MICHAEL E. WHITE

THE NATIONAL AEROSPACE PLANE PROGRAM AND THE APL ROLE

The National AeroSpace Plane program aims to develop and demonstrate the requisite aerospace technologies for achieving single-stage-to-orbit flight using airbreathing engines. This goal is to be achieved through the development of two experimental X-30 vehicles and requires extending the state of the art in nearly every major aerospace discipline. Perhaps the biggest challenge is the development of the airbreathing propulsion system of the vehicles. This article is an overview of the National AeroSpace Plane program and summarizes the Laboratory's contributions to the development of the requisite propulsion and propulsion-related technologies.

THE PRINCIPAL CHALLENGE

The ultimate objective of the National AeroSpace Plane (NASP) program is to develop two X-30 aircraft (one of which is shown conceptually in Fig. 1) that are capable of single-stage-to-orbit (SSTO) flight and horizontal take-off and landing from conventional runways. The aircraft will be hydrogen fueled and will be powered by airbreathing engines to accelerate from takeoff to orbital velocities of more than 17,000 miles per hour, or about Mach 25 (i.e., 25 times the speed of sound). A sophisticated system will power the vehicle up to a flight speed of about Mach 3, at which point the primary ramjet/scramjet engines will take over to power the vehicle up to high hypersonic flight speeds. A rocket will provide the final thrust increment required for orbital insertion and for the reentry burn. Upon completion of the mission, the X-30 will return to land in a manner similar to the space shuttle; unlike the shuttle, however, the airplane-like qualities of the X-30 will enable the vehicle to be powered on approach to landing and capable of rapid turnaround after landing.

To make the NASP program goals a reality, the concurrent development of revolutionary technologies is required in almost every major aerospace discipline, from new tires to handle the high takeoff velocities, to materials and propulsion systems that have never been demonstrated in flight. Therein lies the real national motivation for NASP, that is, to foster a significant advancement of the state of the art in aerospace technology for high-speed flight. Making this challenge especially formidable is the difficulty, and sometimes the impossibility, of

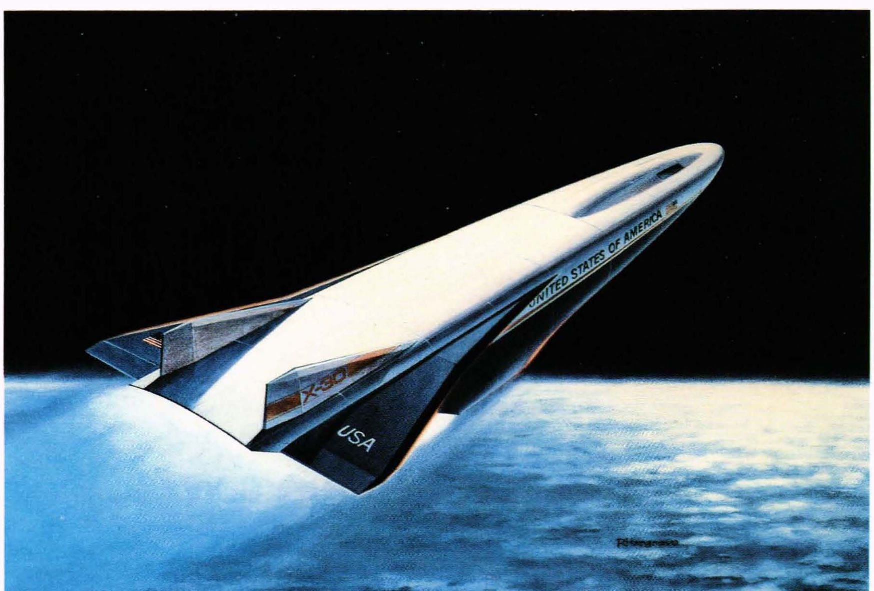


Figure 1. An artist's rendition of the National AeroSpace Plane X-30 vehicle concept developed by the National Team.

conducting in ground test facilities adequate simulations of the extreme range of flight conditions encountered by an SSTO vehicle in going from takeoff to orbit. This problem has led to a high degree of reliance on the development and application of computational fluid dynamics (CFD).

The development and flight test verification of the requisite technology for SSTO flight is the major focus of the NASP program. The program is not a weapons program, nor is it a program to develop an "Orient Express" passenger airliner. Rather, it is an experimental airplane program, in the spirit of the X-1 and X-15 programs, aimed at establishing the technological foundation for the future development of NASP-derived vehicles (NDV's), which would have a variety of applications and missions (Fig. 2).

The NASP program goals are to be achieved through an aggressive flight test program whose operational objective is to demonstrate the following:[1]

1. SSTO flight.
2. Unassisted horizontal takeoff and landing.
3. Hypersonic cruise in the atmosphere.
4. Cross range capability.
5. Powered go-around at landing.
6. Reusability and maintainability improvements over current space launch systems.

Through the flight test program, the basic technological research objectives, listed as follows, will be realized.

1. Development of workable airbreathing propulsion concepts for SSTO flight and definition of their usefulness in NDV's.
2. Development of structural and materials concepts needed for airbreathing SSTO flight and definition of their usefulness in NDV's.
3. Validation of the analytical and design tools needed for NDV design, with particular emphasis on computational fluid dynamics.
4. Determination of the system and subsystem performance and operability needed by airbreathing SSTO vehicles and definition of their usefulness in NDV's.
5. Determination of the ability to totally integrate the technologies needed for this class of vehicle into a complete, functioning system.

The development and application of NASP technology will help to foster continued U.S. leadership in aerospace sciences into the twenty-first century in the face of stiff international competition. That competition is evident today in the growing space launch and commercial airline capabilities of Europe, Japan, and Russia, and it will be even more evident in the future because Germany, France, the United Kingdom, Italy, Japan, and Russia are all working on the development of aerospace plane technology.[2] This international leadership becomes especially important when one realizes that aircraft and aircraft-related hardware is one of the few areas in which the United States still enjoys a positive trade balance.

NASP PROGRAM EVOLUTION

Currently, we are seven years into what has formally been the NASP program. The program evolved from a highly classified Defense Advanced Research Projects Agency (DARPA) activity that investigated the feasibility of building an SSTO airbreathing vehicle. A select group of national experts was assembled to define the technical concept, evaluate the key requisite technologies, identify technical risks, and define approaches to reduce those risks. The principals, under the direction of Robert Williams at DARPA and spearheaded by Frederick Billig of APL, Anthony duPont of duPont Aerospace, and Robert Jones of the NASA Langley Research Center, concluded that the development of such a vehicle, as well as the associated technologies, was feasible with the proper technical, managerial, and fiscal focus. On the basis of that recommendation, the Secretary of Defense established the NASP program in 1985.

A DoD/NASA Joint Program Office was formed at the Wright Patterson Air Force Base in Dayton, Ohio; eight industry participants, three engine companies, and five airframe companies were selected to develop competitive concepts for the two proposed X-30 vehicles. At the same time, it was recognized that a large portion of the national expertise in hypersonic aerodynamics and propulsion-related disciplines resided in government and government-affiliated laboratories; therefore, in conjunction with the industrial activity, a generic technological research program called the Technology Maturation Plan (TMP), or Tech Mat, was established within the government. The ground work for what became known as Phase 2 of the program was established; its goal was the development and demonstration of key aerospace technologies

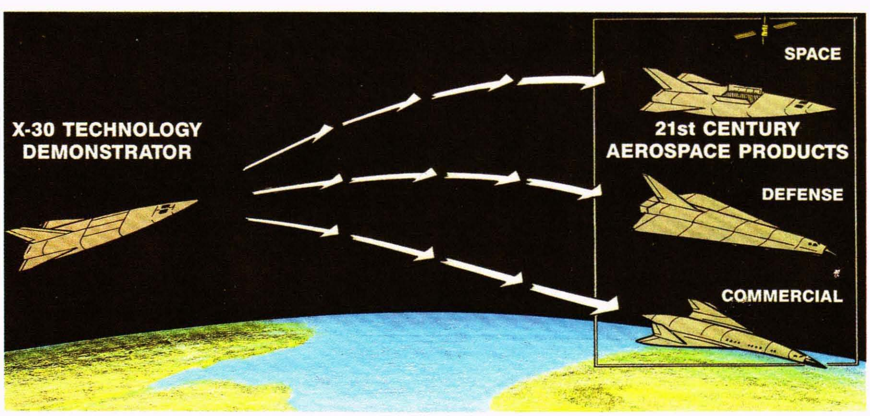


Figure 2. The National AeroSpace Plane (NASP) program is an effort to develop the requisite technologies for single-stage-to-orbit (SSTO) flight using airbreathing engines. This technology will have applicability to the development of NASP-derived vehicles with a wide range of missions. The NASP will demonstrate SSTO flight from horizontal takeoff, sustained hypersonic cruise, and airplane-like operation. (Courtesy of William Lawrence, General Dynamics.)

to establish sufficient confidence for justifying a national commitment to building the X-30 vehicles in Phase 3. This technology demonstration phase was then slated to conclude with a decision to go ahead with Phase 3 in October 1990. A positive Phase 3 decision was to have resulted in an experimental vehicle development program having a goal of first flight in 1994.

In 1987, Phase 2A culminated in the evaluation of the eight industrial participants, and five companies were chosen to continue: the McDonnell Douglas Corporation (MDC), the General Dynamics Corporation/Fort Worth Division (GD/FW), Rockwell International's North American Aircraft (NAA) and Rocketdyne (RD) Divisions, and United Technologies Pratt & Whitney (P&W). Phases 2B and 2C consisted of the continued development of six of the competitive vehicle concepts; each airframe contractor (MDC, GD/FW, and NAA) developed independent vehicle concepts for each of the two engine company concepts (P&W and RD), and the government Tech Mat activities continued to evolve.

It had become evident in the early phases of the program that the NASP goals created a unique national challenge that required a program structure unlike traditional programs. Technical expertise residing at places such as the NASA Langley, Lewis, and Ames Research Centers, The Johns Hopkins University Applied Physics Laboratory, and the Air Force Wright Laboratories was vital to the success of the program since, at its outset, the national industrial base in hypersonics had been the victim of severe atrophy. The result was a program that included joint government/industry decision making at all technical and programmatic levels.[3]

In 1989, the Bush Administration, after initially canceling the program, decided to initiate a program review by the newly formed National Space Council. Led by the Vice President, the Space Council review identified the NASP program as a high-priority national effort and recommended that the technology phase (Phase 2) be extended to 1993 to reduce technical risk and cost. The President approved the Space Council recommendations, giving the program new life and increased visibility (see the boxed insert). At about the same time, it was becoming evident that the national experience base in hypersonics built by this program was a valuable resource; therefore, the previously planned final selection of two or three contractors from industry was eliminated in favor of a unique National Team program structure. Formally started in 1991, the National Team approach combined the resources of the five prime industrial contractors in a joint-venture partnership (the Contractor Team) to focus technical and programmatic capabilities on the development of a single X-30 concept. Taking advantage of the best ideas from the individual competing teams, the National Team developed a single X-30 vehicle configuration (Fig. 1). Although the establishment of the National Team was a departure from the traditional program approach based on competition, the groundwork for such a decision was laid in 1989 when the Joint Program Office established the Materials Consortium to accelerate the advancement of new materials technology.

In addition to maintaining a strong industrial technology base, another benefit of the National Team approach is that the technical expertise residing in the government can be incorporated directly into the development of the focused X-30 concept. This direct incorporation is accomplished through critical path activities called Government Work Packages (GWP's). For this reason, government laboratories are often collectively referred to as USA, Inc., the sixth team member. The truly national nature of the program is evident in Figure 3, which lists just some of the main players.[3] The resulting integrated technology program is carried out through both Industry Work Packages and GWP's in what is now Phase 2D. This final technology phase will lay the groundwork for the Phase 3 development program that will result from a positive go-ahead decision in September 1993. The NASP program evolution can be summarized by the schedule in Figure 4; the first flight of vehicle 1 is currently scheduled for 1998.

STATEMENT ON THE NASP PROGRAM BY THE PRESIDENT'S PRESS SECRETARY

THE WHITE HOUSE

Office of the Press Secretary

For Immediate Release July 25, 1989

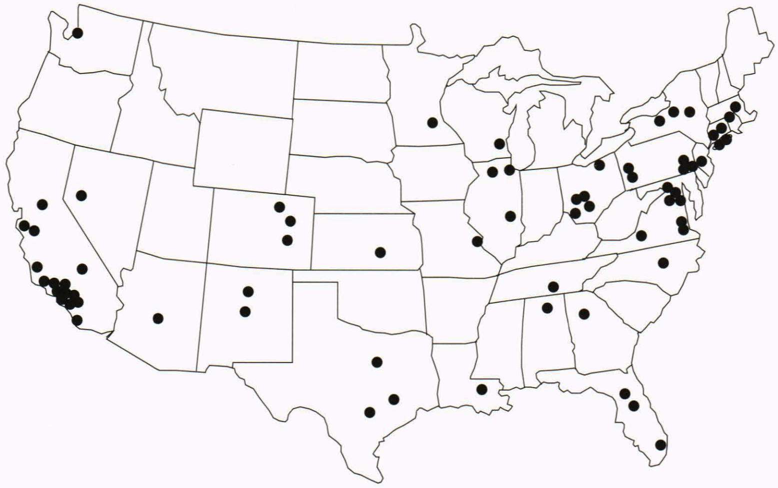
STATEMENT BY THE PRESS SECRETARY

The President, acting upon the recommendation of the Vice President, has approved the continuation of the National AeroSpace Plane (NASP) program as a high priority national effort to develop and demonstrate hypersonic technologies with the ultimate goal of single-stage-to-orbit.

The government will complete the Phase II technology development program, and plans to develop an experimental flight vehicle after completion of Phase II, if technically feasible. The system will be designed to focus on the highest priority research, as opposed to operational, objectives. Unmanned as well as manned designs will be considered, and the program will be conducted in such a way as to minimize technical and cost uncertainty.

The President also approved an implementation plan to carry out this policy. The plan extends technology development until early 1993 to reduce technical and cost risks. It retains an experimental flight vehicle focused on research and technology objectives and retains a joint program management structure with participation by both the Department of Defense and NASA.

The Space Council recommendations approved by the President termed the National AeroSpace Plane a vital national effort which benefits the civil, commercial, and national security interests of the nation. The NASP program promotes industrial competitiveness, fosters U.S. space leadership, and provides the technological basis for greatly expanded access to space in the 21st century. We call on Congress to join in fully implementing the Space Council recommendations and in moving forward with the important NASP program.



Government

DARPA
NASA
- Langley
- Lewis
- Ames
- Dryden

Air Force – AFSC
Navy
- NAVAIR
- ONR
- SPAWAR

SDIO
National Institute of Standards and Technology
and many others

Universities/research laboratories

Argonne National Lab
Los Alamos National Lab
University of California/SB
Carnegie–Mellon University
Harvard University
University of Illinois
Johns Hopkins University/APL
University of New Mexico
State University of New York
North Carolina State University
University of Pittsburgh
Stanford University
University of Texas
Virginia Polytechnic Inst.
University of Wisconsin
and many others

Industry

Aerojet Techsystems
Air Products
Alcoa
American Cyanamid
Astech Inc.
Astronautics Inc.
Avco
Boeing
Calspan
CVI
Directed Technologies
Dupont Aerospace
Dupont Chemical
Englehard Chemical
Garrett Airesearch
General Applied Science
General Dynamics
General Electric
Gould
Kentron
Lockheed
Martin Marietta
Marquardt
McDonnell Douglas
Minneapolis Honeywell
Pratt & Whitney
Rockwell International
SAIC
Sikorsky
Sundstrand
Union Carbide/Linde
UTC Energy Systems
UTC Research Center
Virginia Research Inc.
and many others

Figure 3. The truly national scope of the National AeroSpace Plane program is evident from the extensive list of program participants. (Reprinted from Ref. 3.)

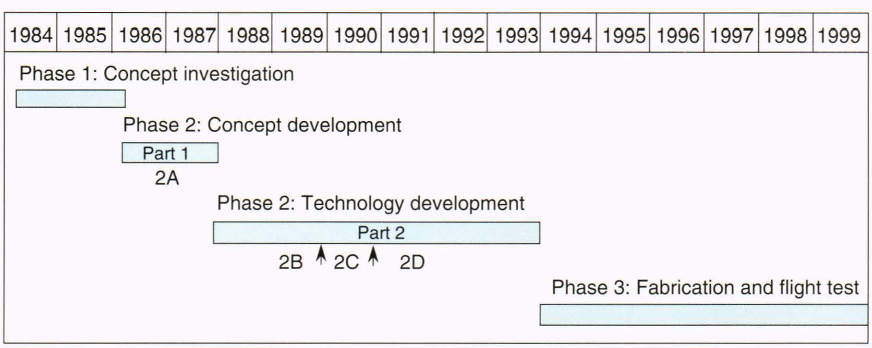


Figure 4. The National AeroSpace Plane program schedule. The airframe contractors are General Dynamics, McDonnell Douglas, and Rockwell. The engine contractors are Pratt & Whitney and Rocketdyne.

THE APL ROLE

The Laboratory contributes to the NASP National Team as the equivalent of a government laboratory supported directly by the NASP Joint Program Office. The Laboratory's role in the program is a direct outgrowth of the nearly forty years of experience in development of advanced ramjet and scramjet propulsion systems, including activity in the first aerospace plane program conducted in the 1960s (see Gilreath[4] and the article by Keirsey in this issue).

The Laboratory's contributions to the NASP program are focused on the development of the X-30's airbreathing engines and can be categorized into three distinct areas, as shown in Figure 5. First, APL researchers are responsible for the execution of experimental test programs that contribute directly to the development of propulsion-related technology for the X-30. These test programs were originally performed under the auspices of the generic TMP in the competitive program phases, Phases 2A through 2C. The TMP was the mechanism through which all of the government and government-affiliated laboratories participated in X-30 technology development before the formation of the National Team. Although this technology was generic so as to prevent the government effort from providing an unfair competitive advantage to any of the industry participants, many significant technical accomplishments were achieved. In Phase 2D, critical path Laboratory technology contributions are accomplished through GWP's.

The technology tasks conducted by APL in the TMP fell under the purview of the High-Speed Propulsion Team and are listed in Figure 6. Two tasks were conducted to address critical technology issues in the area of high-speed inlets. A high-speed inlet test program was conducted to investigate and develop advanced techniques for accurately determining inlet performance in the short run times associated with many hypersonic wind tunnels,

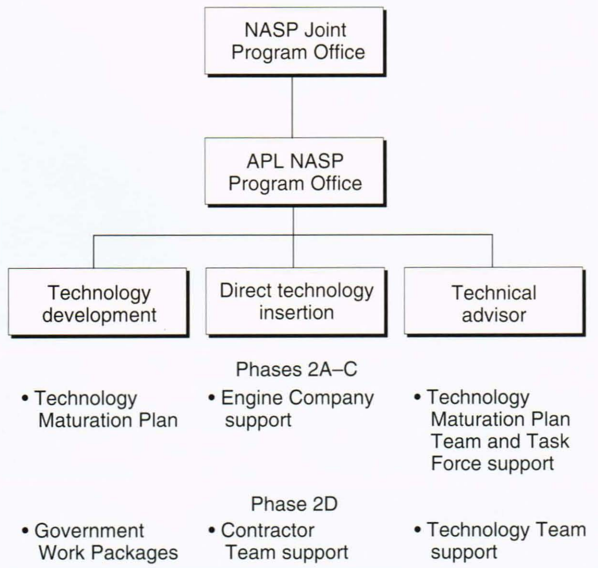


Figure 5. The APL roles in the National AeroSpace Plane program can be categorized into three major areas.

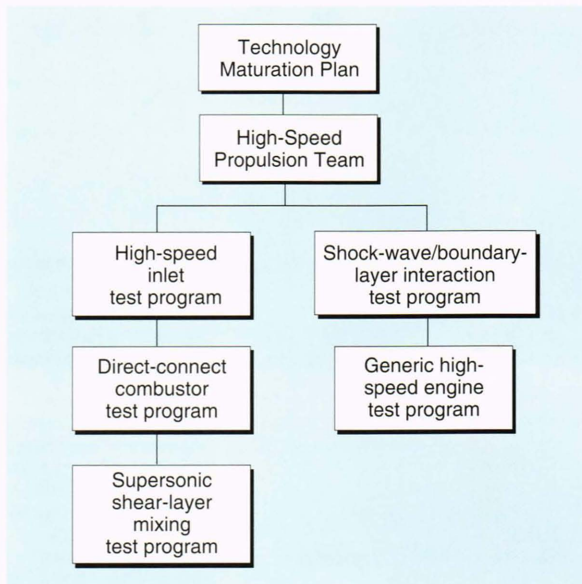
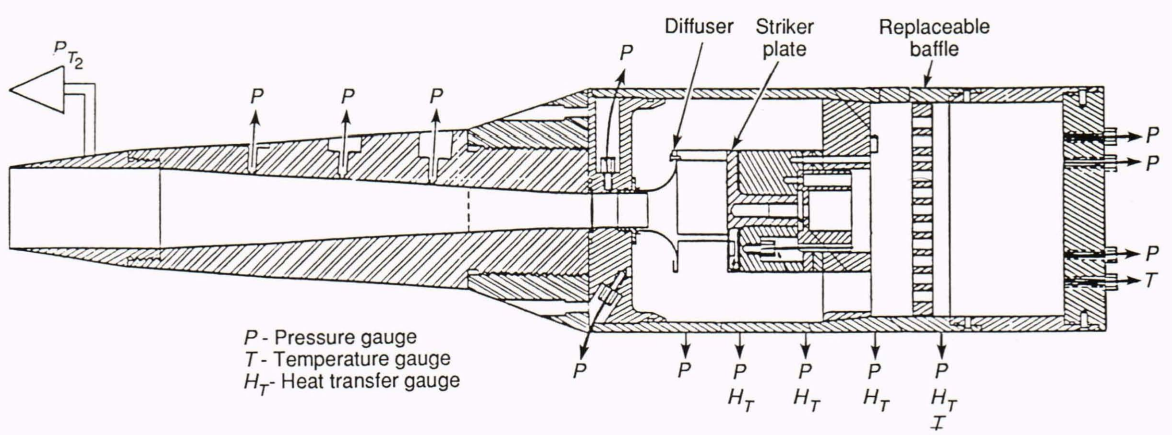


Figure 6. Summary of the Technology Maturation Plan tasks performed by APL.



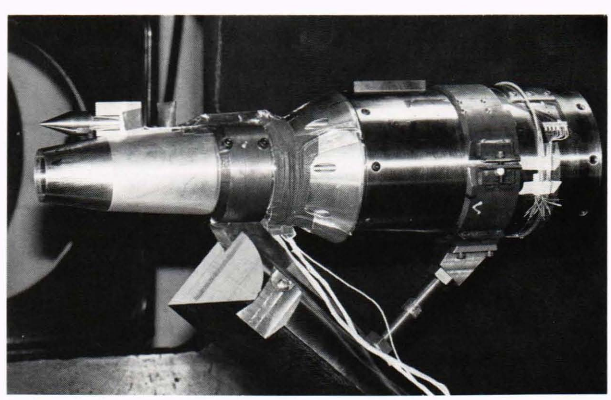


Figure 7. This inlet model was tested to demonstrate the viability of using the plenum filling technique for measuring inlet mass capture in a short-duration facility. (Reprinted from Ref. 6.)

and to use those techniques to evaluate the high–Mach-number operability and performance characteristics of X-30 inlet concepts. Methods were developed for measuring inlet air capture in hypersonic facilities with run times of several milliseconds using a plenum filling technique[5] (Fig. 7) and for determining inlet kinetic energy efficiency using a drag balance technique (Fig. 8). Also, a database was established characterizing the effects of leading-edge bluntness, boundary-layer transition, and internal shock structure on inlet performance and operability at Mach numbers above 10 in a test program funded jointly by NASP and the Air Force Generic Hypersonics Program.[6]

A shock-wave/boundary-layer interaction test program was conducted to characterize those interactions associated with high-speed inlets and to develop techniques to delay the onset of any resultant boundary-layer separation. The application of this technology would provide important information to help in the development of inlet designs, which have a reduced likelihood of those interactions adversely affecting performance and operability. To this end, several test programs were conducted that demonstrated the viability of using tangential mass addition of a supersonic airstream to energize the boundary layer entering an interaction region, eliminating or delaying the onset of boundary-layer separation.[7] In addition, an extensive database was developed to characterize the effects of an expansion corner on hypersonic shock-wave/boundary-layer interactions using the model shown in Figure 9, and to characterize the development of turbulent and transitional hypersonic boundary layers exposed to adverse pressure gradients typical of the X-30 forebody compression.

Three major test programs were undertaken in the area of high-speed combustors. The growth of supersonic shear layers characteristic of axial scramjet fuel injection for high–Mach-number flight conditions was investigated in two separate test programs. A fundamental test program was conducted at the APL Avery Propulsion Research Laboratory (APRL), in which the growth rate of a planar shear layer was characterized for parallel supersonic streams of Mach 3 and Mach 1, and Mach 2 and Mach 1 (Fig. 10).[8] Also, researchers at the Naval Weapons Center/China Lake investigated the use of innovative injector geometries for passive enhancement of shear-layer mixing rates.[9]

To investigate the fundamental operating characteristics of a dual-mode scramjet combustor, a large-scale, direct-connect test program was conducted in APRL Test Cell 1 (Fig. 11). A hydrogen–air combustion heater with oxygen replenishment was used to generate conditions simulating flight Mach numbers from Mach 6 to Mach 8. Some of the important technical contributions made as a result of this test program include the demonstration of the effectiveness of fuel staging in delaying combustor/inlet interactions, the confirmation of the viability of using a constant-area isolator duct to stabilize a precombustion shock system, and the simultaneous application of calorimetry and measurement of thrust to obtain a consistent prediction of combustor performance. In addition, a test series was conducted that successfully demonstrated the unique APRL capability to apply computerized facility controls to enable a dynamic variation of the inflow enthalpy during a test, thus providing the only NASP program data on transition from dual-mode ramjet operation to scramjet operation.[10] To extend this database to higher flight speeds, development of a similar direct-connect scramjet combustor rig was initiated for tests at simulated Mach numbers from 8 to 12. This rig utilizes a flow-path geometry similar to that tested at APRL but takes advantage of the 100-MW arcjet at the NASA Ames Research Center to generate the required high-enthalpy flow conditions. No tests were conducted under TMP, although this task was continued as a GWP, and the initial tests began in February 1992.

To develop a database on a more complete engine flow path, two engine module test programs were planned. One was a semi–direct-connect engine test program designed to characterize the performance of an APL-designed, generic engine at intermediate Mach numbers (Fig. 12). Tests were conducted at Mach numbers of 4.3 and 5.0 in the Combustion-Heated Scramjet Test Facility at the NASA Langley Research Center. Task accomplishments include demonstration of strut fuel injectors as

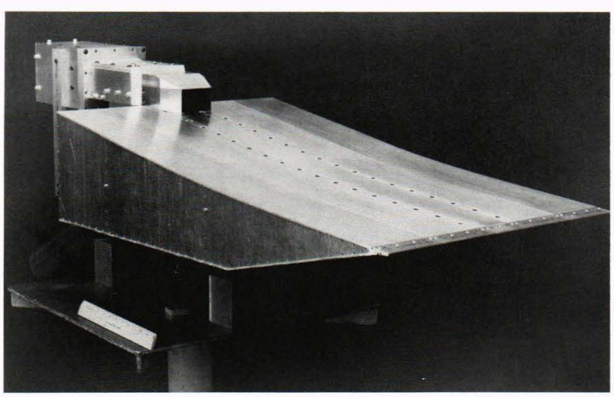


Figure 8. This inlet model was developed to demonstrate the viability of using a force balance for measuring inlet drag and, thereby, determining inlet performance. (Reprinted from Ref. 6.)

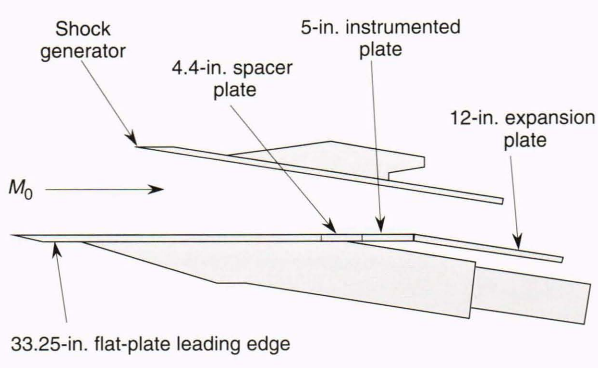


Figure 9. The model shown was used to generate data on the effects of an expansion corner on the interaction of an oblique shock wave and a turbulent boundary layer in hypersonic flow. M_0, the tunnel free-stream Mach number, was 11.5.

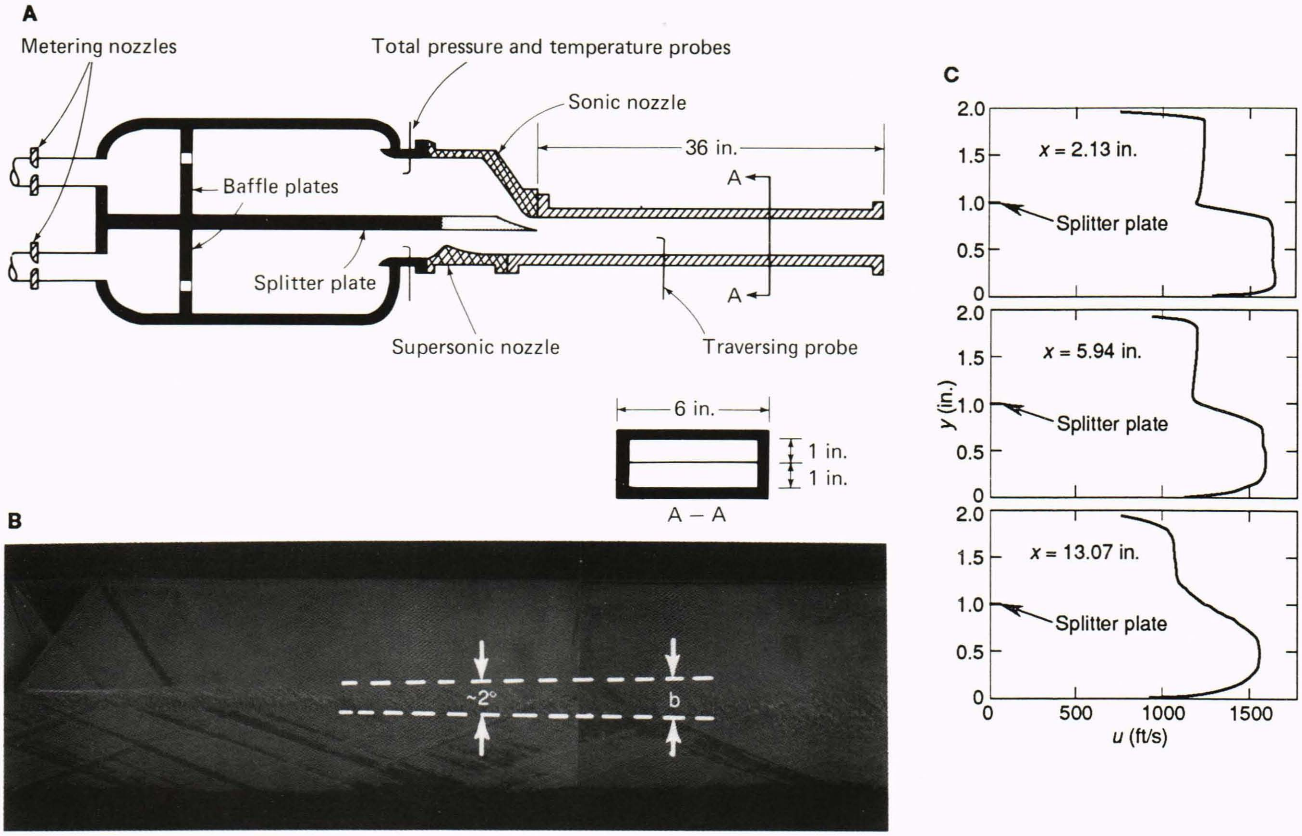


Figure 10. Fundamental data on high-speed mixing were gathered using the supersonic shear-layer mixing rig developed at APL's Avery Propulsion Research Laboratory. **A.** Schematic of the rig. **B.** Schlieren photograph of a shear layer between supersonic streams with matched static pressures. **C.** Shear-layer velocity profiles at various axial locations.

effective isolators, demonstration of high combustion efficiency at moderate fuel equivalence ratios, and documentation of the ineffectiveness of hydrogen film cooling for protection of the combustor walls in this operating regime.[11,12] The second test program was to have been a large-scale, semi-freejet engine test in the NASA Lewis Supersonic Wind Tunnels and the NASA Langley High-Temperature Tunnel to demonstrate the performance and operability characteristics of the APL engine over the Mach 0 to 8 flight regime. This test program was scheduled to begin late in 1989; in a September 1988 review, however, the risk was viewed as being too high, and the program was terminated by the program office. An engine test program of comparable scope will not be run in Phase 2, even with the three-year program stretch-out, and this author believes that this was truly a missed opportunity for the program.

Starting with initiation of Phase 2D and the formation of the National Team, the generic TMP program was completed. The APL technology development activities, like those of all other government and government-affiliated laboratories, were either brought to completion or changed to focus directly on the X-30 vehicle development through GWP's. These packages are highly integrated with the Industry Work Packages and with the GWP's at other government laboratories to form the core Phase 2D NASP technology program. The GWP's in which APL plays a major role are all related to the engine flow path and are listed in Figure 13. These test programs are an integral part of Phase 2D, and they, in many cases, provide the only program data in their respective areas upon which to base a decision to proceed with Phase 3.

The Laboratory is responsible for conducting the high-speed inlet test program designed to provide the X-30 inlet performance and operability characteristics at Mach numbers from 10 to 18. A two-entry test program is scheduled to be conducted in Hypervelocity Wind Tunnel No. 9 at the Naval Surface Warfare Center. The first entry was made in January 1992, and the second entry will be made with an updated design in mid-1993. The principal objectives of this test program are to assess the hypersonic performance of the X-30 inlet at both on-design and off-design operating conditions, to determine the hypersonic operability limits, to measure inlet unstart loads, to investigate inlet operation at speeds above the inlet design point, and to determine inlet throat flow profiles entering the combustor. Wright Laboratories, Rose Engineering, the NASA Langley Research Center, and the Contractor Team are all providing computational support for this inlet test program.

The high-enthalpy (Mach 8–12), direct-connect combustor test program initiated under TMP evolved into a GWP. A three-month test program is in progress in the Direct-Connect Arcjet Facility being developed at the NASA Ames Research Center for scramjet combustor testing at simulated Mach numbers between 8 and 12.

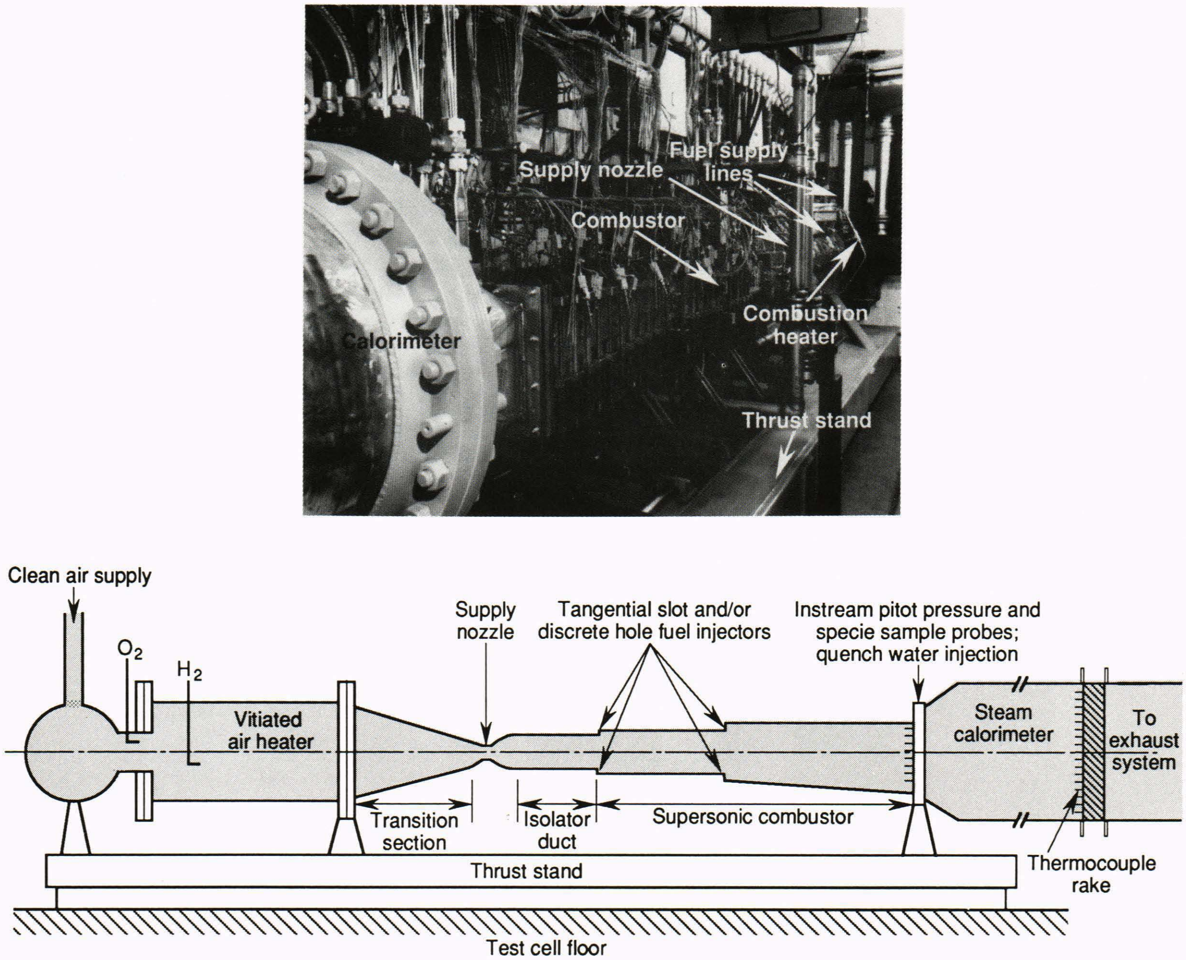


Figure 11. The direct-connect scramjet combustor rig developed for the National AeroSpace Plane program at APL's Avery Propulsion Research Laboratory.

The Laboratory is responsible for the technical direction of the test program and for developing and integrating the scramjet combustor hardware, and NASA Ames is responsible for development and operation of the Direct-Connect Arcjet Facility. The combustor hardware to be tested in the facility is geometrically similar to combustor hardware tested at Mach 6 and 8 at APRL and at Mach 9 in the Calspan 96-in. Shock Tunnel. The GWP data will be the first long-duration NASP combustor data above Mach 8 providing an opportunity to validate short-duration combustor test results (all of the NASP combustor test data obtained thus far above Mach 8 have been in pulse facilities like the Calspan 96-in. Shock Tunnel with test times of about 2-ms or less); compare test data generated in combustion-heated air (like that used in the APRL test program) with that generated using arc-heated air at Mach 8; and generate the first direct-connect Mach 12 combustor database and, thereby, verify test techniques and combustor design philosophies developed and used at lower Mach numbers. Once operational, the Direct-Connect Arcjet Facility will also be well suited for testing alternative combustor and fuel injector geometries, and for conducting materials tests and investigating cooling concepts in a high–heat-flux oxidizing environment.

External burning is currently being considered for use on the X-30 as a drag-reduction mechanism in the subsonic and transonic flight regime. All test data obtained thus far have been for model scales that are relatively small compared with the X-30. The Laboratory is responsible for a GWP test program that focuses on providing a database on external-burning scale effects by testing a large-scale model in the 16T Transonic Wind Tunnel at the Arnold Engineering and Development Center. In addition to scaling, one of the major issues related to the existing external-burning database concerns the potential of tunnel interference effects. To address this issue, a two-part F/A-18 flight test program was conducted in cooperation with the Naval Air Test Center and with assistance from NASA's Lewis, Ames, and Langley Research Centers[13] (Fig. 14). Finally, APL is a participating laboratory in a GWP that is a combined effort, led by NASA Langley, to investigate the effects of boundary-layer relaminarization and film injection on reducing the shear and heat loss in the nozzle at high Mach numbers.

The second category of participation (refer to Fig. 5) for the APL NASP Team is in the direct transfer of APL propulsion technology to the Contractor Team's X-30 technology activity. The distinction between this area and

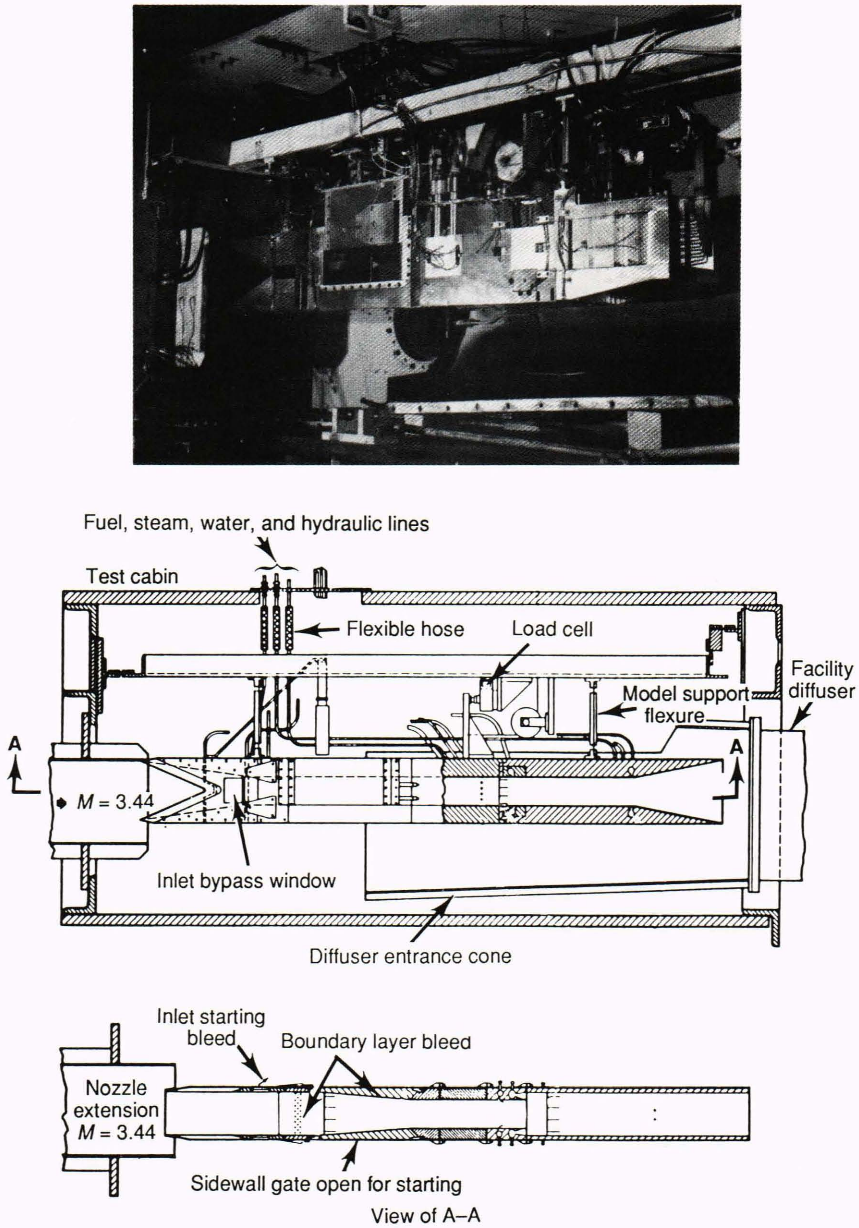


Figure 12. The generic high-speed engine B1. It was tested in the NASA Langley Combustion-Heated Scramjet Test Facility.

the Tech Mat or GWP technology area is that the principal responsibility for development of the individual technologies lies with the Contractor Team. The Laboratory is tasked by the Joint Program Office to provide the Contractor Team with expertise, as appropriate, to enhance its technology development effort. This role originated early in Phase 2 when APL was tasked by the Joint Program Office to identify and evaluate critical propulsion-related technology issues and develop innovative concepts for addressing these issues. Headed by Frederick Billig, a team of APL researchers compiled an assessment of the then-current state of technology for the design, analysis, and testing of mixed-cycle propulsion systems and identified key propulsion-related technical issues. The results of this assessment, along with a proposed analytical and experimental test program to address the identified technical issues, were presented in a publication widely referred to as the *APL Bluebook*. This publication presented two baseline generic engine designs, provided parametric performance estimates for, and an assessment of, vehicle mass fraction requirements for SSTO flight, presented an engine test philosophy, described available computational codes and test facilities, and presented a plan for applying both computation and experiment to an engine technology development plan. With the technology presented in the *APL Bluebook* as a basis, a considerable amount of effort was focused on evolving those generic engine designs into a more in-depth propulsion concept to address the need to have an optimized, highly efficient propulsion flow path over the entire X-30 flight envelope. The result was an APL generic engine concept that incorporated innovative design features. Although at the time, the APL generic engine concept was a significant departure from the concepts being developed by the various engine contractors, the current X-30 engine design has evolved to incorporate many of the innovative features put forth in this concept.

Using the generic engine concept as a basis for focusing the activity, the APL Team set out to identify and address critical propulsion-related technological issues. Two of the major technological barriers identified in proving the viability of the scramjet as an engine for high–Mach-number flight continue to be the ability to get adequate fuel–air mixing with a minimal increase in drag, and the demonstration of combustor wall survivability in light of the enormous global and local heat transfer rates that are inevitable. To address these issues, an effort was initiated to develop a better understanding of the fundamental processes that control the shear-layer mixing between two supersonic streams (i.e., a hydrogen fuel injector that tangentially injects fuel at a supersonic Mach number into a supersonic air stream). Complementing the work carried out in TMP, researchers at APL, The University of Washington, and Virginia Polytechnic Institute and State University planned and conducted a program consisting of both experiment and computational analysis. Ideas were developed, and sometimes tested, for innovative fuel injectors that have the potential to provide both improved mixing and adequate thermal protection for the combustor wall, but still inject all, or nearly all, of the fuel tangentially to utilize the critical thrust increment available from the fuel momentum.[14]

To improve the volumetric efficiency of the vehicle, concepts for using alternative fuels were also developed. Some of the fuel concepts investigated ranged from the relatively straightforward use of a hydrocarbon for powering the engines up to Mach 3, to the use of metallized hydrogen slurries that significantly increased the fuel density with very little, if any, decrease in fuel heating value (energy potential).

Additionally, considerable effort was focused on the enhancement of engineering analytical tools for the dual-mode ramjet engine cycle. Examples of this effort include the early application of CFD codes to investigate the effects of fundamental hypersonic flow phenomena such as equilibrium and nonequilibrium air chemistry, cold walls, and boundary-layer transition on engine cycle performance; the development of a fast "decoding" algorithm to greatly increase the speed at which CFD codes calculate steady flows in chemical equilibrium;[15] the modification and application of the APL-developed ramjet performance analysis code to engine design and experimental data

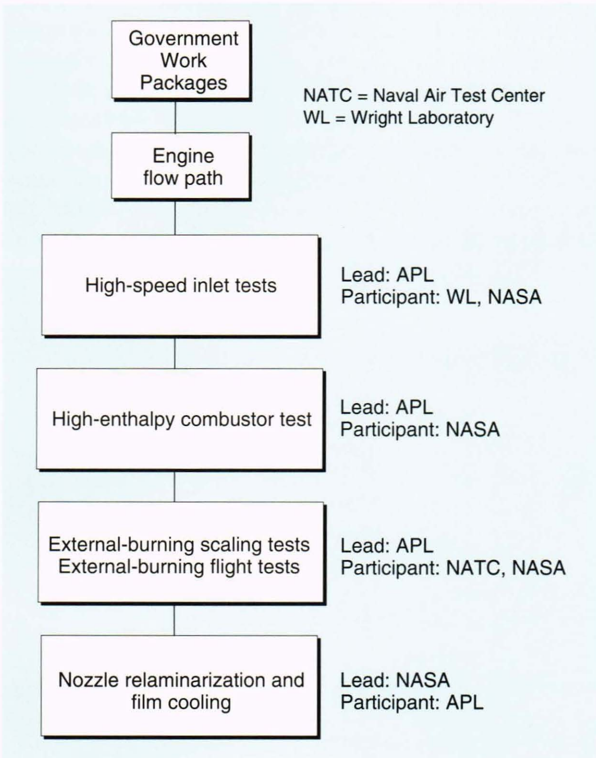


Figure 13. Summary of the National AeroSpace Plane Government Work Packages in which APL is either a lead or a contributing laboratory.

Figure 14. A flight test demonstration of external burning in a transonic airstream was performed on a Naval Air Test Center F/A-18.

interpretation;[16] and the development and application of an empirical model for predicting inlet-combustor isolator requirements for dual-mode ramjet operation.[17]

As the NASP program progressed, but before the formation of the National Team, the Joint Program Office wanted to focus the previously generic APL technology activity more toward the X-30 engine concepts being developed by the prime contractors; concern was expressed, however, as to whether this could be done while competition still existed. To provide a mechanism to accommodate this focus of technology, the Laboratory agreed to assign a senior engineer to each of the competing engine companies (Rocketdyne and Pratt & Whitney) and allow each engineer to be the conduit by which the Laboratory's technology reached the respective contractor activity. The proprietary information was protected by greatly limiting the exposure that each engineer had to the other company's activity. This transfer of APL technology directly to the contractors proved to be successful and has continued through Phase 2D both at APL and now at other government laboratories. The APL Phase 2D effort in this area is focusing on developing a better understanding of shock-wave/boundary-layer interactions in the X-30 inlet; on developing a better understanding of specific X-30 requirements for isolation between the inlet and the combustor; and on supporting inlet, combustor, and nozzle test programs led by the Contractor Team.

The third way in which APL contributes to the NASP program (refer to Fig. 5) is through participation on technology teams sponsored by the NASP Joint Program Office. These teams were established early in Phase 2 as a mechanism by which the technical experts at the various government and government-affiliated laboratories reviewed and coordinated the various technological disciplines. One set of teams participated in the evaluation of the competing contractor concepts, which was accomplished through quarterly technical reviews held at the prime contractor sites. This process provided the technical evaluations that led to the eventual selection of two engine companies (the engine concept review) and three airframe companies (the airframe concept review), and that were to lead to the planned subsequent engine and airframe selection. This final selection was replaced by the formation of the National Team. The second set of teams, called the Tech Mat Teams, was responsible for formulating and tracking the technology plan through which the government laboratories did their technological work within Tech Mat. A major technological issue identified by a Tech Mat Team would be addressed through the establishment of a technology task force. At the end of Phase 2C, transition of the government technology activities into focused work packages and the creation of the National Team resulted in the complementary focusing of the technology team activities. The result was the establishment of a single technology team in each major technical discipline. These teams consist of members from both the Contractor Team and the Government Team, and are responsible for developing, tracking, and oftentimes conducting the technology and design activities in their particular discipline. The Laboratory currently participates on the Inlet Technology, Combustor Evaluation, Nozzle Technology, CFD Technology, and Phase 3 Planning Teams. A summary of the various teams that APL has supported throughout the NASP program is presented in the boxed insert.

SUMMARY

The NASP program is a highly ambitious national effort to develop the requisite technologies for an SSTO flight vehicle and to demonstrate those technologies through the fabrication and flight test of two X-30 aircraft. By applying expertise gained during more than four decades of advanced ramjet and scramjet propulsion technology development, a team of researchers at APL has made, and continues to make, major contributions to the NASP program. These contributions have been made through the conduct of experimental programs in the TMP, through GWP's, through direct technical support of technology development by the Contractor Team, and through participation on numerous technical teams and in technical task force activities.

APL SUPPORT OF NASP TECHNOLOGY TEAMS

PHASES 2A–2C

- Inlet Evaluation Team
- Combustor Evaluation Team
- Nozzle Evaluation Team
- High-Speed Propulsion Team
- Low-Speed Propulsion Team
- CFD Team
- Shock/Boundary-Layer Interaction Task Force
- Inlet Task Force
- Nozzle Task Force
- CFD Validation Task Force
- Film-Cooling Task Force

PHASE 2D

- CFD Technology Team
- Inlet Technology Team
- Combustor Technology Team
- Nozzle Technology Team
- Phase 3 Planning Team

CFD = computational fluid dynamics

REFERENCES

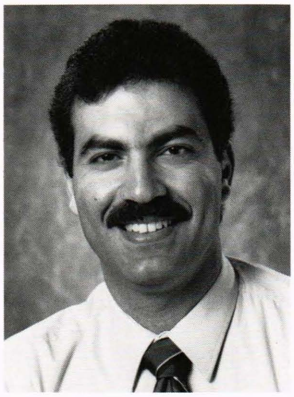
1. *National AeroSpace Plane—A Technology Development and Demonstration Program to Build the X-30*, GAO/NSIAD-88-122 (Apr 1988).
2. *Aerospace Plane Technology—Research and Development Efforts in Europe*, GAO/NSIAD-91-194 (Jul 1991).
3. Barthelemy, R. R., "The National AeroSpace Plane Program: A Revolutionary Concept," *Johns Hopkins APL Tech. Dig.* **11**(3&4), 312–318 (1990).
4. Gilreath, H. E., "The Beginning of Hypersonic Ramjet Research at APL," *Johns Hopkins APL Tech. Dig.* **11**(3&4), 319–335 (1990).
5. Van Wie, D. M., Corpening, G. P., Mattes, L. A., Molder, S., and McGregor, R., *An Experimental Technique for the Measurement of Mass Flow of Scramjet Inlets Tested in Hypersonic Pulse Facilities*, AIAA Paper 89-2331, American Institute of Aeronautics and Astronautics, New York (1989).
6. Van Wie, D. M., White, M. E., and Corpening, G. P., "NASP Inlet Design and Testing Issues," *Johns Hopkins APL Tech. Dig.* **11**(3&4), 353–362 (1990).
7. White, M. E., Lee, R. E., Thompson, M. W., Carpenter, A., and Yanta, W. J., "Tangential Mass Addition for the Control of Shock Wave/Boundary Layer Interactions," in *Proc. 9th International Symposium on Air Breathing Engines*, Athens, Greece (1989).

[8]Gilreath, H. E., and Sullins, G. A., "Investigation of the Mixing of Parallel Supersonic Streams," in *Proc. 9th ISABE Meeting*, Athens, Greece (1989).
[9]Schadow, K. C., Gutmark, E., and Wilson, K. J., *Passive Mixing Control in Supersonic Coaxial Jets at Different Convective Mach Numbers*, AIAA Paper 89-0995, American Institute of Aeronautics and Astronautics, New York (Mar 1989).
[10]Sullins, G. A., Carpenter, D. A., Thompson, M. W., Kwok, F. T., and Mattes, L. A., *A Demonstration of Mode Transition in a Scramjet Combustor*, AIAA Paper 91-2395, American Institute of Aeronautics and Astronautics, New York (Jun 1991).
[11]Bement, D. A., Stevens, J. R., and Thompson, M.W., *Performance Evaluation of Semi-Freejet Tests of the Generic High Speed Engine*, AIAA Paper 91-2163, American Institute of Aeronautics and Astronautics, New York (Jun 1991).
[12]Bement, D. A, Stevens, J. R., and Thompson, M. W., *Measured Operating Characteristics of a Rectangular Combustor/Inlet Isolator*, AIAA Paper 90-2221, American Institute of Aeronautics and Astronautics, New York (16 Jul 1990).
[13]Yungkurth, C. B., Corda, S., Dawson, F., Houck, S., and Trefney, C. J., *The F/A-18 External Burning Flight Test*, AIAA Paper 91-5050, American Institute of Aeronautics and Astronautics, New York (Dec 1991).
[14]King, P. S., Thomas, R. H., Schetz, J. A., and Billig, F. S., *Combined Tangential-Normal Injection into a Supersonic Flow*, AIAA Paper 89-0622, American Institute of Aeronautics and Astronautics, New York (Jan 1989).
[15]Friedman, M. A., Hunter, L. W., and Kuttler, J. R., "The Decoding Problem in Chemically Reacting Flow," *APL Tech. Rev.* (limited distribution) **2**(1), 89–99 (1990).
[16]Pandolfini, P. P., *Instructions for Using Ramjet Performance Analysis (RJPA) IBM-PC Version 1.0*, JHU/APL NASP-86-2, The Johns Hopkins University Applied Physics Laboratory, Laurel, Md. (Nov 1986).
[17]Billig, F. S., Corda, S., and Pandolfini, P. P., *Design Techniques for Dual Mode Ram-Scramjet Combustors*, Paper No. 23, AGARD 75th Symposium on Hypersonic Combined Cycle Propulsion (1990).

ACKNOWLEDGMENT: The author would like to acknowledge the highly talented team of people who have contributed to APL's NASP activities outlined in this article. Although there are far too many team contributors to mention individually, the author would be remiss not to acknowledge the contributions of Frederick S. Billig, who has provided much of the spirit and technical foundation for the APL NASP effort. The reader is encouraged to consult the references to learn more about the significant technical accomplishments of APL's NASP team and the long APL history of technical accomplishments in advanced airbreathing propulsion.

The APL NASP effort has been sponsored through the NASP Joint Program Office, Wright Patterson Air Force Base, Ohio. The author would like to acknowledge the following people: Edward S. Gravlin, Navy Deputy Director, for his enthusiastic overall support of APL contributions to NASP, Curtis D. Snyder, Deputy for GWP flow path integration, for his support of APL GWP's; William Imfeld, Joint Program Office Director for Engineering, for his support of APL technical advisory efforts; and Don Stull, TMP High-Speed Propulsion Team Leader, for his support of our TMP activities.

THE AUTHOR



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