Chapter 5

The National Aero-Space Plane

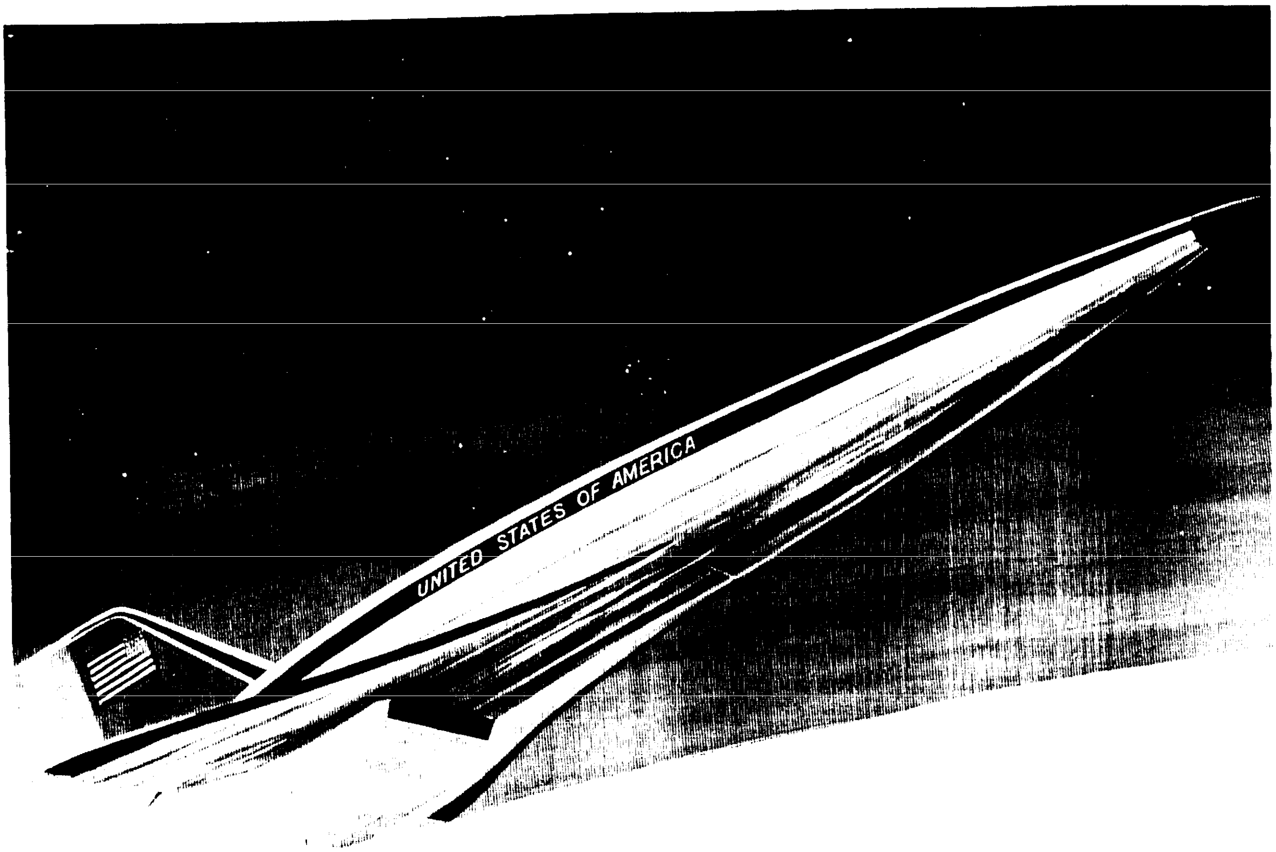

Photo credit: National Aero-Space Plant Joint_ Office

Conceptual design for the X-30 National Aero-Space Plane.

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INTRODUCTION

The National Aero-Space Plane (NASP) program is a research effort funded by the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), and industry to develop and demonstrate the technologies of hypersonic flight in a revolutionary, piloted research vehicle designated the X-30. If successful, the X-30 would demonstrate the capability to reach outer space using a single propulsion stage that would make unprecedented use of air-breathing engines.[2] In a launch demonstration that program officials hope to complete by October 1996, the X-30 would take off horizontally from a conventional 10,000-foot-long runway, accelerate to Mach 25 in the upper atmosphere, enter orbit, and return to Earth, landing on a conventional runway. In contrast, a typical rocket launcher ascends vertically from special launch facilities and jettisons one or more propulsion stages during flight.

The NASP program is currently developing the technology to build the X-30. Although the X-30 is meant to serve as a technology test-bed and not as a prototype, it is being designed as a demonstration vehicle that could resemble prospective operational launch vehicles. Proponents of the X-30 believe it could herald a new era in flight, spawning military and civilian aircraft capable of global range at hypersonic speeds, or low-cost and routine access to space.

OTA included NASP in its assessment of advanced space transportation technologies because of the possibility that operational vehicles of utility for both the civilian and military space programs may evolve from the X-30. These ''NASP-derived vehicles" (NDVs) would offer a radically different approach to space launch and might eventually become important elements of a future space transportation system, ferrying people or cargo into low-Earth orbit with rapid turn-around and low cost. Depending on its eventual configuration and payload-carrying capability, it is conceivable that a NASP-derived vehicle might also supplement or replace the Space Shuttle when the Shuttle fleet reaches the end of its useful lifetime.

Program officials believe that an aerospace plane could lower the cost to reach orbit because its design would allow:

- rapid turn-around;
- manpower support at commercial aircraft levels (in contrast to Shuttle operations);
- complete reusability of the system with minimal refurbishment between flights;
- operations from conventional runways; and
- greater payload fractions,[3] the result of using air-breathing, rather than rocket engines.

Not all of these potential economies would be unique to NASP-derived launch vehicles; some could also be realized in other advanced launch systems.

Although this chapter refers often to vehicles derived from technologies developed in the NASP program, neither the construction of an X-30 vehicle nor a follow-on program to build an operational vehicle has been funded yet. A decision by a DoD/NASA Steering Group on the feasibility of moving beyond the current technology development phase to construct a flight vehicle is now scheduled for September 1990. As the later section, *Policy and Options* explains, recent revisions in the DoD budget submission for fiscal year 1990, if adopted by Congress, would have a dramatic effect on the direction of even the research portion of the NASP program.

OTA did not perform a detailed evaluation of the economic benefits of the NASP program or NASP-derived vehicles, nor did it attempt to evaluate the potential contribution of the NASP program to the Nation's defense or its defense technology base. However, NASP officials believe that these contributions would be among the most important benefits

[1] Hypersonic usually refers t. flight at speeds of at least Mach 5—five times the speed of sound, or about 4,000 miles per hour. The speed of sound in dry air is 331.4 meters per second (742.5 miles per hour) at a temperature of O degrees Celsius (273 degrees Kelvin).

[2] Air-breathing engines burn atmospheric oxygen during combustion instead of carrying an oxidant internally as is typical on rockets. All conventional aircraft engines are air-breathers.

[3] Payload fraction is the weight of the payload expressed as a fraction of the launch vehicle's gross lift-off weight, including fuel.

of their program. The broader implications of the NASP program are beyond the scope of this report and are considered only in so far as they affect the support, schedule, cost, and likelihood of achieving an operational launch capability. This report presents an overview of the NASP program, a short introduction to the technologies of hypersonic flight, and a guide to the issues likely to be faced by Congress as the program nears the point where it could move beyond its current research stage.

BACKGROUND

The X-30 requires the synergism of several major technology advances for success. The propulsion system is based on experimental hydrogen-fueled, supersonic combustion ramjet ("scramjet") engines. A scramjet is designed to allow combustion to occur without slowing the incoming air to subsonic speeds, as is typical in all other air-breathing engines. Ground tests of scramjet engines indicate that they could propel an aircraft to hypersonic speeds, but the X-30 would be the first aircraft to explore fully their potential in flight.

The X-30 airframe would require extremely lightweight and strong structures, some capable of withstanding temperatures thousands of degrees hotter than materials currently used in aircraft construction. In contrast to the thermal protection tiles used on the Space Shuttle, some of the X-30'S high-temperature tolerant materials would be formed into load-bearing structures. In addition, while some of the X-30'S materials, such as carbon-carbon composites, have been used before (although not as load bearing structures), others are still in a laboratory stage of development. Furthermore, even with special materials and coatings, novel cooling techniques would be necessary to keep some leading edges and internal engine parts at tolerable temperatures. The active cooling system would also be used to recover fuel energy that would otherwise be lost as heat. The use of "regenerative' cooling techniques has never been attempted in an aircraft, although the technique is commonly employed in liquid rocket engines. Developing the instrumentation and control system of the X-30 also presents unique technical challenges.

The X-30 would make unprecedented use of numerical aerodynamic simulation as a design aid and as a complement to ground-test facilities that are unable to reproduce the full range of conditions the X-30 would encounter in hypersonic flight. The NASP program is currently utilizing a substantial fraction of the U.S. supercomputer capability in what officials describe as a massive effort to advance the state-of-the-art in the computational techniques needed to design the X-30. In fact, the dependence on supercomputers and numerical simulation models of hypersonic flight is so great they constitute a key "enabling" technology for the X-30, rivaling propulsion systems and materials in importance.[4]

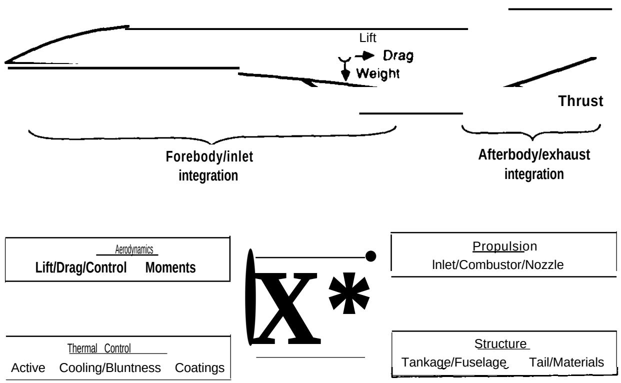
The requirement that aircraft structures be lightweight, reusable, and able to withstand thermal cycling (heating and cooling) over multiple flights stresses all aspects of vehicle design. In addition, the engine, airframe, cooling systems, and control systems would all be melded together in the X-30, thus creating unusual challenges for both vehicle designers and program managers (figure 5-l). For example, the airframe and engine cannot be developed independently; instead, they must be designed from the outset as a single package. The heat load on the X-30 will be a sensitive function of both the vehicle's aerodynamics and of the heat generated by engine combustion. In turn, the thermal requirements affect materials and structural requirements. Finally, aircraft instrumentation and control systems must be matched to airframe designs, which are coupled to propulsion and thermal control systems.

OPERATIONAL VEHICLES

Even if the NASP program proves completely successful, an additional program would still be necessary to develop operational vehicles. The extent of such a program would depend on how well technology issues are resolved by the X-30 and how much modification would be necessary for first-generation follow-on vehicles. Safety, crew escape, environmental compatibility (pollution and noise),

[4]The enabling technologies of NASP were critically reviewed in *Hypersonic Technology For Military Application*, Committee on Hypersonic Technology for Military Application, Air Force Studies Board, National Research Council (Washington DC: National Academy Press, 1989) and *Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP)* (Washington DC: Office of the Under Secretary of Defense for Acquisition, September 1988). See also *National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30* (US. General Accounting Office Report GAO/NSIAD-88-122, April 1988),

Figure 5-1--System Integration



SOURCE: McDonnell Douglas.

production costs, maintenance costs, and the capability for rapid turn-around on a routine basis would all have to be addressed in engineering an operational vehicle. A true operational capability also presumes that the problems of pilot training, maintenance, logistics, and support for the vehicle (including hydrogen handling and storage capability) have been solved. For a military vehicle there is the additional issue of integrating the vehicle into the existing military force structure.

The detailed characteristics of operational launch vehicles that might follow the X-30 are classified. According to program officials, the first-generation of vehicles would not be expected to carry Shuttle-class payloads, although later variants might. How much of the vehicle's gross take-off weight could be devoted to payload would depend on the success of the NASP material and structures development program and the actual engine performance.

The NASP Joint Program Office (JPO) is evaluating a concept for a vehicle about the size of a McDonnell Douglas DC-10 that would be able to carry 20,000 pounds to the low-Earth orbit of the proposed Space Station. In general, a vehicle designed with a larger wingspan, more fuel, and more powerful engines can carry a heavier payload, but there are practical limits. As vehicle weight rises, propulsion requirements become more difficult to meet. Heavier vehicles also place more stress on landing gear and brakes. In addition, take-off and landing from conventional-length runways becomes difficult as vehicle weights rise. Finally, vehicle costs rise, especially if the vehicle is constructed with expensive specialized materials.[5] NASP designers have announced that they are striving for NDV vehicle weights close to 400,000 pounds.[6]

In contrast to a launch vehicle, which would fly directly to low-Earth orbit in about 30 minutes, a hypersonic cruiser might fly for several hours at speeds and altitudes of, for example, Mach 5-14 and 80,000 to 150,000 feet. Using hydrogen as fuel, its range would extend to intercontinental distances. Figure 5-2 compares the trajectory of the Space Shuttle with representative trajectories for an aerospace plane carrying out orbital or hypersonic cruise missions.[7] The NASP effort to develop hypersonic cruise vehicles has sometimes been confused with proposals to develop a commercial hypersonic transport. At present, the vehicles being studied by the NASP JPO *do not* include a commercial hypersonic transport or "Orient Express. " Moreover, the least costly path to the development of such a vehicle would not be via the development of a Mach 25 aerospace plane (see box 5-A).

The relaxed speed requirement makes the design of a hypersonic cruiser less challenging than a Mach 25 orbital vehicle, but extended hypersonic flight within the atmosphere would place a much larger demand on thermal cooling systems (the orbital vehicle experiences a higher peak thermal load than the cruiser but it is for a much shorter duration). Thus the optimum airframe for a hypersonic cruiser would differ in design from a single-stage-to-orbit (SSTO) vehicle, and it is likely that operational versions of these vehicles would each require a separate development program.

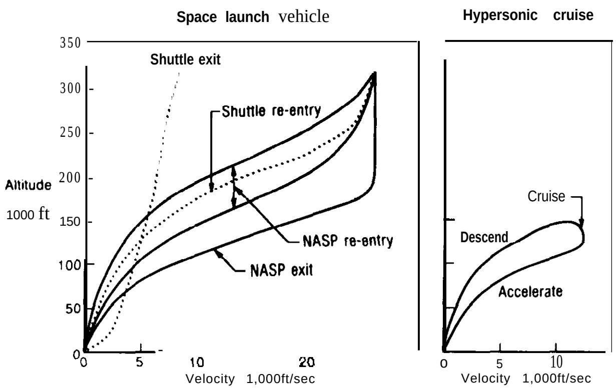
Preliminary projections by NASP contractors of the operating and support costs of an NDV with a

5 However, according to the NASP JPO, the estimated cost to increase the *X-30'S* baseline payload by even a factor Of four would still be only a small fraction of the total development cost for the vehicle.

6 Douglas Isbell, ''NASP, International Space Trade Highlight Symposium,'' ***Washington Technology,*** Apr. *20-May* 10, 1989, p. 20.

7 Maneuvering at hypersonic speeds has some surprising consequences. For example, a turn at hypersonic s@ can t&e an aircraft over a sizable portion of the United States. A pilot in the X-30 making a 2g (one g is the acceleration due to gravity) turn at Mach 10 would travel over a track that would take him from Edwards AFB, California to Denver, Colorado. A Mach 15 turn at 2 g would take the pilot over a ground track from Edwards to Chicago.

Figure 5-2--typical NASP Flight Trajectories



SOURCE: McDonnell Douglas.

payload capability to low-Earth orbit of 65,000 pounds (likely to be a second-generation NDV) range from $1 million to $9 million per flight, exclusive of development or production costs. In terms of mass to orbit, the maximum cost of placing payloads into low-Earth orbit was estimated at $140 per pound. Achieving these remarkably low costs (one to two orders of magnitude improvement over the Space Shuttle)[8] would, among other things, require rapid turn-around and fill reusability.

Rapid turn-around would allow high-rate operation and lower unit launch costs, in part because nonrecurring costs could be spread over a larger number of missions. However, to realize these economies of scale presupposes that sufficient missions exist to support the higher volume operations. In addition, maintenance costs between flights costs would have to prove to be as low as predicted.[9]

A rough extrapolation from the projected X-30 costs indicates that potential unit costs of an operational launch vehicle could be on the order of $1 billion in addition to the costs of research, development, testing, and evaluation.[10] Predictions of the development costs for an operational vehicle are very uncertain at present because they extrapolate from preliminary cost estimates for the X-30. Research and development costs for Shuttle components through 1984 totaled approximately $15 billion*' ($18 billion in current dollars), however, NASP officials believe development costs for operational vehicles derived from the X-30 would be less. Whatever the actual costs, it is clear that a substantial commitment from DoD or NASA would be necessary to build a fleet of launch vehicles.

X-30 DESIGN GOALS

As an experimental vehicle, the most important function of the X-30 would be to serve as a flying test bed where synergistic technologies—propulsion, materials, structures, thermal control, guidance, and flight instrumentation--could be combined and proved. In particular, the X-30 would effectively function as a "flying wind tunnel" for high-Mach scramjet propulsion that cannot be completely validated using only ground-based facilities and computer-based simulation.

Many important characteristics for the X-30 have not been made public. These include size, weight, and vehicle payload. However, NASP officials have stated that the X-30'S size would be between that of a Boeing 727 and a McDonnell Douglas DC-10, and it would carry at least several thousand pounds of instrumentation. The actual size and weight of the X-30 would depend on many factors, including the final airframe and engine design and the required

[8] For a detailed discussion of Shuttle costs see ch. 7 and app. A of U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[9] Achieving rapid turn-around would demonstrate that little maintenance is required, provided maintenance is not simply Shifted from the flight line to the depot, and provided the maintenance man-hours per sortie remains low over the life of each vehicle. Moreover, average vehicle service life must meet or exceed the design service life of 150 sorties (to orbit) if the average cost per launch is to be as low as predicted by estimates based on this assumption. Note too that should payload costs come to exceed mission expenditures, the importance of reducing launch costs would be diminished.

[10] This figure is meant to be illustrative—it is *not* based on any cost estimation model. Reliable cost estimates for an NDV cannot be made until an X-30 is built and flight tested. Even then there would be uncertainties in life-cycle costs. The cost to deliver the new Space Shuttle orbiter Endeavour (OV 105) in 1991 is expected to be more than $2 billion. However, this increase in cost over previous orbiters represents the expense of incorporating new safety and other improvements, and restarting production lines.

[11] A comprehensive accounting of Shuttle development and procurement costs, based on Shuttle direct obligations as presented in NASA budget estimates, was performed in 1984 by David Smart, now with TRW Corp. The figure of $15 billion is a rounded estimate that appears in R.H. Miller, D.G. Stuart, and A. Azarbayejani, "Factors Influencing Selection of Space Transportation Options," paper presented at the 37th Congress of the International Astronautical Federation, ref. No. IAF 86-108, Innsbruck, Austria, Oct. 4-11,1986.

[12] Dr. Robert Barthelemy, briefing on NASP to members of U.S. Senate, Russell Office Building, Apr. 20, 1989.

Box 5-A--NASP, the Orient Express, and High-Speed Commercial Transports

In his January 1986 State of the Union Message, then President Ronald Reagan proclaimed, “We are going forward with research on a new ‘Orient Express’ that could, by the end of the next decade, take off from Dunes Airport [near Washington, DC] and accelerate up to 25 times the speed of sound, attaining low-Earth orbit, or flying to Tokyo within two hours. ” The President’s speech placed NASP on the national agenda, but it also led to considerable confusion over the objectives of the program. At present, the NASP program has no plan to develop an Orient Express.

The principal objective of the NASP program is to build a Mach 25 experiment vehicle, the X-30, that would develop, and subsequently demonstrate, the technologies for single-stage access to space. In contrast, the Orient Express is a *concept* for a commercial hypersonic passenger transport. In addition, the maximum speed of the Orient Express (roughly Mach 5 to Mach 10) would be far less than the Mach 25 orbital speed required for the X-30.

NASA is studying the feasibility of a commercial supersonic transport in its High-Speed Civil Transport Program (HSCT), an effort distinct from NASP. HSCT design objectives include a range of 7,500 statute miles (6,500 nautical miles) with a full payload of 300 passengers (based on Pacific region markets) and a maximum weight of not more than 1,000,000 pounds to maintain compatibility with existing airports. Environmental compatibility and economic viability are the two most important parameters governing HSCT designs. These factors in turn depend on airport noise, sonic boom[1], effects on atmospheric ozone, aircraft productivity, and operating and production costs.

Initial HSCT studies have shown Mach 6 and above to be commercially noncompetitive with supersonic transports in the Mach 2-3 range as a result of the slowing of aircraft productivity with increasing Mach number and the relatively high cost of using hydrogen fuel to achieve the higher speeds. Mach 2-5 supersonic transports could burn conventional petroleum-based fuels or cryogenic methane.

Some HSCT studies suggest that Mach 3.2, the practical speed limit for a kerosene-burning transport would be the optimum choice in the near-term (year 2000+). Using kerosene eliminates the need for the exotic engines, materials, and cryogenic fuel transfer and storage facilities that are necessary for Mach 5+ flight. Studies also show that a Mach 3.2 vehicle could weigh some 450,000 pounds less than a Mach 5 transport, thus lowering vehicle size, cost, and, indirectly, sonic boom. However, an important factor that could undercut the commercial viability of a Mach 3 transport after the year 2,000 is the anticipated improvement in the next generation of sub-sonic transports.

Although there is some overlap in the technical development necessary to realize these aircraft, a Mach 3 supersonic transport would have essentially no value as a stepping stone to building the X-30, and a Mach 5+ Orient Express would have only a limited value. Conversely, while the development of the X-30 could spur the development of the Orient Express, some X-30 materials, propulsion concepts, cooling techniques, etc. would be either unnecessary or too costly for a commercial transport. The NASP program would not provide a direct route to supersonic commercial transport, nor is it likely to be the most economical route to commercial hypersonic transport.

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[1] Assuming similar wing loading (a function of aircraft weight), the sonic boom of a hypersoni“c aircraft could be similar to a supersonic aircraft. Hypersonic transports would cruise at higher altitudes where there are large temperature gradients and inversions. Since the speed of sound has a temperature dependence, these temperature variations break up an aircraft's shock wave and reduce its effect on e particular ground location.

payload (some of which would be devoted to ''margin' for items such as extra fuel). The required orbital trajectory (polar or low inclination) would also affect vehicle size, weight, and payload-carrying capability. The NASP Joint Program Office (JPO) has studied designs that range in weight from less than 200,000 pounds to over 300,000 pounds.

The objectives of the NASP program as currently structured include the following:

- *Single-Stage-To-Orbit (SSTO): The* foremost objective of the X-30 would be to achieve orbit using a single propulsion stage in a fully reusable flight vehicle. An SSTO vehicle would reach low-Earth orbit without carrying expendable booster rockets or external fuel tanks. In principle, a fully reusable SSTO design may have a greater potential to reduce the cost for a vehicle to reach orbit than a multi-stage air-breathing/rocket combination. However, achieving SSTO with a reusable vehicle is also more challenging technically than alternative methods for reaching orbit such as the two-stage vehicles being studied by NASA (see ch. 4).*[3]

  To achieve orbit in a single-stage would require both efficient scramjet performance at high Mach numbers and extremely high propellant fuel fractions. Scramjets must retain their theoretical advantages in performance over conventional rocket engines to high Mach numbers if the X-30 is to achieve SSTO. High propellant fuel fractions can only be accomplished in a design with very low structural weight fractions because the payload is expected to be only a small fraction (on the order of 5 percent) of the vehicle gross weight. Thus, payload could not be reduced to compensate for excessive structural weight. Attaining very low structural weight fractions poses particular challenges in the X-30 because it must contain a large volume of low-density liquid hydrogen (or hydrogen slush) fuel, and its structures must be able to withstand high aerodynamic and aerothermal loads.
- *Air-Breathing Propulsion to Hypersonic Speeds: The* speed necessary to enter low-Earth orbit is approximately Mach 25. As originally conceived, the X-30 would have attempted to reach this speed using only air-breathing propulsion. However, all of the X-30 designs now under consideration by the NASP JPO include options to carry liquid oxygen (LOX) on-board for thrust augmentation. LOX would either be combined with hydrogen in separate reusable rockets, or it could be added directly to the scramjet engines. Some form of rocket assist would also be necessary for propulsion when the vehicle rises above the sensible atmosphere, that is, for final insertion into orbit,[14] maneuvering in space, and de-orbiting.
- *Hypersonic Cruise:* Although the prime focus of the X-30 program is on demonstrating the ability to reach orbit with a single propulsion stage, it would also demonstrate the capability for prolonged flight at hypersonic speeds within the atmosphere.
- Horizontal *Tale-Off and Landing From Conventional-Length Runways:* The X-30 is being designed to enable take-off and landing from 10,000-foot-long runways as part of a plan to demonstrate the potential for responsive and economical operations in military and civilian follow-on vehicles.
- *Powered Approach to Landing and Go-Around Capability: The X-30* and operational follow-*ons* could use their low-speed propulsion systems to allow a landing under power. At a penalty of carrying an extra several thousand pounds of fuel to orbit, this propulsion capability would allow a launch vehicle returning to Earth to have go-around capability—the ability to abort a landing, circle an airfieid, and retry the landing. Go-around is viewed as a desirable, but far from essential, capability in an opera-

12Dr. Robert Barthelemy, briefing on NASP to members of U.S. Senate, Russell Office Building, Apr. 20, 1989.

13There are a number of complex tradeoffs that would have to be evaluated to determine whether SSTO vehicles would, in fact, be more cost effective than TSTO (two-stage-to-orbit) vehicles. TSTO vehicles could use lower-risk technology than SSTO vehicles and they could have larger performance "margins." On the other hand, TSTO vehicles could require more complicated and expensive ground operations. Safety would be of paramount importance for a launch vehicle that would be used to transport humans. Therefore, the costs to certify a launch vehicle as flight ready would also have an important effect in determining which design would be most cost effective.

14The X-30 would follow a steep trajectory during its final ascent to orbit. A small amount of rocket power is necessary to circularize the final Orbit and to place the vehicle at the desired altitude.

tional vehicle. It could be traded for larger payloads or used as 'margin' against performance shortfalls. In that case the vehicle would make a gliding re-entry like the Shuttle.

- *"Aircraft-like" Operability: The X-30* would attempt to demonstrate the potential for operating future hypersonic cruise and launch vehicles in a manner that more closely resembles today's airline industry than the civilian space program. This may be the most challenging objective of the NASP program, for although the X-30 may resemble an aircraft, it would be a radical departure from all previous aircraft designs.

  In particular, the X-30 would attempt to demonstrate the potential for service and maintenance turn-around times of 1 day or less, safety and reliability factors similar to those of aircraft, 150 flights without major refurbishing, and the elimination of the complex launch and support facilities and large 'standing army' of technicians that have typified rocket launches. According to the NASP JPO, rapid turn-around is essential for many military applications and it is the key factor in reducing operation and support costs.

Flight tests of two X-30S would be conducted from Edwards AFB, California over a 2-year test program scheduled to begin in October 1994. The flight control system, the pilot-instrumentation interface, crew escape systems, and solutions to the potential for communication disturbances or blackout (by air heated so hot it forms a plasma around the vehicle) would all be tested in this period. The flight control system for a hypersonic vehicle poses particular challenges, in part because of the coupling between the propulsion system and the vehicle's aerodynamics.

FUNDING AND SCHEDULE

NASP grew out of a $5.5 million 1984 Defense Advanced Research Project Agency (DARPA) study called 'Copper Canyon' that revived interest in the potential for hypersonic propulsion (see box 5-B). At the time of the Copper Canyon study, some 300 people were engaged in research in what is now called NASP. Today that number has risen to over 5,000.15

Federal funding for NASP has come mostly from the Department of Defense (Air Force, Navy, Strategic Defense Initiative organization, DARPA) with smaller contributions from NASA. Beginning in fiscal year 1988, all DoD funding was consolidated within the Air Force.[16] The Air Force and NASA are managing NASP in a Joint Program Office at Wright-Patterson Air Force Base, Ohio. Industry is also making a major contribution to NASP funding.[17] Total industry contributions to the program, now over $500 million, could amount to $700 million by September 1990. Most funding is occurring in the current technology maturation and concept validation phase of the progam. Some of these investments include items of major capital investment such as wind tunnels, supercomputers, and materials research facilities that have applications in projects other than NASP. Figure 5-3 shows the NASP schedule currently envisioned by the NASP Joint program Office.

Table 5-1 gives a breakdown of NASP's funding by NASA and the Department of Defense. Congressional concern that NASA's civilian role in the program was too limited was expressed in the DoD Appropriations Act for fiscal year 1987 and is reflected in subsequent budgets.[18]

The NASP program would undergo dramatic change if the revised budget proposals submitted by Secretary of Defense Cheney, in April 1989, were

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[15] Dr. Robert Barthelemy, NASP Program Director, at OTA briefing, Dec. 13.1988.

[16] See General Accounting Office *National Aero-Space Plane*, p. 19.

[17] Contractors have expressed concern about the burden being imposed on them as a condition to participate in NASP. Dr. Joseph F. Shea, chairman of the *1987-88* Defense Science Board (DSB) study of NASP concurred in this concern, stating in a letter that accompanied the transmission of the *DSB* report, " I am compelled to point out that the concept of heavy cost sharing by the contractors is not realistic. The near-term business potential to be derived is not large enough. . ." Major industrial funding is scheduled to cease after NASP completes the ongoing demonstration, validation, and design activities, and, if approved, enters Phase III development.

[18] See GAO *National Aero-Space Plane*, p.29.

Box 5-B—The Origins of NASP[1]

Supersonic flight fist occurred in 1947 when Chuck Yeager, flying the Bell X-1 to a speed of 700 mph, became the first person to break the sound barrier. The U.S. "X" plane (experimental research aircraft) program to develop supersonic and hypersonic aircraft continued throughout the 1950s and 1960s, culminating in the creation of the X-15, a rocket powered aircraft that set speed and altitude records of Mach 6.7 and 354,200 feet, respectively, before the program was canceled in 1%8. The X-15 was essentially a flying fuel tank that could literally fly to the edge of space, although it lacked the propulsive capabilities to achieve orbit. The program was cancelled in 1%8.

The X-20 "Dyna-Soar" program contributed substantially to the technical database on hypersonic flight, even though a flight vehicle was never built. Before the X-20 program, hypersonic data had been derived primarily from ballistic missile programs using blunt, nonlifting entry bodies. The X-20 was intended to be a piloted space glider that would have been launched by a Titan III missile and its design would have allowed it to glide horizontally within the atmosphere, and land horizontally on a runway. Among its proposed missions were reconnaissanace and satellite inspection.

The X-20 was a costly program and some Administration officials, including Secretary of Defense McNamara, questioned the necessity for a spaceplane to perform the missions proposed for the X-20. McNamara canceled Dyna-Soar in December 1%3, citing the possibility of using a manned orbiting space laboratory for some of the X-20 missions and noting that several hundred million dollars would be necessary to finish the program. At the time of the cancellation government expenditures for the X-20 totaled over $400 million (roughly $1.5 billion in current dollars).

Research on hypersonic vehicles and propulsion systems continued throughout the 1960s and 1970s, but was given a relatively low priority. For example, a late 1970s cooperative effort between NASA and the Air Force to develop a National Hypersonic Flight Research Facility never matured beyond the planning stage. Nevertheless, research into hypersonic technologies never ceased. Research into advanced propulsion concepts led to the fabrication of scramjet components that were tested in wind tunnels at speeds up to Mach 7.

Continued on next page

adopted by Congress.[19] Under the revised DoD budget, overall control of the program would be transferred to NASA, and support in fiscal year 1990 would be cut by 66 percent to $100 million. DoD funding of NASP in subsequent years would cease. NASA's contribution to NASP would also likely be revised if the DoD revisions were enacted. The potential effect of large revisions in the NASP budget is discussed later in this report. In the following discussion of the NASP schedule it is assumed that control of the program is retained within DoD and funding remains close to President Reagan's budget submission of February 9, 1989.

The Copper Canyon study, in effect, was Phase I, ''concept feasibility,' of NASP. Phase II, "concept validation," began in 1985 and is now scheduled to be completed in late 1990. A major part of Phase 11 is the "Technology Maturation Program," an effort to develop the requisite technologies and fabrication techniques for the X-30. Currently, the prime NASP contractors are Rockwell, General Dynamics, and McDonnell Douglas (airframe); and Rocketdyne and Pratt & Whitney (engines). The airframe companies are responsible for the design of the overall system, including the airframe itself, the cryogenic fuel tank, and structures such as leading edges and nose tip.

Out of hundreds of initial airframe/engine configurations, six are presently under consideration (all three airframe contractors have presented plans that use either of the two engine designs). The five contractors are scheduled to be combined into a

[19]The revised budget was submitted by the Secretary of Defense as part of a bipartisan budget agreement between president Bush and congressional leaders that cut some $10 billion of budget authority from President Reagan's fiscal year 1990 DoD budget of $305.6 billion. (Molly Moore, 'Pentagon May Lose Weapons," *The Washington Post,* Apr. 15, 19S9, p.1)

The direct origins of NASP can be traced to Air Force support in the late 1970s and early 19802 for what became known as the transatmospheric vehicle (TAV) concept. TAV may be viewed as a legacy of Dyna-Soar. It was seen by the Air Force as a potential cargo-carrying successor to the Shuttle to carry defense payloads to orbit, and as a military vehicle with the potential for global response. The Air Force studied many configurations of TAV, but in contrast to the current NASP program, most envisioned a vehicle that would incorporate *rocket* propulsion, such as advanced versions of the Space Shuttle's main engines.

By 1984, TAV had grown into a major Air Force study effort. Support for TAV at the Air Force Space Command came from its potential contribution to four key military space missions: Force Enhancement (including global reconnaissance; surveillance; and command, control, and communications) Space Support (including satellite insertion, rendezvous, inspection, servicing, repair, recovery, and support of Space Station) Space Control (including protection of U.S. space assets) and Force Application.[2] Support for TAV *was also* spurred by the Strategic Defense Initiative, announced in March 1983, and by President Reagan's commitment to NASA to build a space station.

In early 1984, DARPA undertook a study to evaluate the possiblilites for hypersonic, air-breathing propulsion. DARPA's "Copper Canyon" study grew to embrace TAV concepts becoming, in effect, a TAV with air-breathing propulsion. By the end of 1985, the Air Force, DARPA, NASA, *SDIO,* and the Navy were all studying concepts for a TAV/Advanced Aerospace Vehicle (AAV), including single-stage-to-orbit concepts. NASP replaced the TAV/AAV designation as of December 1, 1985. It became a national program following president Reagan's 1986 State of the Union Address. Overall control of the program was transferred from DARPA to the Air Force in 1988.

[1] The history of hypersonic flight and the origins of NASP are *discussed in* a remarkably rich and detailed history edited by AK Force historian Richard P. Hallion, *The Hypersonic Revolution: Eight Case Studies in the History of Hypersonic Technology,* vo11, 1924-1967; From Max *Valier 10 Project Prime; vol II 1964-1986, From Scramjet to the National Aerospace Plane,* (Special Staff Office-Aeronautical Systems Division, Wright-Patterson Air Force Base: Dayton, OH 1987). Note: Distribution limited to DoD and DoD contractors. See also Seem Pace, *National* Aerospace *Plane program" Principal Assumptions, Findings, and Policy Goals,* Rand Publication P-7288-RGS (Santa Monica, CA.: The RAND Corp., 1986), 'IA. Heppenheimer, "Can Hard Science Save The Aerospace Plane?" *The Scientist, vol.* 2, No. 19, Oct. 17, 1988, pp. 1-3, and John D. Moteff, *The National Aerospace Plane: A Brief History,* Congressional R esearch Report for Congress # 88-146 SPR (Washington DC: Feb. 17, 1988).

[2] Hallion, *The Hypersonic Revolution,* Ibid., pp. 1341-42.

single national team by 1990. The five engine and airframe contractors have also been combined in a novel cooperative materials consortium that began in March 1988 and is budgeted at $150 million for a 30-month period (see app. D).

NASP's current schedule (see figure 5-3) calls for a decision to be made in September 1990 on the feasibility of proceeding with Phase III of the program, which would include advanced design, fabrication, and flight tests of two X-30s. Portions of a third vehicle would also be built for tests on the ground. In addition to building the X-30s, Phase III would also continue NASP's Technology Maturation program. If the program is able to keep its current schedule, a 2-year flight test program would begin in October 1994. During the test program the X-30 could undergo some modification. A potentially more expensive option would be to build the two X-30 vehicles sequentially and incorporate changes in the second vehicle based on flight data from the first. *Assuming no delays,* officials believe the SSTO objective could be achieved by September 1996.

NASP officials project total costs through fiscal year 1996 to be roughly $3.9 billion. Peak funding levels are expected between fiscal year 1992 and fiscal year 1994, when an estimated $550 million will be requested annually to build the two X-30 vehicles.[20] NASP funding estimates are highly uncertain because some of the full-scale materials production techniques have not been completely developed, manufacturing and fabrication techniques are new, and designers have little or no experience with estimating costs for building a hypersonic vehicle. Furthermore, Phase III budgets are based on an extrapolation from an early DARPA

[20] Statement by NASP program head Dr. Robert Barthelemy reported in *Aerospace Daily,* vol. *147, No. 58,* Sept. 22, 1988, p. 457.

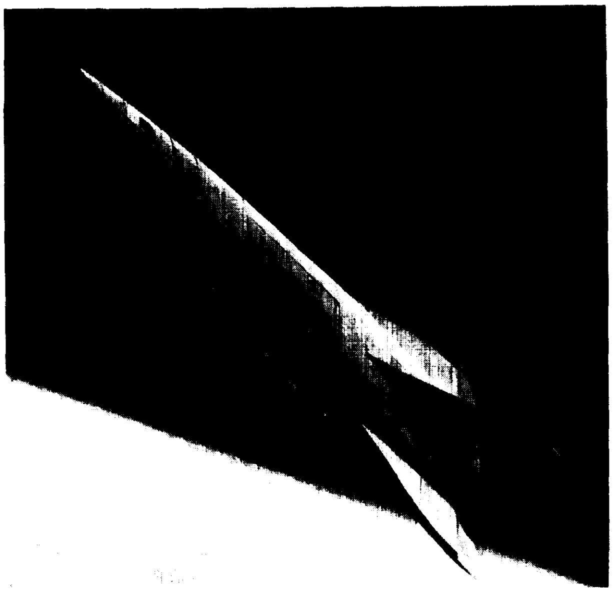


Photo credit: General Dynamics Corp.

One conceptual design for the X-30 National Aero-Space Plane.

Copper Canyon design for an X-30 whose empty weight was only 50,000 pounds.[21] Vehicle weights have increased since then as designers have acquired more test data and adopted more conservative designs.

Designers believe that the empty weight of the X-30 will be the key factor in determining procurement costs. This is because the structural weight of an aircraft influences propulsion requirements and material costs directly, and because it indirectly affects the size and cost of many other aircraft components. The JPO has established a cost estimation group for the X-30 in preparation for its Phase III review.

In an admittedly highly optimistic scenario, NASP officials told OTA that if the NASP program were to make very rapid progress, a concurrent program to build an operational vehicle could commence while the X-30 was being flight-tested in Phase 111. An ambitious schedule projects that an operational vehicle program could be completed before the year 2000. Achieving this goal presumes a completely successful X-30 flight test program without long delays from unexpected technical problems, budgetary restrictions, or cost growth in the program. It also presumes rapid progress in translating X-30 technology into an operational vehicle. Finally, it presupposes that an operational vehicle would bear close similarity to the X-30 in order to minimize new development efforts and flight-testing.

A more conservative approach would wait for the completion of Phase 111 before starting an operational program. If such a program began in the late 1990s, a first-generation operational vehicle would not be expected until approximately the year 2005, assuming the development cycle of the X-30 follows previous development cycles for fighter aircraft derived from experimental vehicles.[22] Second-generation operational vehicles, which might possess increased performance, bear larger (Shuttle-class) payloads, or have better safety and operability than fret-generation X-30 derivatives, would require a longer development cycle. Assuming first-generation follow-ons are available in 2005, a very rough estimate for the date of Initial Operational Capability (IOC) of these vehicles might be 2010 or later,

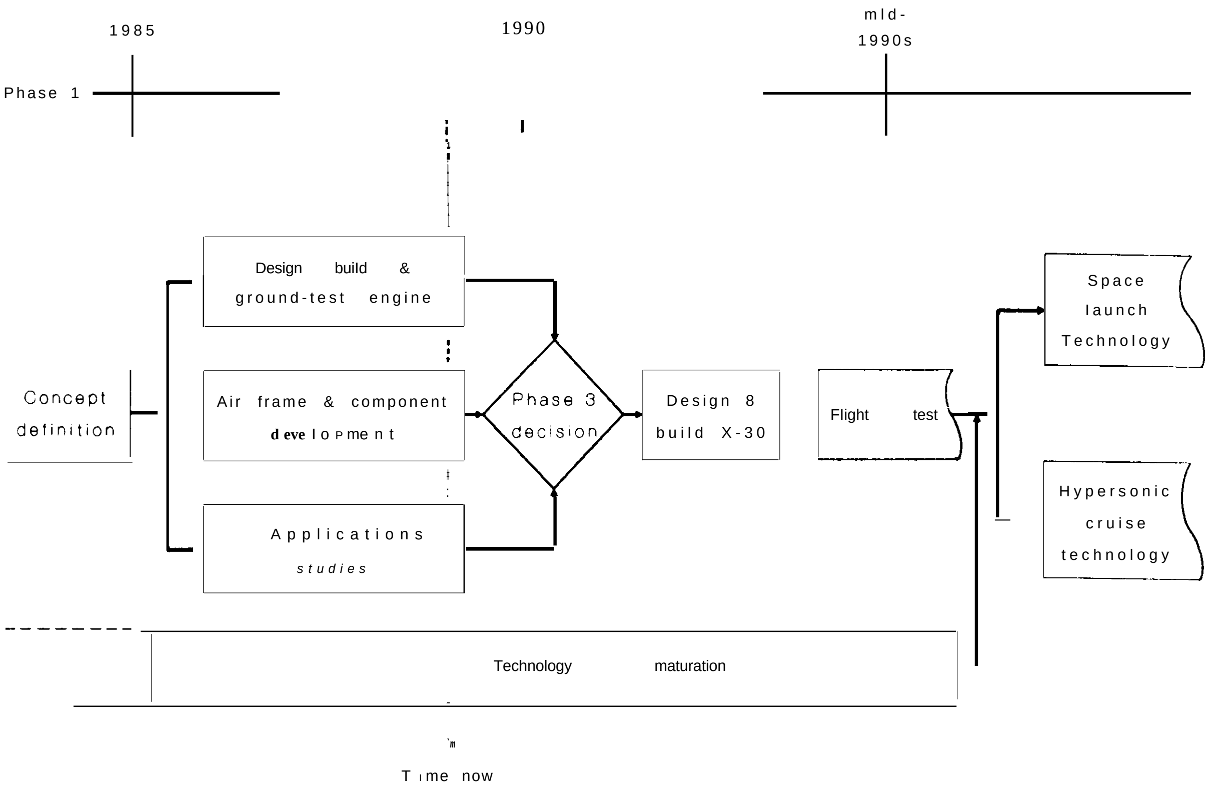
NASP TECHNOLOGIES

There is an inherent risk in building a vehicle that departs radically from all its predecessors and whose design cannot be fully validated before flight testing. Further complicating already challenging engineering problems are the complex interrelationships between technologies caused by the necessity to design the X-30 as an integrated package. The following is a brief review of some of the challenges

21 ' 'Phase III Alternatives: Contractor Findings, '' *in National Aero-Space Plane Program Briefing to NASP Steering Committee, Nov. 7,* 1988, p. *49.* Contractor concerns that Phase 111 costs could exceed preliminary Phase 111 budgets was also expressed.

22 Scott Pace, ''National Aerospace Plane Program: Principal Assumptions, Findings, and Policy Options, '' Publication # P-7288-RGS, The Rand Graduate School Santa Monica, CA, pp. 10-11. NASP officials point to the rapid development cycle of the SR-71 to support their contention that an operational vehicle could be built sooner than 2005. They also note that in some respects the propulsion and materials challenges that faced theSR-71 are analogous to those facing the X-30 and an NDV. However, the SR-71 suffered several years of troubled operation after the delivery of the first production units. The SR-71 example holds lessons for both proponents and critics of accelerated development.

Figure 5-3--NASP Program Schedule



SOURCE: National Aero-Space Plane Office.

Table 5-1--NASP Funding (in millions of dollars)

	FY 86	FY 87	FY 88	FY 89	FY 90 (PB)[a]	FY 90 (RB)[b]	FY 91 (PB)	FY 91 (RB)
DoD	45	110 (149)[c]	183 (236)	228 (245)	300	100	390	0
NASA	16	(62)	71	(104)	127	127d	119	?
Total	61	172 (21 1)	254 (320)	316 (349)	427	227	**509**	**?**

[a]President Reagan's budget submission—February 1989.
[b]DoD revised budget-April 1989.
[c]Numbers in parenthesis represent budget requests from previous fiscal vears.
[d]NASA outlays are expected to be reduced if the revised DOD budget is approved.

SOURCES: For FY 1986-88: "National Aero-Space Plane Program Briefing to NASP Steering Committee," (NASP Joint Program Office, Nov. 7, 1988), p. 21
For FY 1989-91: NASP JPO and Rockwell Corporation.

to be met in developing the key enabling technologies of the X-30.[23]

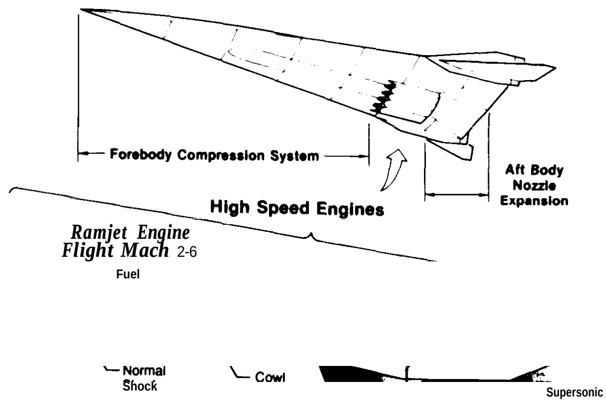
Propulsion

The X-30 would differ from all previous aircraft in its use of air-breathing engines instead of rockets to reach hypersonic speeds. One measure of fuel efficiency is the specific impulse, I_{sp}, which is defined as the thrust delivered per unit mass of propellant burning in one second.[24] By avoiding the necessity to carry an oxidizer, air-breathing engines can achieve higher specific impulses than rockets, although their advantage diminishes with increasing speeds (figure 5-4). The higher I_{sp} of air-breathing engines makes a single-stage-to-orbit vehicle a possibility despite the necessity to carry the weight of wings and landing gear to orbit.

Jet engines generate thrust by admitting air through an inlet, compressing a mixture of fuel and air in a combustion chamber (combustor), igniting the mixture, and letting the hot, compressed exhaust products expand through a nozzle opening at high speed. Compressing the fuel-air mixture before it is ignited raises the temperature and pressure of the mixture; this facilitates combustion and improves the overall fuel efficiency of the engine.

Different configurations of air-breathing engines would be needed to operate at subsonic, supersonic, and hypersonic speeds within the atmosphere (see app. C). Scramjets could, in principle, power an aerospace plane from about Mach 5-6 to orbital speeds (about Mach 25), assuming that theoretical predictions of scramjet performance at high Mach numbers prove accurate, and assuming that the fraction of the spaceplane's weight that was devoted to structures could be made extremely small (the precise number is the subject of some debate). All designs face the challenge of producing a propulsion package that meets stringent aerodynamic and weight constraints.

Figure 5-4-High-Speed Propulsion System



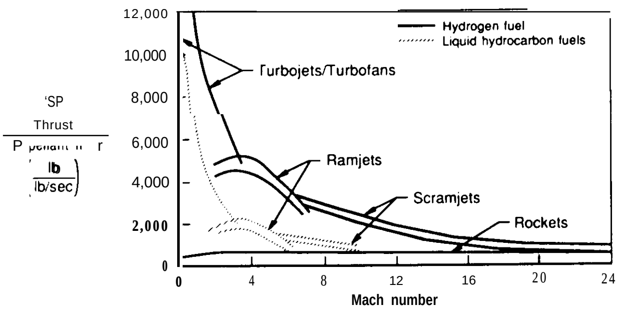
SOURCE: Adapted from NASP Joint Program Office.

The X-30 would be the first vehicle to reach hypersonic speeds propelled by scramjets. All designs envision the placement of a series of scramjet modules side-to-side across the bottom of the aft section of the vehicle (figure 5-5). In this way the long forebody of the aircraft effectively becomes part of the engine inlet, and with careful design it will capture much of the air moving past the vehicle and channel it into the engine inlets. The required air compression in the combustor would be provided by coupling the underside bow shock through the engine inlets. The three airframe contractors have proposed different configurations for the X-30. With

[23] The discussion here and in the appendices is meant to serve as a brief tutorial. More thorough, and technically more Sophisticated reviews, are *Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP)* (Washington DC: Office of the Under Secretary of Defense for Acquisition, 1988); and *Hypersonic Technology For Military Application,* op. cit., footnote 4. NASP's key technical challenges are also reviewed in the GAO report *National Aero-Space Plane,* op. cit., footnote 4. Excellent popular introductions to NASP technologies are found in: T.A. Heppenheimer, "Launching the Aerospace Plane," *High Technology,* July 1986, pp. 46-51; and John Voelcker, "The iffy 'Orient Express'," *IEEE Spectrum,* August *1988, pp. 31-33.*

[24] Thrust, or force, is usually expressed in units of pounds, and propellant mass flow rate is *commonly* expressed in "pounds" per second. Thus, I_{SP} *is usually* expressed in "seconds,' Strictly speaking, the propellant mass flow rate should be measured in units of mass per second, not weight per second, In that case, I_{SP} would have units of velocity.

Figure 5-5—Engine I_{sp}



SOURCE: McDonnell Douglas.

Photo credit: Rocketdyne Corp.

Conceptual airframe and engine design for the X-30 National Aero-Space Plane.

respect to the vehicle forebody, their designs reflect compromises among aerodynamic drag, inlet compression efficiency, and structural considerations. NASP officials have not yet chosen a final design.

All designs also envision making the airframe afterbody part of the engine, in effect serving as a nozzle and surface to expand the exhaust products. This eliminates the weight of a nozzle and can also help reduce the drag that results from the pressure differential that develops between the front and rear surfaces of the aircraft. The amount of forward thrust generated by the scramjets is a sensitive function of the intake airflow and the resultant exhaust expansion. Similarly, vehicle drag at high speeds is a sensitive function of engine geometry. Again, this illustrates the necessity to optimize performance by designing airframe and engine together.

To reach orbit, the X-30 would rely on efficient performance of scramjets at speeds in excess of those that can be fully tested in ground facilities. In addition, although scramjets can in principle produce positive thrust all the way to orbital speeds, their propulsion efficiency as measured by engine specific impulse declines as vehicle speed increases (see figure 5-5). A plot similar to figure 5-5 that included the effect of drag on the vehicle (effective I_{sp}) would show that as vehicle speed increases, the net thrust decreases. Thus, a scramjet-driven hypersonic aircraft will be operating with very little tolerance for unexpected thrust losses, or increases in drag at the higher Mach numbers.[25] The importance of this sensitivity could be lessened, at some penalty in performance, by augmenting scramjet propulsion with auxiliary rocket power. In addition, the high-speed thrust sensitivity of a vehicle would vary greatly with specific engine and airframe designs.

As part of a risk reduction plan, propulsion systems under consideration by the NASP JPO have an option to augment the thrust of scramjet engines with an auxiliary rocket-based propulsion system before the vehicle reaches orbital speeds. In these designs, liquid oxygen is carried on-board the X-30 and either added directly to the scramjet engines or combined with hydrogen to power a separate rocket propulsion system. Either approach involves design tradeoffs. If separate rockets were chosen for thrust augmentation they would be resuable and relatively small, equivalent to the class of rockets needed to

[25] Stephen Korthals-Altes, "The Aerospace Plane: Technological Feasibility and Policy Implications" (S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA: 1986), pp. 50-55. The thrust sensitivity issue is also discussed in Bill Sweetman, "Scramjet: The NASP propulsion goal," *Interavia*, November 1987, p. 1208.

propel an orbital transfer vehicle from low-Earth orbit to geosynchronous orbit.

The speed at which auxiliary power might be used during ascent is a complicated issue dependent on many design factors. The disadvantages of early rocket turn-on, or LOX augmentation of air-breathing engines, includes the need to carry heavy liquid oxygen and tankage on-board. The resulting heavier take-off weight of the vehicle increases the required wing area, take-off speed, and overall size and cost of the vehicle. On the other hand, additional liquid oxygen is 50 percent more dense than jet fuel and thus takes up relatively little space. Hydrogen tankage is necessarily large because of the low density of liquid hydrogen, roughly one tenth of jet fuel. In fact, this is one of the reasons slush hydrogen is being considered as a fuel (see ***Fuel*** discussion below). Furthermore, at the very high speeds where auxiliary power would be used, scramjets would be operating in a mode that consumes extra amounts of hydrogen.[26]

Several other factors would affect the choice of rocket transition point, including:

- the X-30 will be subjected to higher drag while in the atmosphere, but the drag would drop substantially if the vehicle entered a low-drag rocket trajectory;
- the specific impulse of scramjet engines is expected to drop off rapidly at higher Mach numbers; and
- scramjets tend to have less thrust available at higher Mach numbers where rockets have no such limitation.

According to NASP airframe contractors, the X-30 could achieve SSTO even carrying the extra weight associated with an auxiliary propulsion system. However, SSTO performance could be attained only if scramjets perform close to theoretical expectations, and only if extremely low structural weight fractions were achieved. A disputed point among some propulsion and materials/structures experts is whether near-term technology is sufficiently mature to meet both these requirements. The program management implications of this issue are discussed in the *Policy and Options* section of this chapter.

Fuel

Ordinary hydrocarbon fuels like kerosene, or the more specialized derivatives used on some high-performance aircraft, would not be suitable for the X-30'S scramjets. The amount of thrust that could be derived from the combustion of these fuels is too low compared with their weight, and they could not be mixed or burned efficiently in the hypersonic airflow of an X-30-sized combustor. As the X-30 accelerates towards Mach 25, air will sweep fuel through the combustion chamber in times on the order of 1 millisecond. Sustaining combustion and avoiding flameout in these fast flow situations presents complex problems.

One part of the solution to these problems will be the use of hydrogen as fuel, Hydrogen has the highest energy content per unit of mass of any fuel. It also provides a burning velocity improvement of a factor of five relative to conventional hydrocarbon-fuels, and should allow the burning process to be completed without unreasonably long combustion chambers.[27] By itself, however, hydrogen would not solve all of the problems of igniting and burning fuel traveling at hypersonic speeds. For example, engine designers must also incorporate special "flameholding" techniques to stabilize the flame in scramjet combustors without compromising engine aerodynamics or adversely affecting combustor conditions.

Hydrogen fuel offers several other advantages over conventional fuels:

- The large heat capacity of hydrogen provides a possible heat sink for the enormous thermal loads to which the X-30 would be exposed;
- Its exhaust products are predominantly water vapor, which is expected to prove environmen-

[26]At very high speeds a significant fraction of the scramjet's thrust would be derived from hydrogen that was added to the combustor, but did not undergo a chemical reaction with oxygen. As hot hydrogen is expanded from the higher pressure combustor to the lower pressure nozzle, it cools, converting heat into kinetic energy and adding to the thrust.

[27]However, according to the Air Force Studies Board Report on Hypersonic Technology, the reaction between hydrogen and oxygen in the combustor would not be complete before the mixture reached the engine nozzle. Unless the reaction was substantially completed during the expansion process some of the energy available from the propellant would not be used to produce thrust.

tally safe when produced at the very high altitude flight paths of hypersonic vehicles[28];

- It does not produce noxious fumes, and there is less danger from spreading flame than there would be from conventional fuels because it is less dense than air; and
- It could be combined with oxygen in a fuel cell to generate electrical power for the X-30.

Hydrogen gas would be derived from tanks of liquid hydrogen in order to permit enough fuel to be stored in a reasonably sized container. However, despite its higher energy content, liquid hydrogen's low density will result in fuel tanks some five times larger than equivalent hydrocarbon fuel tanks.[29] As a result, NASP engineers are exploring the feasibility of using slush hydrogen-a mixture of 50 percent solid and 50 percent liquid hydrogen that is roughly 15 percent more dense than liquid hydrogen. The slush would have a greater density and greater cooling power than liquid alone. The other major concern with hydrogen is the potential problem of hydrogen embrittlement in materials (see below).

Hydrogen would also be circulated through the engine, and in some designs through the airframe, as a coolant and as a means to increase combustion efficiency. Regenerative cooling is a technique typically employed by designers of liquid rocket engines to recover waste heat. By cooling the engine with fuel, the energy of the propellant is increased before it is injected into the combustion chamber. The addition of thermal energy to the propellant results in an increase in the velocity of the exhaust gases. If the exhaust nozzle is designed properly, the extra energy of the expanding gases will produce more thrust. The use of regenerative cooling techniques in the X-30 would allow waste engine heat, or heat generated by aerodynamic heating (friction), to be recovered and used to increase engine specific impulse. The recovery of fuel energy would be especially important for hypersonic cruise vehicles.

Materials and Thermal Management

Success in the materials and structures program will have a pivotal effect on the pace at which the X-30 can be developed, the X-30'S ability to achieve its design goals, and the extent to which the promised economies of future operational vehicles may be realized (app. D). The projected structural designs for all areas of the vehicle call for high-stiffness, thin-gauge product forms that can be fabricated into efficient load-bearing components. These in turn require high-strength, low-density materials that can retain their characteristics beyond those tolerated by present-day, commercially available materials.

Current challenges center around scaling Up laboratory production processes of advanced materials; developing fabrication and joining techniques to form lightweight sandwich and honeycomb structures; and forming materials and coatings that can withstand thermal cycling of the sort that would be seen in a flight vehicle. The potential for material failure under thermal cycling is a particular concern for the X-30 and its possible derivatives because vehicle structures will be exceptionally light, and therefore thin, and temperature differences between inner and outer layers of airframe and engine structures will be unusually large.[30]

Even if their weight could be tolerated, most metals lose their structural integrity above about 1,800 'F. Without cooling, leading edges of the wings, tail, engine, and nose cap of the X-30 could reach temperatures above 4,000 'F. Shock-heated portions of the vehicle could reach temperatures in excess of 5,000 'F, and large areas of the aircraft

28The impact of hypersonic vehicles on the ozone layer is the largest concern. The NASP JPO has let contracts for preliminary environmental assessments to evaluate the potential effects of water emissions from *X-30* follow-on vehicles, and to evaluate the impact of secondary chemical reactions. Note that the ascending flight profile of a orbital vehicle takes it quickly through the stratospheric band where ozone is concentrated (60,000-75,000 feet),

29Stephen Korthals-A1tes, ''The Aerospace Plane: Technological Feasibility and Policy Implications,'' p.43.

30Consider a thin airframe panel or portion of an engine wall that develops a large temperature gradient during flight because one side is exposed to *higher heat* or cold. Every time the vehicle is flown, the material would flex slightly because of differential expansion. Under repeated thermal cycles, the continual flexing could eventually lead to permanent deformation or even fracture. Notice that it is the peak, or transient, thermal gradients that govern the scale of this problem, The effects are most worrisome on thin gauge materials since they would fail before thicker materials, The plan to use thin gauge, relatively brittle composite materials for portions of the X-30, and their potential to be exposed to large thermal gradients, is the source of some concern among materials researchers.

could be heated to temperatures above 2,500 °F.[31] The greatest stress is within the engine where materials are subjected to the largest simultaneous aerodynamic and aerothermal load.

The Space Shuttle uses thermal protection tiles to insulate the interior of the vehicle from the high temperatures encountered on reentry. Covering most of the X-30 with thermal tiles would increase vehicle weight and, in addition, would defeat regenerative cooling schemes to increase fuel efficiency unless the tiles could be actively cooled. Instead, the X-30 will cool the hottest airframe structures by circulating hydrogen gas or by employing specially designed "heat pipes."[32]

Using hydrogen cooling raises the potential for hydrogen embrittlement.[33] As hydrogen fuel is transported to the engine it will turn from a liquid to a hot gas, which can diffuse into most materials without difficulty and can form brittle compounds within those materials. The NASP JPO considers the development of hydrogen barrier coatings a critical challenge. The X-30 will require coatings that are thin, lightweight, resistant to damage, and can be applied to complex shapes, including internal passages. Embrittlement could make materials prone to cracking and, in addition, it could affect operations costs and turn-around times if increased maintenance and inspection are required. It could also shorten the useful life of a structural component.

The materials problem is especially difficult in structures that are exposed to both large thermal and mechanical stresses. Perhaps the outstanding example of such a structure is the scramjet fuel injector. To facilitate mixing of hydrogen fuel with air it is necessary to place fuel injectors directly within the very hot engine combustor instead of along the cooler combustor walls. The injectors will experience large mechanical forces. In addition, to keep temperatures from rising beyond material limits, relatively cold hydrogen must be circulated at high pressure within the injector. Even small changes in injector placement and shape could have large effects on the resultant airflow and engine performance.[34]

Computational Fluid Dynamics (CFD) and X-30 Design

The design of the X-30 will require unparalleled use of computer simulation to model the vehicle's aerodynamic behavior at high Mach numbers. Wind tunnels can provide only limited data, as existing facilities can replicate flight conditions only to about Mach 8. Computer modeling performed on the fastest supercomputers is playing a key role in designing and optimizing the X-30'S airframe and propulsion system, and predicting the them-ml loads that would be encountered by the vehicle.

Computational fluid dynamics (CFD) simulates the behavior of fluids (both gases and liquids) by solving numerically the fundamental equations of fluid motion on a high-speed digital computer. The process of simulating the airflow around an aircraft begins by mathematically generating a picture of the vehicle. Mathematical algorithms calculate airflows over the simulated body at a number of points that are spread out on a mathematical grid. Finer grids and more sophisticated algorithms simulate the resultant airflows with greater fidelity at the cost of increased demands on computer memory and speed. Furthermore, calculations must extend beyond the surface of the vehicle's body to account for important aerodynamic effects, and they must also include flows through engines to evaluate propulsion performance. The critical areas where CFD is being used on the X-30'S design are the calculation of airflows around the forebody and engine inlets; inside the engine's combustion chamber (the most difficult set of calculations); around the afterbody

31X.30 temperatures from, "National Aero-Space Plane," briefing booklet supplied by Director of NASP Program Development, McDonnell Douglas, St. Louis, MO.

32A heat pipe is a closed system whose working principles resemble that of an ordinary refrigerator. Heat applied to one end of a heat pipe vaporizes a fluid and causes it to travel to the other end which, for example, might be in thermal contact with a large structure that serves as a heat sink. At the cooler end, the fluid condenses giving up its latent heat of vaporization. The fluid then circulates back to the hotter end of the pipe by capillary action along a wick. In the X-30, the working fluid could be lithium.

33Terrence M.F. Ronald, ** Materials Challenges For The National Aero-Space Plane," *Review of Progress in* Quantitative *Non-Destructive Evaluation (New York, NY:* Plenum Press), May 1989, p. 13.

34S. A. Dixon et al., "Structures and Materials Technology Issues for Reusable Launch Vehicles," NASA Technical Memorandum 87626 (Hampton, VA: NASA LRC, October 1985), p. 15, cited in Richard Hallion, *The Hypersonic Revolution, vol.* II, p. 1357.

and nozzle area; and around the entire integrated engine/airframe.[35]

The end result of a CFD simulation of X-30 flight might be a set of pressure contours or temperature profiles around the vehicle. Such a calculation might take many hours or even days depending on the level of approximation, even when performed on the fastest supercomputers using state-of-the-art algorithms. Moreover, these calculations may be limited in their ability to model turbulent airflows (see box 5-C) a critical issue in NASP airframe and propulsion design.

Because turbulence is characterized by extremely small and rapidly changing eddies, a very detailed simulation would be needed to model turbulence faithfully over large volumes or long time spans. CFD simulations typically include turbulent flow only in a semi-empirical way, adding its effects to theoretical models of smooth flow by the ad hoc inclusion of terms based on experimental data. While the resultant models may be valid over some narrow range of conditions, their application at the extreme conditions that would be encountered in reaching orbit introduces uncertainties. Validating CFD models is thus a critical issue for NASP. Unfortunately, no existing or planned ground test facility could simulate ***simultaneously the*** equivalent temperatures, pressures, air speeds, and turbulent effects that a spaceplane would encounter in its ascent to orbit.

Wind tunnels, the primary means to acquire experimental data, cannot produce long-duration air flows with true temperature simulation over Mach 8 in volumes large enough to hold full-size engine and airframe structures. For example, "blowdown" facilities produce gas flows above Mach 8 by gas expansion, but the process also results in very low gas temperatures. However, because the Mach number in the combustor is roughly one-third of free stream,[36] even Mach 8 wind tunnel facilities can provide some engine aerodynamics data over most of the X-30'S speed range. Still, its quality decreases at higher Mach numbers. Other challenges for wind tunnels include simulation of "real gas" effects—effects that are the result of the formation of chemically reactive and excited-state atomic and molecular species as a vehicle moves through the upper atmosphere at hypersonic speeds. It is particularly important to develop models that include real gas effects when describing conditions within the X-30'S engine.

Pulse facilities ("shock tunnels") can simulate the heat content and pressure of air at speeds as high as Mach 20, but the short duration of their flows (typically 10 milliseconds or less) prevents full steady-state conditions from being achieved and makes instrumentation difficult. Moreover, the size of test models is usually restricted in shock experiments. NASP is funding refurbishment and upgrading of several pulse facilities. Anew Rocketdyne test facility that may open in 1990 promises to allow full-scale engine component testing up to Mach 24.[37]

Hypersonic data gathered by the Space Shuttle would be of limited use in designing the X-30 because the Shuttle's shape and trajectory differ too much from prospective NASP vehicles and flight paths (the data would be of some use in validating numerical simulation models of hypersonic flight). Currently, NASP has no plans to gather hypersonic data experimentally by deploying test vehicles from the Shuttle, dropping projectiles from high-altitude balloons, or by using ground or aircraft-carried rockets. The position of the JPO is that such a program would be a significant experimental undertaking that would consume large amounts of time

[35] In a recent report, the chief scientist at the Air Force's Arnold Engineering Development Center stated that it took a year to set up the grid and solve the flow field for the F-16 fighter. Another project to model the F-15 fighter took four engineers working part-time six months. However, automated processes are reducing the time to setup vehicle grids. NASP officials predicted that it will soon be possible to retie changes in airframe configurations and re-grid the model in times on the order of 6 weeks. John Rhea, "The Electronic Wind Tunnel," Air Force Magazine, vol. 72, No, 2, February 1989, pp. 62-66. This article gives an overview of CFD efforts at Arnold Engineering Development Center and other Air Force laboratories.

[36] The fluid Mach number is inversely proportional to the ratio of the square root of the temperature of the gas in the combustor divided by the temperature of the gas in the free stream (the temperature of the gas far out in front of the vehicle).

[37] William B. Scott, "Rocketdyne Developing Facility for Hypersonic propulsion Tests, "*Aviation Week and Space Technology,* Jan. 30, 1989, p. 65. This facility will be a reflected shock tunnel and should be able to simulate some of the temperature, pressure, and real gas effects that would be encountered by the X-30 in an ascent to orbit. However, there will still be some limitations in testing. For example, reflected shock tunnels are limited in their ability to perform combustion tests above the Mach 12-14 region because they produce higher levels of oxygen dissociation (50% at Mach 16) than would be expected during actual flight conditions.

Box 5-C—Limits of Computational Fluid Dynamics

Turbulent phenomena present a sometimes intractable problem for researchers attempting to model gas flows using numerical techniques. While the time evolution of some types of gas motion is predictable, turbulent flows are chaotic and only their gross behavior is amenable to computational analysis. A hallmark of turbulent flow is the presence of disordered motion at all scales. For example, the swirls and eddies of a rising column of smoke contain smaller-scale disturbances, and these enclose smaller ones, and so on. Unfortunately, to understand the large-scale behavior of turbulent motion, it is sometimes necessary to include the effect of the small-scale disturbances.

A faster computer can simulate turbulence at smaller scales, but the practical limits set by storage and speed limit how well any computer can predict flow patterns. For example, if the numerical simulation of a turbulent flow requires calculations every one tenth of a millimeter, then enormous requirements would be made on computer storage.[1] To make their calculations more tractable, computer models of airflows that include turbulence can resort to simplifying assumptions, such as assuming two-dimensional instead of three-dimensional flow. Another simplifying assumption is to neglect the "real gas" effects of chemically reactive species formed in hypersonic airflows. Unfortunately, full three dimensional models that include real gas effects are necessary to predict the aerodynamics and aerothermal loads that a particular airframe and engine configuration will experience in hypersonic flight.

Outside the engine, the most important limitation of CFD is in its ability to characterize the "boundary layer transition." The location and length of the transition from laminar (smooth) to turbulent flow-the boundary layer transition--has a significant impact on all aspects of engine and vehicle performance. For example, it affects the lift and drag on the vehicle, the airflow into the engine, and heat transfer rates. Assumptions about the location of the boundary layer transition therefore have a profound effect on design requirements for the propulsion system and the cooling system.

Although CFD researchers report progress in predicting the location of the boundary layer transition, complete validation of computer models is not possible using only ground-test facilities. NASP designers are making what they describe as conservative assumptions regarding the flow patterns over the X-30 to minimize the effect of boundary layer uncertainties in the performance of prospective vehicles. The boundary layer problem is another illustration of the difficulties engineers have in designing a vehicle meant to explore the outermost regions of the atmospheric flight envelope. It has also fueled disputes over whether the NASP philosophy of attempting to reach orbit without first building an intermediate vehicle(s) is excessively risky.

[1] Edwin Galea, "Smoking Out the Secrets of Fire," *New Scientist*, July 7, 1988, p. 46. See also Edwin Gales, "Supercornput~s and the Need for Speed," *New Scientist*, Nov. 12, 1988, pp. 50-55.

and resources. Instead of a subscale hypersonic test program, the JPO envisions using the X-30 as a flying test-bed to validate scramjet performance at high Mach numbers.

POLICY CONSIDERATIONS

As summarized in earlier sections, the NASP program is currently developing the technology to build an X-30 research vehicle. When this work is complete, the NASP joint program office will report to the Administration and to Congress on the feasibility, timetable, and costs of proceeding with development.

Proponents of the NASP program argue that it would maintain U.S. leadership in competitive technologies critical to the aerospace industry. Furthermore, they assert that the NASP program will lead to hypersonic aircraft and space launch vehicles that would have revolutionary capabilities. However, the Secretary of Defense and other DoD officials have suggested that because the NASP program is a high-risk program whose applications are long-term, it can be deferred in an era of stringent budgets.[38] This section presents several important considerations for Congress as it deliberates the

[38] Craig Covault, "White House Acts to Reverse Aero-Space Plane Cancellation," Aviation Week and Space Technology, Apr. 24, 1989, pp. 20-21.

future of the NASP program in relation to other civilian and military space priorities.

What future vehicles and mission capabilities **could the NASP program lead to, and how would these compare with other alternatives?**

The NASP program is designed to demonstrate technologies that could lead to operational launch systems for both military and civilian use in the early part of the next century. Assuming the X-30 were to complete its test program successfully, the first operational vehicles derived from NASP technology would likely be military launch vehicles, or perhaps military hypersonic cruise vehicles. An aerospace plane designed for military use could also be used for a variety of civilian applications, including transporting people to and from the proposed space station.

Even if **the X-30 proves successful, launch vehicles or hypersonic aircraft derived from NASP technology would have to compete for funding and attention with other means of accomplishing the same military and civilian missions. If Congress believes that the NASP program should proceed only if it would lead to cost-effective operational vehicles, it may wish to examine the results of applications studies before funding Phase III of NASP.** Alternatives to piloted NDVs would include expendable launch vehicles, other reusable concepts that include two-stage-to-orbit vehicles, and supersonic aircraft. An unmanned version of a NASP-derived vehicle is still another possibility. Because of their projected high unit costs, NDVs could not be procurred in large numbers. The NASP program office is comparing the utility of a military aerospace plane against alternative systems for carrying out the same missions. In addition to evaluating how well a small fleet of NDVs might perform versus a larger number of less costly systems, it will also be important for these studies to include both the effect of the long lead time for development of an NDV (operational vehicles are unlikely before 2005) and the effects of probable countermeasures.

Three classes of NASP-derived vehicles are possible:

Option 1: A Military Aerospace Plane

Endo-atmospheric hypersonic aircraft based on NASP technology could perform a variety of global military missions requiring rapid response, including reconnaissance,[39] interdiction, air defense,[40] and air strike. The NASP program has developed preliminary designs for hypersonic military aircraft with ranges from 12,(K)0 to 17,000 nautical miles at speeds of between Mach 7 and 12.[41] Similarly, the second type of military vehicle that could be developed-a survivable, quick-response Mach 25 vehicle with access to space—would also have unique military capabilities.

The relative importance of these capabilities rests on a number of factors, including the comparative costs and capabilities of alternative systems. For example, small launch vehicles developed for DARPA's Lightsat program, which could provide responsive surveillance by placing small dedicated satellites in orbit to be used by field commanders, might compete directly with the capability of launch vehicles developed from NASP technology .42

Other potential missions for a NASP-derived vehicle (NDV) may depend on the continuation of a Strategic Defense Initiative with a space-based component. For example, although an operational spaceplane could not substitute for the Advanced Launch System heavy-lift vehicle being sought for some Strategic Defense System (SDS) payloads, it might be capable of economically launching smaller SDS payloads, such as space-based interceptor satellites, on demand. In addition, a spaceplane

[39] A hypersonic vehicle developed from X-30 technology might extend the speed and altitude limits of the Mach 3+ SR-71 "Blackbird," and could enable operation from more locations with faster response and improved turn-around times.

[40] An effort to develop hypersonic weapons for air defense is being conducted as part of the Air Defense Initiative (ADI), a DoD/DARPA program to counter the threat from low-observable bombers and cruise missiles. One application being studied is the feasibility of combining new surveillance methods with hypersonic, long-range surface-to-air missiles to attack aircraft carrying air-launched cruise missiles at long distances. Current air defense interceptors could not travel fast enough to reach such cruise missile carriers before they were within range of the United States, even if they were detected at the maximum range of new over-the-horizon radars.

[41] NASP Joint Program Office, personal communication, A@ 1989.

[42] U.S. Congress, Office of Technology A-merit, *Alternative Spacecraft Design and Launch Options*, OTA Background Paper, (Washington, DC: U.S. Government Printing Office).

could be valuable for on-orbit maintenance of SDS Satellites.

Option 2: Civilian Aerospace Plane

A launch vehicle derived from NASP technology is one of several concepts being considered for low-cost piloted space transportation to and from low-Earth orbit. As part of its Advanced Manned Launch System (AMLS) Studies, NASA is studying reusable rocket-powered vertically launched vehicles and air breathinghcket horizontal takeoff systems as Shuttle replacements (see ch. 4). In part because of its simplified launch operations, a vehicle requiring only a single stage to reach orbit may have a greater potential to lower operating costs than two-stage AMLS vehicles. However, a single-stage vehicle would also require use of more advanced technology (e.g., scramjet propulsion and new materials), and its development would be inherently more risky.

NASP shares some similarities with concepts for an AMLS, but it has important differences as well. Even though both programs will use new technology in areas like materials and structures, and both plan to incorporate autonomous vehicle operations to reduce launch and operation costs, building an aerospace plane requires a much larger technical leap than building rocket-powered launch vehicles. **Even assuming a rapid resolution of the myriad of technical issues facing the construction of an X-30, translating this technology into an operational spaceplane might come late in the period when an AMLS could be ready, and perhaps after the time when replacements for the shuttle will be necessary.** Presumably, an AMLS program that began in the late 1990s would still allow for completion of an operational vehicle by the year 2010. An AMLS program begun in that time might also benefit from matured NASP technologies, especially in the area of materials and structures.

Prospective first-generation operational follow-ons to the X-30 would almost certainly have less payload capacity than the present Shuttle.[43] They would compare favorably with possible AMLS vehicles (roughly 20,000 to 40,000 pounds into low-Earth orbit). An NDV might be used for civilian applications even without large payload capacity. These could include satellite launch, responsive satellite replenishment, on-orbit maintenance and repair, ferrying of astronauts and cargo to the proposed space station, and serving as a space rescue vehicle.

The cost-effectiveness of these missions should be evaluated in comprehensive applications studies that evaluate the feasibility of using alternative launch vehicles and assess future civilian launch needs. For example, the feasibility of on-orbit maintenance would depend on the operation and support costs of a NASP-derived vehicle and on satellite design. At present, the costs of on-orbit retrieval or repair generally far outweigh the costs of building new spacecraft.

Option 3: Orient Express

Perhaps mindful of the popularity of NASA's piloted space-flight program with the public, some proponents of NASP have made exaggerated claims regarding the civilian benefits of the X-30 program, especially those pertaining to the commercial transport dubbed the Orient Express. Such claims have abated and program managers now appear to be sensitive to the dangers of overselling their program. NASP officials were forthright in explaining to OTA that their program has little to do with creating an Orient Express.

If a Mach 5+ commercial transport is developed, it will likely evolve from NASA's High-Speed Commercial Transport Program. Such a vehicle, currently thought to compare unfavorably in cost and environmental acceptability[44] with slower supersonic transports that would fly between Mach 2 and 3, would benefit from the advanced technology being developed for the X-30. However, as emphasized earlier, the X-30 program is neither the most cost effective nor the most direct route towards facilitating hypersonic civilian aircraft.

In the mid to late 1990s, Congress will have to choose among the competing claims of proponents of a variety of new launch systems, including

43 Roughly 55,000 pounds when launched East into a circular orbit 110 nautical miles high.

44 However, as noted earlier, hypersonic transports would fly at very high altitudes and their exhaust products might not endanger the ozone layer. Sonic boom effects might also be reduced by high altitude flight.

NASP-derived vehicles. If the NASP program achieves its technical goals and can demonstrate the potential for low operational costs, launch systems derived from NASP technology may well replace other prospective launch systems. However, the life-cycle costs, which include development, acquisition, and operations costs of each system, will have to be examined and compared in order to choose the best launch system mix.

What Auxiliary Benefits Could the NASP Program Provide?

By providing a focus for defense research and development on the technologies of hypersonic flight, NASP and follow-on programs could make important contributions to defense programs seeking long-range, fast weapons delivery. For example, an obvious area for coordination in weapons development is the very long-range hypersonic surface-to-air missile being sought by DARPA and the Air Force for applications such as air defense, fleet defense, and long-range targeting of mobile and relocatable assets.[45]

Proponents of the NASP program maintain that it would contribute important new technology to the defense technology base.[46] Although it is clear that the NASP program has contributed to the Nation's ability to manufacture new lightweight materials capable of enduring high thermal and mechanical stresses, has improved computational fluid dynamics techniques, and has advanced the theory and application of hypersonic propulsion, it is too early to assess how much these technologies will benefit defense programs outside of NASP.

The long-term benefits of the NASP program to civilian industry may also be substantial, but they too are uncertain. Proponents of the NASP program believe it would have important benefits in many of the high-technology industries of the next century. In particular, they believe that the program would have great benefit for the civilian aerospace industry. However, other programs, such as a high-speed commercial transport program, would also have the potential to enhance the U.S. competitive position in the civilian aerospace industry, and might do so more directly than the NASP program.

Is the NASP Program Technically Sound?

OTA did not conduct a detailed assessment of the technical soundness of the NASP program. Two advisory bodies, the Defense Science Board (DSB) and the Air Force Studies Board (AFSB) of the National Research Council, have conducted recent technical reviews.

The DSB report. In 1987, the DSB performed a comprehensive technical review of NASP. Members of a special task force said they were impressed by the progress the NASP program had made. However, they were cautious in their outlook and warned that they were "even more impressed by what has yet to be done to reduce the remaining uncertainties to a reasonably manageable level."[47] The DSB study was conducted early in the technology development phase of the NASP program (Phase II) and overlapped internal reviews by project management that also concluded that some redirection of program efforts was desirable. Appendix E presents an overview of the DSB report and its impact on the NASP program.

In response to the DSB report, officials in the NASP program adopted a' 'Risk Closure Program,' a plan to remove uncertainties in the X-30'S component technologies systematically by mapping out in advance a series of technical achievements that must be attained to achieve program objectives. NASP officials have stated that they will not recommend a transition out of the current Phase II research stage unless the risk closure effort is substantially complete.[48] At that time, they believe the technical risks in moving to Phase 111 will center primarily around technology supporting high-Mach scramjet propulsion.

Program managers assert that they have made rapid progress in developing the key enabling technologies for propulsion systems, materials and

45' However, to ~&, these missions practical there is also the necessity to develop near real-time surveillance or other intelligence methods to guide long-range weapons close to targets, At present this is an unsolved problem.

46OTA did not assess in detail the potential benefits of the NASP program to the Nation's defense technology base.

47Defense Science Board Report on the National Aerospace Plane, P.4.

48Statement by NASP JPO director Dr. Robert Barthelemy at OTA briefing, Dec. 13, 1988.

structures, and computational fluid dynamics since the DSB report (app. E). They have also revised designs for the X-30 to use technology possessing lower risk, albeit at penalties such as an increase in vehicle gross take-off weight.

The AFSB report. The Committee on Hypersonic Technology for Military Application of the Air Force Studies Board was formed to evaluate the potential military applications of hypersonic aircraft and assess the status of technologies critical to the feasibility of such vehicles. Part of the Committee's task was to advise the Commander of the Air Force Systems Command on the research and development strategy of the National Aero-Space Plane. The AFSB report followed the DSB report, and there was some overlap in membership of the two committees. Full committee meetings were held from April 1987 through March 1988.

The Committee recommended that the NASP program office retain the ultimate goal of demonstrating the technical feasibility of reaching orbit with a single propulsion stage, but, like the DSB, expressed many concerns about the maturity of the technologies that would be necessary to meet this goal. In particular, the Committee felt that progress in materials and structures would be a probable limiting factor in meeting the JPO's primary objective of demonstrating single-stage access to orbit.

The Committee also made a number of recommendations that would aid in the development of a broad and aggressive research program into the enabling technologies of hypersonic flight. For example, it found an urgent need for the construction of a new hypersonic wind tunnel that would permit testing of hypersonic configurations at close to full-scale conditions through Mach 10. A "quiet" wind tunnel was recommended because of its capability to simulate with good fidelity crucial phenomena such as the boundary layer transition.[49]

The Committee agreed that a flight-test vehicle was both desirable and necessary to complement ground-test facilities. However, uncertainties in the enabling technologies of the X-30 were sufficiently great in the Committee's view that they recommended that the NASP JPO retain an option to build a research vehicle that would not be designed to reach orbit. This recommendation is discussed later in Issue 4.

The decision to recommend a move into Phase III, the construction of the X-30, must be approved by the NASP Steering Committee, chaired by the Undersecretary of Defense for Acquisition. NASA's Office of Aeronautics and Space Technology Administrator serves as vice-chair of the Steering Committee. If approved, the final decision on whether or not to fund development of a flight vehicle would then be made by the Administration and the Congress.

How risky is the NASP development strategy?

This discussion assumes that the NASP program will continue to exist as a development program, leading to an X-30 research vehicle. Recent decisions within DoD cast doubt on that assumption.[50] The potential effects of a range of budget options are discussed below in Issue 6.

Option 1: Go Slow In Phase II?

NASP officials plan to use the X-30 as a flying test-bed that will first explore the hypersonic flight regime and then attempt to reach orbit. NASP program managers face the fundamental choice between attempting to design and build the X-30 as soon as possible, or going slower in Phase II with the expectation that more advanced technologies would lower the risk of subsequent performance shortfalls. Both paths have advantages and risks.

If the X-30 is able to reach orbit with a single stage, it will have achieved a remarkable goal, one that could revolutionize launch concepts. However, if engineers are forced to design a vehicle with little flexibility or little performance margin in order to meet the objective of SSTO, they would face severe cost restrictions should subsequent design modifications prove necessary. Modifying sub-scale models in ground facilities would be much easier and Cheaper than attempting to make modifications in a flight vehicle. A longer ground test program could

[49] According to the AFSB, a quiet wind tunnel would minimize disturbances to gas flow that emanate from wind tunnel settling chambers and acoustic radiation from nozzle wall boundary layers.

[50] In April 1989, the Secretary of Defense decided to cut funding of the NASP program dramatically and recommended that the program be transferred to NASA. However, other decisionmakers, including members of Congress, will also shape the future of the NASP program.

reduce the risk of failing to meet program goals and might also allow the incorporation of more advanced technology. Yet, stretching out the Phase II program could raise the costs of technology development and lead to loss of interest in the goal of building an X-30 test vehicle.

NASP officials have chosen to use the Phase 111 decision points [51] to decide whether or not to build the X-30. The possibility of stretching out Phase II, or moving to some intermediate developmental phase that might allow some full-scale component construction and testing without actual assembly of an X-30, is not a formal option in current plans. Officials believe that slowing the pace of the program at this time is unnecessary and would prove to be wasteful. In a fiscally constrained environment they may also be responding to the perception that research and development programs that have mostly a long-term payoff are especially vulnerable to budget cuts.

Option 2: Build A Series of Vehicles?

The NASP JPO plans to use the X-30 as both a research vehicle, which would acquire test data at hypersonic speeds, and as a demonstration vehicle, which would fly to orbit and cruise within the atmosphere at hypersonic speeds. In some respects, these goals may conflict with one another.

The AFSB report expressed concerns over the performance of the scramjet propulsion system at high Mach numbers. In order to ensure that the X-30 is able to reach the high Mach numbers critical to testing scramjet designs, it recommended that the X-30 incorporate auxiliary rocket propulsion to enable controlled flight with some independence from the air-breathing propulsion system. In addition, the AFSB recommended that JPO consider fabricating a series of flight research vehicles that would incrementally explore the flight regimes of a SSTO vehicle.

This strategy could have at least two advantages. First, it could lower the risk of "failure." Some analysts believe that an X-30 that could not meet its promised objectives, especially single-stage access to space, would risk reducing, or even ending, government interest and investment in hypersonic technologies. Second, it might aid researchers by allowing them to design a better test vehicle. For example, a vehicle that was not designed to reach orbit could use the relaxed materials and propulsion system requirements to fabricate a less expensive vehicle that might be easier and cheaper to instrument and reconfigure during testing. Fabricating a series of aircraft that would culminate in a SSTO spaceplane might be more costly than building the X-30 directly. However, it might also spare the necessity of a costly modification program if the X-30 failed to achieve its design objectives. In summary, a program management strategy that built a series of test vehicles might allow researchers to "learn to crawl before they learn to walk."

NASP officials have rejected the idea of an intermediate vehicle on a variety of technical grounds, including the difficulty in extrapolating data acquired at lower Mach numbers to design a single-stage-to-orbit, Mach 25, vehicle.[52] Furthermore, they dispute the contention that an X-30 designed to achieve orbit conflicts with its role as a technology test bed. For example, they note that the X-30 would carry sufficient payload capacity to carry a full complement of instrumentation.

Officials also believe that the X-30 would have ample margin to reach orbit and serve as a research vehicle, especially if an option to build an X-30 with additional payload capacity is exercised. They also believe that an X-30 designed with rocket thrust augmentation would be almost certain to reach the high Mach numbers desired for scramjet tests. NASP contractors also disputed the claim that the X-30 is excessively risky. For example, Pratt & Whitney and Rocketdyne officials claim their engine designs allow considerable flexibility in engine geometry without an excessive number of moving parts.

While not explicitly acknowledged by NASP officials, the decision over which development strategy to pursue also affects future support for the program. NASP officials report that a survey of potential military users for a Mach 8 to 24 *hyper-*

[51] Under current plans and funding profiles, this would likely occur in September 1990.

[52] An intermediate vehicle might support a two-stage design with an air-breathing bottom stage, but two-stage vehicles are not being considered in the NASP program. Two-stage vehicles are being considered in NASA's AMLS studies.

sonic cruiser found relatively little interest in this vehicle compared to one that could demonstrate an ability to reach orbit. In a limited funding environment, NASP officials may well fear that a multistage program to step up to Mach 25 incrementally would not be funded, regardless of the technical risk. In addition, the cost of building a series of flight vehicles would be higher than building an X-30, if, as implicitly assumed, the X-30 is able to meet program objectives without costly modifications to its original design.

NASP program managers have a delicate task as they balance the advantages of deciding to move into Phase 111, in order to maintain DoD and NASA support, against the risks of selecting an X-30 design that might later fall short of expectations and even impede future hypersonic technology development. Congress may well wish to explore the advantages and shortfalls of both approaches as it debates whether or not to fund development of the X-30 when the current Phase II program is completed.

How much will Phase III of the NASP program cost?

The NASP program has already cost about $800 million in Federal funds and $500 million contributed by industry, exclusive of "infrastructure" costs, such as Air Force and NASA salaries, and overhead costs for facilities. NASP officials have stated that a continuation of funding close to the Phase 11 requests ($427 million for fiscal year 1990) will be sufficient to both meet the technology goals set out in the Risk Closure Plan and to support a Phase 111 decision in late 1990.[53] Current estimates for Phase III costs are very uncertain because they are based on extrapolations from designs now viewed as overly optimistic.[54] This uncertainty is compounded by the inherent difficulty in projecting costs for an aircraft as novel as the X-30. Recent experiences with high-technology programs, such as the B-2 bomber, suggest cost growth in Phase 111 is a very real possibility. The NASP JPO is preparing detailed cost estimates for their Phase 111 review, but preliminary figures will not be available until the fall of 1989.

Whatever the estimates, the fabrication and testing of a flight vehicle in Phase III of the NASP program would require substantial increases in funding over current expenditures. Even without unforeseen cost growth, the NASP budget, as currently projected, will rise from the current level of approximately $320 million to about $500 million in fiscal year 1991. Peak expenditures are expected in fiscal years 1992-1994, when spending is projected to rise to approximately $550 million per year. As a practical matter, funding for Phase III will depend on convincing the Administration and Congress that operational follow-on launch systems show sufficient promise to continue the program. In all likelihood, Air Force support will be essential.

What would be the options for the NASP program if its budget were cut?

As the NASP program nears the end of its technology maturation and concept validation phase, it is coming under increasing scrutiny by lawmakers and defense officials already struggling with steady or declining defense budgets. The revised DoD budget submitted by Secretary of Defense Cheney in April 1989 cut DOD funding for NASP from $300 million to $100 million. DoD would contribute no funds in subsequent years. In addition, the Secretary proposed to transfer responsibility for managing NASP from DoD to NASA and allow NASA to obligate the $100 million of fiscal year 1990 DoD funds.

The proposed cuts and change of management has accelerated a review of the NASP program. Yet, many of the important tests that would be needed to support an informed decision on the technical feasibility of the program are scheduled to be performed in fiscal year 1990, the last year of Phase II. Furthermore, the critical applications and cost studies are not yet complete.

Congress has three broad options on funding for NASP:

531x, Robert Barthelemy, cited in "One On One, " *Defense News*, Oct. 24, 1988, p. 46.

54Early baseline NASP vehicles envisioned a 50,000 pound take-off gross weight vehicle (' 'Phase III Alternatives: Contractor Findings,*National Aero-Space Plane Program Briefing to NASP Steering Committee*, Nov. 7,1988, p. 49) and only air-breathing propulsion from a standing start to Mach 25, Current NASP designs plan to use less exotic materials; the vehicle is much larger and heavier; and, as noted earlier, designs include options to carry on-board liquid oxygen to augment air-breathing engines or fuel a separate rocket propulsion system.

Option 1: Continue to fund the program at or near the original requested rate.

Under this option, NASP would receive $300 million from DoD and $127 million from NASA in fiscal year 1990. Funding of this level ($427 million) would allow the NASP program to continue its Phase II research program and to complete its application and cost studies by the end of the fiscal year. At that point, the Administration and Congress could then decide whether or not to build two X-30 test vehicles.

A decision to continue planned funding of the program would ensure that the contractor teams and the materials consortium were maintained for another year. Even if the Administration and the Congress decided to delay development of an X-30 for several years, the Phase II findings and technologies would be available for a later effort. In addition, the technologies developed in Phase II would be available for other purposes.

If Congress were to restore funding of NASP to a level of roughly 75 percent of its original request, and if the current management arrangement were retained, the Phase III decision would likely slip by a year or so, depending on the size of the cut. Although the program would then risk losing momentum and industry support, testing and evaluation could proceed in an orderly fashion, and, in addition, the extra time might allow for the maturation of more advanced materials, and the refinement of computational fluid dynamics simulations.

Option 2: Accept the current DoD proposal for program cuts.

The DoD proposal would cut the DoD contribution by two-thirds in fiscal year 1990 and turn the program over to NASA. DoD would contribute nothing in subsequent years. Under this option, the NASP program would still be able to pursue important technology studies; however, the program would not focus on the development of a flight vehicle.

With only $100 million of DoD support, and assuming NASA funding did not rise (in fact, a cut in funding would be likely), a decision on whether or not to construct a flight vehicle might be delayed 3 to 4 years. The program would probably need to be transfered back to DoD in the mid-1990s in order to proceed with a test aerospace plane, because NASA has little incentive to build an X-30 on its own. If managed by NASA, the program would compete directly with funding for alternative launch systems such as AMLS and also with the Space Station program, which, along with the Space Shuttle, will command most of NASA's resources for at least the next decade.[55]

The NASP program currently enjoys broad support and financial commitment from industry because it is focused on building a flight-test vehicle that **could lead to the production of operational vehicles.** If the program is restructured into a technology maturation program only, as would likely occur if the program is transferred to NASA and DoD funding is ended, much of what has become a national technology base could be lost. Moreover, there is the risk that a future decision to develop a hypersonic flight-test vehicle would not be supported by industry. The importance of industry support for NASP should not be minimized. In fact, NASP officials believe their greatest accomplishment to date has been the marshaling of the talents of thousands of the Nation's most talented scientists and engineers, and the creation of innovative industry teaming arrangements. Recreating this base of expertise would be both costly and time consuming.

Option 3: Cut funding entirely.

If Congress feels that the long-term goals of the NASP program are less important than other pressing priorities in the Federal budget, it could decide to terminate funding entirely and close the NASP program out. However, some funding would have to be supplied to complete contractual obligations already made. In addition, unless contractors were able to continue their work to a logical conclusion, much of the progress made in the program would be lost.

The diversity of its potential benefits has given NASP a broad base of support; however, a decision to move beyond the concept validation phase of the program will require a demonstration that the

[55] U.S. Congress, Congressional Budget Office, The NASA Program in the 1990s and Beyond (Washington, DC: Congressional Budget Office, May 1988).

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program is technically sound and that it has adopted a prudent management strategy. As a practical matter, the high costs to build and test a flight vehicle imply that Service support, most likely from the Air Force, will be necessary.