome such restrictions, techniques of powder metallurgy were in the forefront. These methods gave direct control of the microstructure of metals by forming them from powder, with the grains of powder sintering or welding together by being pressed in a mold at high temperature. A manufacturer could control the grain size independently of any heat-treating process. Powder metallurgy also overcame restrictions on alloying by mixing in the desired additives as powdered ingredients.

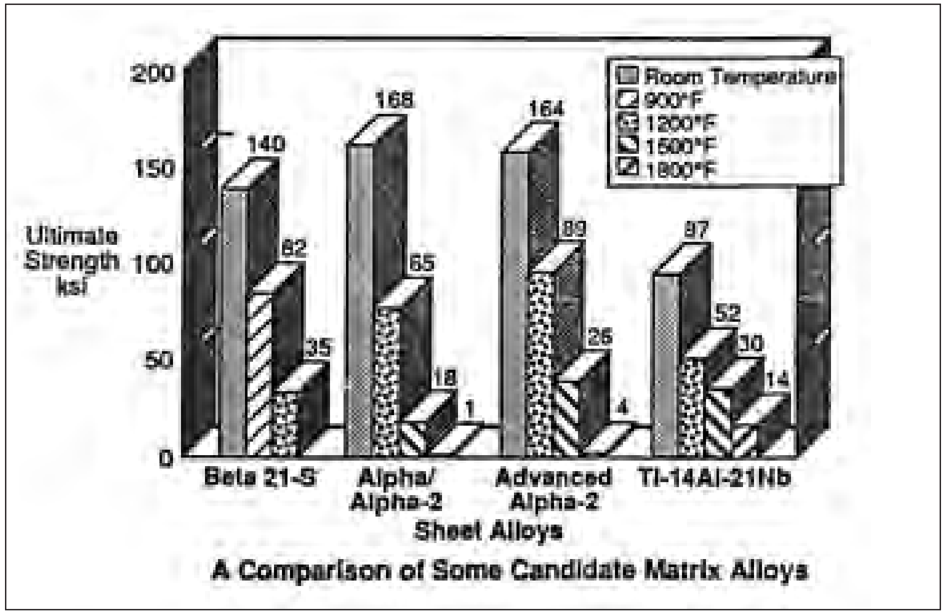
Several techniques existed to produce the powders. Grinding a metal slab to sawdust was the simplest, yielding relatively coarse grains. "Splat-cooling" gave better control. It extruded molten metal onto the chilled rim of a rotating wheel, which cooled it instantly into a thin ribbon. This represented a quenching process that produced a fine-grained microstructure in the metal. The ribbon then was chemically treated with hydrogen, which made it brittle, so that it could be ground into a fine powder. Heating the powder then drove off the hydrogen.

The Plasma Rotating Electrode Process, developed by the firm of Nuclear Metals, showed particular promise. The parent metal was shaped into a cylinder that rotated at up to 30,000 revolutions per minute and served as an electrode. An electric arc melted the spinning metal, which threw off droplets within an atmosphere of cool inert helium. The droplets plummeted in temperature by thousands of degrees within milliseconds, and their microstructures were so fine as to approach an amorphous state. Their molecules did not form crystals, even tiny ones, but arranged themselves in formless patterns. This process, called "rapid solidification," promised particular gains in high-temperature strength.

Standard titanium alloys, for instance, lost strength at temperatures above 700 to 900ºF. By using rapid solidification, McDonnell Douglas raised this limit to 1,100ºF prior to 1986. Philip Parrish, the manager of powder metallurgy at DARPA, noted that his agency had spent some $30 million on rapid-solidification technology since 1975. In 1986 he described it as "an established technology. This technology now can stand along such traditional methods as ingot casting or drop forging."[49]

Nevertheless 1,100°F was not enough, for it appeared that the X-30 needed a material that was rated at 1,700ºF. This stemmed from the fact that for several years, NASP design and trajectory studies indicated that a flight vehicle indeed would face such temperatures on its fuselage. But after 1990 the development of new baseline configurations led to an appreciation that the pertinent areas of the vehicle would face temperatures no higher than 1,500ºF. At that temperature, advanced titanium alloys could serve in "metal matrix composites," with thin-gauge metals being reinforced with fibers.

The new composition came from the firm of Titanium Metals and was designated Beta-21S. That company developed it specifically for the X-30 and patented it in 1989. It consisted of titanium along with 15 percent molybdenum, 2.8 percent columbium, 3 percent aluminum, and 0.2 percent silicon. Resistance to oxidation proved to be its strong suit, with this alloy showing resistance that was two orders of magnitude greater than that of conventional aircraft titanium. Tests showed that it



Comparison of some matrix alloys. (NASA)

also could be exposed repeatedly to leaks of gaseous hydrogen without being subject to embrittlement. Moreover, it lent itself readily to being rolled to foil-gauge thicknesses of 4 to 5 mil when metal matrix composites were fabricated.[50]

Such titanium-matrix composites were used in representative X-30 structures. The Non-Integral Fuselage Tank Article (NIFTA) represented a section of X-30 fuselage at one-fourth scale. It was oblong in shape, eight feet long and measuring four by seven feet in cross section, and it contained a splice. Its skin thickness was 0.040 inches, about the same as for the X-30. It held an insulated tank that could hold either liquid nitrogen or LH_2 in tests, which stood as a substantial engineering item in its own right.

The tank had a capacity of 940 gallons and was fabricated of graphite-epoxy composite. No liner protected the tankage on the inside, for graphite-epoxy was impervious to damage by LH_2. However, the exterior was insulated with two half-inch thicknesses of Q-felt, a quartz-fiber batting with density of only 3.5 pounds per cubic foot. A thin layer of Astroquartz high-temperature cloth covered the Q-felt. This insulation filled space between the tank wall and the surrounding wall of the main structure, with both this space and the Q-felt being purged with helium.[51]

The test sequence for NIFTA duplicated the most severe temperatures and stresses of an ascent to orbit. These stresses began on the ground, with the vehicle being heavy with fuel and subject to a substantial bending load. There was also a large shear load, with portions of the vehicle being pulled transversely in opposite directions. This happened because the landing gear pushed upward to support the entire weight of the craft, while the weight of the hydrogen tank pushed downward only a few feet away. Other major bending and shear loads arose during subsonic climbout, with the X-30 executing a pullup maneuver.

Significant stresses arose near Mach 6 and resulted from temperature differences across the thickness of the stiffened skin. Its outer temperature was to be 800ºF, but the tops of the stiffeners, a few inches away, were to be 350ºF. These stiffeners were spot-welded to the skin panels, which raised the issue of whether the welds would hold amid the different thermal expansions. Then between Mach 10 and 16, the vehicle was to reach peak temperatures of 1,300ºF. The temperature differences between the top and bottom of the vehicle also would be at their maximum.

The tests combined both thermal and mechanical loads and were conducted within a vacuum chamber at Wyle Laboratories during 1991. Banks of quartz lamps applied up to 1.5 megawatts of heat, while jacks imposed bending or shear forces that reached 100 percent of the design limits. Most tests placed nonflammable liquid nitrogen in the tank for safety, but the last of them indeed used LH_2. With this supercold fuel at –423ºF, the lamps raised the exterior temperature of NIFTA to the full 1,300ºF, while the jacks applied the full bending load. A 1993 paper noted "100% successful completion of these tests," including the one with LH_2 that had been particularly demanding.[52]

NIFTA, again, was at one-fourth scale. In a project that ran from 1991 through the summer of 1994, McDonnell Douglas engineers designed and fabricated the substantially larger Full Scale Assembly. Described as "the largest and most representative NASP fuselage structure built," it took shape as a component measuring 10 by 12 feet. It simulated a section of the upper mid-fuselage, just aft of the crew compartment.

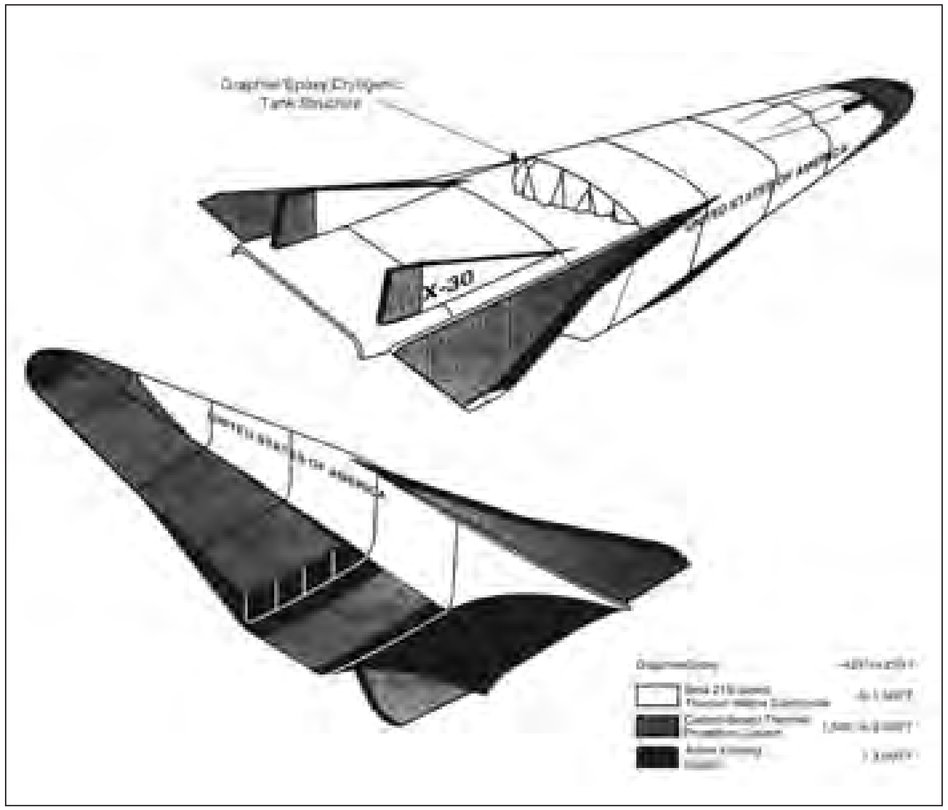
A 1994 review declared that it "was developed to demonstrate manufacturing and assembly of a full scale fuselage panel incorporating all the essential structural details of a flight vehicle fuselage assembly." Crafted in flightweight, it used individual panels of titanium-matrix composite that were as large as four by eight feet. These were stiffened with longitudinal members of the same material and were joined to circumferential frames and fittings of Ti-1100, a titanium alloy that used no fiber reinforcement. The complete assembly posed manufacturing challenges because the panels were of minimum thickness, having thinner gauges than had been used previously. The finished article was completed just as NASP was reaching its end, but it showed that the thin panels did not introduce significant problems.[53]

The firm of Textron manufactured the fibers, designated SCS-6 and -9, that reinforced the composites. As a final touch, in 1992 this company opened the world's first manufacturing plant dedicated to the production of titanium-matrix

composites. "We could get the cost down below a thousand dollars a pound if we had enough volume," Bill Grant, a company manager, told *Aerospace America*. His colleague Jim Henshaw added, "We think SCS/titanium composites are fully developed for structural applications."[54]

Such materials served to 1,500ºF, but on the X-30 substantial areas were to withstand temperatures approaching 3,000ºF, which is hotter than molten iron. If a steelworker were to plunge a hand into a ladle of this metal, the hand would explode from the sudden boiling of water in its tissues. In such areas, carbon-carbon was necessary. It had not been available for use in Dyna-Soar, but the Pentagon spent $200 million to fund its development between 1970 and 1985.[55]

Much of this supported the space shuttle, on which carbon-carbon protected such hot areas as the nose cap and wing leading edges. For the X-30, these areas expanded to cover the entire nose and much of the vehicle undersurface, along with the rudders and both the top and bottom surfaces of the wings. The X-30 was to execute 150 test flights, exposing its heat shield to prolonged thermal soaks while still in the atmosphere. This raised the problem of protection against oxidation.[56]



Selection of NASP materials based on temperature. (General Accounting Office)

Standard approaches called for mixing oxidation inhibitors into the carbon matrix and covering the surface with a coating of silicon carbide. However, there was a mismatch between the thermal expansions of the coating and the carbon-carbon substrate, which led to cracks. An interlayer of glass-forming sealant, placed between them, produced an impervious barrier that softened at high temperatures to fill the cracks. But these glasses did not flow readily at temperatures below 1,500°F. This meant that air could penetrate the coating and reach the carbon through open cracks to cause loss by oxidation.[57]

The goal was to protect carbon-carbon against oxidation for all 150 of those test flights, or 250 hours. These missions included 75 to orbit and 75 in hypersonic cruise. The work proceeded initially by evaluating several dozen test samples that were provided by commercial vendors. Most of these materials proved to resist oxidation for only 10 to 20 hours, but one specimen from the firm of Hitco reached 70 hours. Its surface had been grooved to promote adherence of the coating, and it gave hope that long operational life might be achieved.[58]

Complementing the study of vendors' samples, researchers ordered new types of carbon-carbon and conducted additional tests. The most durable came from the firm of Rohr, with a coating by Science Applications International. It easily withstood 2,000°F for 200 hours and was still going strong at 2,500 °F when the tests stopped after 150 hours. This excellent performance stemmed from its use of large quantities of oxidation inhibitors, which promoted long life, and of multiple glass layers in the coating.

But even the best of these carbon-carbons showed far poorer performance when tested in arcjets at 2,500°F. The high-speed airflows forced oxygen into cracks and pores within the material, while promoting evaporation of the glass sealants. Powerful roars within the arcjets imposed acoustic loads that contributed to cracking, with other cracks arising from thermal shock as test specimens were suddenly plunged into a hot flow stream. The best results indicated lifetimes of less than two hours.

Fortunately, actual X-30 missions were to impose 2,500°F temperatures for only a few minutes during each launch and reentry. Even a single hour of lifetime therefore could permit panels of carbon-carbon to serve for a number of flights. A 1992 review concluded that "maximum service temperatures should be limited to 2,800°F; above this temperature the silicon-based coating systems afford little practical durability," due to active oxidation. In addition, "periodic replacement of parts may be inevitable."[59]

New work on carbon-carbon, reported in 1993, gave greater encouragement as it raised the prospect of longer lifetimes. The effort evaluated small samples rather than fabricated panels and again used the arcjet installations of NASA-Johnson and Ames. Once again there was an orders-of-magnitude difference in the observed lifetimes of the carbon-carbon, but now the measured lifetimes extended into the hundreds of minutes. A formulation from the firm of Carbon-Carbon Advanced

Technologies gave the best results, suggesting 25 reuses for orbital missions of the X-30 and 50 reuses for the less-demanding missions of hypersonic cruise.[60]

There also was interest in using carbon-carbon for primary structure. Here the property that counted was not its heat resistance but its light weight. In an important experiment, the firm of LTV fabricated half of an entire wing box of this material. An airplane's wing box is a major element of aircraft structure that joins the wings and provides a solid base for attachment of the fuselage fore and aft. Indeed, one could compare it with the keel of a ship. It extends to left and right of the aircraft centerline, and LTV's box constituted the portion to the left of this line. Built at full scale, it represented a hot-structure wing proposed by General Dynamics. It measured five by eight feet with a maximum thickness of 16 inches. Three spars ran along its length; five ribs were mounted transversely, and the complete assembly weighed 802 pounds.

The test plan called for it to be pulled upward at the tip to reproduce the bending loads of a wing in flight. Torsion or twisting was to be applied by pulling more strongly on the front or rear spar. The maximum load corresponded to having the X-30 execute a pullup maneuver at Mach 2.2, with the wing box at room temperature. With the ascent continuing and the vehicle undergoing aerodynamic heating, the next key event brought the maximum difference in the temperatures of the top and bottom of the wing box, with the former being 994°F and the latter at 1,671°F. At that moment the load on the wing box corresponded to 34 percent of the Mach 2.2 maximum. Farther along, the wing box was to reach its peak temperature, 1,925°F, on the lower surface. These three points were to be reproduced through mechanical forces applied at the ends of the spars and through the use of graphite heaters.

But several key parts delaminated during their fabrication, seriously compromising the ability of the wing box to bear its specified load. Plans to impose the peak or Mach 2.2 load were abandoned, with the maximum planned load being reduced to the 34 percent associated with the maximum temperature difference. For the same reason, the application of torsion was deleted from the test program. Amid these reductions in the scope of the structural tests, two exercises went forward during December 1991. The first took place at room temperature and successfully reached the mark of 34 percent, without causing further damage to the wing box.

The second test, a week later, reproduced the condition of peak temperature difference while briefly applying the calculated load of 34 percent. The plan then called for further heating to the peak temperature of 1,925°F. As the wing box approached this value, a problem arose due to the use of metal fasteners in its assembly. Some were made from coated columbium and were rated for 2,300°F, but most were of a nickel alloy that had a permissible temperature of 2,000°F. However, an instrumented nickel-alloy fastener overheated and reached 2,147°F. The wing box showed a maximum temperature of 1,917°F at that moment, and the test was terminated because the strength of the fasteners now was in question. This test nevertheless counted as a success because it had come within 8°F of the specified temperature.[61]

Both tests thus were marked as having achieved their goals, but their merits were largely in the mind of the beholder. The entire project would have been far more impressive if it had avoided delamination, successfully achieved the Mach 2.2 peak load, incorporated torsion, and subjected the wing box to repeated cycles of bending, torsion, and heating. This effort stood as a bold leap toward a future in which carbon-carbon might take its place as a mainstream material, suitable for a hot primary structure, but it was clear that this future would not arrive during the NASP program.

Then there was beryllium. It had only two-thirds the density of aluminum and possessed good strength, but its temperature range was limited. The conventional metal had a limit of some 850°F, but an alloy from Lockheed called Lockalloy, which contained 38 percent aluminum, was rated only for 600°F. It had never become a mainstream engineering material like titanium, but for NASP it offered the advantage of high thermal conductivity. Work with titanium had greatly increased its temperatures of use, and there was hope of achieving similar results with beryllium.

Initial efforts used rapid-solidification techniques and sought temperature limits as high as 1,500°F. These attempts bore no fruit, and from 1988 onward the temperature goal fell lower and lower. In May 1990 a program review shifted the emphasis away from high-temperature formulations toward the development of beryllium as a material suitable for use at cryogenic temperatures. Standard forms of this metal became unacceptably brittle when only slightly colder than –100°F, but cryo-beryllium proved to be out of reach as well. By 1992 investigators were working with ductile alloys of beryllium and were sacrificing all prospect of use at temperatures beyond a few hundred degrees but were winning only modest improvements in low-temperature capability. Terence Ronald, the NASP materials director, wrote in 1995 of rapid-solidification versions with temperature limits as low as 500°F, which was not what the X-30 needed to reach orbit.[62]

In sum, the NASP materials effort scored a major advance with Beta-21S, but the genuinely radical possibilities failed to emerge. These included carbon-carbon as primary structure, along with alloys of beryllium that were rated for temperatures well above 1,000°F. The latter, if available, might have led to a primary structure with the strength and temperature resistance of Beta-21S but with less than half the weight. Indeed, such weight savings would have ramified through the entire design, leading to a configuration that would have been smaller and lighter overall.

Overall, work with materials fell well short of its goals. In dealing with structures and materials, the contractors and the National Program Office established 19 program milestones that were to be accomplished by September 1993. A General Accounting Office program review, issued in December 1992, noted that only six of them would indeed be completed.[63] This slow progress encouraged conservatism in drawing up the bill of materials, but this conservatism carried a penalty.

When the scramjets faltered in their calculated performance and the X-30 gained weight while falling short of orbit, designers lacked recourse to new and very light materials—structural carbon-carbon, high-temperature beryllium—that might have saved the situation. With this, NASP spiraled to its end. It also left its supporters with renewed appreciation for rockets as launch vehicles, which had been flying to orbit for decades.

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11 DTIC ADA-274530 (quote, p. i).

12 Heppenheimer, "Tractable"; Lin, *Statistical*, pp. 15-17, 43-45.

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14 AIAA Paper 78-257. Quote: Author interview, Anthony Jameson, 4 June 1990. See *Mosaic*, Spring 1991, p. 30.

15 Quote: AIAA Paper 90-1480, p. 3.

16 Quote: AIAA Paper 83-1693, p. 1.

17 AIAA Paper 85-1652 (quotes, pp. 9, 12).

18 Shapiro, *Compressible*, p. 1085.

19 Quotes: AIAA Paper 90-5247, p. 1.

20 Author interviews: Anatol Roshko, 8 June 1990; Peter Bradshaw, 11 June 1990. See *Mosaic*, Spring 1991, p. 38.

21 Quotes: AIAA Paper 93-0200, p. 2. Author interviews: John Lumley, 5 June 1990; Anthony Jameson, 6 June 1990. See *Mosaic*, Spring 1991, pp. 32, 38.

22 Author interview, Anatol Roshko, 8 June 1990, as noted.

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25 DTIC ADA-274530. Quote: *Aerospace America*, October 1987, 35.

26 AIAA Paper 95-6055, p. 3 (includes quote).

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32 DTIC ADB-192311, task 1561.

33 *Aviation Week*, 3 April 1989, p. 58; Thompson, *Space Log*, Vol. 30 (1994), pp. 5-6.

34 *Aviation Week*, 11 May 1992, p. 54; AIAA Paper 92-5023; General Accounting Office Report NSIAD-92-5.

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36 DTIC AD-350952; also available as CASI 64X-17126.

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38 DTIC ADB-191715 (quote, p. 3-22).

39 Escher, "Cryogenic," pp. 5-6; DTIC ADB-191715, p. 3-20.

40 AIAA Paper 91-1944; DTIC ADB-191715, p. 3-20.

41 Crickmore, *SR-71*, p. 95.

42 Ejector ramjets: AIAA Paper 86-1680, Fig. 3. Turbojets: *Aviation Week*: 3 May 1954, p. 44; 2 May 1960, p. 145.

43 AIAA Paper 89-0008 (quote, p. 1).

44 See also 1989 NASP Technology Maturation Plan, task 2.1.02.

45 DTIC ADB-197041, Attachment D.

46 Ibid.

47 Schweikart, *Quest*, p. 300; quote: DTIC ADB-197041, p. 2.

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53 DTIC ADB-196085.

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55 AIAA Paper 90-5206; Preston, *American Steel*, pp. 8-9.

56 General Accounting Office Report NSIAD-93-71; DTIC ADB-192559.

57 AIAA Paper 89-5010.

58 DTIC ADB-191699, ADB-192559; ADB-190937, pp. 3-5.

59 DTIC ADB-191699 (quotes, p. 9).

60 DTIC ADB-191402, pp. 117-49.

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62 DTIC ADB-191898; AIAA Paper 95-6131.

63 General Accounting Office Report NSIAD-93-71, table, p. 20.

9

Hypersonics After NASP

On 7 December 1995 the entry probe of the Galileo spacecraft plunged into the atmosphere of Jupiter. It did not plummet directly downward but sliced into that planet's hydrogen-rich envelope at a gentle angle as it followed a trajectory that took it close to Jupiter's edge. The probe entered at Mach 50, with its speed of 29.5 miles per second being four times that of a return to Earth from the Moon. Peak heating came to 11,800 BTU per square foot-second, corresponding to a radiative equilibrium temperature of 12,000°F. The heat load totaled 141,800 BTU per square foot, enough to boil 150 pounds of water for each square foot of heatshield surface.[1] The deceleration peaked at 228 g, which was tantamount to slamming from a speed of 5,000 miles per hour to a standstill in a single second. Yet the probe survived. It deployed a parachute and transmitted data from every one of its onboard instruments for nearly an hour, until it was overwhelmed within the depths of the atmosphere.[2]

It used an ablative heatshield, and as an exercise in re-entry technology, the design was straightforward. The nose cap was of chopped and molded carbon phenolic composite; the rest of the main heatshield was tape-wrapped carbon phenolic. The maximum thickness was 5.75 inches. The probe also mounted an aft heatshield, which was of phenolic nylon. The value of these simple materials, under the extreme conditions of Jupiter atmosphere entry, showed beyond doubt that the problem of re-entry was well in hand.[3]

Other activities have done less well. The X-33 and X-34 projects, which sought to build next-generation shuttles using NASP materials, failed utterly. Test scramjets have lately taken to flight but only infrequently. Still, work in CFD continues to flourish. Today's best supercomputers offer a million times more power than the ancestral Illiac 4, the top computer of the mid-1970s. This ushers in the important new topic of Large Eddy Simulation (LES). It may enable us to learn, via computation, just how good scramjets may become.

The DC-X, which flew, and the X-33, which did not. (NASA)

The X-33 and X-34

During the early 1990s, as NASP passed its peak of funding and began to falter, two new initiatives showed that there still was much continuing promise in rockets. The startup firm of Orbital Sciences Corporation had set out to become the first company to develop a launch vehicle as a commercial venture, and this rocket, called Pegasus, gained success on its first attempt. This occurred in April 1990, as NASA's B-52 took off from Edwards AFB and dropped it into flight. Its first stage mounted wings and tail surfaces. Its third stage carried a small satellite and placed it in orbit.[4]

In a separate effort, the Strategic Defense Initiative Office funded the DC-X project of McDonnell Douglas. This single-stage vehicle weighed some 40,000 pounds when fueled and flew with four RL10 rocket engines from Pratt & Whitney. It took off and landed vertically, like Flash Gordon's rocket ship, using rocket thrust during the descent and avoiding the need for a parachute. It went forward as an exercise in rapid prototyping, with the contract being awarded in August 1991 and the DC-X being rolled out in April 1993. It demonstrated both reusability and low cost, flying

with a ground crew of only 15 people along with three more in its control center. It flew no higher than a few thousand feet, but it became the first rocket in history to abort a flight and execute a normal landing.[5]

The Clinton Administration came to Washington in January 1993. Dan Goldin, the NASA Administrator, soon chartered a major new study of launch options called Access to Space. Arnold Aldrich, Associate Administrator for Space Systems Development, served as its director. With NASP virtually on its deathbed, the work comprised three specific investigations. Each addressed a particular path toward a new generation of launch vehicles, which could include a new shuttle.

Managers at NASA Headquarters and at NASA-Johnson considered how upgrades to current expendables, and to the existing shuttle, might maintain them in service through the year 2030. At NASA-Marshall, a second group looked at prospects for new expendables that could replace existing rockets, including the shuttle, beginning in 2005. A collaboration between Headquarters and Marshall also considered a third approach: development of an entirely new reusable launch vehicle, to replace the shuttle and current expendables beginning in 2008.[6]

Engineers in industry were ready with ideas of their own. At Lockheed's famous Skunk Works, manager David Urie already had a concept for a fully-reusable single-stage vehicle that was to fly to orbit. It used a lifting-body configuration that drew on an in-house study of a vehicle to rescue crews from the space station. Urie's design was to be built as a hot structure with metal external panels for thermal protection and was to use high-performing rocket engines from Rocketdyne that would burn liquid hydrogen and liquid oxygen. This concept led to the X-33.[7]

Orbital Sciences was also stirring the pot. During the spring of 1993, this company conducted an internal study that examined prospects for a Pegasus follow-on. Pegasus used solid propellant in all three of its stages, but the new effort specifically considered the use of liquid propellants for higher performance. Its concept took shape as an air-launched two-stage vehicle, with the first stage being winged and fully reusable while the second stage, carried internally, was to fly to orbit without being recovered. Later that year executives of Orbital Sciences approached officials of NASA-Marshall to ask whether they might be interested, for this concept might complement that of Lockheed by lifting payloads of much lesser weight. This initiative led in time to the X-34.[8]

NASA's Access to Space report was in print in January 1994. Managers of the three option investigations had sought to make as persuasive a case as possible for their respective alternatives, and the view prevailed that technology soon would be in hand to adopt Lockheed's approach. In the words of the report summary,

> The study concluded that the most beneficial option is to develop and deploy a fully reusable single-stage-to-orbit (SSTO) pure-rocket launch

vehicle fleet incorporating advanced technologies, and to phase out current systems beginning in the 2008 time period….

The study determined that while the goal of achieving SSTO fully reusable rocket launch vehicles had existed for a long time, recent advances in technology made such a vehicle feasible and practical in the near term provided that necessary technologies were matured and demonstrated prior to start of vehicle development.[9]

Within weeks NASA followed with a new effort, the Advanced Launch Technology Program. It sought to lay technical groundwork for a next-generation shuttle, as it solicited initiatives from industry that were to pursue advances in structures, thermal protection, and propulsion.[10]

The Air Force had its own needs for access to space and had generally been more conservative than NASA. During the late 1970s, while that agency had been building the shuttle, the Air Force had pursued the Titan 34D as a new version of its Titan 3. More recently that service had gone forward with its upgraded Titan 4.[11] In May 1994 Lieutenant General Thomas Moorman, Vice Commander of the Air Force's Space Command, released his own study that was known as the Space Launch Modernization Plan. It considered a range of options that paralleled NASA's, including development of "a new reusable launch system." However, whereas NASA had embraced SSTO as its preferred direction, the Air Force study did not even mention this as a serious prospect. Nor did it recommend a selected choice of launch system. In a cover letter to the Deputy Secretary of Defense, John Deutch, Moorman wrote that "this study does not recommend a specific program approach" but was intended to "provide the Department of Defense a range of choices." Still, the report made a number of recommendations, one of which proved to carry particular weight: "Assign DOD the lead role in expendable launch vehicles and NASA the lead in reusables."[12]

The NASA and Air Force studies both went to the White House, where in August the Office of Science and Technology Policy issued a new National Space Transportation Policy. It divided the responsibilities for new launch systems in the manner that the Air Force had recommended and gave NASA the opportunity to pursue its own wishes as well:

The Department of Defense (DoD) will be the lead agency for improvement and evolution of the current U.S. expendable launch vehicle (ELV) fleet, including appropriate technology development.

The National Aeronautics and Space Administration (NASA) will provide for the improvement of the Space Shuttle system, focusing on reliability, safety, and cost-effectiveness.

The National Aeronautics and Space Administration will be the lead agency for technology development and demonstration for next generation reusable space transportation systems, such as the single-stage-to-orbit concept.[13]

The Pentagon's assignment led to the Evolved Expendable Launch Vehicle Program, which brought development of the Delta 4 family and of new versions of the Atlas.[14]

The new policy broke with past procurement practices, whereby NASA had paid the full cost of the necessary research and development and had purchased flight vehicles under contract. Instead, the White House took the view that the private sector could cover these costs, developing the next space shuttle as if it were a new commercial airliner. NASA's role still was critical, but this was to be the longstanding role of building experimental flight craft to demonstrate pertinent technologies. The policy document made this clear:

The objective of NASA's technology development and demonstration effort is to support government and private sector decisions by the end of this decade on development of an operational next generation reusable launch system.

Research shall be focused on technologies to support a decision no later than December 1996 to proceed with a sub-scale flight demonstration which would prove the concept of single-stage-to-orbit….

It is envisioned that the private sector could have a significant role in managing the development and operation of a new reusable space transportation system. In anticipation of this role, NASA shall actively involve the private sector in planning and evaluating its launch technology activities.[15]

This flight demonstrator became the X-33, with the smaller X-34 being part of the program as well. In mid-October NASA issued Cooperative Agreement Notices, which resembled requests for proposals, for the two projects. At a briefing to industry representatives held at NASA-Marshall on 19 October 1994, agency officials presented year-by-year projections of their spending plans. The X-33 was to receive $660 million in federal funds—later raised to $941 million—while the X-34 was slated for $70 million. Contractors were to add substantial amounts of their own and to cover the cost of overruns. Orbital Sciences was a potential bidder and held no contract, but its president, David Thompson, was well aware that he needed deeper pockets. He turned to Rockwell International and set up a partnership.[16]

The X-34 was the first to go to contract, as NASA selected the Orbital Sciences proposal in March 1995. Matching NASA's $70 million, this company and Rockwell each agreed to put up $60 million, which meant that the two corporations together were to provide more than 60 percent of the funding. Their partnership, called American Space Lines, anticipated developing an operational vehicle, the X-34B, that would carry 2,500 pounds to orbit. Weighing 108,500 pounds when fully fueled, it was to fly from NASA's Boeing 747 that served as the shuttle's carrier aircraft. Its length of 88 feet compared with 122 feet for the space shuttle orbiter.[17]

Very quickly an imbroglio developed over the choice of rocket engine for NASA's test craft. The contract called for use of a Russian engine, the Energomash RD-120 that was being marketed by Pratt & Whitney. Rockwell, which owned Rocketdyne, soon began demanding that its less powerful RS-27 engine be used instead. "The bottom line is Rockwell came in two weeks ago and said 'Use our engine or we'll walk,'" a knowledgeable industry observer told *Aviation Week*.[18]

As the issue remained unresolved, Orbital Sciences missed program milestone dates for airframe design and for selecting between configurations. Early in November NASA responded by handing Orbital a 14-day suspension notice. This led to further discussions, but even the personal involvement of Dan Goldin failed to resolve the matter. In addition, the X-34B concept had grown to as much as 140,000 pounds. Within the program, strong private-sector involvement meant that private-sector criteria of profitability were important, and Orbital determined that the new and heavy configuration carried substantial risk of financial loss. Early in 1996 company officials called for a complete redesign of NASA's X-34 that would substantially reduce its size. The agency responded by issuing a stop-work order. Rockwell then made its move by bailing out as well. With this, the X-34 appeared dead.

But it soon returned to life, as NASA prepared to launch it anew. It now was necessary to go back to square one and again ask for bids and proposals, and again Orbital Sciences was in the running, this time without a partner. The old X-34 had amounted to a prototype of the operational X-34B, approaching it in size and weight while also calling for use of NASA's Boeing 747. The company's new concept was only 58 feet long compared with 83; its gross weight was to be 45,000 pounds rather than 120,000. It was not to launch payloads into orbit but was to serve as a technology demonstrator for an eventual (and larger) first stage by flying to Mach 8. In June 1996 NASA selected Orbital again as the winner, choosing its proposal over competing concepts from such major players as McDonnell Douglas, Northrop Grumman, Rockwell, and the Lockheed Martin Skunk Works.[19]

Preparations for the X-33 had meanwhile been going forward as well. Design studies had been under way, with Lockheed Martin, Rockwell, and McDonnell Douglas as the competitors. In July 1996 Vice President Albert Gore announced that Lockheed had won the prize. This company envisioned a commercial SSTO craft named VentureStar as its eventual goal. It was to carry a payload of 59,000 pounds to low Earth orbit, topping the 51,000 pounds of the shuttle. Lockheed's X-33 amounted to a version of this vehicle built at 53 percent scale. It was to fly to

Mach 15, well short of orbital velocity, but would subject its thermal protection to a demanding test.[20]

No rocket craft of any type had ever flown to orbit as a single stage. NASA hoped that vehicles such as VentureStar not only would do this but would achieve low cost, cutting the cost of a pound in orbit from the $10,000 of the space shuttle to as little as $1,000.[21] The X-33 was to demonstrate the pertinent technology, which was being pursued under NASA's Advanced Launch Technology Program of 1994. Developments based on this program were to support the X-34 as well.

Lightweight structures were essential, particularly for the X-33. Accordingly, there was strong interest in graphite-composite tanks and primary structure. This represented a continuation of NASP activity, which had anticipated a main hydrogen tank of graphite-epoxy. The DC-X supported the new work, as NASA took it over and renamed it the DC-XA. Its oxygen tank had been aluminum; a new one, built in Russia, used an aluminum-lithium alloy. Its hydrogen tank, also of aluminum, gave way to one of graphite-epoxy with lightweight foam for internal insulation. This material also served for an intertank structure and a feedline and valve assembly.[22]

Rapid turnaround offered a particularly promising road to low launch costs, and the revamped DC-XA gave support in this area as well. Two launches, conducted in June 1996, demonstrated turnaround and reflight in only 26 hours, again with its ground crew of only 15.[23]

Thermal protection raised additional issues. The X-34 was to fly only to Mach 8 and drew on space shuttle technology. Its surface was to be protected with insulation blankets that resembled those in use on the shuttle orbiter. These included the High Heat Blanket for the X-34 undersurface, rated for 2,000°F, with a Nextel 440 fabric and Saffil batting. The nose cap as well as the wing and rudder leading edges were protected with Fibrous Refractory Composite Insulation, which formed the black silica tiles of the shuttle orbiter. For the X-34, these tiles were to be impregnated with silicone to make them water resistant, impermeable to flows of hot gas, and easier to repair.[24]

VentureStar faced the demands of entry from orbit, but its re-entry environment was to be more benign than that of the shuttle. The shuttle orbiter was compact in size and relatively heavy and lost little of its orbital energy until well into the atmosphere. By contrast, VentureStar would resemble a big lightweight balloon when it re-entered after expending its propellants. The VentureStar thermal protection system was to be tested in flight on the X-33. It had the form of a hot structure, with radiative surface panels of carbon-carbon, Inconel 617 nickel alloy, and titanium, depending on the temperature.[25]

In an effort separate from that of the X-33, elements of this thermal protection were given a workout by being mounted to the space shuttle *Endeavour* and tested during re-entry. Thoughts of such tests dated to 1981 and finally were realized during Mission STS-77 in May 1996. Panels of Inconel 617 and of Ti-1100 titanium, measuring 7 by 10 inches, were mounted in recessed areas of the fuselage that lay near the vertical tail and which were heated only to approximately 1,000°F during re-entry. Both materials were rated for considerably higher temperatures, but this successful demonstration put one more arrow in NASA's quiver.[26]

For both VentureStar and its supporting X-33, light weight was critical. The X-30 of NASP had been designed for SSTO operation, with a structural mass fraction—the ratio of unfueled weight to fully fueled weight—of 25 percent.[27] This requirement was difficult to achieve because most of the fuel was slush hydrogen, which has a very low density. This ballooned the size of the X-30 and increased the surface area that needed structural support and thermal protection. VentureStar was to use rockets, which had less performance than scramjets. It therefore needed more fuel, and its structural mass fraction, including payload, engines, and thermal protection, was less than 12 percent. However, this fuel included a great deal of liquid oxygen, which was denser than water and drove up the weight of the propellant. This low structural mass fraction therefore appeared within reach, and for the X-33, the required value was considerably less stringent. Its design called for an empty weight of 63,000 pounds and a loaded weight of 273,000, for a structural mass fraction of 23 percent.[28]

Even this design goal imposed demands, for while liquid oxygen was dense and compact, liquid hydrogen still was bulky and again enlarged the surface area. Designers thus made extensive use of lightweight composites, specifying graphite-epoxy for the hydrogen tanks. A similar material, graphite-bismaleimide, was to serve for load-bearing trusses as well as for the outer shell that was to support the thermal protection. This represented the X-30's road not taken, for the NASP thermal environment during ascent had been so severe that its design had demanded a primary structure of titanium-matrix composite, which was heavier. The lessened requirements of VentureStar's thermal protection meant that Lockheed could propose to reach orbit using materials that were considerably less heavy—that indeed were lighter than aluminum. The X-33 design saved additional weight because it was to be unpiloted, needing no flight deck and no life-support system for a crew.[29]

But aircraft often gain weight during development, and the X-33 was no exception. Starting in mid-1996 with a dry weight of 63,000 pounds, it was at 80,000 a year later, although a weight-reduction exercise trimmed this to 73,000.[30] Managers responded by cutting the planned top speed from Mach 15 or more to Mach 13.8. Jerry Rising, vice president at the Skunk Works that was the X-33's home, explained that such a top speed still would permit validation of the thermal protection in flight test. The craft would lift off from Edwards AFB and follow a boost-glide trajectory, reaching a peak altitude of 300,000 feet. The vehicle then would be lower in the atmosphere than previously planned, and the heating rate would consequently

be higher to properly exercise the thermal protection. The X-33 then was to glide onward to a landing at Malmstrom AFB in northern Montana, 950 miles from Edwards.[31]

The original program plan called for rollout of a complete flight vehicle on 1 November 1998. When that date arrived, though, the effort faced a five-month schedule slip. This resulted from difficulties with the rocket engines.[32] Then in December, two days before Christmas, the program received a highly unwelcome present. A hydrogen fuel tank, under construction at a Lockheed Martin facility in Sunnyvale, California, sustained major damage within an autoclave. An inner wall of the tank showed delamination over 90 percent of its area, while another wall sprang loose from its frame. The tank had been inspected using ultrasound, but this failed to disclose the incipient problem, which raised questions as to the adequacy of inspection procedures as well as of the tank design itself. Another delay was at hand of up to seven months.

By May 1999 the weight at main engine cutoff was up to 83,000 pounds, including unburned residual propellant. Cleon Lacefield, the Lockheed Martin program manager, continued to insist bravely that the vehicle would reach at least Mach 13, but working engineers told *Aviation Week* that the top speed had been Mach 10 for quite some time and that "the only way it's getting to Malmstrom is on the back of a truck."[33] The commercial VentureStar concept threatened to be far more demanding, and during that month Peter Teets, president and CEO of Lockheed Martin, told the U.S. Senate Commerce and Science Committee that he could not expect to attract the necessary private-sector financing. "Wall Street has spoken," he declared. "They have picked the status quo; they will finance systems with existing technology. They will not finance VentureStar."[34]

By then the VentureStar design had gone over to aluminum tanks. These were heavier than tanks of graphite-epoxy, but the latter brought unacceptable technical risks because no autoclave existed that was big enough to fabricate such tankage. Lockheed Martin designers reshaped VentureStar and accepted a weight increase from 2.6 million pounds to 3.3 million. (It had been 2.2 million in 1996.) The use of graphite-epoxy in the X-33 tank now no longer was relevant to VentureStar, but this was what the program held in hand, and a change to aluminum would have added still more weight to the X-33.

During 1999 a second graphite-epoxy hydrogen tank was successfully assembled at Lockheed Martin and then was shipped to NASA-Marshall for structural tests. Early in November it experienced its own failure, showing delamination and a ripped outer skin along with several fractures or breaks in the skin. Engineers had been concerned for months about structural weakness, with one knowledgeable specialist telling *Aviation Week*, "That tank belonged in a junkyard, not a test stand." The program now was well on its way to becoming an orphan. It was not beloved by NASA, which refused to increase its share of funding above $941 million, while the in-house cost at Lockheed Martin was mounting steadily.[35]

The X-33 effort nevertheless lingered through the year 2000. This was an election year, not a good time to cancel a billion-dollar federal program, and Al Gore was running for president. He had announced the contract award in 1996, and in the words of a congressional staffer, "I think NASA will have a hard time walking away from the X-33 until after the election. For better or worse, Al Gore now has ownership of it. They can't admit it's a failure."[36]

The X-34 was still in the picture, as a substantial effort in its own right. Its loaded weight of 47,000 pounds approached the 56,000 of the X-15 with external tanks, built more than 30 years earlier.[37] Yet despite this reduced weight, the X-34 was to reach Mach 8, substantially exceeding the Mach 6.7 of the X-15. This reflected the use of advanced materials, for whereas the X-15 had been built of heavy Inconel X, the X-34 design specified lightweight composites for the primary structure and fuel tank, along with aluminum for the liquid-oxygen tank.[38]

Its construction went forward without major mishaps because it was much smaller than the X-33. The first of them reached completion in February 1999, but during the next two years it never came close to powered flight. The reason was that the X-34 program called for use of an entirely new engine, the 60,000-pound-thrust Fastrak of NASA-Marshall that burned liquid oxygen and kerosene. This engine encountered development problems, and because it was not ready, the X-34 could not fly under power.[39]

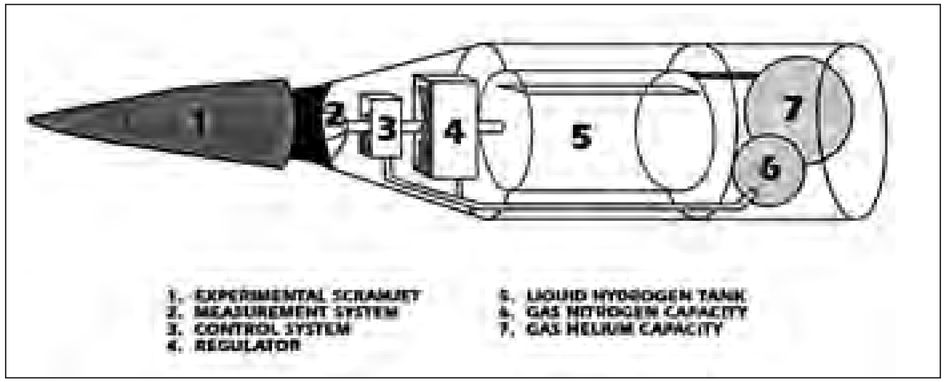
Early in March 2001, with George W. Bush in the White House, NASA pulled the plug. Arthur Stephenson, director of NASA-Marshall, canceled the X-34. This reflected the influence of the Strategic Defense Initiative Office, which had maintained a continuing interest in low-cost access to orbit and had determined that the X-34's costs outweighed the benefits. Stephenson also announced that the cooperative agreement between NASA and Lockheed Martin, which had supported the X-33, would expire at the end of the month. He then pronounced an epitaph on both programs: "One of the things we have learned is that our technology has not yet advanced to the point that we can successfully develop a new reusable launch vehicle that substantially improves safety, reliability, and affordability."[40]

One could say that the X-30 effort went farther than the X-33, for the former successfully exercised a complete hydrogen tank within its NIFTA project, whereas the latter did not. But the NIFTA tank was subscale, whereas those of the X-33 were full-size units intended for flight. The reason that NIFTA appears to have done better is that NASP never got far enough to build and test a full-size tank for its hydrogen slush. Because that tank also was to have been of graphite-epoxy, as with the X-33, it is highly plausible that the X-30 would have run aground on the same shoal of composite-tank structural failure that sank Lockheed Martin's rocket craft.[41]

Scramjets Take Flight

On 28 November 1991 a Soviet engine flew atop an SA-5 surface-to-air missile in an attempt to demonstrate supersonic combustion. The flight was launched from the Baikonur center in Kazakhstan and proceeded ballistically, covering some 112 miles. The engine did not produce propulsive thrust but rode the missile while mounted to its nose. The design had an axisymmetric configuration, resembling that of NASA's Hypersonic Research Engine, and the hardware had been built at Moscow's Central Institute of Aviation Motors (CIAM).

As described by Donat Ogorodnikov, the center director, the engine performed two preprogrammed burns during the flight. The first sought to demonstrate the important function of transition from subsonic to supersonic combustion. It was initiated at 59,000 feet and Mach 3.5, as the rocket continued to accelerate. Ogorodnikov asserted that after fifteen seconds, near Mach 5, the engine went over to supersonic combustion and operated in this mode for five seconds, while the rocket accelerated to Mach 6 at 92,000 feet. Within the combustor, internal flow reached a measured speed of Mach 3. Pressures within the combustor were one to two atmospheres.



Russian flight-test scramjet. (Aviation Week and Space Technology)

The second engine burn lasted ten seconds. This one had the purpose of verifying the design of the engine's ignition system. It took place on the downward leg of the trajectory, as the vehicle descended from 72,000 feet and Mach 4.5 to 59,000 feet and Mach 3.5. This burn involved only subsonic combustion. Vyacheslav Vinogradov, chief of engine gasdynamics at CIAM, described the engine as mounting three rows of fuel injectors. Choice of an injector row, out of the three available, was to help in changing the combustion mode.

The engine diameter at the inlet was 9.1 inches; its length was 4.2 feet. The spike, inlet, and combustor were of stainless steel, with the spike tip and cowl leading edge being fabricated using powder metallurgy. The fuel was liquid hydrogen, and the system used no turbopump. Pressure, within a fuel tank that also was stainless steel, forced the hydrogen to flow. The combustor was regeneratively cooled; this vaporized the hydrogen, which flowed through a regulator at rates that varied from 0.33 pounds per second in low-Mach flight to 0.11 at high Mach.[42]

The Russians made these extensive disclosures because they hoped for financial support from the West. They obtained initial assistance from France and conducted a second flight test a year later. The engine was slightly smaller and the trajectory was flatter, reaching 85,000 feet. It ignited near Mach 3.5 and sustained subsonic combustion for several seconds while the rocket accelerated to Mach 5. The engine then transitioned to supersonic combustion and remained in this mode for some fifteen seconds, while acceleration continued to Mach 5.5. Burning then terminated due to exhaustion of the fuel.[43]

On its face, this program had built a flightworthy scramjet, had achieved a supersonic internal airflow, and had burned hydrogen within this flow. Even so, this was not necessarily the same as accomplishing supersonic combustion. The alleged transition occurred near Mach 5, which definitely was at the low end for a scramjet.[44] In addition, there are a number of ways whereby pockets of subsonic flow might have existed within an internal airstream that was supersonic overall. These could have served as flameholders, localized regions where conditions for combustion were particularly favorable.[45]

In 1994 CIAM received a contract from NASA, with NASA-Langley providing technical support. The goal now was Mach 6.5, at which supersonic combustion appeared to hold a particularly strong prospect. The original Russian designs had been rated for Mach 6 and were modified to accommodate the higher heat loads at this higher speed. The flight took place in February 1998 and reached Mach 6.4 at 70,000 feet, with the engine operating for 77 seconds.[46]

It began operation near Mach 3.5. Almost immediately the inlet unstarted due to excessive fuel injection. An onboard control system detected the unstart and reduced the fuel flow, which enabled the inlet to start and to remain started. However, the onboard control failed to detect this restart and failed to permit fuel to flow through the first of the three rows of fuel injectors. Moreover, the inlet performance fell short of predictions due to problems in fabrication.

At Mach 5.5 and higher, airflow entered the fuel-air mixing zone within the combustor at speeds near Mach 2. However, only the two rear rows of injectors were active, and burning of their fuel forced the internal Mach number to subsonic values. The flow reaccelerated to sonic velocity at the combustor exit. The combination of degraded inlet performance and use of only the rear fuel injectors ensured that even at the highest flight speeds, the engine operated primarily in a subsonic-combustion mode and showed little if any supersonic combustion.[47]

It nevertheless was clear that with better quality control in manufacturing and with better fault tolerance in the onboard control laws, full success might readily be achieved. However, the CIAM design was axisymmetric and hence was of a type that NASA had abandoned during the early 1970s. Such scramjets had played no role in NASP, which from the start had focused on airframe-integrated configurations. The CIAM project had represented an existing effort that was in a position to benefit from even the most modest of allocations; the 1992 flight, for instance, received as little as $200,000 from France.[48] But NASA had its eye on a completely American scramjet project that could build on the work of NASP. It took the name Hyper-X and later X-43A.

Its background lay in a 1995 study conducted by McDonnell Douglas, with Pratt & Whitney providing concepts for propulsion. This effort, the Dual-Fuel Airbreathing Hypersonic Vehicle Study, gave conceptual designs for vehicles that could perform two significant missions: weapons delivery and reconnaissance, and operation as the airbreathing first stage of a two-stage-to-orbit launch system. This work drew interest at NASA Headquarters and led the Hypersonic Vehicles Office at NASA-Langley to commission the conceptual design of an experimental airplane that could demonstrate critical technologies required for the mission vehicles.

The Hyper-X design grew out of a concept for a Mach 10 cruise aircraft with length of 200 feet and range of 8,500 nautical miles. It broke with the NASP approach of seeking a highly integrated propulsion package that used an ejector ramLACE as a low-speed system. Instead it returned to the more conservative path of installing separate types of engine. Hydrocarbon-fueled turboramjets were to serve for takeoff, acceleration to Mach 4, and subsonic cruise and landing. Hydrogen-burning scramjets were to take the vehicle to Mach 10. The shape of this vehicle defined that of Hyper-X, which was designed as a detailed scale model that was 12 feet long rather than 200.[49]

Like the Russian engines, Hyper-X was to fly to its test Mach using a rocket booster. But Hyper-X was to advance beyond the Russian accomplishments by separating from this booster to execute free flight. This separation maneuver proved to be trickier than it looked. Subsonic bombers had been dropping rocket planes into flight since the heyday of Chuck Yeager, and rocket stages had separated in near-vacuum at the high velocities of a lunar mission. However, Hyper-X was to separate at speeds as high as Mach 10 and at 100,000 feet, which imposed strong forces from the airflow. As the project manager David Reubush wrote in 1999, "To the program's knowledge there has never been a successful separation of two vehicles (let alone a separation of two non-axisymmetric vehicles) at these conditions. Therefore, it soon became obvious that the greatest challenge for the Hyper-X program was, not the design of an efficient scramjet engine, but the development of a separation scenario and the mechanism to achieve it."[50]

Engineers at Sandia National Laboratory addressed this issue. They initially envisioned that the rocket might boost Hyper-X to high altitude, with the separation taking place in near-vacuum. The vehicle then could re-enter and light its scramjet. This approach fell by the wayside when the heat load at Mach 10 proved to exceed the capabilities of the thermal protection system. The next concept called for Hyper-X to ride the underside of its rocket and to be ejected downward as if it were a bomb. But this vehicle then would pass through the bow shock of the rocket and would face destabilizing forces that its control system could not counter.

Sandia's third suggestion called for holding the vehicle at the front of the rocket using a hinged adapter resembling a clamshell or a pair of alligator jaws. Pyrotechnics would blow the jaws open, releasing the craft into flight. The open jaws then were to serve as drag brakes, slowing the empty rocket casing while the flight vehicle sailed onward. The main problem was that if the vehicle rolled during separation, one of its wings might strike this adapter as it opened. Designers then turned to an adapter that would swing down as a single piece. This came to be known as the "drop-jaw," and it served as the baseline approach for a time.[51]

NASA announced the Hyper-X Program in October 1996, citing a budget of $170 million. In February 1997 Orbital Sciences won a contract to provide the rocket, which again was to be a Pegasus. A month later the firm of Micro Craft Inc. won the contract for the Hyper-X vehicle, with GASL building the engine. Work at GASL went forward rapidly, with that company delivering a scramjet to NASA-Langley in August 1998. NASA officials marked the occasion by changing the name of the flight aircraft to X-43A.[52]

The issue of separation in flight proved not to be settled, however, and developments early in 1999 led to abandonment of the drop-jaw. This adapter extended forward of the end of the vehicle, and there was concern that while opening it would form shock waves that would produce increased pressures on the rear underside of the flight craft, which again could overtax its control system. Wind-tunnel tests showed that this indeed was the case, and a new separation mechanism again was necessary. This arrangement called for holding the X-43A in position with explosive bolts. When they were fired, separate pyrotechnics were to actuate pistons that would push this craft forward, giving it a relative speed of at least 13 feet per second. Further studies and experiments showed that this concept indeed was suitable.[53]

The minimal size of the X-43A meant that there was little need to keep its weight down, and it came in at 2,800 pounds. This included 900 pounds of tungsten at the nose to provide ballast for stability in flight while also serving as a heat sink. High stiffness of the vehicle was essential to prevent oscillations of the structure that could interfere with the Pegasus flight control system. The X-43A thus was built with steel longerons and with steel skins having thickness of one-fourth inch. The wings were stubby and resembled horizontal stabilizers; they did not mount ailerons but moved

as a whole to provide sufficient control authority. The wings and tail surfaces were constructed of temperature-resistant Haynes 230 alloy. Leading edges of the nose, vertical fins, and wings used carbon-carbon. For thermal protection, the vehicle was covered with Alumina Enhanced Thermal Barrier tiles, which resembled the tiles of the space shuttle.[54]

Additional weight came from the scramjet. It was fabricated of a copper alloy called Glidcop, which was strengthened with very fine particles of aluminum oxide dispersed within. This increased its strength at high temperatures, while retaining the excellent thermal conductivity of copper. This alloy formed the external surface, sidewalls, cowl, and fuel injectors. Some internal surfaces were coated with zirconia to form a thermal barrier that protected the Glidcop in areas of high heating. The engine did not use its hydrogen fuel as a coolant but relied on water cooling for the sidewalls and cowl leading edge. Internal engine seals used braided ceramic rope.[55]

Because the X-43A was small, its engine tests were particularly realistic. This vehicle amounted to a scale model of a much larger operational craft of the future, but the engine testing involved ground-test models that were full size for the X-43A. Most of the testing took place at NASA-Langley, where the two initial series were conducted at the Arc-Heated Scramjet Test Facility. This wind tunnel was described in 1998 as "the primary Mach 7 scramjet test facility at Langley."[56]

Development tests began at the very outset of the Hyper-X Program. The first test article was the Dual-Fuel Experiment (DFX), with a name that reflected links to the original McDonnell Douglas study. The DFX was built in 1996 by modifying existing NASP engine hardware. It provided a test scramjet that could be modified rapidly and inexpensively for evaluation of changes to the flowpath. It was fabricated primarily of copper and used no active cooling, relying on heat sink. This ruled out tests at the full air density of a flight at Mach 7, which would have overheated this engine too quickly for it to give useful data. Even so, tests at reduced air densities gave valuable guidance in designing the flight engine.

The DFX reproduced the full-scale height and length of the Hyper-X engine, correctly replicating details of the forebody, cowl, and sidewall leading edge. The forebody and afterbody were truncated, and the engine width was reduced to 44 percent of the true value so that this test engine could fit with adequate clearances in the test facility. This effort conducted more than 250 tests of the DFX, in four different configurations. They verified predicted engine forces and moments as well as inlet and combustor component performances. Other results gave data on ignition requirements, flameholding, and combustor-inlet interactions.

Within that same facility, subsequent tests used the Hyper-X Engine Module (HXEM). It resembled the DFX, including the truncations fore and aft, and it too was of reduced width. But it replicated the design of the flight engine, thereby overcoming limitations of the DFX. The HXEM incorporated the active cooling of the flight version, which opened the door to tests at Mach 7 and at full air density. These took place within the large Eight-Foot High Temperature Tunnel (HTT).

The HTT had a test section that was long enough to accommodate the full 12-foot length of the X-43A underside, which provided major elements of the inlet and nozzle with its airframe-integrated forebody and afterbody. This replica of the underside initially was tested with the HXEM, thereby giving insight into the aerodynamic effects of the truncations. Subsequent work continued to use the HTT and replaced the HXEM with the full-width Hyper-X Flight Engine (HXFE). This was a flight-spare Mach 7 scramjet that had been assigned for use in ground testing.

Mounted on its undersurface, this configuration gave a geometrically accurate nose-to-tail X-43A propulsion flowpath at full scale. NASA-Langley had conducted previous tests of airframe-integrated scramjets, but this was the first to replicate the size and specific details of the propulsion system of a flight vehicle. The HTT heated its air by burning methane, which added large quantities of carbon dioxide and water vapor to the test gas. But it reproduced the Mach, air density, pressure, and temperature of flight at altitude, while gaseous oxygen, added to the airflow, enabled the engine to burn hydrogen fuel. Never before had so realistic a test series been accomplished.[57]

The thrust of the engine was classified, but as early as 1997 Vince Rausch, the Hyper-X manager at NASA-Langley, declared that it was the best-performing scramjet that had been tested at his center. Its design called for use of a cowl door that was to protect the engine by remaining closed during the rocket-powered ascent, with this door opening to start the inlet. The high fidelity of the HXFE, and of the test conditions, gave confidence that its mechanism would work in flight. The tests in the HTT included 14 unfueled runs and 40 with fuel. This cowl door was actuated 52 times under the Mach 7 test conditions, and it worked successfully every time.[58]

Aerodynamic wind-tunnel investigations complemented the propulsion tests and addressed a number of issues. The overall program covered all phases of the flight trajectory, using 15 models in nine wind tunnels. Configuration development alone demanded more than 5,800 wind-tunnel runs. The Pegasus rocket called for evaluation of its own aerodynamic characteristics when mated with the X-43A, and these had to be assessed from the moment of being dropped from the B-52 to separation of the flight vehicle. These used the Lockheed Martin Vought High Speed Wind Tunnel in Grand Prairie, Texas, along with facilities at NASA-Langley that operated at transonic as well as hypersonic speeds.[59]

Much work involved evaluating stability, control, and performance characteristics of the basic X-43A airframe. This effort used wind tunnels of McDonnell Douglas and Rockwell, with the latter being subsonic. At NASA-Langley, activity focused on that center's 20-inch Mach 6 and 31-inch Mach 10 facilities. The test

models were only one foot in length, but they incorporated movable rudders and wings. Eighteen-inch models followed, which were as large as these tunnels could accommodate, and gave finer increments of the control-surface deflections. Thirty-inch models brought additional realism and underwent supersonic and transonic tests in the Unitary Plan Wind Tunnel and the 16-Foot Transonic Tunnel.[60]

Similar studies evaluated the methods proposed for separation of the X-43A from its Pegasus booster. Initial tests used Langley's Mach 6 and Mach 10 tunnels. These were blowdown facilities that did not give long run times, while their test sections were too small to permit complete representations of vehicle maneuvers during separation. But after the drop-jaw concept had been selected, testing moved to tunnel B of the Von Karman Facility at the Arnold Engineering Development Center. This wind tunnel operated with continuous flow, in contrast to the blowdown installations of Langley, and provided a 50-inch-diameter test section for use at Mach 6. It was costly to test in that tunnel but highly productive, and it accommodated models that demonstrated a full range of relative orientations of Pegasus and the X-43A during separation.[61]

This wind-tunnel work also contributed to inlet development. To enhance overall engine performance, it was necessary for the boundary layer upstream of this inlet to be turbulent. Natural transition to turbulence could not be counted on, which meant that an aerodynamic device of some type was needed to trip the boundary layer into turbulence. The resulting investigations ran from 1997 into 1999 and used both the Mach 6 and Mach 10 Langley wind tunnels, executing more than 300 runs. Hypulse, a shock tunnel at GASL, conducted more than two dozen additional tests.[62]

Computational fluid dynamics was used extensively. The wind-tunnel tests that supported studies of X-43A separation all were steady-flow experiments, which failed to address issues such as unsteady flow in the gap between the two vehicles as they moved apart. CFD dealt with this topic. Other CFD analyses examined relative orientations of the separating vehicles that were not studied at AEDC. To scale wind-tunnel results for use with flight vehicles, CFD solutions were generated both for the small models under wind-tunnel conditions and for full-size vehicles in flight.[63]

Flight testing was to be conducted at NASA-Dryden. The first X-43A flight vehicle arrived there in October 1999, with its Pegasus booster following in December. Tests of this Pegasus were completed in May 2000, with the flight being attempted a year later. The plan called for acceleration to Mach 7 at 95,000 feet, followed by 10 seconds of powered scramjet operation. This brief time reflected the fact that the engine was uncooled and relied on copper heat sink, but it was long enough to take data and transmit them to the ground. In the words of NASA manager Lawrence Huebner, "we have ground data, we have ground CFD, we have flight CFD—all we need is the flight data."[64]

Launch finally occurred in June 2001. Ordinarily, when flying to orbit, Pegasus was air-dropped at 38,000 feet, and its first stage flew to 207,000 feet prior to second-stage ignition. It used solid propellant and its performance could not readily be altered; therefore, to reduce its peak altitude to the 95,000 feet of the X-43A, it was to be air-dropped at 24,000 feet, even though this lower altitude imposed greater loads.

The B-52 took off from Edwards AFB and headed over the Pacific. The Pegasus fell away; its first stage ignited five seconds later and it flew normally for some eight seconds that followed. During those seconds, it initiated a pullout to begin its climb. Then one of its elevons came off, followed almost immediately by another. As additional parts fell away, this booster went out of control. It fell tumbling toward the ocean, its rocket motor still firing, and a safety officer sent a destruct signal. The X-43A never had a chance to fly, for it never came close to launch conditions.[65]

A year later, while NASA was trying to recoup, a small group in Australia beat the Yankees to the punch by becoming the first in the world to fly a scramjet and achieve supersonic combustion. Their project, called HyShot, cost under $2 million, compared with $185 million for the X-43A program. Yet it had plenty of technical sophistication, including tests in a shock tunnel and CFD simulations using a supercomputer.

Allan Paull, a University of Queensland researcher, was the man who put it together. He took a graduate degree in applied mathematics in 1985 and began working at that university with Ray Stalker, an engineer who had won a global reputation by building a succession of shock tunnels. A few years later Stalker suffered a stroke, and Paull found himself in charge of the program. Then opportunity came knocking, in the form of a Florida-based company called Astrotech Space Operations. That firm was building sounding rockets and wanted to expand its activities into the Asia and Pacific regions.

In 1998 the two parties signed an agreement. Astrotech would provide two Terrier-Orion sounding rockets; Paull and his colleagues would construct experimental scramjets that would ride those rockets. The eventual scramjet design was not airframe-integrated, like that of the X-43A. It was a podded axisymmetric configuration. But it was built in two halves, with one part being fueled with hydrogen while the other part ran unfueled for comparison.[66]

Paull put together a team of four people—and found that the worst of his problems was what he called an "amazing legal nightmare" that ate up half his time. In the words of the magazine *Air & Space*, "the team had to secure authorizations from various state government agencies, coordinate with aviation bodies and insurance companies in both Australia and the United States (because of the involvement of U.S. funding), perform environmental assessments, and ensure their launch debris would steer clear of land claimed by Aboriginal tribes…. All told, the preparations took three and a half years."[67]

The flight plan called for each Terrier-Orion to accelerate its scramjet onto a ballistic trajectory that was to reach an altitude exceeding 300 kilometers. Near the peak of this flight path, an attitude-control system was to point the rocket downward. Once it re-entered the atmosphere, below 40 kilometers, its speed would fall off and the scramjet would ignite. This engine was to operate while continuing to plunge downward, covering distance into an increasingly dense atmosphere, until it lost speed in the lower atmosphere and crashed into the outback.

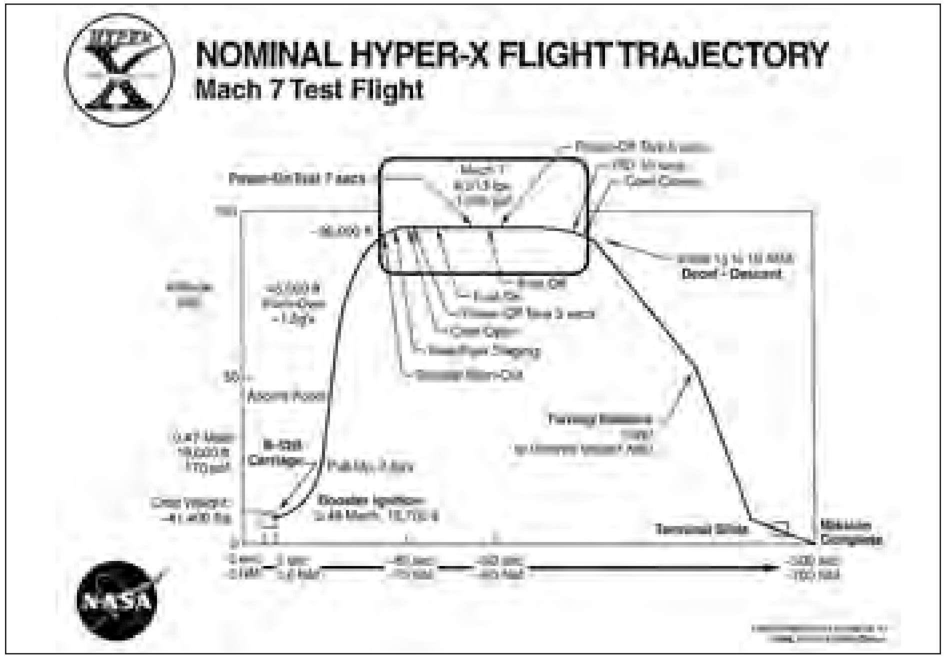
The flights took place at Woomera Instrumented Range, north of Adelaide. The first launch attempt came at the end of October 2001. It flopped; the first stage performed well, but the second stage went off course. But nine months later, on 30 July 2002, the second shot gained full success. The rocket was canted slightly away from the vertical as it leaped into the air, accelerating at 22 g as it reached Mach 3.6 in only six seconds.

This left it still at low altitude while topping the speed of the SR-71, so after the second stage with payload separated, it coasted for 16 seconds while continuing to ascend. The second stage then ignited, and this time its course was true. It reached a peak speed of Mach 7.7. The scramjet went over the top; it pointed its nose downward, and at an altitude of 36 kilometers with its speed approaching Mach 7.8, gaseous hydrogen caused it to begin producing thrust. This continued until HyShot reached 25 kilometers, when it shut down.

It fired for only five seconds. But it returned data over 40 channels, most of which gave pressure readings. NASA itself provided support, with Lawrence Huebner, the X-43A manager, declaring, "We're very hungry for flight data." For the moment, at least, the Aussies were in the lead.[68]

But the firm of Micro Craft had built two more X-43As, and the second flight took place in March 2004. This time the Pegasus first stage had been modified by having part of its propellant removed, to reduce its performance, and the drop altitude was considerably higher.[69] In the words of *Aviation Week*,

> The B-52B released the 37,500-lb. stack at 40,000 ft. and the Pegasus booster ignited 5 sec. later…. After a few seconds it pulled up and reached a maximum dynamic pressure of 1,650 psf. at Mach 3.5 climbing through 47,000 ft. Above 65,000 ft. it started to push over to a negative angle of attack to kill the climb rate and gain more speed. Burnout was 84 sec. after drop, and at 95 sec. a pair of pistons pushed the X-43A away from the booster at a target condition of Mach 7 and 95,000 ft. and a dynamic pressure of 1,060 psf. in a slight climb before the top of a ballistic arc.
>
> After a brief period of stabilization, the X-43A inlet door was opened to let air in through the engine…. The X-43A stabilized again because the engine airflow changed the trim…. Then silane, a chemical that burns upon contact with air, was injected for 3 sec. to establish flame to ignite the



X-43A mission to Mach 7. (NASA)

> hydrogen. Injection of the gaseous hydrogen fuel ramped up as the silane ramped down, lasting 8 sec. The hydrogen flow rate increased through and beyond a stoichiometric mixture ratio, and then ramped down to a very lean ratio that continued to burn until the fuel was shut off…. The hydrogen was stored in 8,000-psi bottles.
>
> Accelerometers showed the X-43A gained speed while fuel was on…. Data was gathered all the way to the splashdown 450 naut. mi. offshore at about 11 min. after drop.

Aviation Week added that the vehicle accelerated “while in a slight climb at Mach 7 and 100,000 ft. altitude. The scramjet field is sufficiently challenging that producing thrust greater than drag on an integrated airframe/engine is considered a major accomplishment.”[70]

In this fashion, NASA executed its first successful flight of a scramjet. The overall accomplishment was not nearly as ambitious as that planned for the Incremental Flight Test Vehicle of the 1960s, for which the velocity increase was to have been much greater. Nor did NASA have a follow-on program in view that could draw on the results of the X-43A. Still, the agency now could add the scramjet to its list of flight engines that had been successfully demonstrated.

The program still had one unexpended X-43A vehicle that was ready to fly, and it flew successfully as well, in November. The goal now was Mach 10. This called for beefing up the thermal structure by adding leading edges of solid carbon-carbon to the vertical tails along with a coating of hafnium carbide and by making the nose blunter to increase the detachment of the bow shock. These changes indeed were necessary. Nose temperatures reached 3,600°F, compared with 2,600°F on the Mach 7 flight, and heating rates were twice as high.

The Pegasus rocket, with the X-43A at its front, fell away from its B-52 carrier aircraft at 40,000 feet. Its solid rocket took the combination to Mach 10 at 110,000 feet. Several seconds after burnout, pistons pushed the X-43A away at Mach 9.8. Then, 2.5 seconds after separation, the engine inlet door opened and the engine began firing at Mach 9.65. It ran initially with silane to ensure ignition; then the engine continued to operate with silane off, for comparison. It fired for a total of 10 to 12 seconds and then continued to operate with the fuel off. Twenty-one seconds after separation, the inlet door closed and the vehicle entered a hypersonic glide. This continued for 14 minutes, with the craft returning data by telemetry until it struck the Pacific Ocean and sank.

This flight gave a rare look at data taken under conditions that could not be duplicated on the ground using continuous-flow wind tunnels. The X-43A had indeed been studied in 0.005-second runs within shock tunnels, and *Aviation Week* noted that Robert Bakos, vice president of GASL, described such tests as having done “a very good job of predicting the flight.” Dynamic pressure during the flight was 1,050 pounds per square foot, and the thrust approximately equaled the drag. In addition, the engine achieved true supersonic combustion, without internal pockets of subsonic flow. This meant that the observations could be scaled to still higher Mach values.[71]

Recent Advances in Fluid Mechanics

The methods of this field include ground test, flight test, and CFD. Ground-test facilities continue to show their limitations, with no improvements presently in view that would advance the realism of tests beyond Mach 10. A recently announced Air Force project, Mariah, merely underscores this point. This installation, to be built at AEDC, is to produce flows up to Mach 15 that are to run for as long as 10 seconds, in contrast to the milliseconds of shock tunnels. Mariah calls for a powerful electron beam to create an electrically charged airflow that can be accelerated with magnets. But this installation will require an e-beam of 200 megawatts. This is well beyond the state of the art, and even with support from a planned research program, Mariah is not expected to enter service until 2015.[72]

Similar slow progress is evident in CFD, for which the flow codes of recent projects have amounted merely to updates of those used in NASP. In designing the X-43A, the most important such code was the General Aerodynamic Simulation Program (GASP). NASP had used version 2.0; the X-43A used 3.0. The latter continued to incorporate turbulence models. Results from the codes often showed good agreement with test, but this was because the codes had been benchmarked extensively with wind-tunnel data. It did not reflect reliance on first principles at higher Mach.

Engine studies for the X-43A used their own codes, which again amounted to those of NASP. GASP 3.0 had the relatively recent date of 1996, but other pertinent literature showed nothing more recent than 1993, with some papers dating to the 1970s.[73]

The 2002 design of ISTAR, a rocket-based combined-cycle engine, showed that specialists were using codes that were considerably more current. Studies of the forebody and inlet used OVERFLOW, from 1999, while analysis of the combustor used VULCAN version 4.3, with a users' manual published in March 2002. OVERFLOW used equilibrium chemistry while VULCAN included finite-rate chemistry, but both solved the Navier-Stokes equations by using a two-equation turbulence model. This was no more than had been done during NASP, more than a decade earlier.[74]

The reason for this lack of progress can be understood with reference to Karl Marx, who wrote that people's thoughts are constrained by their tools of production. The tools of CFD have been supercomputers, and during the NASP era the best of them had been rated in gigaflops, billions of floating-point operations per second.[75] Such computations required the use of turbulence models. But recent years have seen the advent of teraflop machines. A list of the world's 500 most powerful is available on the Internet, with the accompanying table giving specifics for the top 10 of November 2004, along with number 500.

One should not view this list as having any staying power. Rather, it gives a snapshot of a technology that is advancing with extraordinary rapidity. Thus, in 1980 NASA was hoping to build the Numerical Aerodynamic Simulator, and to have it online in 1986. It was to be the world's fastest supercomputer, with a speed of one gigaflop (0.001 teraflop), but it would have fallen below number 500 as early as 1994. Number 500 of 2004, rated at 850 gigaflops, would have been number one as recently as 1996. In 2002 Japan's Earth Simulator was five times faster than its nearest rivals. In 2004 it had fallen to third place.[76]

Today's advances in speed are being accomplished both by increasing the number of processors and by multiplying the speed of each such unit. The ancestral Illiac-4, for instance, had 64 processors and was rated at 35 megaflops.[77] In 2004 IBM's BlueGene was two million times more powerful. This happened both because it had 512 times more processors—32,768 rather than 64—and because each individual processor had 4,000 times more power. Put another way, a single BlueGene processor could do the work of two Numerical Aerodynamic Simulator concepts of 1980.

Analysts are using this power. The NASA-Ames aerodynamicist Christian Stemmer, who has worked with a four-teraflop machine, notes that it achieved this speed

by using vectors, strings of 256 numbers, but that much of its capability went unused when his vector held only five numbers, representing five chemical species. The computation also slowed when finding the value of a single constant or when taking square roots, which is essential when calculating the speed of sound. Still, he adds, "people are happy if they get 50 percent" of a computer's rated performance. "I do get 50 percent, so I'm happy."[78]

THE WORLD'S FASTEST SUPERCOMPUTERS (Nov. 2004; updated annually)

	Name	Manufacturer	Location	Year	Rated speed teraflops	Number of proces-sors
1	BlueGene	IBM	Rochester, NY	2004	70,720	32,768
2	Numerical Aerodynamic Simulator	Silicon Graphics	NASA-Ames	2004	51,870	10,160
3	Earth Simulator	Nippon Electric	Yokohama, Japan	2002	35,860	5,120
4	Mare Nostrum	IBM	Barcelona, Spain	2004	20,530	3,564
5	Thunder	California Digital Corporation	Lawrence Livermore National Laboratory	2004	19,940	4,096
6	ASCI Q	Hewlett-Packard	Los Alamos National Laboratory	2002	13,880	8,192
7	System X	Self-made	Virginia Tech	2004	12,250	2,200
8	BlueGene (prototype)	IBM, Livermore	Rochester, NY	2004	11,680	8,192
9	eServer p Series 655	IBM	Naval Oceanographic Office	2004	10,310	2,944
10	Tungsten	Dell	National Center for Supercomputer Applications	2003	9,819	2,500
500	Superdome 875	Hewlett-Packard	SBC Service, Inc.	2004	850.6	416

Source: http://www.top500.org/list/2004/11

Teraflop ratings, representing a thousand-fold advance over the gigaflops of NASP and subsequent projects, are required because the most demanding problems in CFD are four-dimensional, including three physical dimensions as well as time. William Cabot, who uses the big Livermore machines, notes that "to get an increase in resolution by a factor of two, you need 16" as the increase in computational speed because the time step must also be reduced. "When someone says, 'I have a new computer that's an order of magnitude better,'" Cabot continues, "that's about a factor of 1.8. That doesn't impress people who do turbulence."[79]

But the new teraflop machines increase the resolution by a factor of 10. This opens the door to two new topics in CFD: Large-Eddy Simulation (LES) and Direct Numerical Simulation (DNS).

One approaches the pertinent issues by examining the structure of turbulence within a flow. The overall flowfield has a mean velocity at every point. Within it, there are turbulent eddies that span a very broad range of stress. The largest carry most of the turbulent energy and accomplish most of the turbulent mixing, as in a combustor. The smaller eddies form a cascade, in which those of different sizes are intermingled. Energy flows down this cascade, from the larger to the smaller ones, and while turbulence is often treated as a phenomenon that involves viscosity, the transfer of energy along the cascade takes place through inviscid processes. However, viscosity becomes important at the level of the smallest eddies, which were studied by Andrei Kolmogorov in the Soviet Union and hence define what is called the Kolmogorov scale of turbulence. At this scale, viscosity, which is an intermolecular effect, dissipates the energy from the cascade into heat. The British meteorologist Lewis Richardson, who introduced the concept of the cascade in 1922, summarized the matter in a memorable sendup of a poem by England's Jonathan Swift:

> Big whorls have little whorls
> Which feed on their velocity;
> And little whorls have lesser whorls,
> And so on to viscosity.[80]

In studying a turbulent flow, DNS computes activity at the Kolmogorov scale and may proceed into the lower levels of the cascade. It cannot go far because the sizes of the turbulent eddies span several orders of magnitude, which cannot be captured using computational grids of realistic size. Still, DNS is the method of choice for studies of transition to turbulence, which may predict its onset. Such simulations directly reproduce the small disturbances within a laminar flow that grow to produce turbulence. They do this when they first appear, making it possible to observe their growth. DNS is very computationally intensive and remains far from ready for use with engineering problems. Even so, it stands today as an active topic for research.

LES is farther along in development. It directly simulates the large energy-bearing eddies and goes onward into the upper levels of the cascade. Because its computations do not capture the complete physics of turbulence, LES continues to rely on turbulence models to treat the energy flow in the cascade along with the Kolmogorov-scale dissipation. But in contrast to the turbulence models of present-day codes, those of LES have a simple character that applies widely across a broad range of flows. In addition, their errors have limited consequence for a flow as a whole, in an inlet or combustor under study, because LES accurately captures the physics of the large eddies and therefore removes errors in their modeling at the outset.[81]

The first LES computations were published in 1970 by James Deardorff of the National Center for Atmospheric Research.[82] Dean Chapman, Director of Astronautics at NASA-Ames, gave a detailed review of CFD in the 1979 AIAA Dryden Lectureship in Research, taking note of the accomplishments and prospects of LES.[83] However, the limits of computers restricted the development of this field. More than a decade later Luigi Martinelli of Princeton University, a colleague of Antony Jameson who had established himself as a leading writer of flow codes, declared that "it would be very nice if we could run a large-eddy simulation on a full three-dimensional configuration, even a wing." Large eddies were being simulated only for simple cases such as flow in channels and over flat plates, and even then the computations were taking as long as 100 hours on a Cray supercomputer.[84]

Since 1995, however, the Center for Turbulence Research has come to the forefront as a major institution where LES is being developed for use as an engineering tool. It is part of Stanford University and maintains close ties both with NASA-Ames and with Lawrence Livermore National Laboratory. At this center, Kenneth Jansen published LES studies of flow over a wing in 1995 and 1996, treating a NACA 4412 airfoil at maximum lift.[85] More recent work has used LES in studies of reacting flows within a combustor of an existing jet engine of Pratt & Whitney's PW6000 series. The LES computation found a mean pressure drop across the injector of 4,588 pascals, which differs by only two percent from the observed value of 4,500 pascals. This compares with a value of 5,660 pascals calculated using a Reynolds-averaged Navier-Stokes code, which thus showed an error of 26 percent, an order of magnitude higher.[86]

Because LES computes turbulence from first principles, by solving the Navier-Stokes equations on a very fine computational grid, it holds high promise as a means for overcoming the limits of ground testing in shock tunnels at high Mach. The advent of LES suggests that it indeed may become possible to compute one's way to orbit, obtaining accurate results even for such demanding problems as flow in a scramjet that is flying at Mach 17.

Parviz Moin, director of the Stanford center, cautions that such flows introduce shock waves, which do not appear in subsonic engines such as the PW6000 series, and are difficult to treat using currently available methods of LES. But his colleague

Heinz Pitsch anticipates rapid progress. He predicted in 2003 that LES will first be applied to scramjets in university research, perhaps as early as 2005. He adds that by 2010 "LES will become the state of the art and will become the method of choice" for engineering problems, as it emerges from universities and begins to enter the mainstream of CFD.[87]

Hypersonics and the Aviation Frontier

Aviation has grown through reliance upon engines, and three types have been important: the piston motor, turbojet, and rocket. Hypersonic technologies have made their largest contributions, not by adding the scramjet to this list, but by enhancing the value and usefulness of rockets. This happened when these technologies solved the re-entry problem.

This problem addressed critical issues of the national interest, for it was essential to the success of Corona and of the return of film-carrying capsules from orbit. It also was a vital aspect of the development of strategic missiles. Still, if such weapons had proven to be technically infeasible, the superpowers would have fallen back on their long-range bombers. No such backup was available within the Corona program. During the mid-1960s the Lunar Orbiter Program used a high-resolution system for scanning photographic film, with the data being returned using telemetry.[88] But this arrangement had a rather slow data rate and was unsuitable for the demands of strategic reconnaissance.

Success in re-entry also undergirded the piloted space program. In 40 years of effort, this program has failed to find a role in the mainstream of technical activity akin to the importance of automated satellites in telecommunications. Still, piloted flight brought the unforgettable achievements of Apollo, which grow warmer in memory as the decades pass.

In a related area, the advent of thermal-protection methods led to the development of aircraft that burst all bounds on speed and altitude. These took form as the X-15 and the space shuttle. On the whole, though, this work has led to disappointment. The Air Force had anticipated that airbreathing counterparts of the X-15, powered perhaps by ramjets, would come along in the relatively near future. This did not happen; the X-15 remains sui generis, a thing unto itself. In turn, the shuttle failed to compete effectively with expendable launch vehicles.

This conclusion remains valid in the wake of the highly publicized flights of SpaceShipOne, built by the independent inventor Burt Rutan. Rutan showed an uncanny talent for innovation in 1986, when his Voyager aircraft, piloted by his brother Dick and by Dick's former girlfriend Jeana Yeager, circled the world on a single load of fuel. This achievement had not even been imagined, for no science-fiction writer had envisioned such a nonstop flight around the world. What made it possible was the use of composites in construction. Indeed, Voyager was built at Rutan's firm of Scaled Composites.[89] Such lightweight materials also found use in the construction of SpaceShipOne, which was assembled within that plant.

SpaceShipOne brought the prospect of routine commercial flights having the performance of the X-15. Built entirely as a privately funded venture, it used a simple rocket engine that burned rubber, with nitrous oxide as the oxidizer, and reached altitudes as high as 70 miles. A movable set of wings and tail booms, rotating upward, provided stability in attitude during re-entry and kept the craft's nose pointing upward as well. The craft then glided to a landing.

There was no commercial follow-on to Voyager, but today there is serious interest in building commercial versions of SpaceShipOne that will take tourists on brief hops into space—and enable them to win astronauts' wings in the process. Richard Branson, founder of Virgin Airways, is currently sponsoring a new enterprise, Virgin Galactic, that aims to do just that. He has formed a partnership with Scaled, has sold more than 100 tickets at $200,000 each, and hopes for his first flight late in 2008.

And yet…. The top speed of SpaceShipOne was only 2,200 miles per hour, or Mach 3.3. Rutan's vehicle thus stands today as a brilliant exercise in rocketry and the design of reusable piloted spacecraft. But it is too slow to qualify as a project in hypersonics.[90]

Is that it, then? Following more than half a century of effort, does the re-entry problem stand as the single unambiguous contribution of hypersonics? Air Force historian Richard Hallion has written of a "hypersonic revolution," but from this perspective, one may regard hypersonics less as an extension of aeronautics than as a branch of materials science, akin to metallurgy. Specialists in that field introduced superalloys that extended the temperature limits of jet engines, thereby enhancing their range and fuel economy. Similarly, the hypersonics community developed lightweight thermal-protection systems that have found use even in exploring the planet Jupiter. Yet one does not speak of a "superalloy revolution," and hypersonics has had similarly limited application.

There remains the issue of the continuing effort to develop the scramjet. This work has gone forward as part of an ongoing hope that better methods might be devised for ascent to orbit, corresponding perhaps to the jet airliners that drove their piston-driven counterparts to the boneyard. Access to space holds undeniable importance, and one may speak without challenge of a "satellite revolution" when we consider the vital role of such craft in a host of areas: weather forecasting, navigation, tactical warfare, reconnaissance, as well as telecommunications. Yet low-cost access remains out of reach and hence continues to justify work on advanced technologies, including scramjets.

Still, despite 40 years of effort, the scramjet continues to stand at two removes from importance. The first goal is simply to make it work, by demonstrating flight to orbit in a vehicle that uses such engines for propulsion. The X-30 was to fly in this fashion, although present-day thinking leans more toward using it merely in an airbreathing first stage. But at least within the next decade the most that anyone hopes for is to accelerate a small test vehicle of the X-43 class.[91]

Yet even if a large launch vehicle indeed should fly using scramjets, it then will face a subsequent test, for it will have to win success in the face of competition from existing launchers. The history of aerospace shows several types of craft that indeed flew well but that failed in the market. The classic example was the dirigible, which was abandoned because it could not be made safe.[92]

The world still remembers the *Hindenburg*, but the problems ran deeper than the use of hydrogen. Even with nonflammable helium, such airships proved to be structurally weak. The U.S. Navy built three large ones—the *Shenandoah*, *Akron*, and *Macon*—and quickly lost them all in storms and severe weather. Nor has this problem been solved. Dirigibles might be attractive today as aerial cruise ships, offering unparalleled views of Caribbean islands, but the safety problem persists.

More recently the Concorde supersonic airliner flew with great style and panache but faltered due to its high costs. The Saturn V Moon rocket proved to be too large to justify continued production; it lacked payloads that demanded its heft. Piloted space flight raises its own questions. It too is very costly, and in the light of experience with the shuttle, perhaps it too cannot be made completely safe.

Yet though scramjets face obstacles both in technology and in the market, they will continue to tantalize. Hallion writes that faith in a future for hypersonics "is akin to belief in the Second Coming: one knows and trusts that it *will* occur, but one can't be certain *when*." Scramjet advocates will continue to echo the defiant words of Eugen Sänger: "Nevertheless, my silver birds will fly!"[93]

1 Milos et al., *Journal of Spacecraft and Rockets*, May-June 1999, pp. 298-99.

2 Young et al., *Science*, 10 May 1996, pp. 837-38 (228 g: Table 3).

3 Milos et al., *Journal of Spacecraft and Rockets*, May-June 1999, pp. 298-99.

4 *Aerospace America*: December 1989, pp. 48-49; December 1990, p. 73.

5 Miller, *X-Planes*, pp. 341-42. Launch crew size: *Acta Astronautica*, February-April 1996, p. 326.

6 NASA SP-4407, Vol. IV, pp. 585-88, 591.

7 *Aviation Week*, 8 July 1996, p. 21.

8 AIAA Paper 95-3777.

9 NASA SP-4407, Vol. IV, pp. 585-86.

10 *Acta Astronautica*, February-April 1996, p. 323.

11 Heppenheimer, *Development*, pp. 365-66; Hanley, *Aerospace America*, July 1991, pp. 34-38.

12 NASA SP-4407, Vol. IV, p. 604; quotes, pp. 605, 617, 624.

13 Ibid., pp. 626-27 (includes extended quote).

14 *Acta Astronautica*, February-April 1996, p. 324.

15 NASA SP-4407, Vol. IV, pp. 628-29.

16 *Aviation Week*, 31 October 1994, pp. 22-23; AIAA Paper 95-3777, p. 1. $941 million: NASA SP-4407, Vol. IV, p. 634.

17 *Aviation Week*, 3 April 1995, pp. 44, 48 (X-34B, p. 48). $60 million: *Aviation Week*, 5 February 1996, p. 86.

18 Miller, *X-Planes*, pp. 352-353. Quote: *Aviation Week*, 6 November 1995, p. 30.

19 Miller, *X-Planes*, p. 353. Concept comparisons: AIAA Paper 95-3777, pp. 3-4; *Aviation Week*, 17 June 1996, p. 31.

20 Miller, *X-Planes*, p. 344. Payloads: *Aviation Week*, 8 July 1996, table, pp. 20-21. 53 percent: Rising, *X-33*, p. 6.

21 General Accounting Office Report NSIAD-99-176, p. 4.

22 *Acta Astronautica*, February-April 1996, pp. 325-26, 329.

23 *Aviation Week*, 26 April 1999, p. 78.

24 *Journal of Spacecraft and Rockets*, March-April 1999, pp. 189, 218; Jenkins, *Space Shuttle*, p. 395.

25 Miller, *X-Planes*, p. 346; AIAA Paper 96-4563.

26 *Aviation Week*, 3 June 1996, p. 92.

27 Air Force Studies Board, *Hypersonic*, p. 5.

28 *Aviation Week*, 8 July 1996, table, pp. 20-21.

29 AIAA Paper 96-4563.

30 *Aviation Week*: 8 July 1996, p. 21; 30 June 1997, p. 28; 10 November 1997, p. 50.

31 Rising, *X-33*, figure 10; author interview, Jerry Rising, 11 January 1999.

32 Miller, *X-Planes*, p. 344; *Aviation Week*, 2 November 1998, pp. 26-27.

33 *Aviation Week*, 25 January 1999, pp. 68-69 (weight, p. 68; quote, p. 68).

34 Sietzen, "Wall Street" (includes quotes).

35 *Aviation Week*, 15 November 1999, pp. 28-30 (quote, p. 28). 2.2 million pounds: *Aviation Week*, 8 July 1996, p. 21.

36 Quote: *Aviation Week*, 15 November 1999, p. 30.

37 Miller, *X-Planes*, pp. 203, 357.

38 Ibid., p. 356; AIAA Paper 98-3516.

39 Miller, *X-Planes*, pp. 354-57.

40 *Aviation Week*, 5 March 2001, p. 24 (includes quote).

41 NIFTA: AIAA Paper 91-5008.

42 *Aviation Week*, 30 March 1992, pp. 18-20.

43 *Aviation Week*, 14/21 December 1992, pp. 70-73.

44 The Incremental Scramjet of the mid-1960s was to achieve transition between Mach 5.4 and 6. See Hallion, *Hypersonic*, pp. VI-xvii to VI-xx. Work at the Applied Physics Laboratory demonstrated transition between Mach 5.9 and 6.2: see AIAA Paper 91-2395.

45 Author interview, Lawrence Huebner, 24 July 2002.

46 NASA/TP 1998-206548, pp. 1, 8-10.

47 AIAA Paper 99-4848.

48 $200,000: *Aviation Week*, 14/21 December 1992, p. 71.

49 AIAA Papers 99-4818, p. 2; 2002-5251, pp. 1-2 (length and range, p. 2).

50 AIAA Paper 99-4818 (quote, p. 1).

51 Ibid.

52 Miller, *X-Planes*, p. 389. Contract awards: AIAA Paper 2001-1910, p. 791.

53 AIAA Paper 99-4818. 13 feet per second: AIAA Paper 2001-1802, p. 257.

54 AIAA Paper 2002-5251, p. 3; Miller, *X-Planes*, pp. 391-92 (2,800 pounds, p. 392).

55 *Journal of Spacecraft and Rockets*, November-December 2001, pp. 846-47.

56 Quote: AIAA Paper 98-1532, p. 4.

57 AIAA Papers 98-1532 (numbers, p. 4), 2001-1809.

58 AIAA Paper 2001-1809, pp. 292-93; Vince Rausch: *Aviation Week*, 9 June 1997, p. 32.

59 *Journal of Spacecraft and Rockets*, November-December 2001, pp. 829-30.

60 *Journal of Spacecraft and Rockets*, November-December 2001, pp. 828-35.

61 *Journal of Spacecraft and Rockets*, November-December 2001, pp. 803-10.

62 *Journal of Spacecraft and Rockets*, November-December 2001, pp. 853-64 (300 runs, table 1).

63 *Journal of Spacecraft and Rockets*, November-December 2001, p. 806.

64 AIAA Paper 2001-1910, p. 793. Mission plan: *Aviation Week*, 11 June 2001, p. 50. Quote: author interview, Lawrence Huebner, 24 July 2002.

65 *Aviation Week*, 11 June 2001, pp. 50-51.

66 *Air & Space*, November 2002, pp. 74-81; AIAA Paper 2003-7029.

67 Quote: *Air & Space*, November 2002, p. 81.

68 Internet postings: Google, "Hyshot Australia." Quote: *Air & Space*, November 2002, p. 79.

69 *Aviation Week*, 28 July 2003, pp. 37-38.

70 *Aviation Week*, 5 April 2004, pp. 28-29.

71 *Aviation Week*, 22 November 2004, pp. 24-26.

72 *Aviation Week*, 5 March 2001, p. 66.

73 *Journal of Spacecraft and Rockets*, November-December 2001, p. 838.

74 AIAA Paper 2002-5127.

75 Dongarra, "Performance."

76 *Science*: 16 January 1981, pp. 268-69; 29 November 2002, p. 1713. Also http://www.top500.org/list/1994/11, http://www.top500.org/list/1996/11

77 AIAA Paper 83-0037, table 1.

78 Author interview, Christian Stemmer, 22 April 2003.

79 Author interview, William Cabot, 23 April 2003.

80 Pope, *Turbulent*, pp. 182-183.

81 Author interview, Christian Stemmer, 23 April 2003.

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83 *AIAA Journal*, December 1979, pp. 1300-1302.

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85 Jansen: "Preliminary"; "Large-Eddy."

86 Mahesh et al., "Large-Eddy."

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89 Heppenheimer, "Voyager"; *1989 Yearbook of Science and the Future* (Encyclopedia Britannica), pp. 142-59.

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91 Malakoff, *Science,* 9 May 2003, pp. 888-889.

92 Brooks, "Airship"; Botting, *The Giant Airships*.

93 Quotes: Hallion, *Hypersonic*, p. 98-iii; Sänger: *Spaceflight*, May 1973, p. 166.

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He has also written twelve hardcover books. Three of them–*Colonies in Space* (1977), *Toward Distant Suns* (1979) and *The Man-Made Sun* (1984)-have been alternate selections of the Book-of-the-Month Club. His *Turbulent Skies* (1995), a history of commercial aviation, is part of the Technology Book Series of the Alfred P. Sloan Foundation. It also has been produced as a four-part, four-hour Public Broadcasting System television series *Chasing the Sun*.

Under contract to NASA, Heppenheimer has written that agency's authorized history of the Space Shuttle, in two volumes. Volume 1, *The Space Shuttle Decision* (1999), has been reissued in paperback by the Smithsonian Institution Press and has been selected as an Outstanding Academic Title. The present book reflects his longstanding activity in hypersonics, for which he has written three technical reviews for Pasha Publications.

He holds a Ph.D. in aerospace engineering from the University of Michigan, and is an associate fellow of the American Institute of Aeronautics and Astronautics. He has also held research fellowships in planetary science at the California Institute of Technology and at the Max Planck Institute in Heidelberg, Germany.

About the Cover: *Hypersonic Plane* by Leslie Bossinas. Artist's concept of an aerospace plane showing aero-thermal heating effects caused by friction as the vehicle flies hypersonically through the atmosphere. The National Aero-Space Plane program provided technology for space launch vehicles and hypersonic cruise vehicles. This vehicle with advanced airbreathing engines would have the capability to take off horizontally from and land on conventional runways, accelerate to orbit, and cruise hypersonically in the atmosphere between Earth destinations. (NASA Art Program, Image 86-HC-217).

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